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ORIGINAL ARTICLE

Effect of soil amendments on soil respiration in the midland agroecological environment, Ethiopia

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Abstract

The effects of soil amendments on soil respiration (SR) rate have not yet been fully evaluated. In the Upper Blue Nile Basin, Ethiopia, we investigated seasonal variations in SR rates between and within soil amendments. We set up 24 plots with 8 treatments—polyacrylamide (PAM), gypsum (G), biochar (B), lime (L), control (C), PAM + L, PAM + G, and PAM + B—in 3 replicates. Soil temperature, moisture, and SR data were collected monthly. Data were evaluated by paired *t*-test and nonparametric repeated-measures ANOVA. The SR rates were significantly lower ($P < 0.05$) in PAM + B (3.43 ± 0.55 μmol m^{-2} s^{-1}) than in B (4.23 ± 0.61 CO_2 μmol m^{-2} s^{-1}) and PAM + L (4.14 ± 0.57 μmol m^{-2} s^{-1}). The SR rate differed significantly in all plots between the wet and dry seasons. The relationships between SR rate and soil properties were not significant, although there was a non-significant positive association with soil organic carbon, total nitrogen, soil pH, and clay content. There was a significant ($P < 0.01$) association between soil moisture and SR in all treatments. PAM + B offers a practical means of enhancing carbon storage efficiency. Comprehensive studies should be conducted in a variety of agroecological settings to determine optimal techniques to reduce SR emissions.

Keywords Semi-arid · Biochar · Soil moisture · Polyacrylamide · Upper Blue Nile basin

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Introduction

Land degradation leading to soil erosion reduces agricultural production and threatens food security worldwide (Powlson et al. 2011). In Ethiopia, large-scale soil erosion has occurred as population growth has turned forests, pastures, and even hillsides into farmland without sustainable management. Soil erosion is a major problem in many parts of Ethiopia (Haregeweyn et al. 2015). The eastern and northern regions of the Ethiopian Highlands suffer significant damage through land degradation (Hurni 1988; Shiferaw 2011). Other potential contributing factors are the increased use of steep slopes for agricultural purposes and reduced vegetation cover (Amede et al. 2001); biophysical factors (Hurni et al. 2010); conversion of natural ecosystems to cultivated ecosystems (Seyoum 2016); anthropogenic factors (Nyssen et al. 2007); and increasing influence on resources (Guyassa and Raj 2013). National soil erosion rates are estimated at up to 220 t ha^{-1} y^{-1}, with a mean of 37 t ha^{-1} y^{-1} (Tamene et al. 2022). Soil loss reduces agricultural productivity by depleting soil nutrients, robbing large amounts of soil organic matter (SOM), and altering soil properties (Haileslassie et al. 2006).

A number of soil amendment approaches have been tested and used to avert soil erosion in Ethiopia and elsewhere (Mamedov et al. 2021; Mulualem et al. 2021, 2022; Awad et al. 2012; Kebede et al. 2022; Albalasmeh et al. 2021; Asghari et al. 2011). Polyacrylamide (PAM), biochar (B), lime (L), and gypsum (G) are common amendments used to modify soil properties in order to reduce soil erosion. PAM stabilizes soil aggregates and improves cohesiveness (Mamedov et al. 2021), reduces soil nutrient depletion, and increases nutrient utilization (Mulualem et al. 2022). As a result, CO_2 emissions are reduced (Awad et al. 2012). In acidic soils, the use of PAM with biochar and lime increased the yield of teff (Mulualem et al. 2021). PAM is more effective than other soil additives in improving the physical quality of sandy loam soils (Albalasmeh et al. 2021; Asghari et al. 2011). The addition of PAM increased water infiltration and decreased soil erosion (Kebede et al. 2022; Sojka and Entry 2000), and it promoted the growth and survival of some fungal and bacterial species that bind soil aggregates (Caesar-Tonthat et al. 2008).

Lime is often used to reduce soil acidity; applying lime alone or in combination with other additives such as gypsum is a viable way to improve soil health and crop yield (Bossolani et al. 2020). Biochar improves soil quality (Smith et al. 2010). It improved the properties of heavily weathered soil and reduced soil loss (Jien and Wang 2013). Chen et al. (2018) detailed its long-term effects on soil physiochemical properties. One long-term benefit may be reducing additional carbon (C) mineralization in compost (Jien et al. 2015). Using biochar to improve soil moisture and nutrient retention is beneficial for plant growth (Sales et al. 2022).

Soil amendments can increase crop yield (Aina et al. 2018). The improvement of SOM is one of the best management strategies for ensuring soil sustainability in subtropical and tropical regions (Jien et al. 2015). Organic fertilizers improve the content of microbial biomass, the content of SOM, the structure of microbial communities, and the activity of enzymes involved in the degradation of OM (Nett et al. 2012). Organic additives improve soil nutrient status and chemical properties (Angelova et al. 2013). Cow dung solids can improve soil physical and chemical properties (Loper et al. 2010). The co-use of organic fertilizers with mineral fertilizers increases crop yields, reduces mineral fertilizer consumption, and conserves soil resources (Bayu et al. 2006).

Soil respiration (SR) is the major mechanism of C exchange between the soil surface and the atmosphere (Sheng et al. 2010) and largely determines C accumulation in ecosystems. SR is an important indicator of soil fertility and a measure of soil quality (Staben et al. 1997). Good land management reduces CO_2 emissions (Abegaz et al. 2020; Lemma et al. 2021), mitigates climate change (Mekonnen and Getahun 2020), and increases soil organic carbon (SOC) content. The type and proportion of applied OM additives (Ray et al. 2020) and SOC distribution (Menichetti et al. 2013) have the greatest influence on soil respiration. Compared with OM alone and OM + gypsum, gypsum alone reduced cumulative respiration within the top 5 cm of soil (Wong et al. 2009). The addition of digestive-rich organic additives to the soil improved microbial richness and respiration (Holatko et al. 2021). Biochar reduces heterotrophic soil respiration by enhancing recalcitrant fraction of carbon (Li et al. 2018). Therefore, understanding the regulation of SR is important, as small changes in SR rates can have large effects on atmospheric CO_2 emissions and soil C sequestration (Bowden et al. 2004). Furthermore, understanding the sensitivity of the terrestrial C cycle to climate change requires knowledge of the mechanisms that control the release of CO_2 from the soil via SR to the atmosphere (Savage et al. 2008). However, to the best of our knowledge, the effect of soil modification on SR rates has not been adequately assessed in Ethiopia. Hence, soil respiration study on soil amendments could inspire different institutions to provide various options for reducing carbon emissions by implementing amendments practices in different land uses and enhancing carbon sequestration in the soil. This study was designed to identify optimal soil amendments that minimize SR and increase SOC storage. The objectives were: (1) to assess differences in SR rates between soil amendments; (2) to evaluate SR rates between the wet and dry seasons; and (3) to pinpoint soil-related and environmental factors (soil moisture and temperature) that contribute to SR.

Materials and methods

Study site

The study was conducted in the Aba Gerima catchment (11° 38′ 0″–11° 40′ 30″ N, 37° 29′ 30″–37° 31′ 0″), Bahir Dar Zuri District, which was chosen as representative of the midland agroecological zone of the Upper Blue Nile basin, northwestern Ethiopia (Fig. 1).

We collected climate data from the Ethiopian National Meteorological Agency station in Bahir Dar spanning 21 years, 2000 to 2020. The average annual rainfall in the study area was 1486 mm, and the average monthly temperature ranged from 18 to 23 °C (Fig. 2). The main rainy season (growing season) starts in June and ends in September (Mihretie et al. 2021). According to FAO's soil classification system (2006), Leptosols are the predominant soil type here (Getahun 2016). Teff (*Eragrostis tef* (Zucc.) Trotter), finger millet (*Eleusine coracana* Gaertn.), maize (*Zea mays* L.),

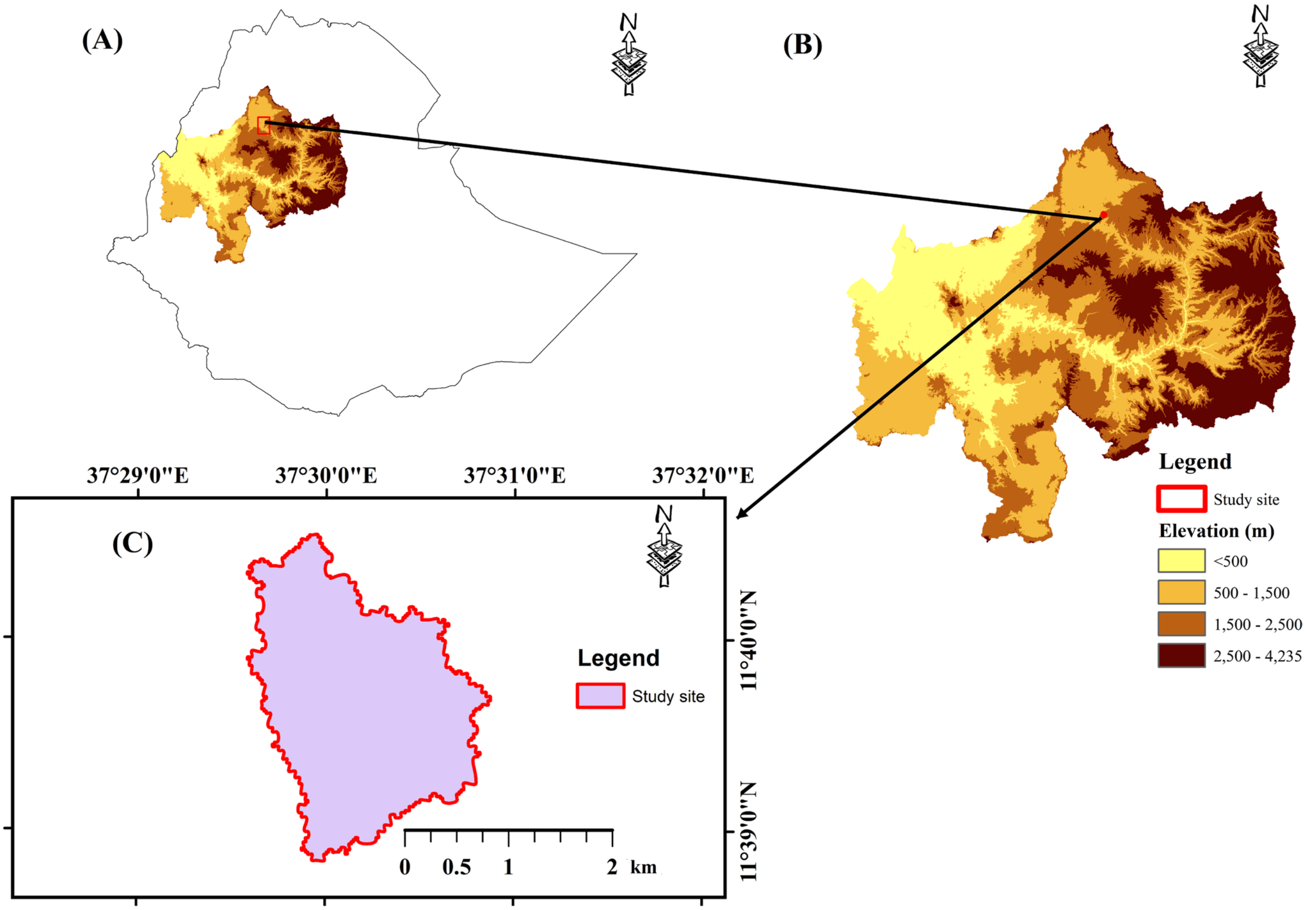

Fig. 1 The study site in **A** Ethiopia, **B** Upper Blue Nile basin, and **C** Aba Gerima watershed

and lupin (*Lupinus albus* L.) are the most commonly grown crops (Ebabu et al. 2019).

Setup of experimental plots

We used 8 treatments—control (C), gypsum (G), biochar (B), lime (L), polyacrylamide (PAM), PAM + B, PAM + G, and PAM + L—with 3 replications in a randomized complete block design with 24 plots. We used lime ($CaCO_3$) with 98% neutralizing value for the experiment. We did not analyze the purity of gypsum due to lack of finance and time. The source of Gypsum and lime was from local distributers or suppliers. JICA (Japan international cooperation agency) imported anionic PAM from Japan. It comprised, by weight, 50%, 22%, 20% and 8% of C, O, N and H, respectively. Biochar was made from wood charcoal from stem and branches of *Acacia decurrens*. An *acacia decurrens* with a diameter of 0.1–0.2 m were cut in different sizes for burning, arranged on soil (0.5–1 m height, 2–3 m diameter), and were set on fire for burning. The pile was covered by a layer of corn debris, and soil to avoid complete burning of biomass into ash. The burning process took on 3–5 days on average. The pyrolysis temperature for preparation of biochar was 400–450 °C as described by Geng et al. (2022). After burning this, the charcoal was taken out and manually crushed and sieved to get uniform sizes (< 4 mm diameter) by mixing the biochar before application on experimental plots. For the study, we used blocking to minimize the effect of slope differences among the treatments. The average slope for experimental plots was 10% for experimental site (Mulualem et al. 2021). The size of the plot was 1.3 m width by 4.5 m length (5.85 m^2). The perimeter of each plot was bordered by a 0.35 m metal sheet, of which 0.15 m was inserted into the ground to delineate nutrients from plot surroundings. Runoff trenches with trapezoidal cross-sections (2.5 m length and 1 m width on the upper, 1.5 m length and 0.5 m width on the foot, and 0.6 m deep) were dug beneath each plot and lined with a geo-membrane plastic sheet to avoid water loss by infiltration. In 2018, we applied PAM $(CH_2{=}CH{-}CONH_2)_n$ at 40 kg ha^{-1}, biochar at 8 t ha^{-1}, gypsum ($CaSO_4{\cdot}2H_2O$) at 5 t ha^{-1}, and lime ($CaCO_3$) at 4 t ha^{-1}. In 2019, we reapplied only PAM at 20 kg ha^{-1}. The experimental field was hoed and the full rates of all amendments except PAM were broadcasted manually 20–25 days before sowing (July) and

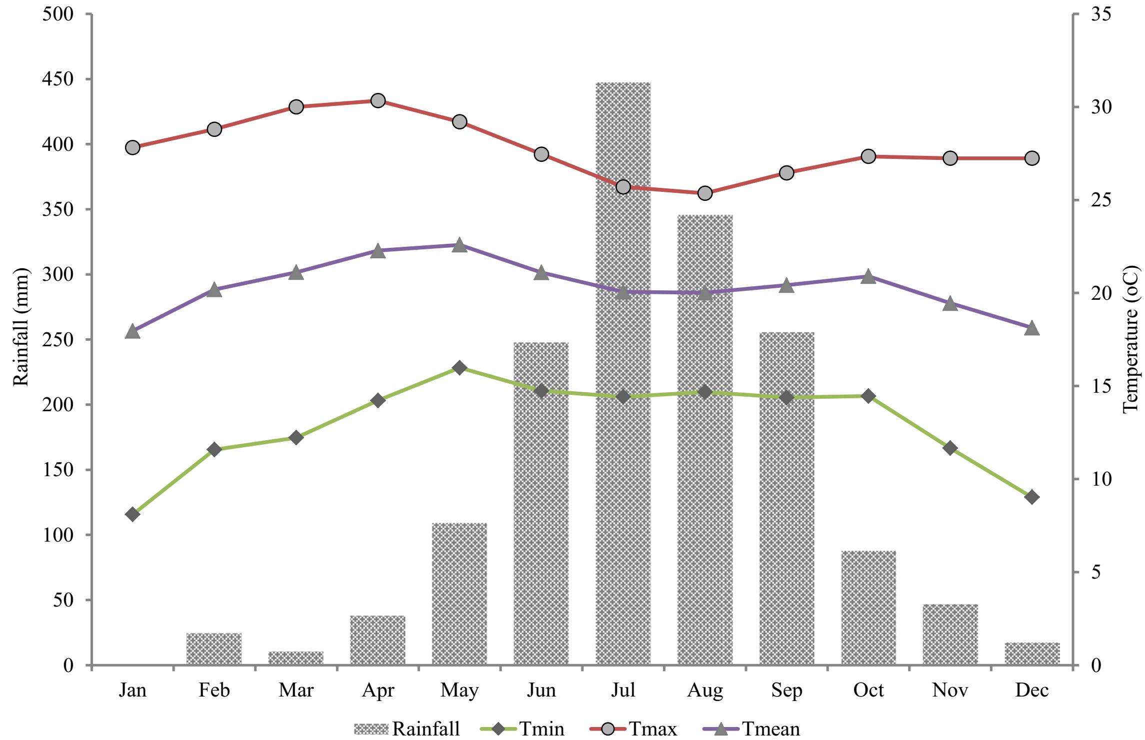

Fig. 2 Rainfall and temperature distribution in the study area

immediately mixed into the upper 0.15–0.20 m of the soil in the first year of the experiment (2018), whereas the granular (solid) PAM was applied to the soil surface (0.3–0.5 m) by hand in two applications, half at the start of the rainy season (i.e., 20–25 days before sowing) and the other half immediately after teff sowing in both study seasons. Moreover, in 2019 we applied only PAM by half rate. The ratings values were chosen from the literature (Kebede et al. 2020; Mulualem et al. 2021). The test plots were hand-plowed 3 times a year: during the dry season (May), at the beginning of the wet season (June), and at the end of July, when the teff was sown. During the test period, all plots were planted with teff, which is the most important staple crop in Ethiopia (Hunegnaw et al. 2021), even though it is low-yielding, unprofitable, and resource-intensive (Mihretie et al. 2022).

SR measurement and data collection

Data on SR, soil moisture, and soil temperature were collected from October 2019 to August 2021, with interruption from April to August 2020 due to COVID-19. Later, we started data collection on September 2020 until August 2021. Our interest was to compare two years soil respiration data however; due to interruption we analyzed the merged soil respiration data. SR was measured monthly in each test plot (Liang et al. 2019; Powers et al. 2018; Xiao et al. 2021). A PVC pipe collar (19 cm diameter, 11 cm height) was carefully inserted 5 cm into the soil in each plot (Fekadu, et al. 2023a, b, c). Soil respiration data were collected between 09:00 and 12:00 on rainless mornings (Fekadu et al. 2023a, b, c; Jiang et al. 2013; Sheng et al. 2010). SR was measured for 90 s (Table 1), and the average SR of 90 readings for each collar was used.

Soil sampling and analysis

Soil sampling was collected at 0–20 cm soil depth from each experimental plot using hand auger. For every experimental

Table 1 Parameters and methods of soil analysis or tools used

Parameter	Method or instrument
Available P	Sodium bicarbonate method (Olsen et al. 1954)
Organic C and total N	CN Corder (Macro Corder JM1000CN, J-Science Lab, Kyoto, Japan)
pH (1:2.5 soil:water)	Peech (1965)
Soil bulk density	Core sample method, oven-dried at 105 °C for 24 h
Texture	Hydrometer method (Bouyoucos 1962)
Soil respiration	LI-8100 automated soil CO_2 flux system (LI-8100, LI-COR, Lincoln, NE, USA)
Soil moisture (M_S)	Gravimetric method
Soil temperature (T_S)	Omega probe 6000-09TC (LI-COR)

plot, we collected four samples in north, south, east and west direction of the experimental plot, and later we mixed four soil samples of the experimental plot and took 200 g soil for further physico-chemical analysis. The time for soil sampling data collection was after crop harvest in February 2020. Soil samples were air-dried at room temperature, ground, and sieved through a 2-mm sieve for soil physical and chemical analyses (Table 1). All plots had a clay-loam soil texture (Table 2).

Statistical analysis

One-way ANOVA was used to assess the effects of soil amendments on soil properties. Tukey's HSD test at $P<0.05$ was used to detect significant differences between mean values of soil properties in several comparative tests between treatments in experiments. SR data were not normally distributed, so they were analyzed by the nonparametric Friedman's test, followed by Wilcoxon's post hoc analysis to isolate means with $P<0.05$. Significance values for some tests were adjusted by Bonferroni's correction. A paired *t*-test analysis was used to determine the significance of differences between seasons (wet and dry) among treatments. Pearson's correlation analysis was used to assess the relationships of SR with soil properties, soil temperature, and soil moisture (Gomez and Gomez 1983).

Results and discussion

Effects of soil amendments on soil respiration

The amendments altered the soil physico-chemical properties. PAM + L increased soil pH by (6.05 ± 0.09) relative to the control (5.35 ± 0.10; Table 2), and soil pH was significantly higher ($P<0.01$) in PAM + L than in other plots (C, G, PAM and PAM + G). This is due to the lime, which increases the Ca^{2+} content at cation exchange sites, where H^{+} can be displaced. Lime application is well known to increase soil pH. Dissolution of lime significantly reduced exchangeable Al^{3+} and increased exchangeable Ca^{2+} (Li et al. 2018). Liming generally creates a more favorable environment for microbial activity and can lead to the net mineralization of organic forms of P (Ameyu 2019).

Available phosphorus (P_{av}) was lowest in the gypsum-treated plots (G) and highest in PAM + B (Table 2). P_{av} was significantly higher ($P<0.001$) in PAM + B than in G only. The elevated P_{av} was associated with the improvement in soil pH (Table 2; $r=0.75$**; Table 5), and the decreased loss of P_{av} increased P_{av} in PAM + B. Our results are supported by similar studies (Li et al. 2019; Mulualem et al. 2021) showing that soil amendment with B and PAM reduces runoff, sedimentation, and washout, and that PAM improves soil cohesion and water-holding capacity (Mulualem et al. 2021). Furthermore, the PAM + B and B plots had significantly higher SOC concentrations ($P<0.001$) than the control (C) and G plots. Biochar alters soil microbial abundance, activity, and community structure (Hardy et al. 2019), enhancing SOM degradation and SOC levels. Increased SR by microorganisms is thought to promote SOM degradation and improve soil fertility (Anjum and Khan 2021). Sorption to biochar-mediated aggregates is one of the most important reasons for the stabilization of SOC. A study in a maize field in the Central Plains of China showed that biochar additives increased SOC (Zhang et al. 2012).

However, TN, soil bulk density (SBD), and sand, silt, and clay contents did not change significantly among soil amendments during the study (Table 2). In contrast, Abdulrahman

Table 2 Physico-chemical properties (mean ± SE) of topsoil samples (0–20 cm): all are clay loam

Amendment	$P_{av\ (ppm)}$	SOC (%)	TN (%)	pH (H_2O) 1:2.5	BD (g cm^{-3})	Clay (%)	Sand (%)	Silt (%)
B	13.5 ± 0.41^{ab}	1.84 ± 0.04^{a}	0.16 ± 0.01	5.89 ± 0.03^{abcd}	1.29 ± 0.03	36 ± 2.67	32 ± 1.65	32 ± 1.46
C	10.5 ± 0.96^{ab}	1.51 ± 0.04^{b}	0.14 ± 0.01	5.35 ± 0.10^{cd}	1.30 ± 0.03	37 ± 1.76	31 ± 1.65	32 ± 1.46
G	8.6 ± 0.32^{b}	1.52 ± 0.04^{b}	0.14 ± 0.01	5.28 ± 0.04^{d}	1.31 ± 0.03	34 ± 1.76	33 ± 1.65	33 ± 1.46
L	15.1 ± 0.56^{ab}	1.64 ± 0.04^{ab}	0.15 ± 0.01	5.91 ± .06^{abc}	1.29 ± 0.03	35 ± 3.06	33 ± 1.65	32 ± 1.46
PAM	13.1 ± 0.12^{ab}	1.62 ± 0.04^{ab}	0.14 ± 0.01	5.38 ± .08^{bcd}	1.24 ± 0.03	35 ± 1.15	31 ± 1.65	34 ± 1.46
PAM + B	16.3 ± 1.14^{a}	1.87 ± 0.04^{a}	0.16 ± 0.01	6.00 ± 0.19^{ab}	1.23 ± 0.03	36 ± 0.67	30 ± 1.65	34 ± 1.46
PAM + G	10.2 ± 0.90^{ab}	1.59 ± 0.04^{ab}	0.15 ± 0.01	5.34 ± 0.04^{cd}	1.25 ± 0.03	35 ± 2.96	31 ± 1.65	34 ± 1.46
PAM + L	14.3 ± 1.11^{ab}	1.66 ± 0.04^{ab}	0.15 ± 0.01	6.05 ± 0.09^{a}	1.23 ± 0.03	35 ± 1.15	31 ± 1.65	34 ± 1.46
P value	***	***	ns	**	ns	ns	ns	ns

Treatment levels within a column that doesn't share the same letters are significantly different

ns non-significant, *B* biochar, *C* control, *G* Gypsum, *L* lime, *PAM* Polyacrylamide, P_{av} available phosphorus, *SOC* soil organic carbon, *TN* Total nitrogen, *BD* bulk density, ($n=3$)

**, ***Indicate the ANOVA *p* value is significant at $P<0.01$, and $P<0.001$, respectively, by Tukey test et al. (2020) showed that B and PAM had a significant effect on SBD.

Paired *t*-test analysis comparing treatments with the control revealed a significantly increased mean SR in B, L, and PAM + L only (Table 3). These increases may be related to the improvement of pH, P_{av}, and SOC (Table 2). Improvement of soil property could have direct impact on soil microbial population. As soil property improved in the soil, the microbial activate for decomposition of soil organic matter becomes faster. This ultimately enhances soil respiration. Various studies have reported the function of soil amendments on soil properties; biochar affects soil physical and chemical properties (Chintala et al. 2013; Gross et al. 2021; Kookana et al. 2011; Layek et al. 2022; Li et al. 2017; Nigussie et al. 2012). Polyacrylamide and biochar also improve properties of soil (Alkhasha et al. 2018). PAM alone improves the structural stability of the soil (Mamedov et al. 2021). Biochar and lime improve the characteristics of acidic soils (Wu et al. 2020). Increased inputs of TN and SOC from the soil substrate were associated with an increase in SR (Wang et al. 2013).

Friedman's ANOVA revealed a significant difference ($\chi^2 = 28.86$, d.f. = 7, $P = 0.0003$) in the effects of soil amendments on SR (Table 4). Soil respiration was significantly less in PAM + B (3.43 ± 0.55 μmol m^{-2} s^{-1}) than in B (4.23 ± 0.61 CO_2 μmol m^{-2} s^{-1}) and PAM + L (4.14 ± 0.57 μmol m^{-2} s^{-1}; $P < 0.05$; Table 4). The reason could be due to the addition of soil amendments in the soil mainly polyacrimide and biochar. Our study is supported by Awad et al. (2017) who studied that, PAM + B inhibits microbial biomass C and reduces plant residue decomposition. Biochar reduces the organic C mineralization rate (Geng et al. 2022). PAM + B could be an excellent tool to reduce soil loss (Lee et al. 2015). The SOC (mean ± SE) was slightly higher in PAM + B (1.87 ± 0.04) than in B (1.84 ± 0.04) and PAM + L (1.66 ± 0.04), though statistically not significant (Table 2). PAM + B similarly increased SOM (Abulaiti et al. 2022). The addition of PAM and B improved soil properties (Alkhasha et al. 2018), mainly because PAM significantly improves soil cohesion without increasing the rate of decomposition (Awad et al. 2013), and B significantly increases soil C sequestration and SOM (Hua et al. 2014). On the other hand, Awad et al. (2016) found that B and PAM, both individually and in combination, had no significant effect on total CO_2 emissions owing to their very slow rates of decomposition. Using B alone as a soil amendment increased SR (Li et al. 2021) and soil CO_2 production (Smith et al. 2010). Biochar addition improved soil microbial abundance, soil enzyme activity, community structure, and microbial biomass C (Hardy et al. 2019; Oladele 2019; Zhang et al. 2014). However, Šlapáková et al. (2018) found that it did not increase SR.

SR was significantly higher in PAM + L than in PAM + B (Table 4). The reason could be related to change in soil pH. Addition of lime may enhance the microbial activity and then soil respiration in the soil. As soil pH increases until optimum (5.5–6.5), more CO_2 is released into the atmosphere owing to increased soil microbial activity (Yusnaini et al. 2021). Liming increased the contribution of respiration to total C loss (Andersson and Valeur 1994). Lime in the soil is principally added to reduce soil pH (Mulualem et al. 2021). Moreover, addition of lime in the soil

Table 3 Paired *t*-test analysis of soil respiration between control and each soil amendment

No	Amendment	CO_2 flux (μmol m^{-2} s^{-1})	*P* value (*n* = 18)
1	C	3.60^b	0.0361
	B	4.19^a	
2	C	3.60^a	0.3931
	G	3.94^a	
3	C	3.60^b	0.0472
	L	4.20^a	
4	C	3.60^a	0.6008
	PAM	3.47^a	
5	C	3.60^a	0.3839
	PAM + B	3.38^a	
6	C	3.60^a	0.7338
	PAM + G	3.72^a	
7	C	3.60^b	0.0067
	PAM + L	4.09^a	

Different letters in the same column for paired treatments indicated significant difference at $P < 0.05$. See the section "Setup of experimental plots" for treatment codes

Table 4 ANOVA results of soil respiration in different soil amendments

Soil amendment	Min	Median	Max	Mean ± SE	MR
	CO_2 flux (μmol m^{-2} s^{-1})				
C	0.59	1.69	16.01	3.64 ± 0.54	4.57^{ab}
B	0.40	2.06	17.04	4.23 ± 0.61	5.88^a
G	0.45	1.87	21.97	4.00 ± 0.66	4.53^{ab}
L	0.34	2.09	21.39	4.23 ± 0.67	5.11^{ab}
PAM	0.40	1.86	14.60	3.53 ± 0.53	4.46^{ab}
PAM + B	0.42	1.94	14.99	3.43 ± 0.55	3.79^b
PAM + G	0.31	2.41	14.83	3.70 ± 0.44	5.33^{ab}
PAM + L	0.70	2.39	19.52	4.14 ± 0.57	5.93^a
χ^2	28.86				
d.f	7				
P-value	0.0003				

Treatment levels with the same letter within a column are not significantly different at $P < 0.05$ ($n = 18$). *SE* standard error of the mean, *MR* mean rank. See the section "Setup of experimental plots" for treatment codes is a soil-forming process which involves the deposition and accumulation of calcium carbonate in soil, resulting in hardening of the soil. Among long-term no-till soils, limed soils had a higher SR and greater microbial C biomass than unlimed soils, attributed to the higher soil pH (Fuentes et al. 2006), which may increase soil turnover and organic mineralization (Rowley et al. 2018).

SR in each amendment in dry and wet seasons

We compared SR between the rainy season (June–August) and the dry season (December–February). Means differed significantly between seasons in all plots (Fig. 3). This seasonal difference in SR may be due to that in soil moisture. In all plots, soil moisture was significantly higher ($P < 0.05$) during the wet season, and soil temperature was significantly higher ($P < 0.05$) during the dry season (Fig. S1). This suggests that at our study site, soil moisture limits SR more than soil temperature does, especially during the dry season. Hashimoto et al. (2004) similarly reported that SR is higher during the rainy season. In addition, changes in soil moisture affect the activity of soil microbes (Orchard and Cook 1983).

The effect of soil moisture on SR can be assessed seasonally to represent environmental changes affecting their interaction (Jeong et al. 2018). In general, SR increases as soil moisture increases. Soil moisture was significantly correlated with SR, soil enzymes, and microbial biomass C (Tomar and Baishya 2020). Emissions in the wet season are significantly higher than those in the dry season owing to improved hydrothermal conditions, which are more favorable for soil microbes and the survival of plant roots (Cui et al. 2020; Orchard and Cook 1983; Rodtassana et al. 2021; Tomar and Baishya 2020). Boonriam et al. (2021) reported that SR in the rainy season is double that in the dry season in Thailand. Here, during the dry season, SR was similar among treatments (Fig. 3). Lacking enough water, drier soils cannot use available energy substrates (Orchard and Cook 1983).

Factors contributing to SR in various treatments

The rate of CO_2 release from the soil is used as a measure of microbial activity (Orchard and Cook 1983). It is determined mainly by the soil and by environmental parameters such as soil moisture and soil temperature. We found no significant correlation ($P > 0.05$) of SR with any soil property. However, we found positive associations ($P > 0.05$) with clay content ($r = 0.21$), soil pH ($r = 0.05$), TN ($r = 0.12$), and SOC ($r = 0.02$; Table 5).

Soil moisture was significantly ($P < 0.01$) related to SR in all treatments. The coefficients of the correlation between SR and soil moisture ranged from 0.42 to 0.64 (Table S1). Li et al. (2021) similarly showed that SR was positively correlated with soil moisture. Microbial respiration is linearly related to soil moisture (Cook and Orchard 2008). The influence of soil moisture on estimating SR in semi-arid habitats has also been reported (Meena et al. 2020).

There was no association with soil temperature during the dry season, but the daily variation of SR was positively correlated with that of soil temperature during the rainy season (Adachi et al. 2009). Soil temperature was significantly negatively correlated with SR in all plots (Table S1). Soil moisture but not soil temperature determines the incidence of SR (Hashimoto et al. 2004). In our case, soil moisture

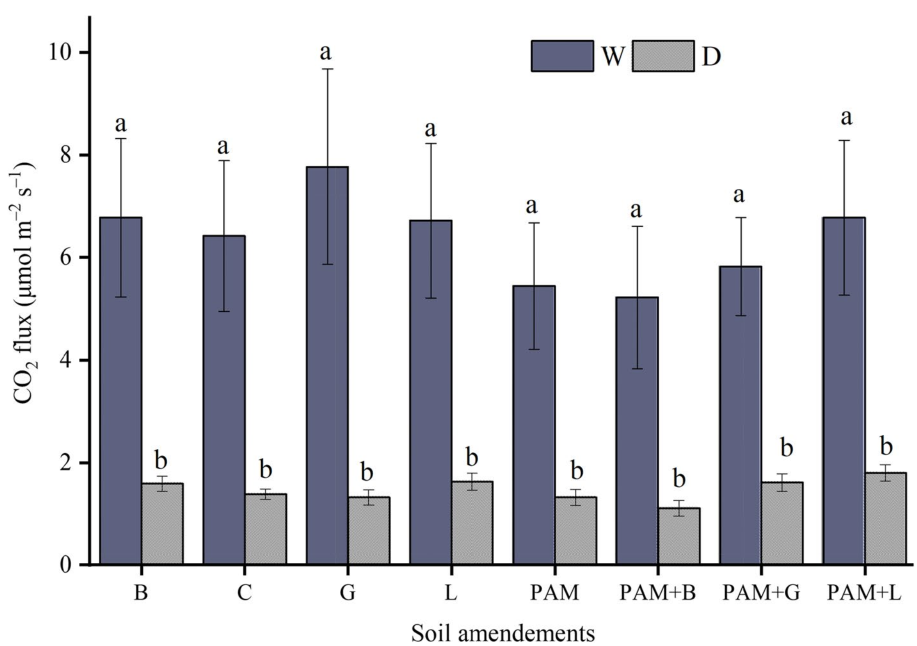

Fig. 3 Pairwise comparison of SR (mean ± SE) between wet (W) and dry (D) seasons within treatments. Paired treatments with the different letters in the bars are significantly different at $P < 0.05$

Table 5 Pearson's correlations of soil respiration with soil factors

	SR	P_{av}	SOC	TN	pH	SBD	Sand	Silt	Clay
SR	1								
P_{av}	−0.095 ns	1							
SOC	0.015 ns	0.600**	1						
TN	0.118 ns	0.296 ns	0.498**	1					
pH	0.051 ns	0.745**	0.568**	0.486*	1				
SBD	−0.065 ns	−0.235 ns	−0.279 ns	−0.357 ns	−0.117 ns	1			
Sand	0.048 ns	−0.016 ns	−0.224 ns	−0.315 ns	−0.076 ns	0.377 ns	1		
Silt	−0.329 ns	−0.018 ns	0.099 ns	0.155 ns	0.043 ns	0.282 ns	−0.297 ns	1	
Clay	0.211 ns	0.029 ns	0.126 ns	0.165 ns	0.036 ns	−0.559**	−0.676**	−0.503**	1

SR soil respiration (μmol CO_2 m^{-2} s^{-1}), P_{av} available *P* (mg kg^{-1}), *SOC* soil organic C (%), *TN* total *N* (%), *SBD* soil bulk density (g cm^{-3}) , *ns* not significant ($n=3$)

*$P<0.05$, **$P<0.01$

played an important role in influencing the change in SR relative to soil temperature.

Conclusions

Applications of soil amendments will have positive impact for improving soil properties so as to increase crop production. The applied soil amendment practices contributed to soil respiration in different ways during the study period. Soil respiration was significantly lower ($P<0.05$) in PAM + B (3.43 ± 0.55 μmol m^{-2} s^{-1}) than in other treatments, including the controls, and was significantly higher ($P<0.05$) in B (4.23 ± 0.61 CO_2 μmol m^{-2} s^{-1}) and PAM + L (4.14 ± 0.57 μmol m^{-2} s^{-1}). Higher soil respiration values were observed in the wet season than in the dry season in all plots. This was mainly due to the influence of soil moisture effect on soil respiration. Since we focused on some soil amendments practices, further studies with different rates are required to assess the effect of soil amendments on soil respiration which is not yet studied to have more understanding on the relationship between soil respiration and soil amendments. More detailed studies are needed in a variety of agroecological settings to determine the best soil amendment methods that minimize CO_2 emissions.

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Author contributions Genetu Fekadu: conceptualization, methodology, data collection, writing–draft manuscript, review editing, and visualization. Enyew Adgo, Derege Tsegaye Meshesha, Nigussie Haregeweyn, Fei Peng, Atsushi Tsunekawa, and Mitsuru Tsubo: writing–review and editing, visualization, supervision, funding acquisition. Temesgen Mulualem, Simeneh Demissie, Birhanu Kebede and Gizachew Ayalew Tiruneh: writing–review and editing.

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Declarations

Conflict of interest The authors declare no competing interests.

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