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Environ Monit Assess (2023) 195:65
https://doi.org/10.1007/s10661-022-10705-5

Seasonal and diurnal soil respiration dynamics under different land management practices in the sub-tropical highland agroecology of Ethiopia

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Received: 3 July 2022 / Accepted: 25 October 2022

Abstract The temporal dynamics of soil respiration change in response to different land management practices are not well documented. This study investigated the effects of soil bunds on the monthly and diurnal dynamics of soil respiration rates in the highlands of the Upper Blue Nile basin in Ethiopia. Six plots (with and without soil bunds, three replicates) were used for measurement of seasonal soil respiration, and 18 plots were used for measurement of diurnal soil respiration. We collected seasonal variation data on a monthly basis from September 2020 to August 2021. Diurnal soil respiration data were collected four times daily (5 a.m., 11 a.m., 5 p.m., and 11 p.m.) for 2 weeks from 16 to 29 September 2021. A Wilcoxon signed-rank test showed that seasonal soil respiration rates differed significantly ($p<0.05$) between soil bund and control plots in all seasons. In plots with soil bunds, seasonal soil respiration rates were lowest in February (1.89 ± 0.3 μmol CO_2 m^{-2} s^{-1}, mean ± SE) and highest in October (14.54 ± 0.5 μmol CO_2 m^{-2} s^{-1}). The diurnal soil respiration rate was significantly ($p<0.05$) higher at 11 a.m. than at other times, and was lowest at 5 a.m. Seasonal variation in soil respiration was influenced by soil temperature negatively and moisture positively. Diurnal soil respiration was significantly affected by soil temperature but not by soil moisture. Further study is required to explore how differences in soil microorganisms between different land management practices affect soil respiration rates.

Keywords Drought-prone · Guder · Soil bund · Soil moisture · Soil temperature · Teff crop

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-022-10705-5.

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Published online: 03 November 2022

Introduction

According to Etsay et al. (2019), degradation of land has been a bottleneck to the development of African countries and lowers productivity in rural communities in Ethiopia (Molla & Sisheber, 2017). It is an urgent agenda that requires a lot of time and money to improve the problem (Jiru & Wegari, 2022). Between 2001 and 2012, global agriculture activities—particularly in tropical areas—increased soil erosion rates by 0.22 Mg ha^{-1} $year^{-1}$ (Hu et al., 2021). Soil loss has greatly reduced agricultural production during cropping seasons (Boardman et al., 2009), and it has forced farmers to turn forested areas into farmland in order to find additional cultivable lands (Philor & Daroub, 2011). The loss of top soil that supports the growth of crops has decreased biomass production in terrestrial ecosystems (Pimentel & Kounang, 1998) and caused losses of ecosystem services (Welemariam et al., 2018).

The effect of soil erosion has been strongest in cultivated areas of highland Ethiopia (Hurni et al., 2010). Moreover, the severity of soil erosion by water and associated driving factors in Ethiopia has been reported by (Bewket & Teferi, 2009; Girmay et al., 2020; Tamene & Vlek, 2008) in cultivated and grazing lands. Ethiopian soil loss is estimated to be 1.5 billion tons $year^{-1}$ (Tamene & Vlek, 2008). Haregeweyn et al. (2017) reported that approximately 27.5 t ha^{-1} $year^{-1}$ of soil is lost from the Upper Blue Nile Basin (UBNB) in Ethiopia.

In response to these problems and to improve crop productivity, different physical and biological management practices have been introduced in different parts of Ethiopia (Mekonen & Tesfahunegn, 2011). Conservation of natural resources is an essential feature of sustainable development (Ashoori et al., 2016). The soils of agro-ecosystems need to be protected through the application of effective conservation measures (Lal, 2020).

Previous research found that various land management practices reduced annual soil loss in Ethiopia (Engdayehu et al., 2016; Herweg & Ludi, 1999; Sultan et al., 2018). Soil and water conservation measures improve rain infiltration rates (Nyssen et al., 2015). Hishe et al. (2017) found that in northern Ethiopia, various measures such as bench terraces, soil bunds, stone bunds, check dams, trenches, area exclosures, and re-afforestation are important for soil erosion control and soil fertility conservation. Integrating soil bunds with fodder trees can improve soil physical and chemical properties (Tadesse et al., 2016). Adgo et al. (2013) reported that terracing contributes to food security and household income, thereby reducing poverty in the Anjenie catchment, Ethiopia. Soil bunds have been shown to have a substantial impact on many soil properties in Ethiopia (Ebabu et al., 2020; Husen et al., 2017). Soil organic matter retention was better in treated watersheds than in untreated watersheds (Getie et al., 2020). In addition to improving soil water content, soil bunds can be utilized to efficiently reduce surface runoff, sediment concentration in runoff water, and soil loss (Demissie et al., 2022).

Soil respiration, or CO_2 efflux, has been defined as the flux of carbon dioxide from soil surfaces to the atmosphere (Bond-Lamberty & Thomson, 2010; Xu & Shang, 2016). It is the main source of carbon emissions from terrestrial ecosystems to the atmosphere (Cui et al., 2020) and the second-largest carbon flux in ecosystems (Davidson et al., 2006). Bond-Lamberty and Thomson (2010) estimate that global soil respiration in 2008 was 98 ± 12 Pg C and that it increased by 0.1 Pg C $year^{-1}$ between 1989 and 2008. There are different factors contributing to soil respiration. The recent increase in global soil respiration rates is related to climate-related increases in the abundance of metabolically active soil microbes (Salazar et al., 2019). Land use is responsible for 25% of total anthropogenic greenhouse gas emissions (Paustian et al., 2016). Tillage also has a large impact on CO_2 emissions, with deeper tillage releasing more emissions (Carbonell-Bojollo et al., 2019). Soil microorganism biomass and edaphic conditions mostly explain the spatial inconsistency of soil respiration (Luo & Zhou, 2006). A study showed that the changes in soil surface temperature were mostly responsible for the variable soil respiration rate at different times of the day or during different seasons (Wang et al., 2018). Soil respiration is primarily controlled by the combination of soil temperature and moisture (Ming et al., 2014; Shi et al., 2014). The soil organic carbon content and pH of the soil, among other physical–chemical characteristics, are key factors in regulating soil respiration (Wang et al., 2018). Several investigations into soil respiration, both seasonal and diurnal, have been conducted (Cui et al., 2020; Deqiang et al., 2006; Fan et al., 2017; Liu et al., 2010; Meena et al., 2020; Ming et al., 2014; Song et al., 2021; Tang & Baldocchi, 2005; Wen et al., 2018). Greenhouse gas emissions are one of the top global issues that need great attention. However, no research has been done on how land management influences the seasonal and diurnal patterns of soil respiration in Ethiopia or in our study area specifically. Thus, soil respiration research on land management techniques could inspire different organizations to provide various solutions for reducing carbon emissions in managed areas and enhancing carbon storage. Our study's objectives were to (1) investigate the impact of soil bunds on soil respiration; (2) assess monthly patterns of soil respiration; and (3) examine diurnal fluctuations of soil respiration. We hypothesized that soil respiration would vary significantly between managed and control plots and on a monthly and daily basis in the study area.

Materials and methods

Study site

The research was carried out in the Guder watershed (10° 59′ 30″–11° 1′0″ N, 36° 54′ 0″–36° 56′ 0″ E, 2498–2857 m a.s.l., average 2590 m a.s.l.) in the UBNB, Ethiopia (Fig. 1), in the sub-tropical agro-ecological region's highlands. The soil in the experimental plot was a Malabon silty clay loam (Pachic Ultic Argixerolls) (Soil Survey Staff, 2014).

Temperature and precipitation data were obtained from Dangila and Enjibara meteorological stations, respectively. At Guder, the average yearly rainfall was 2394 mm, with a monthly temperature averaging 16–20 °C. The lowest temperatures ranged from 4.94 °C in January to 12.88 °C in June. Temperatures reached 21.98 °C in August and 28.72 °C in March (Fig. 2). The highest rainfall occurs in summer (June to Aug), and the lowest rainfall occurs in winter (Dec to Mar). Autumn

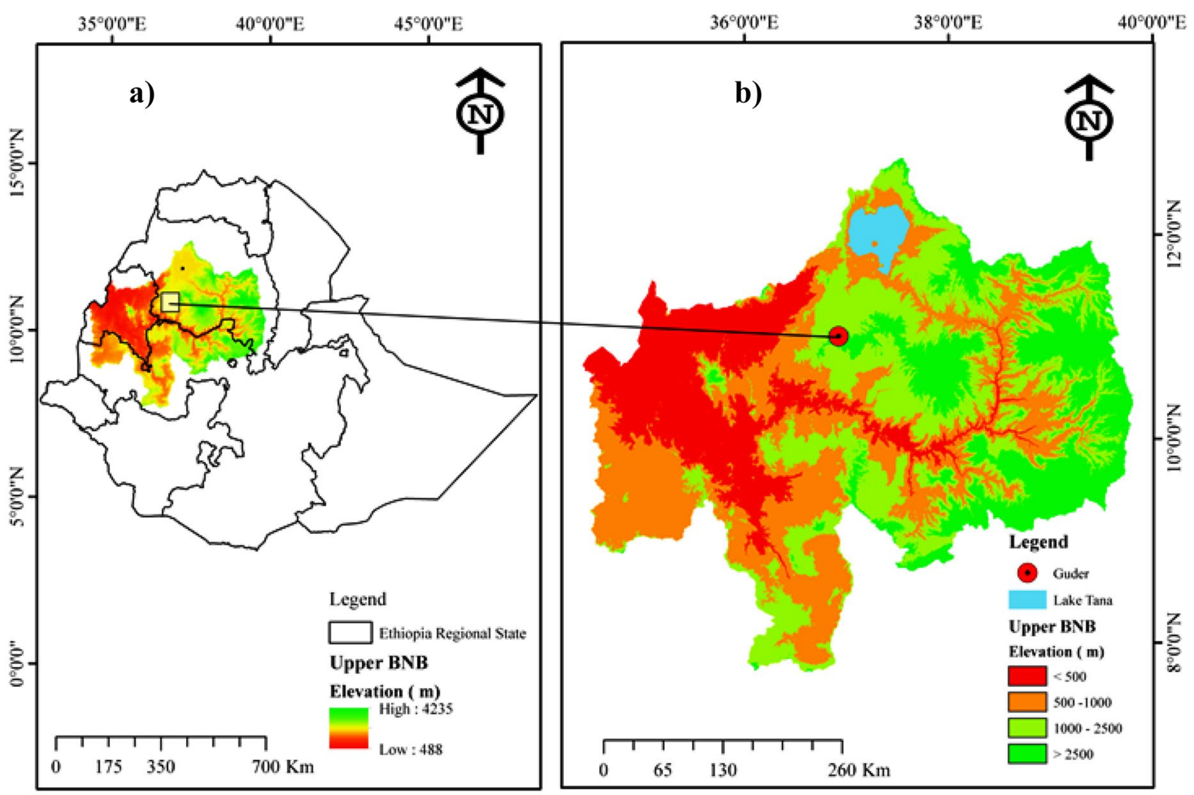

Fig. 1 The research experimental area: **a** Ethiopia; **b** UBNB

(Sept to Nov), when the soil is still moist, is the grain harvest season. In spring (Mar to May), the weather transitions from the dry season to the rainy season, with rains usually beginning in May. The research site's main crops are potato (*Solanum tuberosum*), teff (*Eragrostis tef*), barley (*Hordeum vulgare*), and wheat (*Triticum aestivum*). Natural forests (3.8%), grazing land (9.5%), bush land (17.5%), acacia plantations (30.1%), and farmland (39.1%) are the predominant land use types (Sultan et al., 2017).

Experimental plots

Soil bunds (SB), a common land management (LM) practice in the study watershed, were established in 2015 in an area with an average slope of 15%. The spacing between bunds was 5.5 m. The number of bunds in treated plots was three. The bund covered an area of 2133 m^2 ha^{-1}. We planted teff, the main crop in Guder (Mulualem et al., 2021) and the major food crop in Ethiopia (Asargew et al., 2021), during two experimental years [from September 2020 to August 2021 for seasonal soil respiration, and September 16–29, 2021 for diurnal soil respiration].

Polyvinyl chloride (PVC) collars (diameter 0.19 m, length 0.11 m, insertion depth 0.05 m) were used to measure soil respiration. All collars were installed at least a week before the initial flux measurements and were not moved at any point throughout the experiment in order to minimize the impact of soil disturbance. Six PVC collars (for each control and the soil bund treatments, there are three replicates) were used to examine seasonal variation. In these same experimental plots, 18 fixed PVC collars were established in the second year (nine replicates with two treatments: control and soil bund) (Fig. 3).

Data collection

Soil respiration was monitored using a LI-8100A soil gas flux system (LI-COR, Lincoln, NE, USA).

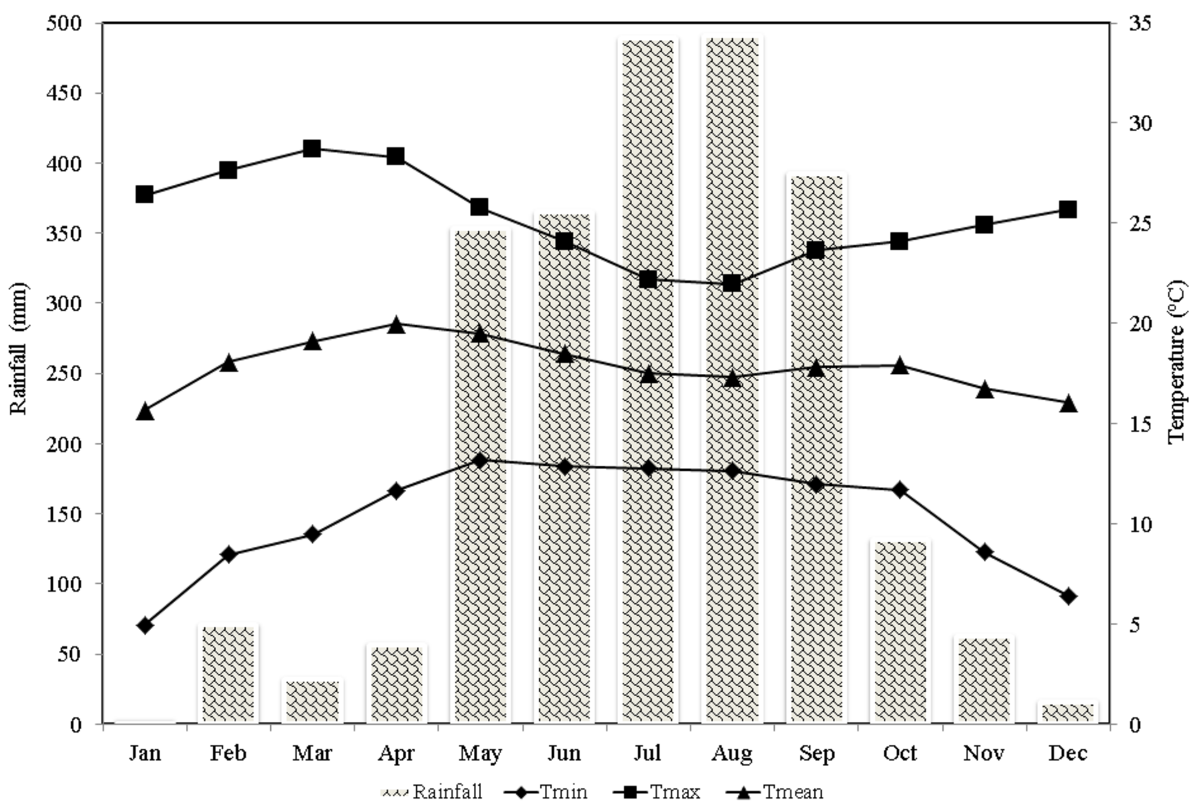

Fig. 2 Temperature and rainfall averages monthly in the study area from 2000 to 2020

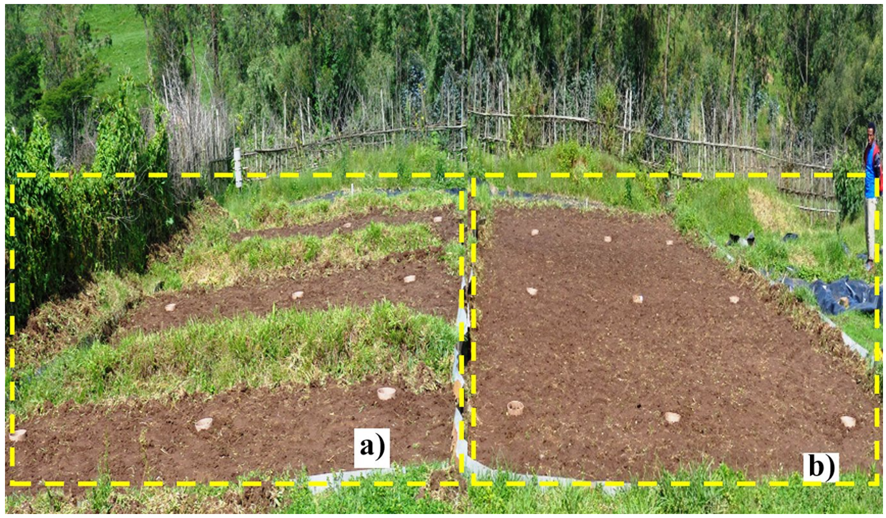

Fig. 3 Experimental plots at Guder with respiration collars installed. **a** Soil bunds and **b** control plots for diurnal soil respiration

To assess seasonal fluctuations, soil respiration was assessed monthly (Liang et al., 2019) in SB and control plots. Data on seasonal soil respiration were collected between 9 a.m. and 12 a.m. on mornings without rain (Sheng et al., 2010). We took soil respiration measurements in the middle of every month from September 2020 to August 2021. Each soil respiration reading lasted for 90 s, and the average value was calculated for each PVC collar.

To examine diurnal fluctuations in soil respiration, we collected data four times each day at a 6-h interval from 18 PVC collars [9 SB and 9 control plots] for 2 weeks (16–29 September 2021, at 11 a.m., 5 p.m., 11 p.m., and 5 a.m.) (Fig. 3).

Using linear models of CO_2 accumulation vs. time, we evaluated the linearity of CO_2 accumulation for each collar on each sample day. Observations that did not meet the $R^2 \geq 0.9$ threshold were discarded (Savage et al., 2008). During short enclosure periods (1–3 min), this technique yields more consistent soil respiration results (Kandel et al., 2016).

Soil moisture and temperature were measured concomitantly with both diurnal and seasonal soil respiration. We took 200-g soil samples for soil moisture analysis in each experimental plot while collecting data on soil respiration (Fig. 4c, d). Soil samples were dried in an oven for 24 h at 105 °C. The weight difference between wet and dry soil samples was divided by that of the dry sample, and then multiplied by 100 to yield the gravimetric soil moisture content (%). Soil temperature was measured using a soil temperature Omega probe 6000-09TC (Li-Cor, Lincoln, NE, USA) at the same depth (0.05 m) as the soil respiration measurements.

Soil sample analysis

Soil samples for physical and chemical analysis were collected from every plot. Soil samples were crushed and sieved with a 2-mm mesh sieve after air drying at room temperature. A pH meter was used to test the pH of the soil in the supernatant suspension of

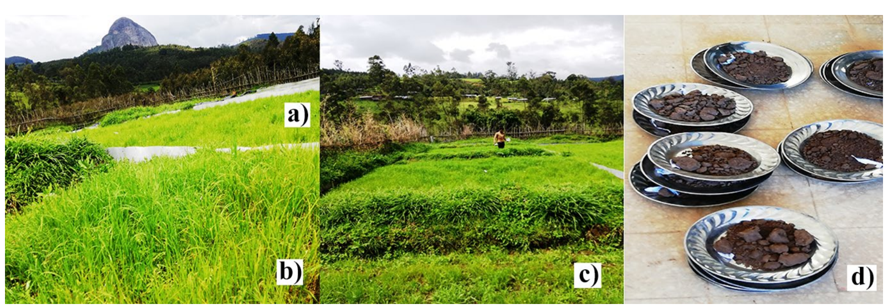

Fig. 4 Depicts control plots (**a**), soil bund (**b**), soil sample collection (**c**), and preparation of soil samples for oven drying (**d**)

a 1:2.5 soil and water combination (Peech, 1965). A C/N analyzer (Macro Corder JM1000CN, J-Science Lab, Kyoto, Japan) was used to analyze soil total nitrogen and carbon. The Olsen method was used to determine the amount of available phosphorus in the soil (Olsen et al., 1954). Oven-dried soil mass was divided by its volume to determine its bulk density. Soil texture analysis was performed by using a hydrometer (Bouyoucos, 1962).

Statistical analysis

The mean differences in seasonal soil respiration data between SB and control plots were checked for normality, and the mean difference was not normal. Thus, to test whether soil respiration differed significantly between plots with and without soil bunds, we used the Wilcoxon signed-rank test.

Diurnal soil respiration data were not normally distributed and were transformed by using the square root data transformation; the Kolmogorov–Smirnov normality test was applied at $p<0.05$. The homogeneity of variances for diurnal soil respiration and temperature was tested using Mauchly's sphericity test. One-way repeated measure analysis of variance (RMA) was used to examine the significance of differences between plots. After determining the significance of differences between mean values, the least significant difference test (LSD) was used to determine mean separation at $p<0.05$. Diurnal soil temperature data were normally distributed (Kolmogorov–Smirnov normality test at $p<0.05$) and were analyzed using a one-way repeated measure ANOVA. A paired *t*-test analysis was employed to evaluate differences in soil moisture between SB and control plots.

Pearson's correlation coefficient was used to assess the association between soil respiration and soil moisture and temperature. The SPSS Statistics software was used to conduct the statistical analysis (v.26 for Windows, IBM Corp., Armonk, NY, USA). Graphs were generated using Origin Pro 2019b (Origin Lab. Corp., Northampton, Mass., USA).

Soil CO_2 flux was calculated by using the following equation (LI-COR, 2015) (Eq. 1).

$$Rs = \frac{VP_o}{RS\left(T_o + 273.15\right)}\frac{dC}{dt}, \tag{1}$$

where Rs is soil respiration rate (μmol m^{-2} s^{-1}), V is chamber volume (cm^3), P_o is initial pressure (kPa), R is the universal gas constant (0.008314 cm^3 kPa mol^{-1} K^{-1}), S is soil surface area (cm^2), T_o is initial air temperature (°C) and dC/dt is the initial rate of CO_2 mole fraction change (μmol mol^{-1} s^{-1}).

An exponential function was used to simulate the relationship between soil respiration and temperature (Lloyd & Taylor, 1994) (Eq. 2):

$$Rs = ae^{bT}, \tag{2}$$

where Rs is CO_2 flux (μmol m^{-2} s^{-1}), T is the soil temperature (°C); a and b are the model coefficients, and e, base of the natural logarithm (~2.718281828459).

A polynomial function was used to estimate the link between soil moisture and soil respiration (Peng et al., 2015) (Eq. 3):

$$Rs = am^2 + bm + c, \tag{3}$$

where Rs is as defined above; m is soil moisture (%); a, b, and c are the model coefficients.

To determine how soil temperature and moisture interact to affect soil respiration, we used multiple regression (Cui et al., 2020) (Eq. 4):

$$Rs = a + bT + cm, \tag{4}$$

where all variables are as defined in the above equations.

Results

Soil characteristics

The soil texture in the soil bunds and control plots was similar (sandy loam) (Table 1). Soil bulk density (BD) was low (mean ± SD) for control (1.15 ± 1.0 gm cm^{-3}) and soil bund (1.03 ± 0.1 gm cm^{-3}) plots, as defined by Hazelton and Murphy (2007) (Table 1). Five years after soil bund installation, soil bulk density was 10% lower in soil bunds than in control plots. Similarly, in SB plots, total nitrogen (TN), soil organic carbon (SOC) content, and pH were 23%, 4%, and 7% higher, respectively, compared to controls (Table 1). However, soil pH and SOC were low in both control and SB plots, and TN was medium as defined by Landon (1991). Available phosphorus (P_{av}) was 17% higher in SB than in control plots, but it remained below the optimum level for crop production as suggested by Jones (2002).

Impact of land management practices on soil respiration

In SB plots, the yearly mean soil respiration rate was 6.07 μmol CO_2 m^{-2} s^{-1}. In control plots, the value was 3.84 μmol CO_2 m^{-2} s^{-1} (Fig. 5). Thus, the soil respiration rate was 58% higher in SB plots than in control plots. A Wilcoxon signed-rank test revealed that soil respiration rates were significantly lower ($p<0.05$) in control than in SB plots in all seasons (Table 2). The highest rates of soil respiration, in both treatment and control plots, were recorded in the autumn, followed by summer, winter, and spring.

Monthly variation in soil respiration

The rate of soil respiration varied with the seasons (Fig. 5c). In SB plots, the soil respiration rate was lowest in February (1.89 ± 0.3 μmol CO_2 m^{-2} s^{-1}, mean ± SE) and highest in October (14.54 ± 0.5 μmol CO_2 m^{-2} s^{-1}). In control plots, the lowest soil respiration rate was measured in April (1.22 ± 0.1 μmol CO_2 m^{-2} s^{-1}) and the highest in October (10.92 ± 1.1 μmol CO_2 m^{-2} s^{-1}).

The mean soil temperature was 24.9 °C in both the control and SB plots. The annual average soil moisture was significantly ($p<0.01$, paired t-test) higher in soil bunds (29.06% ± 1.71%) than in control (27.11% ± 1.66%) plots. Soil temperatures were lowest in September (15.46 ± 0.3 °C in soil bund and 13.9 ± 0.3 °C in control plots) and highest in April (33.3 ± 0.6 °C in SB plots and 32.47 ± 0.1 °C in control plots). Similarly, soil moisture was lowest in December (16.2% ± 1.5% in soil bund and 13.7% ± 2.4% in control plots) and highest in July (42.8% ± 1.4% in soil bund and 41.1% ± 0.4% in control plots) (Fig. 5b). It is evident that hydrothermal conditions regulate monthly fluctuations in soil respiration rates in our study site (Fig. 5).

We observed an exponential relationship between soil temperature and CO_2 flux ($R^2=0.24$ for soil bund and $R^2=0.29$ for control plots) and a quadratic relationship between soil moisture and CO_2 flux ($R^2=0.20$ for soil bund plots) (Fig. 6a–d). The combination of soil temperature and moisture showed a linear relationship with soil respiration in both SB and control plots ($R^2=0.32$ for SB and $R^2=0.37$ for control) (Table 3). The Pearson correlation analysis showed significant associations between soil temperature and moisture "$r=-0.60$, $p<0.01$," between soil temperature and soil respiration rate "$r=-0.52$, $p<0.01$," and between soil moisture and soil respiration rate "$r=0.26$, $p<0.05$" (Table S2).

Diurnal variation in soil respiration

On the basis of repeated measures, RMA analysis was performed to evaluate diurnal fluctuations in CO_2 flux in the SB and control plots. In both soil bund and control plots, CO_2 flux differed significantly ($p<0.05$) between all times of day (Table 4). Soil respiration rates were lowest at 5 a.m. and highest at 11 a.m. in both control and SB plots. At all measurement times, soil respiration rates were significantly higher in SB plots than in untreated plots. Soil temperature differed significantly ($p<0.05$, RMA) among measurement times in both control and SB plots (Table 5). Diurnal daily average soil moisture was significantly ($p=0.038$, paired t-test) higher in soil bund (41.66% ± 3.4%) compared to control plots (39.81% ± 3.3%).

Table 1 Characteristics of topsoil (0–20 cm) samples (mean ± SD) (n = 3)

LM practice	Texture	BD (gm cm^{-3})	pH (H_2O) 1:2.5	SOC (%)	TN (%)	P_{av} (mg kg^{-1})
C	SL	1.15 ± 1.0	4.9 ± 0.22	2.81 ± 1.6	0.22 ± 0.10	7.67 ± 0.96
SB	SL	1.03 ± 0.1	5.23 ± 0.11	2.93 ± 1.3	0.27 ± 0.07	9.01 ± 0.61
Change (%)		−10	7	4	23	17

The formula ([SB – C] / C) × 100 was used to determine the percent change in each soil property. Abbreviations for soil properties described in "Soil characteristics"

SL sandy loam, *C* control, *SB* soil bund

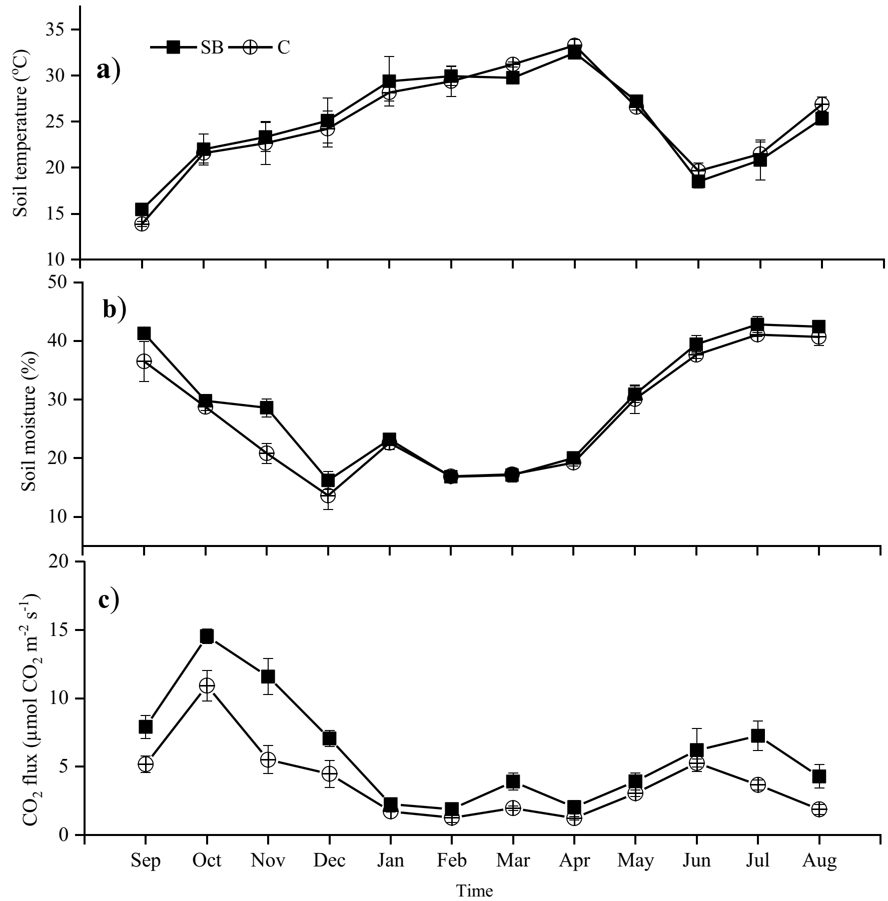

Fig. 5 The Mean monthly variation in **a** soil temperature, **b** soil moisture, and **c** soil respiration in SB and control plots. SB, soil bund; C, control. The bars represent standard errors ($n=3$)

We observed an exponential association between soil temperature and diurnal CO_2 flux in both SB and control plots (Fig. 7). However, soil moisture alone had no effect on diurnal CO_2 flux. The combination of soil temperature and moisture was linearly related to rates of soil respiration in both SB and control plots at 5 p.m. and 11 p.m. (Table 6). The Pearson correlation analysis showed a significant correlation between diurnal CO_2 flux and soil temperature in SB and control plots at 5 p.m. "$r=0.31$, $p<0.01$" for soil bund and "$r=0.50$, $p<0.01$" for control plots) and 11 p.m. "$r=0.36$, $p<0.01$" for soil bund and "$r=0.22$, $p<0.01$" for control plots) (Table S3).

Table 2 Results of Wilcoxon signed-rank tests in each season for control and SB plots from September 2020 to August 2021, $n=3$ for each month

Seasons	LM practice	Soil respiration (μmol CO_2 m^{-2} s^{-1})					*Z*	Asymp. sig (2-tailed)
		Average	SE	Min	Max	Median		
Autumn	C	7.20	1.05	4.41	12.67	6.39		
	SB	11.34	1.07	6.61	15.35	12.78	−2.666	0.008
Winter	C	2.48	0.58	0.83	6.43	1.82		
	SB	3.73	0.86	1.50	7.83	2.55	−2.547	0.011
Spring	C	2.08	0.28	1.03	3.39	2.08		
	SB	3.28	0.43	1.46	5.10	3.04	−2.429	0.015
Summer	C	3.60	0.52	1.28	5.75	3.28		
	SB	5.91	0.74	3.30	9.37	6.00	−2.073	0.038

C control, *SB* soil bund, *SE* standard error

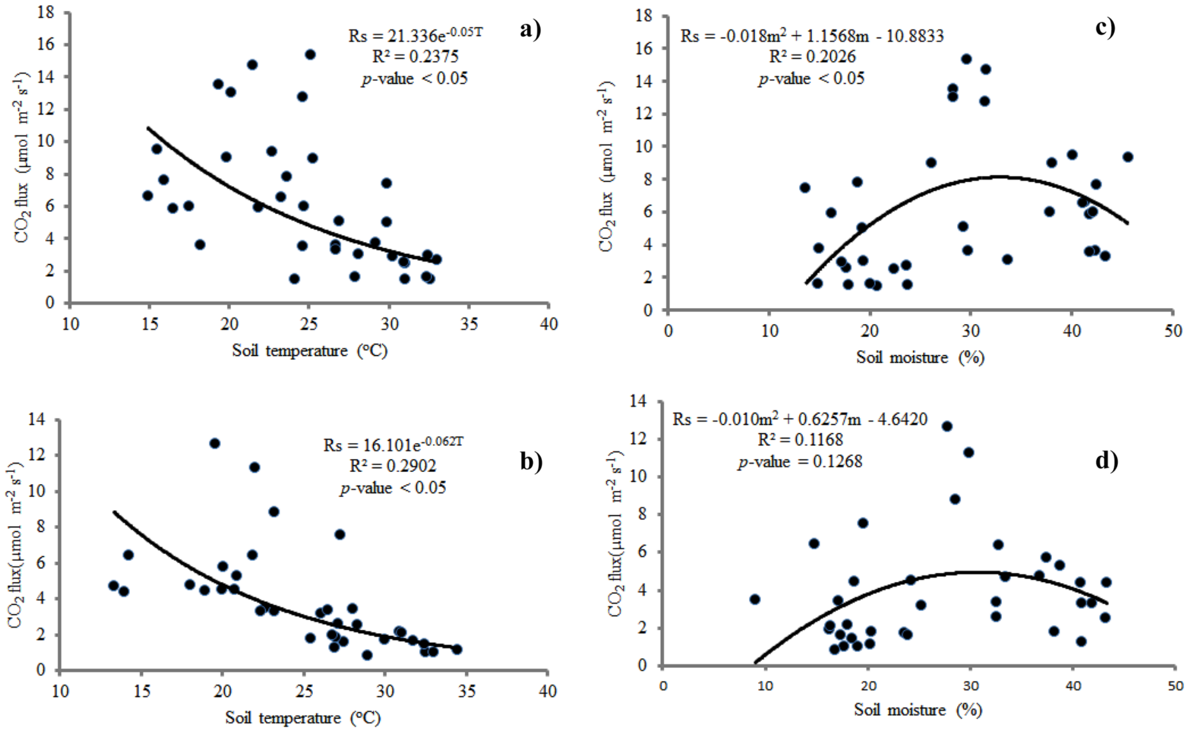

Fig. 6 The relationship between soil temperature and seasonal soil respiration at **a** soil bund and **b** control, and soil moisture and seasonal soil respiration at **c** soil bund and **d** control ($n = 36$)

Discussion

Soil properties

Land management practices have amended soil conditions in the study area by reducing run-off and sediment transport. Soil bulk density was 10% lower in soil bund compared to control plots. We found a negative, non-significant association between soil bulk density and soil respiration (Table S1). Untreated plots had a higher bulk density because of the loss of soil organic matter, exposing heavier soil particulates (Belayneh et al., 2019). The higher soil pH in treated plots (7%) was due to excessive removal of soil organic matter and basic cations via erosion from untreated plots (Guadie et al., 2020). A study suggested that

Table 3 Multiple linear regression models between seasonal soil respiration rate and soil moisture and temperature

LM practice	Multiple linear regression equation	R^2	p-value
SB	$Rs = 21.4 - 0.50T + 0.16m$	0.32	$p < 0.05$
C	$Rs = 13.08 - 0.33T + 2.89m$	0.37	$p < 0.05$

$n = 3$ per plot in each month for 1 year, where Rs is CO_2 flux (µmol m^{-2} s^{-1}), T is the soil temperature (°C); m is the soil moisture (%)

C control plot, *SB* soil bund plots

Table 4 One-way repeated measure ANOVA of soil respiration (mean ± SE) at different times of day in SB and control plots from September 16–29, 2021 at Guder

Time (h)	CO_2 flux (µmol CO_2 m^{-2} s^{-1})	
	SB	C
11 a.m	3.19 ± 0.04^a	2.76 ± 0.04^a
5 p.m	2.83 ± 0.04^b	2.31 ± 0.08^b
11 p.m	2.23 ± 0.03^c	1.88 ± 0.09^c
5 a.m	1.84 ± 0.06^d	1.50 ± 0.07^d
p-value	*	*

The LSD test found that the mean values (*square root transformed*) marked with different letters differ significantly at $p < 0.05$; $n = 14$ per time and LM practice

C control, *SB* soil bund

Table 5 One-way repeated measure ANOVA of soil temperature (mean ± SD) at different times of day in SB and control plots from September 16–29, 2021 at Guder

Time	Soil temperature (°C)	
	SB	C
11 a.m	18.9 ± 1.10^{b}	19.1 ± 0.97^{b}
5 p.m	21.8 ± 1.60^{a}	22.3 ± 2.21^{a}
11 p.m	17.9 ± 1.00^{c}	17.6 ± 1.09^{c}
5 a.m	16.0 ± 0.76^{d}	15.5 ± 0.61^{d}

Mean values marked with different letters differ significantly at $p < 0.05$ by LSD test; $n = 14$ per time and LM practice

C control, *SB* soil bund

the effect on microbes primarily stemmed from soil acidity (Chen et al., 2016). Available phosphorus has increased by 17% over the last 5 years under land management practices at Guder. P_{av} plays a pivotal role in plant growth, and microbial activity may also affect soil respiration (Liu et al., 2020a, b). Our results for the increment of P_{av} were consistent with the results of other studies (Adimassu et al., 2017; Guadie et al., 2020; Husen et al., 2017). The Pearson correlation analysis revealed that there was a significant correlation between P_{av} ($r = 0.86$, $p < 0.05$) and pH ($r = 0.88$, $p < 0.05$) with soil respiration (Table S1). Improvements in TN and SOC were also observed in many studies (Belayneh et al., 2019; Guadie et al., 2020; Hishe et al., 2017; Husen et al., 2017). SOC and TN were positively associated, although there was a non-significant correlation between soil respiration and these variables (Table S1). Belayneh et al. (2019) also found that TN and SOC increased significantly in the Gumara catchment, UBNB, as a result of soil and water conservation practices. Adimassu et al. (2017) found that land management implementations, mainly soil and stone bunds, are very effective in reducing run-off. Furthermore, land management supports nutrient recycling and the availability of water within ecosystems (Ripl & Eiseltová, 2009).

Effects of soil bunds on soil respiration

In all seasons, soil respiration rates were significantly higher in soil bunds than in control plots (Table 2). These higher soil respiration rates could be attributed to improvements in soil properties (Table 1). Our results are consistent with those of Li et al. (2019), who reported a summit profile emits less CO_2 than a depositional profile, mainly due to its low amount and poor quality of SOC, and Terefe et al. (2020) also reported that CO_2 storage in untreated watersheds is much lower than in treated watersheds. Furthermore, because SOC content was low in control plots, it could not provide much substrate for soil microorganisms, inhibiting soil microbial activities and reducing soil heterotrophic respiration (Hou et al., 2021). A study by Chen et al. (2021) found nutrient levels and soil pH were the principal soil variables explaining variability in the composition and diversity of microbial communities. In our study, there was an improvement in soil pH and nutrient content under land management practices (Table 1). Moreover, effective erosion control can create a net sink of atmospheric CO_2 (Lal, 2020) and a reduction in SOC mobilization (Ran et al., 2018).

The availability of respiratory input plays a fundamental role in the response of the CO_2 flux to environmental factors (Liu et al., 2006). Soil temperature and moisture vary with the seasons at our study site (Fig. 5). Moreover, plots with soil bunds retain more soil moisture compared to control plots (Fig. 5b). Rainfall fluctuations influence the amount of soil moisture, which in turn determines rates of soil respiration (Meena et al., 2020). Soil temperature contributes to increasing the pool of carbon available for respiration by soil microbes through decomposition (Zogg et al., 1997). Soil temperature is crucial for soil microorganisms in the process of decomposition. The improvement in soil properties may permit soil microorganisms' abundance as well as diversity to contribute more to soil respiration in SB compared to control plots (Table 1 and Fig. 4a, b). Soil microorganisms play key roles in nutrient cycling and soil health (Šlapáková et al., 2018), and their metabolic activities convert soil organic matter to CO_2 (Liu et al., 2006). Soil pH strongly correlates with the abundance of the bacterial community (Abebe et al., 2020). Chen et al. (2021) observed that soil pH as well as nutrient levels contributed to variability in the composition and diversity of microbial communities. Extremely low or high soil moisture levels lead to depression of microbial activity and then to low rates of soil respiration (Moriyama et al., 2013). Soil aeration is a major factor that controls microbial activity; when more than 60% of the pore space is water-filled, obligate aerobic processes decline rapidly with increasing water content (Linn & Doran, 1984). Soil

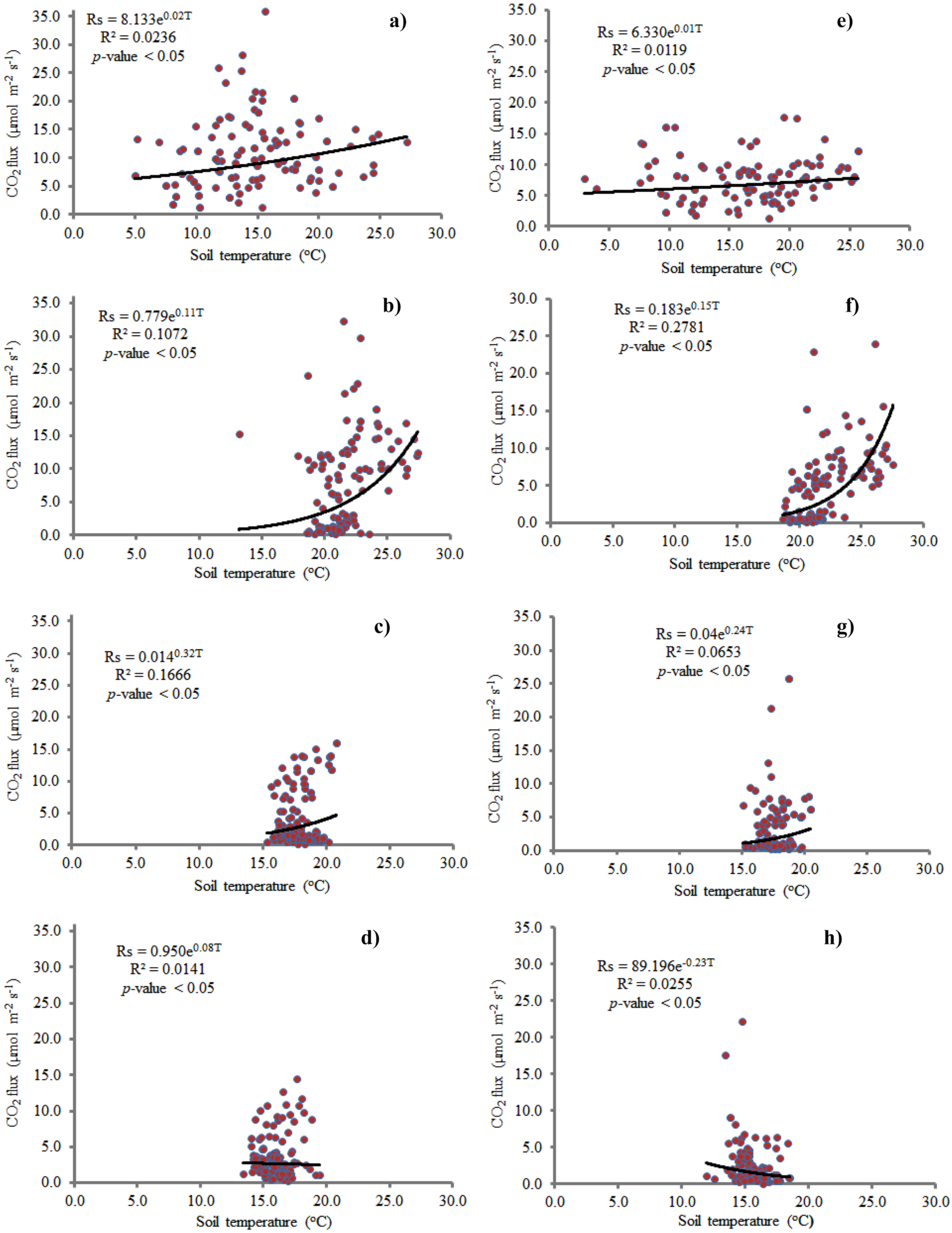

Fig. 7 Exponential relationship between soil temperature and diurnal soil respiration at different times in a soil bund: **a** 11 a.m., **b** 5 p.m., **c** 11 p.m., **d** 5 a.m.; and in a control plot: **e** 11 a.m., **f** 5 p.m., **g** 11 p.m., **h** 5 a.m. ($n = 126$)

Table 6 Multiple linear regression models between diurnal soil respiration rate and soil moisture and temperature

LM	Time	Regression equation	R^2	*p*-value
SB	11 a.m	$Rs = 12.94 + 0.2T - 0.1m$	0.04	>0.05
	5 p.m	$Rs = -9.31 + 0.94T - 0.05m$	0.10	<0.05
	11 p.m	$Rs = -17.04 + 1.31T - 0.03m$	0.13	<0.05
	5 a.m	$Rs = -0.32 + 0.30T - 0.02m$	0.02	>0.05
C	11 a.m	$Rs = 10.04 + 0.06T - 0.07m$	0.02	>0.05
	5 p.m	$Rs = -18.83 + T + 0.04m$	0.25	<0.05
	11 p.m	$Rs = -12.41 + 0.81T + 0.03m$	0.05	<0.05
	5 a.m	$Rs = 10.48 - 0.55T + 0.01m$	0.04	>0.05

$n=9$ per plot each day for 2 weeks, where *Rs* is CO_2 flux (μmol m^{-2} s^{-1}), *T* is the soil temperature (°C); *m* is the soil moisture (%)

C control plot, *SB* soil bund plot

CO_2 emission processes influence the soil substrate and organic matter content, as well as the growth and activity of soil microorganisms (Deqiang et al., 2006). The significant association between fungal abundance and soil respiration suggests that fungal activities are important in soil respiration (Goupil & Nkongolo, 2014).

Different soil amendment techniques such as polyacrylamide (PAM) and biochar may be used to better minimize CO_2 flux emission from bunds than untreated plots. Awad et al. (2012) reported that PAM is a technique that reduces carbon emissions. This is mainly due to applying PAM profoundly improves soil aggregation without accelerating decomposition (Awad et al., 2013), whereas biochar has an important effect on soil carbon sequestration and can be used as a new medium to reduce the greenhouse gas emissions resulting from the decomposition of organic matter and biomass in soil (Hua et al., 2014).

Monthly fluctuations in soil respiration

Rates of soil respiration fluctuated with the seasons in both SB and control plots (Fig. 5c), as did soil temperature and moisture (Fig. 5a, b). *Rs* was highest in October, when rainfall is not heavy enough to cause saturation of soil pores and reduce oxygen levels in the soil, and the temperature is high. From October to April, temperatures are increasing, whereas rainfall is decreasing. Thus, soil moisture controls the CO_2 flux during these months. Previous studies have reported that soil moisture and temperature affect rates of seasonal soil respiration (Carbonell-Bojollo et al., 2019; Cui et al., 2020; Davidson et al., 2000; Fan et al., 2015; Guntiñas et al., 2013; Sheng et al., 2010). Here, we observed an exponential relationship between soil temperature and soil respiration in both plot types, and a quadratic relationship between soil moisture and soil respiration in SB plots. Soil temperature and moisture in combination also had an impact on soil respiration rates (Table 3). A Pearson correlation analysis revealed a significant relationship between seasonal soil respiration rate and soil temperature "$r=-0.52$, $p<0.01$" and soil moisture at Guder watershed "$r=0.26$, $p<0.05$" (Table S2). The average soil respiration rate was highest in autumn (Sept to Nov) and lowest in spring (Mar to May) (Fig. 5).

Variation in soil respiration rates was affected by soil environmental factors and cropping seasons. Soil CO_2 effluxes vary seasonally, corresponding to soil temperature changes (Ming et al., 2014). Soil temperature regulates microbial activity and shapes the soil microbial community (Pietikainen et al., 2005). The population of active microorganisms influences seasonal rates of soil respiration in the soil (Salazar et al., 2019). The optimum temperature for fungal and bacterial growth rates is around 25–30 °C, as described by Pietikainen et al. (2005). Warm and moist soils are less sensitive to temperature, whereas cool and moist soil conditions are more sensitive to temperature (Liu et al., 2006). Seasonal soil respiration rates can be predicted by soil moisture alone at stable temperature conditions (Liu et al., 2006). Several studies have reported that CO_2 flux is controlled by soil moisture (Jiang et al., 2013; Sugasti & Pinzón, 2020; Sugihara et al., 2012).

Because autumn is the cropping season at our study site, roots contribute more to soil respiration in autumn than in other seasons. Liu et al. (2010) reported that different crop growing seasons affect predictions of soil respiration differently. This could be because, in crop-growing seasons (Qi et al., 2010), surface soil moisture is highly correlated with soil respiration. Similarly, the study by Luo and Zhou (2006) suggests that soil respiration increases dramatically during active growing seasons. In a 4-year study in Tanzanian farmland, seasonal variation in CO_2 efflux rates was found to be a function of soil texture (Sugihara et al., 2012). However, in our study, there was no soil texture variation in plots.

Diurnal variation in soil respiration

Our diurnal soil respiration data, collected over 2 weeks, showed significant diurnal fluctuations in the rate of soil respiration. Soil respiration rates were significantly ($p < 0.05$) higher at 11 a.m. than at other times of the day (Fig. 6). The lowest soil respiration rate was recorded at 5 a.m. Soil temperature differed significantly ($p < 0.05$) between all measurement times (Table 5). Within 2 weeks of the study period, the average daily fluctuations of soil moisture were very low in both the SB and control plots. This might be due to uniform rainfall during the study period.

Soil temperature variability was the principal factor influencing diurnal soil respiration rates in soil bund and control plots (Tables 5 and S1). Diurnal variability in soil respiration can be expressed as a function of soil temperature because, in cool areas such as the Guder watershed, soil temperature changes strongly on a diurnal scale (Rayment & Jarvis, 1997). A study at Temperate *Leymus Chinensis* Meadow Steppes in the Western Songnen Plain, China, found that soil temperature influenced diurnal soil respiration fluctuations (Ming et al., 2014).

Soil moisture exerts a greater influence over seasonal patterns than over diurnal patterns in soil respiration (Tang et al., 2005). Diurnal variation in soil respiration can be better explained by the synergistic effects of soil temperature and moisture (Fan et al., 2017). Here, the soil moisture–temperature combination influenced diurnal soil respiration rates in the SB and control plots at 5 p.m. and 11 p.m. (Table 5).

At 5 a.m., soil respiration was significantly lower than at any other measurement time ($p < 0.05$; Table 4), likely because of low soil temperature (Table 5), which inhibits microbial decomposition; and low wind speed, calm air, and absence of photosynthesis (Luo & Zhou, 2006). The study also found that, on a daily scale, photosynthesis controls soil respiration (Han et al., 2014). Moreover, the dynamics of soil respiration are influenced by interactions between photosynthesis and the environment (Liu et al., 2020a, b).

Conclusion

Land management affects soil properties, and edaphic and hydrothermal factors contribute to diurnal and seasonal fluctuations in soil respiration. The CO_2 flux was 58% higher in SB than in control plots. Different amendment approaches, such as polyacrylamide and biochar, are required to reduce greenhouse gas emissions and increase carbon storage in the soil. The lowest and highest seasonal mean CO_2 flux rates were observed in SB plots in February and October, with mean values of 1.89 ± 0.3 and 14.54 ± 0.5 μmol CO_2 m^{-2} s^{-1}, respectively. In contrast, in control plots, the lowest monthly soil respiration rate was 1.22 ± 0.1 μmol CO_2 m^{-2} s^{-1} in April, whereas the maximum value was observed in October (10.92 ± 1.1 μmol CO_2 m^{-2} s^{-1}). The lowest and highest daily CO_2 flux rates were measured in the early morning at 5 a.m. and at 11 a.m., respectively, in both control and SB plots. Seasonal CO_2 flux was influenced by soil temperature, soil moisture, and the combination of soil temperature and soil moisture. Available phosphorus and pH were found to significantly correlate with soil respiration. At the diurnal scale, soil temperature played a crucial role, and the combination of soil temperature and soil moisture contributed to the variation in soil respiration. Further study is required to examine how the effects of land management on soil respiration are mediated by soil microorganisms.

Author contribution Genetu Fekadu: conceptualization, methodology, data collection, writing—draft manuscript, review editing, and visualization. Enyew Adgo: conceptualization, methodology, writing—review and editing, visualization, supervision, funding acquisition. Derege Tsegaye Meshesha: conceptualization, methodology, writing—review and editing, visualization, supervision, project administration, funding acquisition. Atsushi Tsunekawa: writing—review and editing, visualization, supervision, project administration, funding acquisition. Nigussie Haregeweyn: conceptualization, methodology, writing—review and editing, visualization, supervision, project administration, funding acquisition. Fei Peng: conceptualization, methodology, writing—review and editing, visualization. Mitsuru Tsubo: writing—review and editing, visualization, supervision, project administration, funding acquisition. Tsugiyuki Masunaga: writing—review and editing, visualization, supervision, project administration, funding acquisition. Asaminew Tassew: writing—review and editing, visualization, supervision, project administration, funding acquisition. Temesgen Mulualem: data collection, writing—draft manuscript, review and editing. Simeneh Demissie: data collection, writing—draft manuscript, review and editing.

Funding This research was funded by the Science and Technology Research Partnership for Sustainable Development (SATREPS, grant number JPMJSA1601), and the Japan International Cooperation Agency (JICA) / Japan Science and Technology (JST).

Data availability The authors confirmed that the data supporting the findings of this study are available within the article and/or its supplementary materials.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors".

Competing interests The authors declare no competing interests.

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