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Spatial variation in soil properties and crop yield on stone bund terraces in southwest Ethiopia

Kebede Wolka[1,2] | Birhanu Biazin[3] | Vegard Martinsen[1] | Jan Mulder[1]

[1]Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Science, Aas, Norway

[2]Wondo Genet College of Forestry and Natural Resource, Hawassa University, Shashemene, Ethiopia

[3]International Crop Research Institute for Semi-Arid Tropics, Addis Ababa, Ethiopia

Correspondence
Kebede Wolka, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Science, P.O. Box 5003, NO 1432, Aas, Norway.
Email: kebedewolka@gmail.com

Funding information
Wondo Genet College of Forestry and Natural Resource

Abstract

Erosion and associated soil degradation are major threats to cropland productivity on the steep slopes of the Ethiopian highlands. To limit erosion from cultivated land on sloping terrain, stone bunds for soil conservation have been used for decades, resulting in the formation of terraces. Although qualitatively well known, the difference in soil properties and crop performance between the upper and lower sections of the terraces (intra-bund areas) has not been documented quantitatively. Here, we assess differences in soil properties of the plough layer and crop performance in the upper and lower sections of terraces in between stone bunds in southwest Ethiopia. A total of 27 terraces, with a length of 28.5–57 m and a distance of 6.5–14.7 m in between adjacent stone bunds, were sampled on six different farms during the 2018 and 2019 cropping seasons. The difference in soil properties was analysed using analysis of variance (ANOVA). Results showed that, in the lower section of a terrace, the concentration of soil organic carbon (18.6 g kg^{-1}), total soil nitrogen (2.1 g kg^{-1}) and exchangeable potassium (328 mg kg^{-1}) was significantly greater ($p < .01$) than in the upper section. Also, grain yield and biomass of maize, teff, broad bean and sorghum were significantly greater ($p < .05$) in the lower section. This was particularly true for maize for which the yield in 2018 increased from 0.7 t ha^{-1} in the upper sections to 2.6 t ha^{-1} in the lower sections. Optimizing crop yields on terraces requires adaptive fertilizer application and crop choice.

KEYWORDS

erosion, maize, nutrients, soil and water conservation, soil moisture, soil organic carbon

1 | INTRODUCTION

Terraces on sloping agricultural land exist in many parts of the world (Arnáez et al., 2015; Brandolini, 2017; Stanchi et al., 2012; Wei et al., 2016). In different parts of Ethiopia, terraces have been common for centuries on steep cultivated lands (Engdawork & Bork, 2014). The construction of terraces requires significant hand-labour (e.g. *Fanya juu*, i.e. 'throw the soil uphill') or machinery (Cots-Folch et al., 2006). Alternatively, terraces may form above stone bunds, soil bunds, *Fanya juu* or hedgerows, following erosion below the barrier and accumulation of sediment above the adjacent barrier further downslope. The reduction of the steepness of slopes (Nyssen et al., 2019; Subhatu et al., 2018) helps limiting the generation of surface runoff and soil erosion in response to rainfall.

About 23% of the Ethiopian land area is affected by land degradation, particularly in the highland area where population density is high and much of the cultivated lands are on sloping terrain (Gebreselassie et al., 2016).

In the highlands, soil erosion is a significant threat to food production, removing about 30 t $ha^{-1}year^{-1}$ of soil from cultivated lands (e.g. Haregeweyn et al., 2015; Wolka et al., 2018, 2021). The eroded material is relatively rich in silt, organic matter and plant nutrients (Wolka et al., 2021), which, if lost from the system, makes food production unsustainable. According to Adgo et al. (2013), land degradation, due to soil erosion, results in 2% decline of annual crop yield in Ethiopia. To curb soil erosion, watershed management approaches, including the construction of soil and stone bunds, have been promoted by the Ethiopian government, with support from several national and international organizations (Abera et al., 2019; Haregeweyn et al., 2015). If stones are easily available at or near the soil surface on cultivated sloping land, stone bunds are preferred despite their greater labour demand, due to their relatively high stability (Hurni et al., 2016). In the Ethiopian highlands, where conventional tillage using two-oxen-driven 'maresha' and hand tools are common practice, stone removal from the soil surface also makes the land more suitable for cultivation (Wolka et al., 2013).

Stone bunds, constructed along contours, decrease surface runoff by reducing slope length, flow connectivity and eventually slope steepness (Wei et al., 2016). Several studies have reported that stone bunds effectively reduce soil loss, while enhancing crop yield (Hammad et al., 2004; Taye et al., 2013). According to Wolka et al. (2018), stone bunds reduce surface runoff by about 50% and soil loss by 50%–70%, but this depends on slope steepness and age of the conservation structures (Gebrernichael et al., 2005; Taye et al., 2013).

Eroded materials tend to deposit above stone bunds at their upslope sides. While the area of erosion gradually declines in elevation, the area of accumulation increases in elevation and eventually a stone bund terrace is formed. In between two consecutive bunds, Subhatu et al. (2017) estimated that, in northern Ethiopia on 4%–17% slope, up to 74% of the total eroded soil mass was re-deposited in areas of accumulation for soil bunds. In addition to soil erosion by water, also tillage contributes to the downslope transport of soil materials towards accumulation areas, as shown in northern Ethiopia (Nyssen et al., 2000). The magnitude of the translocated soil material by tillage decreases with decreasing slope (Li et al., 2007) and with the increasing age of stone bund terraces (Gebrernichael et al., 2005). Also, water erosion decreases with age of stone bunds due to a gradual declining slope of the terraces.

Selective translocation of soil material due to erosion is likely to result in a spatial variation in soil properties within a terrace, with finer material, soil organic matter (SOM) and plant nutrients getting depleted upslope, while accumulating above stone bunds (Vancampenhout et al., 2006). Thus, an important fraction of the transferred soil material consists of SOM (Dabney et al., 1999; Zhao et al., 2018), which accumulates in the lower sections of intra-bund terraces (Walle & Sims, 1999). Similarly, increased plant-available phosphorous (P) and total nitrogen (N) were found in sediment accumulation zones in the lower sections of intra-bund terraces (Alemayehu et al., 2020; Vancampenhout et al., 2006; Zougmoré et al., 2002). Similar observations were made for terraces above planted hedgerows in Uganda (Siriri et al., 2005), Rwanda and China (Kagabo et al., 2013; Lin et al., 2009). However, studies by Siriri et al. (2005) and Lin et al. (2009) did not show significant differences in soil concentrations of P and potassium (K), respectively, between the upper and lower sections of a terrace.

Some studies in Ethiopia indicate that, associated with the spatial variation in soil parameters on stone bund terraces, yields of crops such as sorghum, maize and wheat were highest in the lower sections of terraces (Alemayehu et al., 2006, 2020; Vancampenhout et al., 2006). Similar observations of crop yields were made for wheat, maize and potato on terraces developed above hedgerows and in areas with *Fanya juu* in Ecuador, Ethiopia and Rwanda (Amare et al., 2013; Dercon et al., 2006; Kagabo et al., 2013). The spatial differences in soil properties, providing better fertility in lower than in upper sections of terraces, are believed to be responsible for enhanced crop growth in lower sections.

In the Bokole-Karetha watershed of the Omo-Gibe River basin, southwest Ethiopia, stone bunds play cultural (Abebe, 2014) and agricultural roles. The major part of the watershed is in the highlands (>1500 m above sea level) and has high annual rainfall (>1800 mm; NMA, 2019). On cultivated lands, with abundant stones, the traditional hand-made construction of stone bunds has been practiced for centuries. During the last 15 years, improved stone bunds have been introduced according to specific guidelines, including spacing, foundation, width and height, promoted by agricultural experts of the government and partner institutions (Abera et al., 2019; Hurni et al., 2016). In the Bokole-Karetha watershed, farmers practice periodic shifting of the position of stone bunds in order to redistribute fine material, SOM and plant nutrients across their fields. Soil fertility is expected to be greater in the sediment-dominated lower sections of intra-bund areas (terraces) than upper sections. Despite widespread implementation of stone bunds, studies of the spatial variability of soil fertility in intra-bund areas and its effect on yields of the dominant crops are rare (Alemayehu et al., 2020; Vancampenhout et al., 2006).

Here, we quantify the effects of stone bunds on the spatial variability of soil fertility and the yield of maize (*Zea mays*), teff (*Eragrostis tef*), broad bean (*Vicia faba*), haricot bean (*Phaseolus vulgaris*) and sorghum (*Sorghum bicolor*) in intra-bund areas on steep slopes with stone bunds of the Bokole-Karetha watershed. This study is important to understand the magnitude of spatial variation of soil properties and crop yield and to derive adaptive management strategies in intra-bund areas. For the study, we divided 27 intra-stone bund areas (terraces) on six farms into three sections (upper, middle and lower). The study was done during 2018 and 2019, each year having two cropping seasons.

We hypothesize that in intra-stone bund areas: I) long-term erosion and sedimentation significantly increase SOM and nutrient concentration in the lower sections; II) the plough layer of soils in the lower sections has significantly greater soil moisture than the upper sections; and III) the combined effect of increased soil moisture, SOM and soil nutrients in the lower sections results in significantly larger crop yields.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted in Ella, southwest Ethiopia, at 6°58′45″–6°59′08″N latitude and 37°17′22″–37°17′39″E longitude (Figure 1). The site is in the Bokole-Karetha watershed, which is at about 40 km from Tarcha town. The watershed drains into the Omo River just above the Gibe III hydro-electric dam. The elevation of the study site is between 1600 and 1795 m above sea level. Mean annual rainfall is 1886 mm, while minimum and maximum daily temperatures are 12.5°C and 23°C, respectively (NMA, 2019; Wolka & Zeleke, 2017). The soils are dominated by dystric Nitisols (WRB, 2015). Mixed crop-livestock farming systems are common in the area, and smallholder farmers rely on crops such as maize (*Zea mays*), teff (*Eragrostis tef*), sorghum (*Sorghum bicolor*), haricot bean

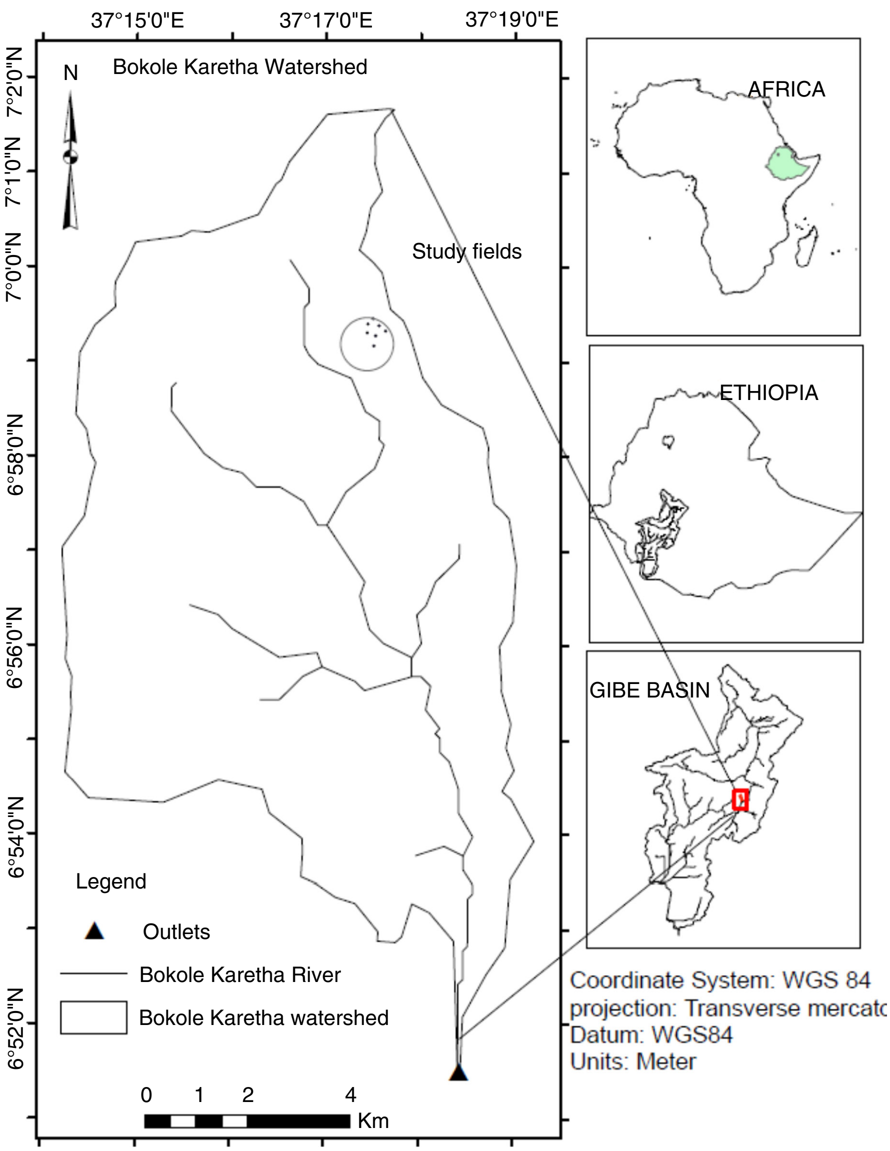

FIGURE 1 Location map of the study area, Bokole-Karetha Watershed, SW Ethiopia

TABLE 1 Description of the sampled stone bund terraces in the Bokole-Karetha watershed, southwest Ethiopia

Characteristics/Management	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6
Terrace age in 2018, year	14	14	14	14	14 and 8	14 and 9
Number of stone bund terraces considered	3	6	3	6	3	6
Terrace width, m	14.5 ± 1.1	13.5 ± 1.1	6.5 ± 0.3	8.3 ± 1.5	14.7 ± 4.7	11.2 ± 1.0
Terrace length, m	30.8 ± 2.1	28.5 ± 0.9	33.0 ± 3.0	33.7 ± 4.1	57.0 ± 0.0	40.4 ± 4.3
Original slope, degree	10.8 ± 0.0	12.6 ± 0.5	13.2 ± 1.4	21.5 ± 0.9	21.8 ± 2.0	17.1 ± 1.2
Terrace current slope, degree	8.4 ± 0.9	7.4 ± 0.9	8.10 ± 1.4	14.5 ± 0.8	13.7 ± 2.0	10.3 ± 1.9
Terrace height[a], m	na	1.5	2.2	1.1	1.8	1.8
Slope decrease of terrace compared to the original, %	22.7	41.1	38.4	32.6	37.4	39.9
Crops grown						
'belg' 2018	Maize	Maize	Maize	Maize	Teff	Maize & Haricot bean
'meher' 2018	Teff	Teff		Teff		
'belg' 2019		Sorghum		Haricot bean & Sorghum		Maize
'meher' 2019	Broad bean	Sorghum	Teff & Broad bean	Teff & Sorghum	Teff	Teff & Haricot bean

Note: 'belg' season is from February to June and 'meher' from July to October.

[a]Stone bund terrace height was measured at its downslope side from foot to top. This includes, original stone bund, the soil accumulated on the top of stone bund and the eroded part at the bottom of stone bund.

(*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), broad bean (*Vicia faba)* and sweet potato (*Ipomoea batatas*). Livestock includes cattle (*Bos taurus*), chicken (*Gallus gallus domesticus*), goat (*Capra aegagrus hircu*) and sheep (*Ovis aries*). Livestock grazing is common on marginal lands and croplands in between cropping seasons, and much of the aboveground biomass produced is fed to livestock. Farmers in the area plough their cropland about three times prior to sowing. Due to the sloping terrain, cultivated land experiences severe water erosion. As a soil conservation technique, stone bunds, gradually developing into stone bund terraces, are constructed from available rock fragments.

In the study area, there are two cropping seasons, viz. 'belg' (February to June) and 'meher' (July to October). In 'belg' season, maize, haricot bean, sorghum (continue into 'meher'), groundnut and sweet potato are grown. Teff, broad bean and haricot beans are grown in 'meher' (Table 1).

2.2 | Methods of sampling and data collection

Six cultivated fields (field 1–6) with expert-designed (viz. designed by a trained person on agriculture and natural resources in the government office) stone bunds were selected. Each field was managed by a farm household, and fields were within ~2.5 km distance from each other. The selection required all fields to have intra-stone bund areas that had eventually developed into terraces, and with at least five consecutive, non-broken stone bunds along the contour lines. Three of the fields were on east-facing slopes while the other three were on west-facing slopes. All fields were located downslope from the farmhouses and used for annual crops. All bunds and their terraces were 8–14 years old. Land management in the cultivated fields has been similar with respect to crops, cultivation techniques, frequency of tillage and fertilizer use. Only teff received inorganic NPSB fertilizer of about 100 kg ha^{-1}, containing nitrogen (N), phosphorus (P), sulphur (S) and boron (B) (18.9% N, 37.7% P_2O_5, 6.95% S and 0.1% B) (Assefa et al., 2016). Among the stone bund terraces, a total of 27 were selected. The length of the stone bunds on the six fields was from 28.5 to 57 m, whereas the distance between two consecutive bunds was 6.5–14.7 m. Initially, the stone bunds have about 10 cm foundation below the soil surface, 50 cm height above the ground and 30 cm top width. Differences in width and length of the selected stone bund terraces (Table 1) were due to variations in slope, land area and farmers preference. The original slope of the land was estimated from the mid-point of a stone bund terrace to the mid-point of the next stone bund terrace (Gebrernichael et al., 2005).

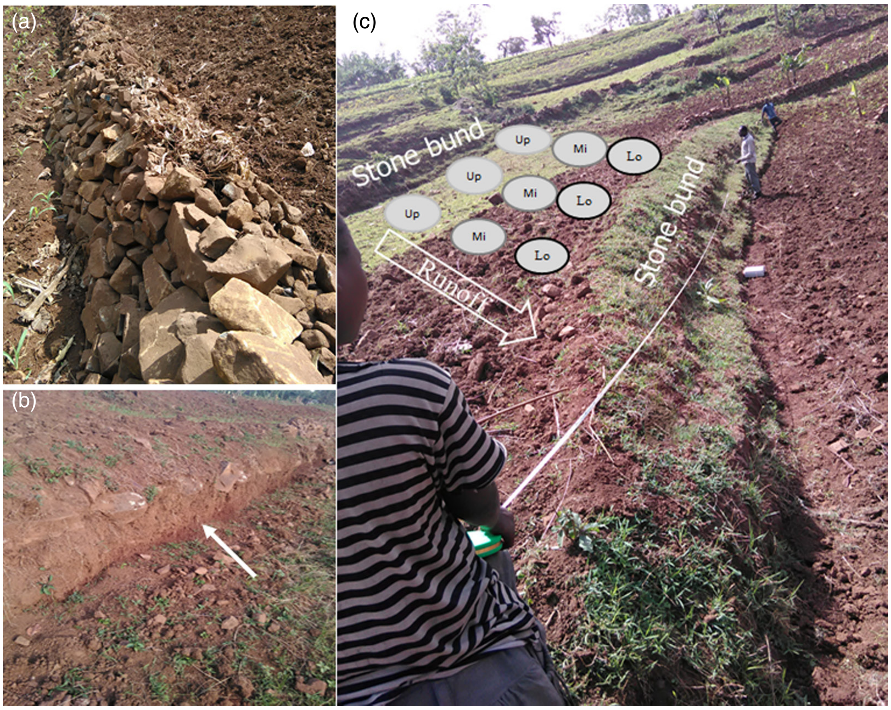

FIGURE 2 Newly constructed stone bund after shifting location (a), stone bunds having formed intra-bund terrace (b) and terraces formed after 14 years (c) in the Bokole-Karetha watershed, SW Ethiopia. In Figure (c), Up is approximate upper, Mi middle and Lo lower sections of the terrace. In picture (b), the subsoil (reddish coloured) has been exposed due to erosions at downslope side of the terrace

Before planting crops (Table 1) in 2018, soil samples were collected from the upper, middle and lower sections of each stone bund terrace (Figure 2). The upper and lower sections were sampled at 1 m distance from the upper and lower stone bunds, respectively. From each of the upper, middle and lower sections (a total of 27 terraces × 3 sections = 81 sampling plots), soil samples were collected from 0 to 20 cm depth, using an auger. Samples were collected from pits when stones or sticky soil prevented the use of an auger. In each of the three sections of all 27 terraces, composite samples (consisting of three subsamples spaced 10 m apart) were taken. Soil samples were air-dried, sieved (2 mm) and analysed for pH, soil organic carbon (SOC), ammonium acetate (NH_4OAc) extractable potassium (exchangeable K; K_{Exch}), Olsen-extractable phosphorus (P_{Olsen}), total nitrogen (N_{tot}) and texture. Soil pH was measured using a digital pH meter in a soil to water ratio of 2.5 (10 g soil in 25 ml distilled water). The SOC was analysed according to Walkley and Black (1934; Meersmans et al., 2009). K_{Exch} was determined by flame photometry, following soil extraction with NH_4OAc (Isaac & Kerbert, 1971). The P_{Olsen} was analysed using the Olsen method (Sims, 2000), and the Kjeldahl method was used to determine N_{tot} (Bremner, 1960; Rhee, 2001). The hydrometer method was used for soil texture analysis according to Gee and Bauder (1986). Bulk density was determined on undisturbed samples, collected from the centre of each of the three sections of all 27 terraces, using steel rings of 406 cm^3, after oven-drying at 105°C to constant weight.

Soil moisture content was measured in situ in triplicate all three sections of the 27 terraces, at ~10 cm soil depth with a hand-held time-domain reflectometer (TDR, Delta-T devices) three to four times during the 2018 and 2019 crop growing seasons. The measurements were conducted 2, 5 and 7 days after rainfall in 2018 and 1, 3 and 8 days after rainfall in 2019. The measurements were done in the 'belg' season (crops sown in March/April). Farmers managed their crops based on common practice and experience. In 2018 and 2019, crop yield and biomass were determined in triplicate on 1–4 m^2 areas, depending on the width of the stone bund terrace, in all three sections of the 27 terraces. In each section of a terrace, average value of the triplicate was considered for analysis. Crop yield and aboveground biomass were determined during the farmer's regular harvest. Sub-samples of crop yield were air-dried for 2 weeks and weighed. Sub-samples of aboveground biomass of maize were oven-dried at 70°C to constant weight but other crops such as teff, sorghum and broad bean were sun dried for 2–3 weeks in the field as the harvest was at the end of the rainy season.

2.3 | Data analysis

Model checking of constancy of variance and normality of errors was based on visual inspection of residual and QQ plots. The differences in soil properties, crop yield and aboveground biomass between upper, middle and lower sections were analysed using ANOVA and Tukey honest significant difference (TukeyHSD). Differences between means were considered significant if $p < .05$ (Table 2 and Figures 4 and 5). Regression was used to assess

TABLE 2 Soil properties at 0–20 cm depth in the upper, middle and lower sections of stone bund terraces ($n = 27$) in the Bokole-Karetha watershed, southwest Ethiopia (mean ± standard error)

Soil properties	Section in stone bund terrace			MS	*F*	*p*-Value
	Upper, mean	Middle, mean	Lower, mean			
BD, g cm^{-3}	1.14 ± 0.02	1.12 ± 0.02	1.14 ± 0.02	0.003	0.23	.69
pH_{H2O},1:2.5	6.18 ± 0.03	6.14 ± 0.03	6.16 ± 0.02	0.01	0.59	.46
Sand, %	28.55 ± 1.47	27.73 ± 1.45	29.72 ± 1.26	26.5	0.51	.60
Clay, %	43.45 ± 1.54	42.50 ± 1.63	38.97 ± 1.34	147.2	2.41	.09
Silt, %	28.00 ± 0.97a	29.77 ± 0.87ab	31.31 ± 0.73b	72.7	3.62	.03
SOC, g kg^{-1}	13.1 ± 0.7a	15.4 ± 0.9b	18.6 ± 1.1c	206.2	9.30	.00
N_{tot}, g kg^{-1}	1.4 ± 0.1a	1.6 ± 0.1ab	2.1 ± 0.1b	3.00	8.80	.00
K_{Exch}, mg kg^{-1}	228.3 ± 20.2a	232.9 ± 17.10a	328.1 ± 25.7b	97585	9.68	.00
P_{Olsen}, mg kg^{-1}	6.22 ± 1.64a	7.64 ± 1.86b	9.29 ± 2.11b	62.3	0.66	.52

Note: Means and standard errors followed by different letters differ significantly ($p < .05$) between upper, middle and lower sections of stone bund terraces. MS, mean square; *F*, *F*-statistics.

relationships between nutrient concentrations and soil moisture content on the one hand and grain yield on the other (Table 3; Figure S1). Statistical analyses were conducted using R 3.6.2 (R core Team).

3 | RESULTS

3.1 | Soil properties and soil moisture content

The slope of stone bund terraces was considerably smaller than the original slope, due to erosion in the upper sections and accumulation of sediment in the lower sections of the terrace (Table 1). On the stone bund terraces, the silt fraction increased significantly ($p < .05$) from the upper to the lower sections (Table 2). By contrast, the sand and clay fractions did not differ significantly between the sections ($p > .05$). Like the silt fraction, also the concentration of SOC, N_{tot}, K_{Exch} and P_{Olsen} increased significantly from the upper to the lower sections of the stone bund terraces (Table 2). On average, SOC concentrations were 21% and 42% greater in the lower sections than in the middle and upper sections, respectively. The concentration of P_{Olsen} and N_{tot} in the lower section was about 50% greater than in the upper section, whereas the concentration of K_{Exch} in the lower sections was about 40% greater than in the middle and upper sections.

The soil moisture content in the plough layer during the 'belg' season of both years increased from upper section to the lower section (Figure 3). The average soil moisture content in the lower section was 17.9% and 17.3% greater than in the upper section in the 2018 and 2019 'belg' seasons, respectively. Also, it was 13.5% and 10.7% greater in the lower than in the middle section in both years.

3.2 | Crop yield and biomass

The grain yields of maize, teff, broad bean and sorghum increased significantly ($p < .05$) from the upper to the lower sections in the stone bund terraces. Haricot bean showed the same tendency, but the differences were not significant, despite the average yield being about 50% greater in the lower section (Figure 4). The differences in grain yield of maize between the upper (0.7 and 1.4 t ha^{-1} in 2018 and 2019, respectively) and lower sections (2.6 and 4.6 t ha^{-1} in 2018 and 2019, respectively) were remarkable. In the lower section, the maize yield increased by almost 300% compared with the upper section of the stone bund terrace. The grain yields of teff, broad bean and sorghum were 30%–70% ($p < .05$) greater in the lower section than in the upper section. Like crop yield, the aboveground biomass of maize, teff, broad bean and sorghum was greater in the lower section compared with the upper and middle sections (Figure 5). For most crops, the differences between lower and upper sections were significant ($p < .05$).

The grain yields of maize, teff, haricot bean, broad bean and sorghum in the upper, middle and lower sections of stone bund terraces were positively correlated with the concentration of macronutrients (N_{tot}, P_{Olsen} and K_{Exch}) in the soil (Figure S1; Table 3). The N_{tot} had significant relationship with teff, maize and sorghum yield ($.33 < R^2 < .64$, $p < .05$), while P_{Olsen} showed a significant relationship with teff ($R^2 = .14$, $p < .05$). The K_{Exch} showed a significant relationship with maize, haricot bean and teff

TABLE 3 Relationship between crop yields and total nitrogen (N_{tot}), Olsen-extractable phosphorus (P_{Olsen}), NH_4OAc extractable potassium (K_{Exch}) and soil moisture content in the three sections of the stone bund terraces in the Bokole-Karetha watershed, southwest Ethiopia

Grain yield	N_{tot}	P_{Olsen}	K_{Exch}	Moisture
Haricot bean	ns	ns	y = 0.006K + 0.35	ns
Maize	y = 1.76N − 1.41	ns	y = 0.008K − 0.59	ns
Teff	y = 0.29N + 0.34	y = 0.03P + 0.82	y = 0.001K + 0.55	na
Broad bean	Ns	ns	ns	na
Sorghum	y = 2.02N + 1.04	ns	ns	y = 0.26M − 4.39

Note: na, not available; ns, not significant ($p > .05$). For significant linear regression ($p < .05$), the regression equation is given. In equation, y = yield, N = total nitrogen, P = Olsen-extractable phosphorus; K = NH_4OAc extractable potassium; M = moisture

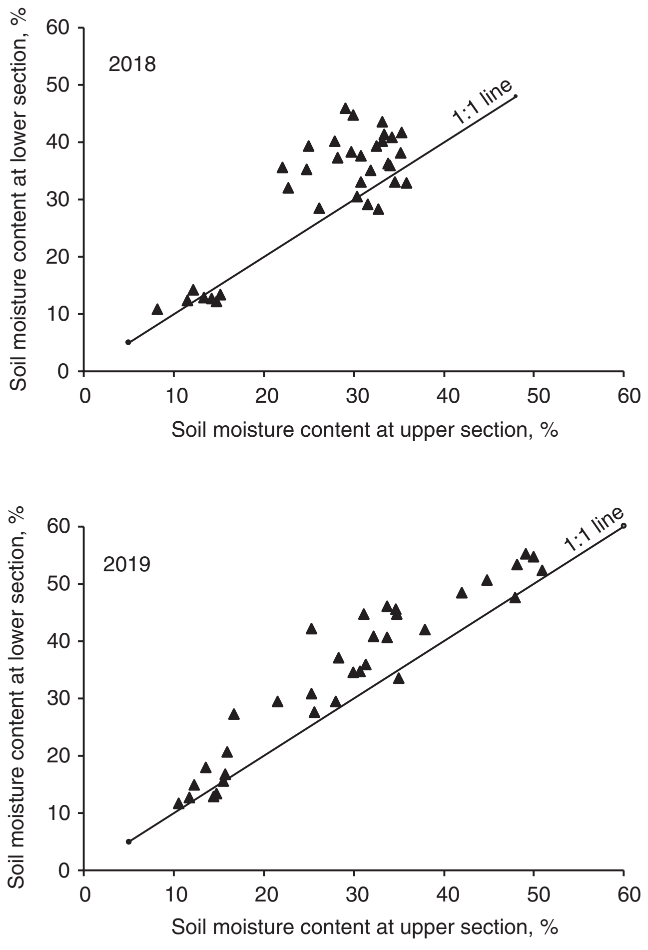

FIGURE 3 Scatter plot of volumetric soil moisture content ($n = 34$) in the upper and lower sections of stone bund terraces in 2018 (upper panel) and 2019 (lower panel) in the Bokole-Karetha watershed, southwest Ethiopia. Note: soil moisture content was measured for crops in the 'belg' season. The line represents the 1:1 reference line. Values above the 1:1 line indicate greater soil moisture content in the lower sections of stone bund terraces

($.29 < R^2 < .59$, $p < .05$). Also, the soil moisture content of the stone bund terraces had a positive relationship with maize, haricot bean and sorghum yield (Figure S1; Table 3) and significant relationships ($p < .05$) were observed between soil moisture and sorghum.

4 | DISCUSSION

Physical barriers such as stone bunds minimize surface flow connectivity, thus reducing erosion and increasing deposition of sediment (Subhatu et al., 2017; Wei et al., 2016). Sediment transport to the lower section of the intra-bund area is exacerbated by tillage erosion, which moves topsoil downslope (Gebrernichael et al., 2005). Long-term erosion in the upper section of intra-bund areas and deposition of sediment in the lower sections decreases the slope of the cultivated area, forming terraces. Compared to the original slope in the uplands of the Bokole-Karetha watershed, southwest Ethiopia, the slope of the terraces in the intra-stone bund areas was 23% (field 1) and by 33%–41% (fields 2–6) smaller (Table 1). Similar decreases in steepness were reported for slopes of terraces resulting from *Fanya juu* (Subhatu et al., 2018). By contrast, Mekonnen (2021) reported a decline in steepness only about 3% in northwest Ethiopia for >10-year-old soil bunds and *Fanya juu*. This may be attributed to topography, land management and soil type. Most likely, the gradual decline of the slope in intra-stone bund areas will result in reduced erosion, but to our knowledge the dynamics of the slopes of terraces has not been studied so far.

Our study showed that in the uplands of the Bokole-Karetha watershed after 8–14 years, the erosion-related decline in elevation of the soil surface at the base of the stone bunds in the upper section of the terrace was on average 0.98 m. Simultaneously, the deposition of sediment caused a 0.5 m increase in the elevation of the soil surface at the upslope side of the next soil bund. These values are large and somewhat greater than those reported for 3- to 21-year-old stone bunds in northern Ethiopia (0.7 m average stone bund height; Nyssen et al., 2007). A study in China, with annual rainfall of 966 mm, reported a more

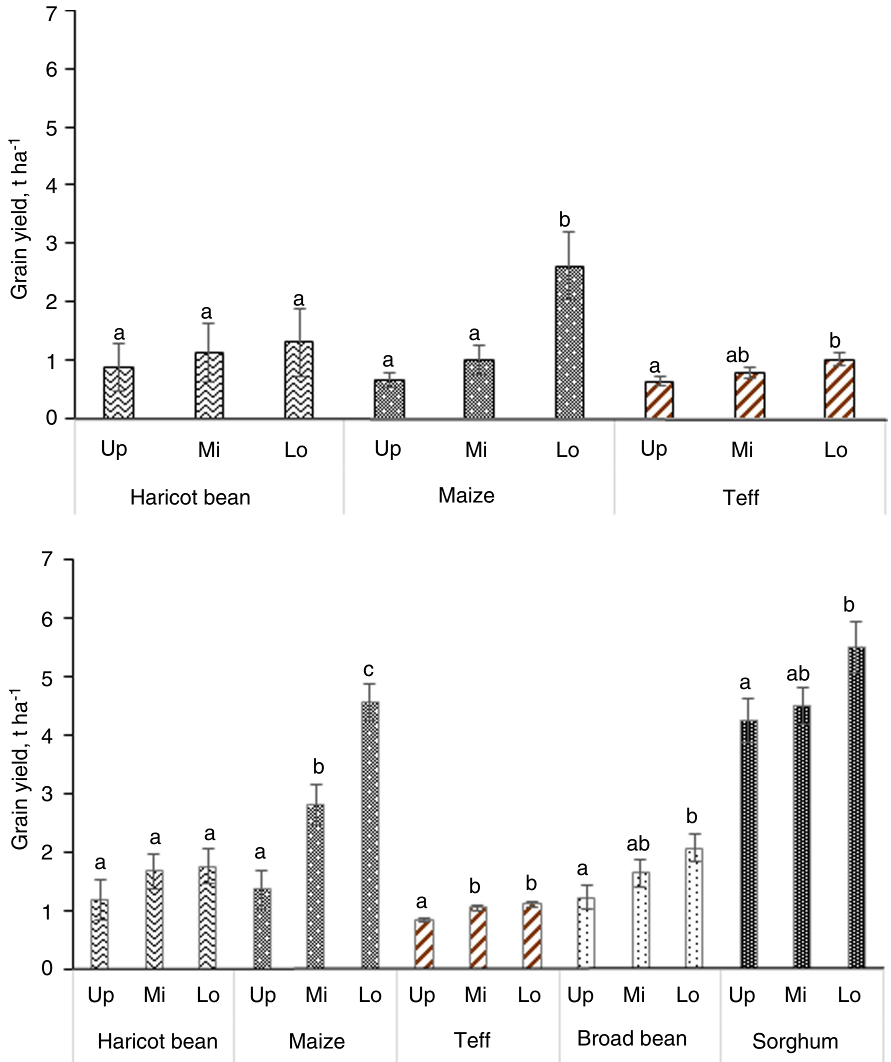

FIGURE 4 Grain yield in 2018 (upper panel) and 2019 (lower panel) in the upper (Up), middle (Mi) and lower (Lo) sections of stone bund terraces in the Bokole-Karetha watershed, southwest Ethiopia. Values are means and standard errors. Different letters indicate significant differences ($p < .05$) between sections. In 2018, $n = 2$, 7 and 11 for haricot bean, maize and teff, respectively; in 2019, $n = 2$, 2, 9, 3 and 7 for haricot bean, maize, teff, broad bean and sorghum, respectively. Note that '*n*' refers to the number of terraces, in each of which triplicate samples were collected in the upper, middle and lower sections

modest soil loss of up to 0.35 m at the downslope side of grass hedgerow terraces after 18 years of tillage on light textured Entisol (Liu et al., 2018). The greater soil loss in the Bokole-Karetha watershed than reported in other studies may be due to two seasons of cropping per year resulting in frequent cultivation and more tillage erosion. In addition, the relatively high rainfall and large contents of silt in the soil's parent material could increase soil transfer. The considerable increase in the silt fraction in the lower section of the stone bund terraces (Table 2) supports earlier studies indicating that in particular the silt fraction is susceptible to erosion (Kuhn et al., 2012; Wischmeier & Smith, 1978). In a recent study in the same area, Wolka et al. (2021) found that soil erosion was enhanced by silt content. Also, several other studies suggest the sensitivity of the soil's silt fraction to erosion, for example Walle and Sims (1999) and Siriri et al., (2005).

As hypothesized (Hypothesis I), our result showed greater concentrations of SOC and nutrients (N, P and K) in the lower sections of stone bund terraces, indicating that water erosion transfers SOC-rich materials (Müller-Nedebock et al., 2016). Essential plant nutrients including N, P and K are concentrated in the topsoil (upper 20 cm), due to decomposition of organic matter (Jobbágy & Jackson, 2001) and occasional fertilizer input after planting of, for example teff. Due to the transfer of macronutrients to the lower sections of the stone bund terraces, both in dissolved and suspended form (e.g. Wolka et al., 2021), greater concentrations of N_{tot}, P_{Olsen} and K_{Exch} and SOC were observed here than in the upper sections. Also, enhanced plant production in the lower section (Figures 4–6) may add SOC. Our findings confirm previous studies reporting increased SOC and nutrient concentrations in surface soils of the lower sections of stone bund terraces in Burkina Faso (Zougmoré et al., 2002) and in Honduras (Walle & Sims, 1999), and in terraces developed from *Fanya juu* in Anjeni watershed, northwest Ethiopia (Amare et al., 2013). By contrast, Vancampenhout et al. (2006) reported insignificant difference in SOC between upper and lower section in stone bund terraces of northern Ethiopia, where comparatively little change in slope (viz. little erosion and

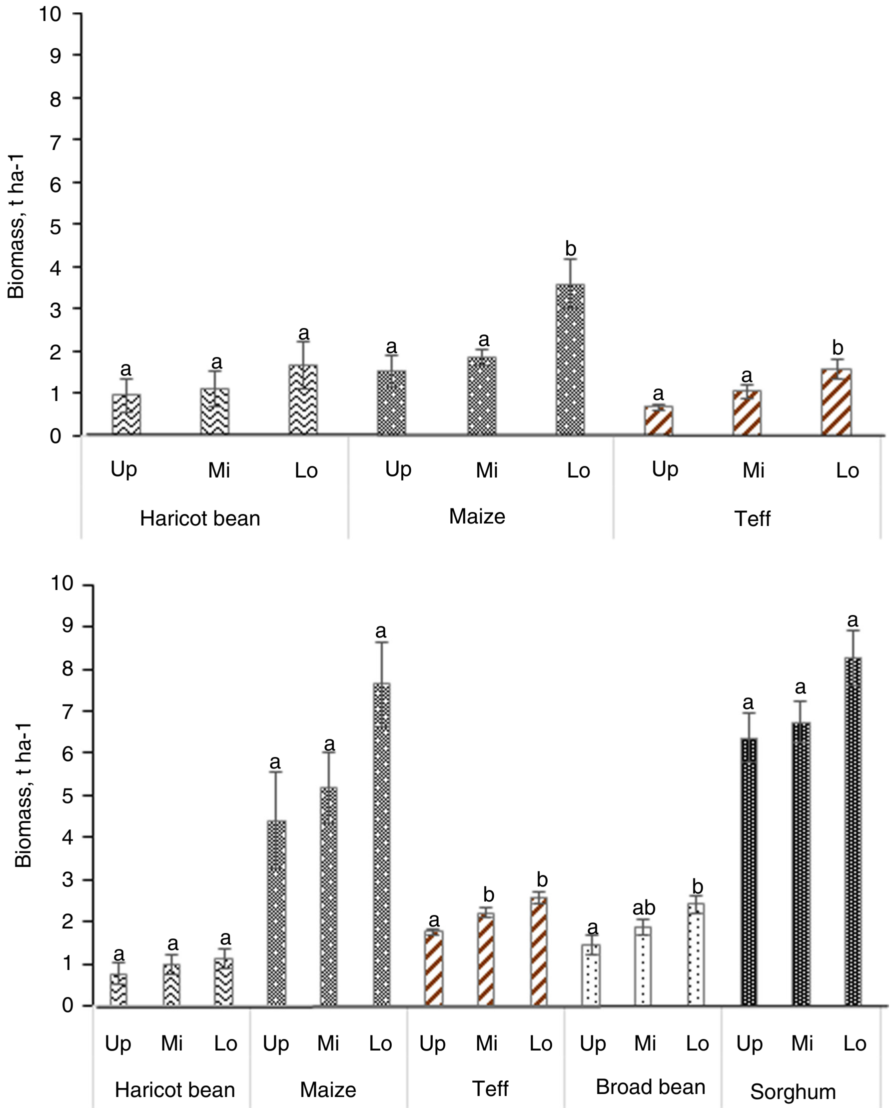

FIGURE 5 Aboveground biomass in 2018 (upper panel) and 2019 (lower panel) at upper (Up), middle (Mi) and lower (Lo) plots of stone bund terrace in the Bokole-Karetha watershed, southwest Ethiopia. Values are means and standard errors. Different letters indicate significant differences ($p < .05$) between sections in the field. In 2018, $n = 2$, 7 and 11 for haricot bean, maize and teff, respectively; in 2019, $n = 2$, 2, 9, 3 and 7 haricot bean, maize, teff, broad bean and sorghum, respectively. Note that 'n' refers to the number of intra-stone bund area, or terrace, in each of which triplicate samples collected

sedimentation) most likely resulted in not much difference in SOC between the upper and lower sections. Both age of the stone bund terrace and magnitude of erosion and deposition are important factors of variation.

Despite enhanced plant growth and yield in the lower section of stone bund terraces (Table 2, Figures 4–6), causing greater evapotranspiration and thus loss of soil water (Zhang & Schilling, 2006), their relatively high soil moisture content may be attributed to the transfer of water from the higher sections. In addition, the relatively high SOC content in the lower sections enhances the soil's water holding capacity (Franzluebbers, 2002). The greater soil moisture content in the lower section of terraces, which supports the second hypothesis, has received little attention in previous studies and most likely is a contributing factor to enhanced plant growth generally seen upslope from stone bunds.

The increased biomass production and crop yield in the lower section of the terraces are significantly correlated with soil moisture and soil nutrient content (Table 3; Figure S1), supporting the third hypothesis. The variations in crop growth can also be observed by differences in the greenness between the upper, middle and lower sections, where differences were particularly clear if no inorganic fertilizer was applied, for example sorghum (Figure 6). Our findings are confirmed by other studies, which reported greater yield of maize, wheat and sorghum in lower sections of terraces above naturally formed hedgerows and *Fanya juu* (Amare et al., 2013; Kagabo et al., 2013; Siriri et al., 2005).

In the Bokole-Karetha watershed, the yield of most crops increased by about 30%–70% in the lower section of the terraces. However, maize showed even more remarkable increases (~300%) when comparing upper and lower sections of stone bund terraces. Even though maize is among the crops most sensitive to moisture and nutrient availability (Folberth et al., 2013), the observed spatial difference was significantly higher than reported in earlier studies, for example ~60% in Ethiopia (Amare et al., 2013) and 19% in Kenya (Mbugua et al., 2019). Also, teff

FIGURE 6 Difference in greenness of fertilized teff (upper panel) and non-fertilized sorghum (lower panel) between upper, middle and lower plots of a stone bund terrace in the Bokole-Karetha watershed, southwest Ethiopia

in the Bokole-Karetha watershed showed significantly greater grain yield and aboveground biomass in the lower sections, even after applying inorganic fertilizer. The observed differences between upper and lower sections are significantly higher than those reported for northern Ethiopia by Vancampenhout et al. (2006).

In the Bokole-Karetha watershed, controlling soil erosion is a priority to maintain cropland productivity. Although stone bunds are effective in counteracting erosion and loss of soil fertility, the significant difference in crop yields between upper and lower sections of the terraces has implications for the management of stone bund terraces. Commonly, farmers dismantle old stone bunds and construct new ones in the mid-sections, using the same stone. In this way, sediment that has accumulated for many years in the lower section is redistributed to less productive areas that previously were the upper section of the next stone bund terrace. Also, in Uganda farmers re-position bunds and destroy terraces every 5–10 years (Siriri et al., 2005). Since the generally low yields in the upper section of terraces are due to deteriorating soil quality, associated with erosion, adaptive management targeted to the upper sections, for example through the addition of soil nutrients and organic matter may be advised. Wibawa et al. (1993) show that applying fertilizer following spatial variability in soil fertility increases yield. That means, targeted fertilizer application to low fertility spots in agricultural fields, for example, upper sections of intra-stone bund area could improve yield. In addition, adapting crop selection to the different sections (upper, middle and lower) may improve yield. Farmers should be technically supported to implement adaptive fertilizer application and crop choice.

5 | CONCLUSIONS

In southwest Ethiopia, erosion-related soil degradation is a challenge in cultivated hilly areas with steep slopes. Cross slope barrier soil and water conservation techniques such as stone bunds have been practiced in watershed management for more than a decade in areas such as the Bokole-Karetha watershed. Here, the stone bunds gradually result in stone bund terraces with a smaller slope. The formation of terraces introduces spatial variability in soil quality and crop growth. The soil and water conservation effect of the 8- to 14-year-old stone bund terraces resulted in lateral increases in soil fertility and crop yield, when comparing upper and lower sections. Erosion in upper sections removes surface soil and transfers particularly the silt fraction and soil organic carbon to the lower sections. In addition, there is a significant transfer of plant nutrients (N_{tot}, K_{Exch} and P_{Olsen}) to the lower sections. Enhanced SOM content and downslope transfer of water increases soil moisture of the plough layer in the lower sections. Both grain yield and aboveground biomass in the lower sections of the terraces were greater than in the upper sections for all considered crops (haricot bean, maize, teff, broad bean and sorghum), with greatest increases (up to fourfold) being observed for maize yield. Farmers in the Bokole-Karetha watershed dismantle old stone bunds and construct new ones in the mid-sections of the terraces to re-distribute SOM and plant-available nutrients in new intra-bund areas. Alternatives such as improved fertilizer applications and crop selections may be considered to compensate for lower yields in the upper sections. To implement management options, farmers should get technical support.

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DATA AVAILABILITY STATEMENT:

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Kebede Wolka https://orcid.org/0000-0002-8121-4961
Birhanu Biazin https://orcid.org/0000-0002-9895-7796

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