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Agricultural sediment reduction using natural herbaceous buffer strips: a case study of the east African highland

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Abstract

Buffer strips are permanently vegetated areas situated immediately adjacent to streams and provide an efficient and economical way to reduce nutrient loads from agricultural areas, but no studies exist of their effectiveness from the East African highlands. We thus evaluated the sediment filtering capabilities of natural herbaceous buffer strips under tropical highland climatic conditions. Overland flow samples were collected at field edges and at various positions in herbaceous buffers and tested for total suspended sediment, nitrate-nitrogen and total phosphorus. There was a significant effect ($P < 0.05$) of distance from field edge on the mean values of nutrients. On average, a 10.0 m herbaceous buffer reduced the total phosphorus by 99%, total suspended sediment by 94% and nitrate-nitrogen by 85%. Altogether, the results suggest that herbaceous buffer strips are important to include in watershed management in agriculturally dominated tropical highlands in order to control sediment loss, stream siltation and the washout of nutrients.

Introduction

Runoff from agricultural fields results in the transport of excess sediments and nutrients to receiving streams (Guo *et al*. 2015; Valle Junior *et al*. 2015), and this has been indicated as a major source of nutrients, causing eutrophication and sedimentation of streams (Adela 2015). Buffer strips, which are permanently vegetated areas adjacent to rivers or streams, can provide an efficient and economical way to reduce agricultural nonpoint source pollution (Mander *et al*. 1997; Weller *et al*. 2011; Guo *et al*. 2015). Several studies have investigated the effectiveness of buffer strips in removing suspended solids, nutrients and pesticides from agricultural overflow (Le Bissonnais *et al*. 2004; Borin *et al*. 2005; Mankin *et al*. 2007). The efficiency of buffer strips depends on factors such as overflow volume and characteristics of the surrounding area (e.g. slope, size, land use) and the plant composition of the buffer strips (herbaceous, woody or both) (Yuan *et al*. 2009). Further, the pollutant-trapping potential of buffer strips can range from 50 to 98% for suspended solids (Rudra & Whiteley 2000), 70–98% for phosphorus and 70–95% for nitrate (Aguiar *et al*. 2015).

Buffer strips, act as filters by increasing surface roughness, which augments infiltration and decreases flow volumes and speed. This decreases the transport capacity of runoff and increases sediment deposition in the buffer strip (Rose *et al*. 2002). According to Schmitt *et al*. (1999), these processes have a direct impact on sediment-bound nutrient transport and an indirect impact on soluble compounds by increasing infiltration (Lee *et al*. 2003).

The width of buffer strips has been shown to be the main factor influencing the efficiency of buffer strips (Liu *et al*. 2008). The minimum buffer width for pollution control differs among studies; some authors suggest a minimum buffer width of 7 m in order to remove sediment and nutrients (Lee *et al*. 2003), other studies have shown 50–80% removal of sediment with 3–5 m wide buffer strips (Schmitt *et al*. 1999) and Rudra & Whiteley (2000) reported that doubling the flow path from 10 to 20 m enhanced removal effectiveness by less than 5%.

Most studies on the efficiency of buffer strips are from temperate zones (Borin *et al*. 2005; Smiley *et al*. 2011; Otto *et al*. 2012), and few studies have addressed the use of buffer strips in tropical areas (Garrity 1999; Spaan *et al*. 2004). In the southwest Ethiopian highlands, where this study was conducted, land degradation and soil erosion are the main factors that affect streams (Keddi & Moges 2016). Accordingly, agricultural runoff is considered to be the main source of pollution, sedimentation and eutrophication of streams (Adela 2015). In East Africa, where sheet and rill flow represent a major part of the runoff from agricultural fields (Haregeweyn *et al*. 2012), the implementation of natural buffer strips has been suggested as an effective management tool against pollution, sedimentation and eutrophication (Ambelu *et al*. 2010; Demissie *et al*. 2013).

Local research is also necessary to gain information on buffer strip performance. However, the importance of natural herbaceous buffer strips in tropical highlands has not been evaluated in field-based experiments. Accordingly, to answer if there is a significant reduction in sediment across buffer strips, we evaluated the effect of a buffer on a plot established in the highland area of Jimma, which experiences higher agricultural and anthropogenic activities compared to lowland areas. The results are of interest to managers of riparian areas in tropical humid zones. Furthermore, we know of no other study that has explored the effects of buffer strips based on field-based data in the tropical highlands of Africa. Thus, this study serves as a useful case study to evaluate the performances of buffer strips. The aim of the present study was to examine the effectiveness of herbaceous buffer strips in reducing the concentrations of nonpoint source nutrients and sediments from agricultural fields in the East African highland.

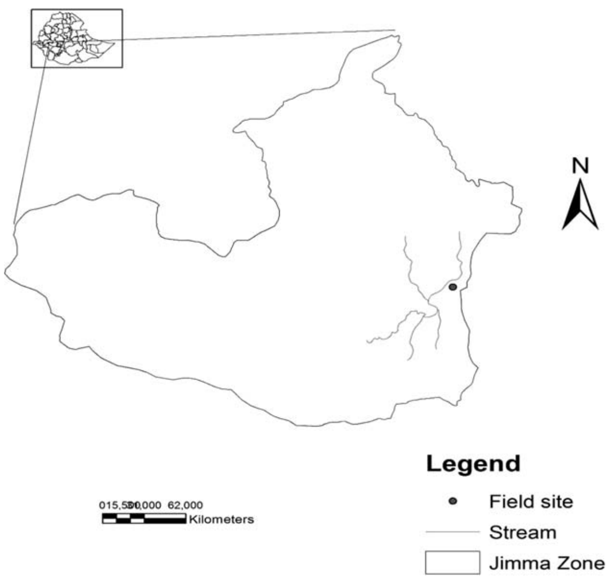

Fig. 1. Map of the study area.

Materials and methods

The study site was located on a private farm near the Gilgel Gibe I reservoir in Sekoru, Jimma zone, Ethiopia (Fig. 1) and was dominated by a multispecies herbaceous buffer strip. Vegetation covers 75% of the buffer strip and the dominant plant species were *Digitaria ternata* (A. Rich.) Stapf, *Trifolium rueppellianum* Fresen and *Guizotia scabra* (Vis.) Chiov. The site is considered representative of buffer strips found throughout the area. A 10- by 20-m wide field plot was established. The surrounding area draining into the field site was 50×50 m^2, or 0.25 ha, with an average slope of 4%. The buffer strip received runoff predominately in the form of sheet flow from the same field where a wheat crop was being grown. The soils within the buffer strip and the adjacent agricultural field were classified as a sandy loam (Ethiopian Mapping Agency (EMA) 1994). The agricultural field had a history of annual rotation between corn and wheat, with fertilizers being added during both crop years. The climate of the study area is classified as tropical humid and belongs to the high altitude cool tropic area of the country. The seasonal rainfall distribution has a unimodal pattern, with up to 60% of the rainfall falling during the rainy season, lasting from May to September (Demissie *et al*. 2013).

The experiment was conducted in the field during periods of rainfall and in the agricultural season of 2015. Flow collectors were installed to sample overland flow at the field site (Fig. 2). The overland flow collectors were adapted from Schoonover *et al*. (2006) allowed for the collection of sheet

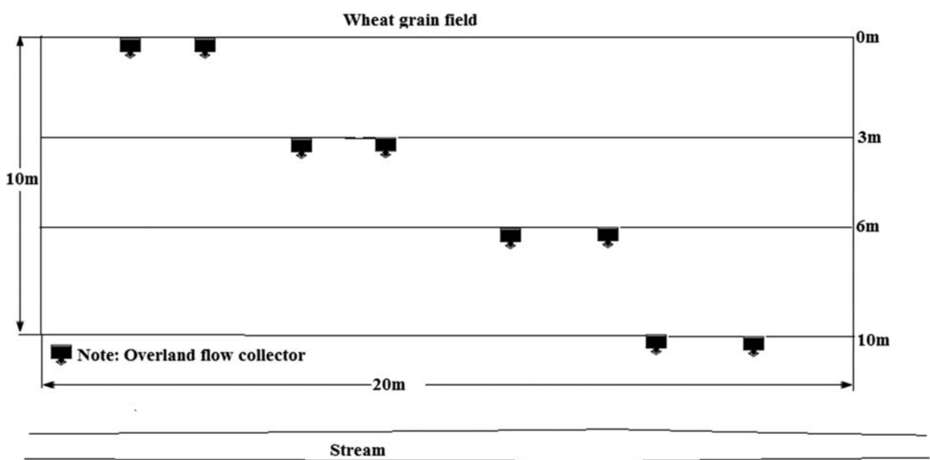

Fig. 2. Schematic illustration of the sampling plots. The first two overland flow collectors at 0 m (field edge) directly received runoff from the wheat grain field. These overland flow collectors were thus used as a baseline. Overland flow that passed into the herbaceous buffer was sampled at three-, six- and ten-m distances.

flow draining from the agriculture field. Overland flow collectors were made from 0.20-gauge galvanized steel and had a collecting surface width of 45 cm. Eight overland flow collectors were installed in the plot, with two replicates (1.0 m apart) per treatment [0.0 m (benchmark), 3.0, 6.0 and 10.0 m]. Water passing through the collectors (Fig. 2) was directed into a 2-cm plastic tube and subsequently into a buried 2-L plastic bottle.

Overland flow samples collected in the field were transported back to the laboratory within 12 h of each runoff event and were stored at 4°C until further analysis. A tipping bucket rain gauge obtained from the National Meteorological Agency, Jimma Branch, was installed at the site to measure precipitation.

Sediment, nitrate nitrogen and total phosphorous analysis

Following two successive rain events, a total of 16 (2×8) samples were collected and analyzed for total suspended sediment (TSS), nitrate-nitrogen (NO_3-N) and total phosphorus (TP). The runoff samples were stirred to suspend the sediment before two aliquots were taken for analysis. A 0.05-L aliquot was used for the determination of TSS, and a 0.025-L aliquot was used to determine NO_3-N and TP. TSS, NO_3-N and TP were measured in the laboratory according to standard methods (APHA *et al*. 1995).

The data were tested for normality and were later log ($x + 1$) transformed to improve normality. Significant effects of distance from the field edge on nutrient concentrations were determined using a one-way ANOVA, and significant differences among treatment groups were identified using Tukey's multiple range test ($\alpha = 0.05$). A regression analysis was used to study the relationships between buffer distance and sediment reduction. The statistical analyses were performed using Sigma Plot version 12 software.

Results and discussion

We recorded precipitation of 23 mm in the first and 35 mm in the second event. The first precipitation event lasted for 7 h, while the second occurred for 5 h. The total precipitation in the two sampling periods was 58 mm, with an average intensity of 4.8 mm h^{-1}.

The result revealed that the buffer strips reduced runoff, sediment and nutrients from the crop field to the stream (Table 1). For example, TSS at the field edge was 0.826 mg L^{-1} but only 0.051 mg L^{-1} at the site that is 10 m from the crop field. The TP at the field edge was 0.066 mg L^{-1} and only 0.006 mg L^{-1} at the site that is 10 m from the crop field. A one-way ANOVA indicated that the average TSS concentration at 10 m was significantly ($P < 0.05$) lower than that observed at the field edge, and a similar trend was observed for TP. The average NO_3-N concentration at the field edge was 0.31 (0.12) mg L^{-1}, whereas the average NO_3-N concentration at the 10-m buffer distance was 0.048 (0.03) mg L^{-1}, with significant differences (Tukey's post hoc test; $P < 0.05$).

Table 1 Runoff, sediment, total nitrate and total phosphate collected from herbaceous buffer strip plots

Buffer strip distances (m)	Runoff (L)	TSS (mg^{-l})	Total-P (mg^{-l})	Nitrate-nitrogen (mg^{-l})
0	1.970a	0.826a	0.066a	0.310a
	(0.02)	(0.16)	(0.008)	(0.06)
3	1.780a	0.469ab	0.035b	0.224ab
	(0.10)	(0.08)	(0.002)	(0.03)
6	1.307b	0.195bc	0.008c	0.156bc
	(0.13)	(0.01)	(0.0005)	(0.02)
10	0.971c	0.051c	0.0007d	0.048c
	(0.08)	(0.02)	(0.0005)	(0.01)

Each value is the mean of two precipitation events from two replicated plots. The cropland source area for each plot was 50 by 50 m (0.25 h), and the average intensity of the events was 4.8 mm h^{-1}. Values within a column with the same letter code are not significantly different (Tukey's post hoc test; $P < 0.05$)

Since the volume of the surface runoff was reduced as it travelled through the buffers, the concentration of nutrients was reduced to a much greater degree. Herbaceous buffer width and configuration may affect the distribution and migration of TSS, TP and NO_3-N; nutrient concentrations were not constantly reduced over the entire buffer strips (Fig. 3). The results show that the first 3 m of a buffer is responsible for a significant reduction in TP of 47% (Tukey's post hoc test; $P < 0.002$), whereas there is no significant reduction in TSS and NO_3-N in this first buffer width (Tukey's post hoc test; $P > 0.05$ for both). The natural herbaceous buffer showed a significant reduction of TSS and NO_3-N at the 6-m buffer width (Tukey's post hoc test; $P < 0.05$). In the first 6 m, 76% of the TSS in the runoff had been removed, while at 10 m, 94% had been retained (Fig. 3a). Similarly, 88% of the TP was removed at the 6-m distance and 99% at the 10-m distance (Fig. 3b). Nitrogen was removed from the surface runoff, although to a lesser extent than the TSS and TP. Nitrate uptake seems to be linear with distance from the source, with an average of 50 and 85% removed by 6 and 10 m, respectively (Fig. 3c).

Buffer width is an important characteristic affecting the performance of buffer strips (Yuan *et al*. 2009). In the present study, the concentrations of TSS, TP and NO_3-N declined from the field edge toward the end of the 10-m buffer strip. There were significant differences in nutrient levels for buffer distances. The nutrient trapping efficiencies reported here are comparable with those found in the literature. For example, the TSS declined by 76% within the first 6 m of buffer. A similar result was reported by Daniels & Gilliam (1996). Related research has shown that buffer widths of 4–6 m can

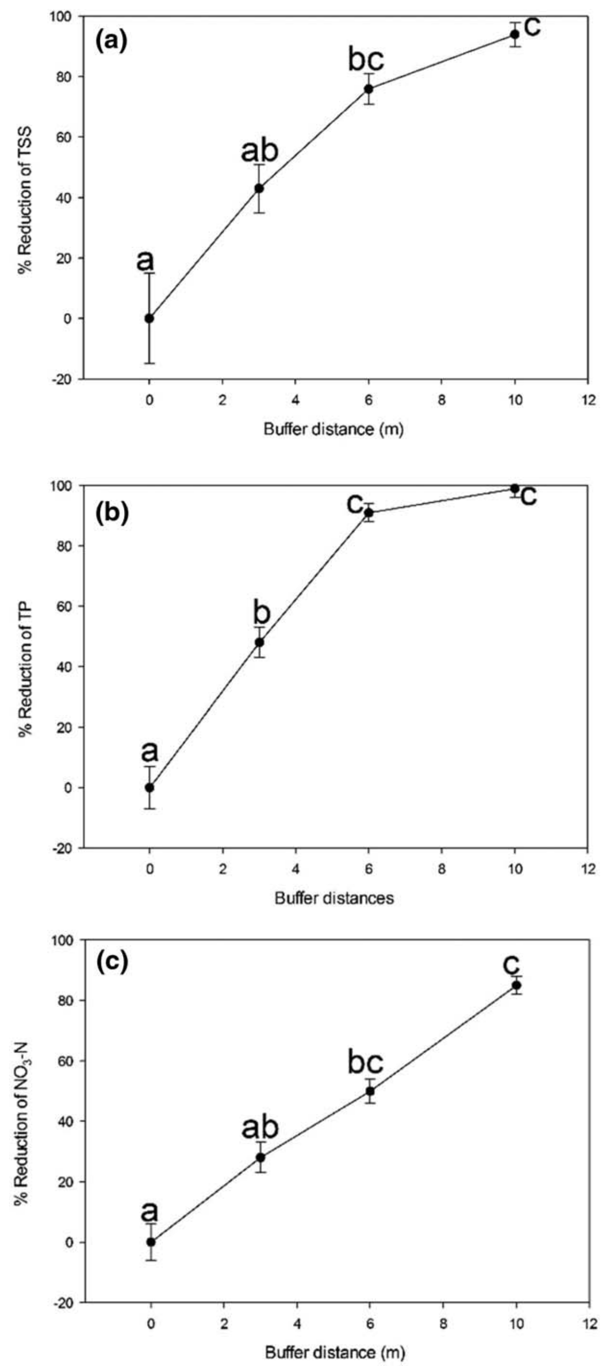

Fig. 3. Percentage nutrient reduction using buffer strips. Reduction in (a) total suspended sediment, (b) total phosphorus and (c) nitrate-nitrogen across the experimental grass buffer strip. Different letters designate significant differences (Tukey's post hoc test; $P < 0.05$) among buffer distances.

reduce sediment loading by more than 50% (Blanco-Canqui *et al*. 2004; Borin *et al*. 2005).

Herbaceous buffers can decrease the sediment and nutrient overflow from cultivated fields mainly due to the ability

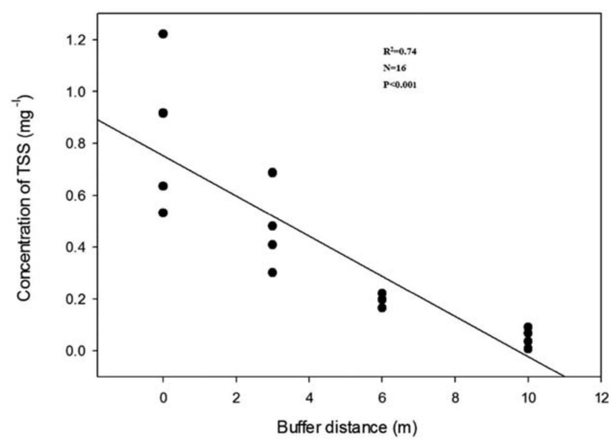

Fig. 4. Regression between buffer distance and concentration of total suspended solids based on two-time data. Each point represents the concentration of total suspended sediment at different buffer distances ($P < 0.001$).

to delay surface runoff, promote infiltration and absorb nutrients (Helmers *et al*. 2008). The uniform distribution of the plants on the buffer strip may be responsible for the removal of sediment (Lee *et al*. 1998). The results indicate that the 10-m wide herbaceous buffer strip was effective in removing sediment and sediment-bound nutrients. The contribution of buffer strips in retaining soil structure and permeability is well known (Snyder *et al*. 1998). Buffer strips modify the soil structure by adding organic matter, which improves soil aggregates and thereby increases the infiltration capacity (Blanco-Canqui *et al*. 2004). Infiltration also occurs within the buffer, which leads to an overall reduction in the outflow of water and other contaminants. During infiltration, sediment-bound nutrients may be sieved from the water through the soil profile (Abu-Zreig *et al*. 2003). Infiltration into the buffer soil decreases surface runoff, which in turn reduces the ability of runoff to transport soil particles.

Buffer strips are an effective technique to protect rivers and streams from the negative impacts of adjacent land uses, including pasture and agriculture. The sediment trapping efficiency-to-buffer width relationship can be best fitted with a regression model (Fig. 4). According to this relationship, the sediment trapping efficiency is close to its maximum value at 10 m. It was additionally observed that the effectiveness differed among buffer width categories. The efficiency of buffer strips depends on external factors including but not limited to buffer width, slope, area ratio of buffer to source field, vegetation composition and soil type (Yuan *et al*. 2009). Buffer width is the most studied factor. It has been reported that the sediment filtering performance of buffer strips is a partial function of buffer width (Abu-Zreig *et al*. 2004). Herbaceous buffer strips could thus be established at sites with high erosion risk, such as agricultural fields. Regardless of the area ratio of buffer to an agricultural

Table 2 Summary of published data on percentage reduction of total suspended sediment from surface runoff in grass riparian buffer zones

Location	Vegetation type	Width in meter	Buffer history/ age(year)	% reduction of sediment	Reference
USA	Grass	6	Remnant	80	Daniels & Gilliam (1996)
France	Grass	6	Planted/1.5	91	Patty *et al*. (1997)
		12	Planted/1.5	97	
		18	Planted/1.5	98	
USA	Grass	30	Planted	92	Clausen *et al*. (2000)
USA	Grass	7.5	Planted/2.5	77	Schmitt *et al*. (1999)
		17	Planted/2.5	83	

field, a 10 m buffer optimized the sediment trapping capability, similar results were reported in Rudra & Whiteley (2000).

Sediment is one of the most prevalent and significant pollutants of streams in southwestern Ethiopia (Adela 2015). Buffer strips are considered to be the best method for improving stream water quality by reducing sediment and the nutrient load in runoff (Mander *et al*. 1997; Weller *et al*. 2011; Guo *et al*. 2015). Several studies have investigated the effectiveness of buffer strips in removing sediment and nutrients (Le Bissonnais *et al*. 2004; Borin *et al*. 2005; Mankin *et al*. 2007). Accordingly, despite differences in the experimental conditions of the work presented here, such as the length of the experiments and the limited seasonal coverage, the sediment trapping efficiencies in the present study were quite comparable with those found in other studies looking at buffer strips (Daniels & Gilliam 1996; Patty *et al*. 1997; Schmitt *et al*. 1999; Clausen *et al*. 2000); for details, see Table 2.

Conclusions

(1) This study evaluated the performances of herbaceous buffer strip in the tropical Ethiopian highland. The result demonstrated that buffer strip can be effective filters of agricultural sediment.
(2) This provides justification for the incorporation of buffer strip management and restoration designs into watershed management plans in the tropical highland areas.
(3) Future investigations comparing buffer strip performance across different seasons, soil type, slopes, land use and field size are essential for effective future utilization of buffer strips in Ethiopia.

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