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Critical slope length for soil loss mitigation in maize-bean cropping systems in SW Kenya

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ABSTRACT

Soil erosion and land fragmentation threaten agricultural production of sub-Saharan African highlands. At our study site in Western Kenya, farm size is mostly < 2 ha, laid out in narrow strips in slope direction and ploughed downhill. Soil conservation measures like hedgerows and green manures can reduce effective slope length for erosion, but compete with crops for space and labour. Knowledge of critical slope length can minimise interventions and trade–offs. Hence, a maize–bean intercrop (MzBn) slope length trial on 20, 60 and 84 m long plots, replicated twice on three farms was carried out in Rongo, Migori County, during one rainy season. Soil loss from 84 m slope length (SL) plots was 250 % higher than from 60 m and 710% higher than from 20 m plots, while soil loss from 20 and 60 m plots did not differ ($p < 0.05$). Conversely, runoff was lower on the 84 m than on the 60 m ($p < 0.05$) or the 20 m SL ($p < 0.05$). Across all three farms slope gradient and length had highest explanatory power to predict soil loss. At individual farm level, under similar slope and soil texture, slope length and profile curvature were most influential. Regarding results of the slope length experiments, food crop plot lengths < 50 m appear essential considering soil loss, sediment load, and soil loss to yield ratio under the given rainfall, soil and slope (10–14%) conditions. Our results call for designing integrating slope length options and cropping systems for effective soil conservation. We recommend planting Mucuna and Calliandra–hedgerows as buffer strips below the critical slope length, and legume cash crops and maize uphill. Such approaches are critical against the backdrop of land fragmentation and labour limitation to sustainably maximise food production from the available land area in the region.

1. Introduction

Soil erosion by water constitutes a major threat to agricultural land use and ecosystem functions in the humid tropics, and detrimentally impacts agricultural productivity and food production (Defersha and Melesse, 2012a). For instance, the Kenyan highland regions are prone to water–driven soil erosion due to erosive rainfall, steep topography and intensive cropping systems (Defersha and Melesse, 2012b). Many farmers are aware of causes, indicators and consequences of erosion in the landscape (Okoba and Sterk, 2006). Lack of adequate soil cover particularly in maize–based systems adds to soil vulnerability to erosion (Chaplot et al., 2005; Dung et al., 2008). Erosion rates in Kenya range from 15 to 61 Mg $ha^{-1}yr^{-1}$, and rates up to 90 Mg $ha^{-1}yr^{-1}$ have been reported for erosion prone areas (Angima et al., 2003). Gachene et al. (1997) observed that erosion depletes soil fertility by selectively removing the smallest size fractions, particularly rich in C or nutrients, posing a major threat to small-scale crop production (Tiffen et al., 1994).

Typical family farms in South–Western Kenya are mostly fragmented due to a rapidly growing population (Muyanga and Jayne, 2014), with farm sizes typically between 0.5 and 2 ha (David and Swinkels, 1994). Farms are mostly laid out in strips in slope direction and fields ploughed downhill. In this context, slope length and gradient have a pronounced influence on water erosion, equating them to energy factors that maximise surface runoff (Bagio et al., 2017). On steep slope gradients, precipitated water spends less time to infiltrate the soil, and this increases the magnitude and rapid flow of runoff which subsequently has a higher erosive power to erode the land (Morgan, 2005; Poesen et al., 2003). Slope length on the other hand affects soil erosion through exponentially increasing speed and volume of runoff water, resulting in increased capacity of the runoff to disaggregate soil and transport sediments (Bagarello and Ferro, 2010). These processes can result in a shift from sheet to rill and gully erosion. Slope length related studies in

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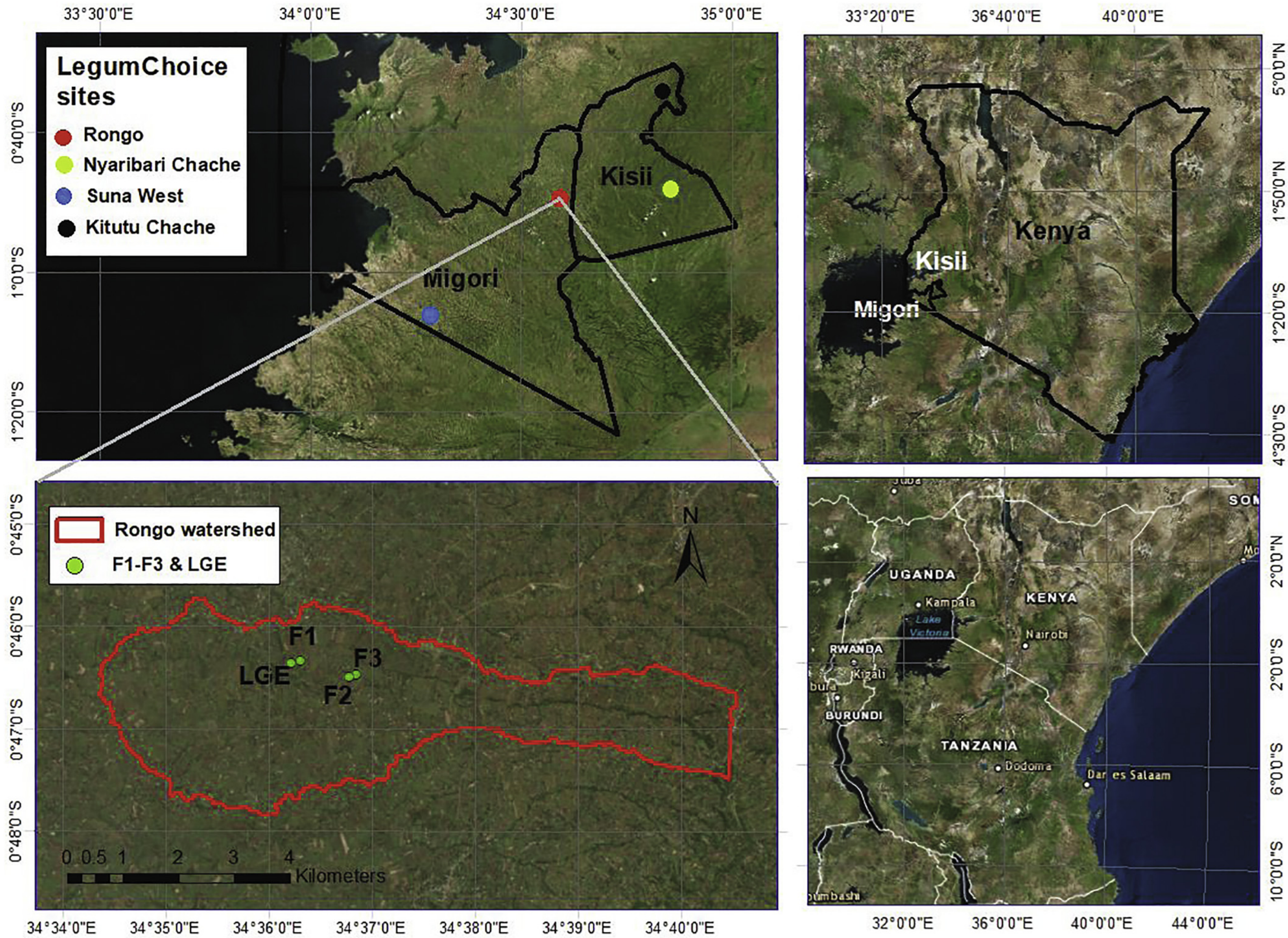

Fig. 1. Study sites of the LegumeChoice project and locations of legume groundcover experiment (LGE) and slope length study farms F1-F3 in Rongo watershed.

temperate regions have chronicled different and contradicting relationships between slope length, soil erosion and runoff (Bagio et al., 2017). These findings are not necessarily transferable to tropical conditions in Africa due to the role of different clay minerals and sesquioxides on soil erodibility in the context with slope length, and the exponential increase of soil loss with slope length due to structural degradation (Lal, 1997). Few studies on critical slope length have been conducted in Africa, often not under typical land tenure conditions, e.g. neglecting crucial small–scale topography and local drain direction, or limited to short slopes of a few metres. Thus, effects of slope length on soil erosion are not yet sufficiently understood (Bagio et al., 2017).

Traditional soil fertility restoration practices such as shifting cultivation, fallowing and crop rotations are no longer practiced under conditions of land fragmentation (Mugendi et al., 2011). For these reasons several soil management practices and strategies of soil loss mitigation in conservation agriculture have received global attention, especially practices that encourage maintenance of soil surface cover (Bescansa et al., 2006; Jordán et al., 2010). Criteria for effective soil conservation according to (Wang et al., 2017) are provision of cover to absorb kinetic energy of raindrops, reducing splash erosion and overland flow velocity (Sadeghi et al., 2015); improving the physical and chemical properties of soil, e.g. aggregate stability (Jordán et al., 2010); and creating a rough surface to decrease runoff velocity and enhance infiltration (Vermang et al., 2015).

Although the use of cover legumes as a (cost-) effective soil conservation measure against erosion (Thomas, 2000) has been recommended to farmers in Kenya, their adoption rate, however, is still low. Govers et al. (2017) stated that adoption of soil conservation measures is not attractive to farm households unless accompanied by economic added value. Many grain and fodder legumes offer this added value, if planted in the appropriate socio–ecological context (Ojiem et al., 2006). Along the same lines, soil conservation measures that reduce slope gradient and length (e.g. terraces, grass filter strips, hedgerows) are recognized for their efficacy but only implemented if providing added value or incentive is obtained. Among the main trade–offs of these measures are labour costs and availability (Saint-Macary et al., 2010) and competition with crops for space, water and plant nutrients (Tuan et al., 2014). The application of soil conservation measures at specific parts of the slope rather than over the entire slope length can be an effective approach to reduce installation costs and minimise competition between crops and legumes, which increases the likelihood of implementation.

The purpose of this study was to better understand slope length impact on runoff and erosion under typical maize (*Zea mays*) and common bean (*Phaseolus vulgaris*) intercropping system. We analysed 19 rain events in a range between 0.2 and 40 mm precipitation representing different stages of groundcover during the course of the season. We hypothesized that under uniform land use and management system on an inclined plane of strongly sloping terrain (10–15%), runoff and soil loss will increase exponentially with slope length due to exponentially increasing flow velocity. Specifically, we assessed the impact for different slope lengths on event–based runoff, soil erosion and agronomic yield and the role of slope length compared to other factors causing erosion.

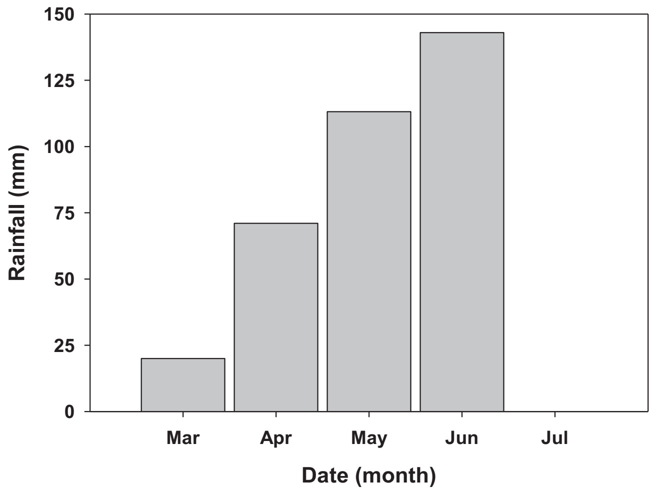

Fig. 2. Monthly rainfall distribution at Rongo site during the LR 2017 growing season.

We conclude by recommending management options that are effective in reducing soil erosion and show potential of adoption.

2. Materials and methods

2.1. Study site

The study was carried out in a small catchment (24.3 km^2) of Rongo Sub-County, Migori County of Southwestern Kenya (Fig. 1). The catchment is located between 0^{0}0.45′42.84′′S and 34^{0}34′20.28′′E (North–West corner) and 0^{0}47′50.64′′S and 34^{0}40′31.44′′E (South–East corner). Elevation of the catchment ranges from 1370 to 1840 m above sea level (m.a.s.l). Slope inclination in Rongo varies from 5 to 40% representing sloping to steep terrain (FAO 2006), while slopes in our core study area in the Western part of the watershed reach up to 20%. The study site was selected as representative for family-run farming systems in Migori County. Average farm size was around 0.8 ha (Jaetzold et al., 2009) per household, and the ancestral form of landholdings is in narrow strips with slope lengths up to about 200 m from upper slope position towards the stream. Valleys are characterized by gentle foot slopes. Rainfall is bi–modally distributed (long (LR) and short rainy season (SR)) permitting two cropping seasons per year. The LR occurs between March and July, the SR between September and November. Long-term annual rainfall varies between 700 and 1800 mm. Seasonal rainfall during our experiment in LR 2017 was 347 mm (Fig. 2). Soils in the catchment differ in texture from sandy to clayey. In the lower part of the watershed, our core study area, Acrisols and Cambisols prevail, while upper parts are dominated by Nitosols and Phaeozems (Wielemaker and Boxem, 1982). Agricultural practices are dominated mainly by subsistence farming, characterized by lack of proper soil conservation techniques. Given the typical spatial farm lay-out, farmers' practice involves downhill ox-ploughing of plots. The watershed confines a mosaic of land use types dominated by agricultural crops (maize, sugarcane (*Saccharum officinarum*) and banana (*Musa* sp.) and planted trees, mainly Eucalyptus (*Eucalyptus robusta*).

2.2. Slope length study

Field experiments were set up to monitor runoff and sediment loss on bounded erosion plots. The slope length experiment (SLE) aimed to assess the critical slope length to balance trade-off in runoff, erosion and yield in a maize-common bean intercrop (MzBn) system.

The SLE assessed runoff and erosion in a maize-common bean intercrop system under three different slope lengths (SL). They were established on three farms on Acrisols with different slope gradients (Table 1) within the watershed (Fig. 1). The selected plots were representative of the typical landholding slope lengths in the area, and had been planted to maize-common bean intercrop systems for over five years. Farms 1, 2 and 3 were located at 1462, 1486, 1495 m.a.s.l, altitude, respectively. Slopes were 14, 10 and 11% on Farm 1, 2 and 3, respectively.

Bounded slope length plots measuring 20 (SL20), 60 (SL60) and 84 m (SL84) × 4 m were replicated twice per farm and planted to MzBn. Maize was sown at 0.75 × 0.3 m, and common bean sown in–between the maize rows spaced at 0.20 m using the regional recommended plant population at two seeds per hole and thinned to one per hill after emergence (two weeks). 100 kg ha^{-1} diammonium phosphate (DAP) fertilizer (18% N, 46% P2O5, and 0% K) was applied to maize and 50 kg ha^{-1} to common bean at planting. This was farmers practice and applied mainly to supply P. For common bean, it was applied only as basal to give a good start for root development given low soil fertility. Maize was top dressed with calcium ammonium nitrate (CAN) fertilizer (27% N, 0% P_2O_5, and 0% K) four weeks after planting. Plots were installed a week after traditional ox–ploughing downhill at the beginning of the LR 2017. Planting days slightly differed between farms, but all plots were sown before the rains started. Runoff and sediment loss were measured for all rainfall events that generated runoff during the entire cropping season of LR of 2017.

2.2.1. Soil sampling and analyses for physical and chemical characterization

Soil samples were collected from each farmer plot prior to the study. The SLE plots were divided into upper, middle and lower slope subplots for sampling and into grids to derive slope curvature (see Table A1 in Appendix). Nine top - and subsoil samples, respectively, were bulked into one sample per subplot. Samples were air–dried, sieved through a 2 mm screen and ball milled for wet chemical analyses. Soil pH was measured in 0.01 M $CaCl_2$ with soil: extraction solution ratio of 1:2.5 using an inoLab1 Labor–pH–Meter, WTW GmbH, Weilheim, Germany. Total C and N were measured by dry combustion using Flash EA 1112 Elemental Analyser, Thermo Fisher Scientific. Available P was determined by Bray I with a Beckman coulter Du, UV – Du 640 spectrophotometer. Plant available K was analysed by Calcium–Acetate–Lactate–extraction method using ICP – OES (Agilent 5100). Soil texture was determined

Table 1
Site and top soil (0–20 cm) characteristics on the slope length plots (farms).

Farm	Slope gradient [%]	Slope position	pH	Total C	Total N	C/N ratio	Avail P	Avail K	Bulk Density	Sand	Silt	Clay
			[]	[%]		[]	[mg kg^{-1}]	[cmol 100 g^{-1}]	[Mg m^{-3}]	[%]		
1 (n = 2)	14	Upper	4.54	0.41	0.03	13.7	4.0	0.038	1.39	79	8	13
1 (n = 2)		Lower	4.52	0.46	0.03	15.3	4.5	0.028	1.45	82	5	13
2 (n = 2)	10	Upper	5.17	0.92	0.05	18.4	7.3	0.049	1.12	69	7	24
2 (n = 2)		Lower	5.21	0.65	0.06	10.8	7.8	0.030	1.16	77	2	21
3 (n = 2)	11	Upper	5.35	0.79	0.06	13.2	6.4	0.028	1.10	67	11	22
3 (n = 2)		Lower	5.24	1.29	0.10	12.9	8.4	0.042	1.08	54	19	27

by the pipette method (Böttcher, 1996) after removal of organic matter with 35% hydrogen peroxide and dispersion by agitating the sample in 200 ml of 0.05 M ammonium hydroxide.

2.2.2. Weather monitoring

Automatic weather stations were positioned next to SLE fields to monitor rainfall, air and soil temperature, relative humidity, solar radiation and wind speed and direction. Rain gauges measured events, the logging interval was set to ten minutes and other devices to hourly logging interval. One of the rain gauges was positioned near farms 2 and 3, which were adjacent. The other was closer to Farm 1 (about 100 m away) and less than 500 meters away from farms 2 and 3. The rainfall measuring device comprised of a tipping bucket rain gauge (MD532–HOBO, UP GmbH, Germany) connected to a logger (HOBO–UA 003–64 Pendant, Onset Computer corp., USA). The rainfall intensity summarization tool (RIST) version 3.6 (Dabley and Justice, 2012) and the equation of McGregor et al., (1995) were used to calculate storm kinetic energy (EI_{30}):

$$EI_{30} = 1099\left[1 - 0.72^{-1.27i}\right] \quad (1)$$

where, i is the maximum intensity of 30 min. The kinetic energy of the rainstorms occurring on each day was summed to obtain daily kinetic energy, E. A Decagon DS–2 sonic anemometer, VP–3 humidity/air temperature sensor, and an RT–1 soil temperature sensor were connected to a data logger (Decagon EM50). Recordings were averaged to obtain representative daily data for over two years (2015–2017).

2.2.3. Runoff and sediment measurements

Bounded erosion plots for runoff and soil loss measurements were delineated with iron metal sheets inserted 20 cm deep into the soil and 30 cm left above the ground surface. A triangulated head was adjoined to the iron sheets at the lower plot end and directed into collection tanks through a 1 m long steel pipe (50 mm internal diameter). Soil loss and runoff water were collected after each rainfall. Each tank (210 L) was levelled and nineteen holes of 2.5 cm diameter each were created equidistant from the bottom. A polyvinyl pipe (2.5 cm diameter) connected one of the splitters to a second tank as it was not possible to collect all potential runoff from a plot. Runoff volume was measured by emptying the tanks using a calibrated bucket. For the splitter tank, the volume of runoff water measured was multiplied by the number of splitters. After collection of runoff water the wet sediments were weighed. Where > 0.5 kg of sediment had been collected during an event, an aliquot of 0.5–1 kg fresh material was dried to calculate dry weight in kg ha^{-1}. For the SLE, measured runoff, soil loss and sediment load apart from their absolute values were also expressed in relative terms using averages of experimental plots as reference. Sediment load (kg ha^{-1} mm^{-1}), the amount of sediment transported by runoff water, was computed as ratio of soil loss to runoff (Lal, 1997). Relative soil loss, runoff, sediment load and soil-loss-to-maize-yield-ratio under different SL was calculated using Eq. (2) as an example for relative soil loss.

$$Sloss\mathrm{R} = \frac{Sloss_{SL}}{Sloss_{\mu SL}} \quad (2)$$

where $Sloss_R$ is relative soil loss, $Sloss_{SL}$ is soil loss under different SL, and $Sloss_{\mu SL}$ is mean soil loss under different SL. Critical slope length was defined as SL prior to exponential increase in relative soil loss, sediment load and soil-loss-to-maize-yield-ratio.

2.2.4. Groundcover measurements

Groundcover by crops and weeds was measured by taking photos from 2.5 m above ground using a digital camera mounted perpendicularly to the ground on a pole (Tuan et al., 2014). Three images were taken per plot at upper, middle and lower slope, covering more than half of the plot area. These images were evaluated by 'sample point' image analysis software (ARS-USDA, 2011). Groundcover was assessed during tillage operations, one month after sowing (<30% groundcover), mid–season (30 – 70% groundcover) and late growing season (>70% groundcover) and before and after every weeding operation (twice per season depending on cropping system). Cover provided by fallen leaves and weeds was estimated by the software and subsumed.

2.2.5. Profile curvature

Profile curvature measures the rate at which the slope surface changes in the direction of the slope or flow line (Peckham, 2011). It indicates the shape of the surface around the sample point within the vertical plane. Positive curvature shows convex slope and negative indicates concave slope. Profile curvature was derived in PCRaster software (Schmitz et al., 2016) using elevation data measured on 4 × 4 m subplots of the SL plots. A moving window of 3 × 3 cells was used to calculate the curvature of the central raster cell by referring to the elevation of its eight neighbours (Corripio, 2003; Tarolli et al., 2012). The nine elevation data points of the window were first approximated by a type of polynomial surface (Zevenbergen and Thorne, 1987; Florinsky, 1998; Hurst et al., 2012) from which the profile curvature values were derived.

2.2.6. Plant sampling

Above–ground biomass (AGB) and maize grain yield of the SLE were measured at physiological maturity. Grain and AGB were harvested row–wise on 54 m^2 excluding border plants and weighed in the field to obtain their fresh weight. Fresh subsamples of these materials were weighed and oven–dried at 60 °C until constant weight to determine fresh/dry conversion factors.

2.3. Data analysis

Experimental data on the effects of slope lengths on runoff, soil loss, maize grain and AGB yields, and groundcover were subjected to ANOVA using Statistical Analysis Software program SAS version 9.4 (SAS Institute, 2016). Prior to that the data was checked for normality and homoscedasticity on model residuals using quantile–quantile (Q–Q) plots, histograms and studentized residual plots. A linear mixed model was fitted in the SAS MIXED model procedure. The log base 10 transformation was used to transform runoff and soil loss data to achieve normality of the residuals. Randomized complete block design (RCBD) was specified with block factors: column nested within farm, and slope length plots nested within column, and their interactions as random effects on the response variables (i.e. runoff, soil loss) (Fig. S1 in Appendix). Repeated measurements (events) within the fixed effects (i.e. slope length, rainfall, groundcover, gradient, and profile curvature) were accounted for by fitting an error term with power model (SP (POW)) covariance structure to the data. The final model over all farms combined was used to predict soil loss for the LR 2017. Models were selected using the Akaike Information Criterion (AIC). Statistical significance of all effects was assessed at a significance level of $p < 0.05$ and treatment means were compared using the PDIFF option of the LSMEAN in SAS.

3. Results

3.1. Impact of slope length on runoff and soil loss

Cumulative soil loss increased with increasing slope length from 20 to 84 m, whereas the reverse was observed for runoff (Table 2). Runoff per hectare was similar at SL20 and SL60 across all farms, but was significantly lower on SL84. Overall soil loss on Farm 1 exceeded that on Farm 2 and 3.

Table 2
Effect of slope length on total runoff and soil loss for the 2017 long rainy season on three farms. Data show means and standard errors of 19 events. Treatments with different superscript letters differed among same slope lengths at $p < 0.05$ at each farm (F1, F2, F3) and on all farms combined.

Farm	Slope length (m)	Cumulative runoff (m^3 ha^{-1})	Cumulative soil loss (kg ha^{-1})
F1	20	565 ± 77^a	6450 ± 3298^a
	60	477 ± 8^a	10393 ± 1902^a
	84	330 ± 22^b	14284 ± 1120^a
F2	20	576 ± 4^a	80 ± 38^c
	60	437 ± 29^a	216 ± 41^b
	84	287 ± 38^b	1238 ± 100^a
F3	20	654 ± 137^a	184 ± 73^b
	60	619 ± 13^a	316 ± 63^b
	84	338 ± 5^b	1644 ± 312^a
All farms	20	605 ± 73^a	2238 ± 1136^c
	60	511 ± 16^a	3642 ± 668^b
	84	319 ± 22^b	5722 ± 511^a

Seasonal totals of runoff and soil loss showed opposite trends with regards to slope length. Therefore, we examined the event–based runoff and soil loss data more closely. Runoff peaked early in the season on all three farms (Fig. 3) and was reduced towards the middle of the season despite major rain events. Heavy rain events were recorded at the end of the season and major runoff during this period occurred particularly on F2 and F3. Regarding different slope lengths, SL60 generated the highest runoff on F1 at the beginning of the season, while runoff under SL20 was highest on F2 and F3 at the beginning of the season. In the mid-season and late season SL20 was always greater in runoff than SL60 and SL84.

Event observations for soil loss showed high soil loss at the beginning of the season on all farms. Soil loss also peaked in mid-season in contrast to runoff, but was again low at the end of the season. Event–based soil loss was always higher on F1 than F2 and F3.

The impact of different slope lengths on relative soil loss, runoff, sediment load and soil loss to maize grain yield ratio was evaluated for all the farms combined (Fig. 4). Runoff decreased gradually with increasing slope length, and was more pronounced at SL > 50 m. Soil loss, sediment

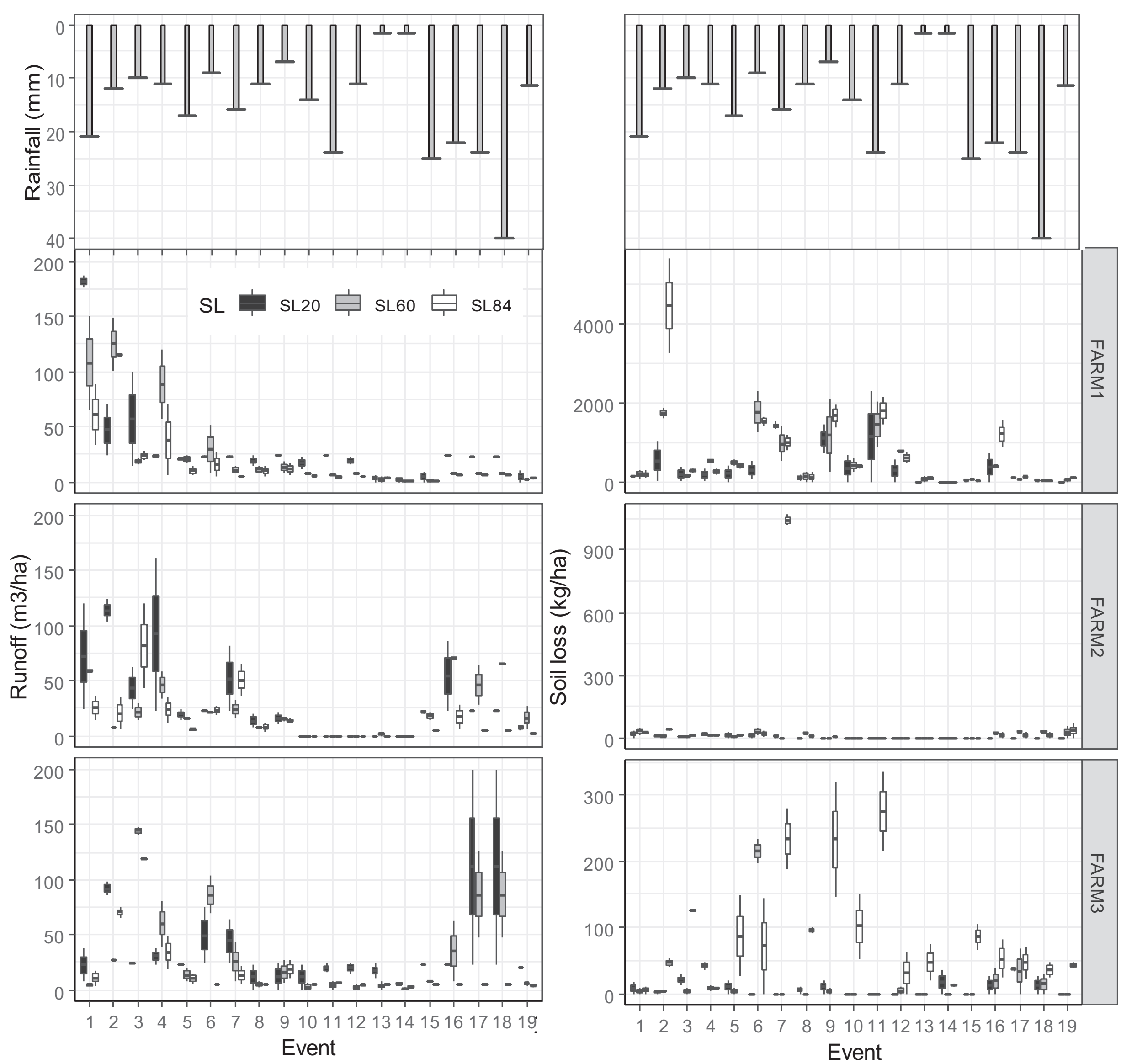

Fig. 3. Event–based runoff and soil loss under different slope lengths. Note the different y-axis scales for soil loss.

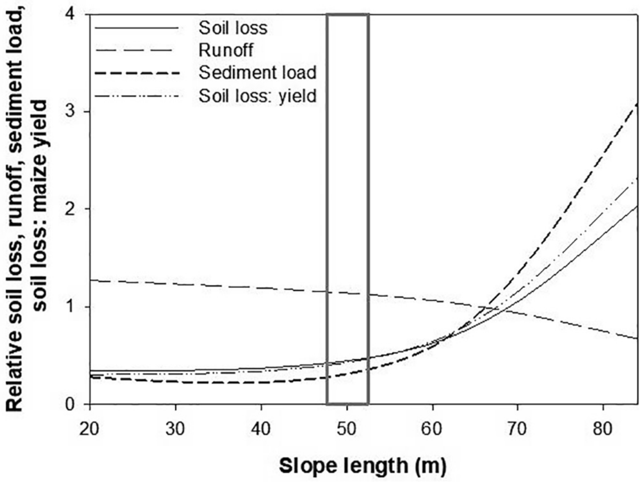

Fig. 4. Impact of slope length on soil loss, runoff, sediment load and soil-loss-to-maize-yield-ratio relative to averages across all three farms. The Vertical bar indicates critical slope length.

load and soil loss to yield ratio also ascended gently with increasing slope length up to the 50 m slope length and thereafter, began to show a sharp increase. Beyond 50 m slope length, sediment load showed the highest increase on the long slopes.

3.2. Assessing the relative influence of predictor variables on soil loss

Slope length and profile curvature showed the strongest effect on soil loss on F1, F2 and F3 *individually* (Table 3) in the statistical mixed effect model that best predicted soil loss (selected by AIC). Soil loss at F1 and F2 was mainly dominated by slope length and at F3 by profile curvature. Slope gradient and texture were not included in the individual farm models, because they were uniform. Assessing the impact *over all farms combined* indicated that slope gradient was the strongest factor affecting soil loss, followed by slope length and profile curvature.

The established mixed model over all farms combined [Eq. (3)] based on Table 3 was used to predict soil loss for all rainfall events of the LR 2017 cropping season (Fig. S2 in Appendix). Overall, the model showed good prediction ($R^2 = 0.54$). Assessing soil loss prediction under the different slope lengths showed that the model performed quite well for SL84 ($R^2 = 0.44$) and even better for SL60 ($R^2 = 0.58$) and SL20 ($R^2 = 0.64$).

$$\log_{10}(y) = 1.75 + 0.18SL + 0.06RO + 0.48GR - 0.12PC \quad (3)$$

where y is soil loss, 1.75 is the intercept, SL, RU, GR and PC are the regression coefficients or estimates of slope length, runoff, slope gradient and slope profile curvature, respectively.

3.3. Slope length, above-ground biomass and yield of maize

Crop above ground biomass (AGB) and yields were measured in the LR 2017 and compared among slope length treatments on the three farms. Grain yield and AGB appeared to decrease with increasing slope length, but showed no statistical difference (Table A2 in Appendix). Harvest index showed no consistent trend with slope length ranging between 32 and 47%. Under SL20, grain yield and ABG were similar at F2 and F3, but significantly ($p < 0.05$) lower at F1 (Table A2 in Appendix). Grain yield and AGB on SL60 and SL84 were not different among the farms.

Table 3
Mixed model of explanatory variables on log transformed soil loss in LR 2017. Absolute magnitude of *B-value* indicates explanatory power, and sign indicates direction. Soil loss data were log transformed for analysis.

Dependent variable	Explanatory variable	Standardized coeff.		Confidence limit	
		B–value	Std. error	Lower	Upper
Farm 1					
Soil loss (kg ha^{-1})	(Constant)	2.4101	0.1149	2.1706	2.6497
	Slope length (m)	0.2026	0.0581	0.0806	0.3246
	Runoff (m^3 ha^{-1})	0.1160	0.0508	0.0141	0.2179
	Groundcover (%)	−0.0738	0.1201	−0.3195	0.1717
	Rainfall (mm)	−0.1242	0.1241	−0.3845	0.1362
	Profile curvature ()	−0.1609	0.0502	−0.2669	−0.0550
Farm 2					
	(Constant)	1.3070	0.0980	1.0922	1.5219
	Slope length	0.1492	0.0932	−0.0505	0.3490
	Runoff	0.0613	0.0393	−0.0203	0.1431
	Groundcover	0.0310	0.0925	−0.1605	0.2226
	Rainfall	0.1026	0.1082	−0.1320	0.3371
	Profile curvature	−0.1012	0.0438	−0.1931	−0.0093
Farm 3					
	(Constant)	1.5198	0.1559	1.0542	1.9854
	Slope length	0.1468	0.2026	−0.3246	0.6181
	Runoff	0.0554	0.0613	−0.0683	0.1792
	Groundcover	0.1078	0.0937	−0.0881	0.3037
	Rainfall	0.0275	0.0729	−0.1310	0.1860
	Profile curvature	−0.1690	0.1499	−0.4942	0.1563
All farms					
	(Constant)	1.7518	0.0676	1.6145	1.8891
	Slope length	0.1886	0.0531	0.0810	0.2962
	Runoff	0.0639	0.0296	0.0052	0.1226
	Gradient	0.4858	0.0657	0.3526	0.6191
	Profile curvature	−0.1215	0.0393	−0.2016	−0.0413

[1]Texture and gradient did not appear in the individual farm models, because only one bulked topsoil sample was analysed and only one slope gradient existed per farm.

4. Discussion

4.1. Assessing critical slope length for erosion mitigation

Soil loss increased exponentially with the increase in slope length in accordance with the second part of our hypothesis, with the critical length being around 50 m. While there was a gradual decrease in runoff beyond 50 m, soil loss and sediment load increased exponentially. This sharp increase in soil loss was attributed to higher flow velocity, which increases the transport capacity of sediments in runoff water. Bagio et al. (2017) also explained such an exponential rise in soil loss with increasing slope length by the greater erosive power of surface runoff, influenced primarily by the increase in volume and speed of runoff. Foster et al. (1977) attributed this kind of sharp increase in soil loss to a shift from sheet to rill erosion on long slope lengths, which was also observed on SL3 plots in Rongo. Contrarily to soil loss, runoff in our case followed a negative quadratic function against slope length, i.e. it decreased – even in absolute terms – with increasing slope length. The high runoff on SL1 may theoretically have been an overestimation on the artificially short bounded plots that were not representative for infiltration in the landscape. Likewise, Silva and de Maria (2011) attributed decreased runoff to greater potential water infiltration into the soil and evaporation on longer slopes with greater variation in slope compared to shorter slopes. Han et al. (2019) described the gradual decrease in runoff beyond their 30 and 40 m slope as “runoff degradation” phenomenon, and concluded that the 30 and 40 m slope lengths were the runoff continuity threshold. Van de Giesen et al. (2005) in a modelling study interpreted the reduction in run-off as scaling effect due to longer time for infiltration on longer slopes. Decreasing run-off and at the same time increasing soil erosion with increasing slope length has been observed by Free and Bay (1969) in a tillage and slope study.

In a related study with settings similar to ours, Lal (1997) - on an Nigerian Alfisol on 7–9% slope in a maize–cowpea rotation under slope lengths varying between 10 and 60 m – found that soil erosion and sediment loads increased exponentially with slope length, while runoff per unit area decreased slightly. Under his specific settings the degradative effects of soil erosion increased sharply beyond a critical slope length of 25 m. Lal's process–based explanation attributes the degradative effects of long slopes to high sediment load and aggravated risk of soil erosion from the decay of soil structure caused by preferential loss of soil organic matter and clay over longer times. The soil loss to yield ratio which measures the susceptibility of crops or cropping systems to accelerated soil erosion (Lal, 1997) also increased beyond the critical slope length due to the high soil loss rate.

The critical slope length of about 50 m obtained in this study was higher than that from Lal's and this could be attributed to differences in cropping systems, soil properties (particularly texture and type of clay minerals) and rainfall intensity.

The Western part of the catchment, where our study sites were located, has been classified as humic Acrisols, humic and ferralic Cambisols by Wielemaker and Boxem (1982). Our soil survey in 2016 (two transects E-W and N-S with 100 augers and 11 detailed soil profiles) showed that soil texture was similar between both and comparable to the Alfisol in Lal's study. All are characterised by clay illuviation into a Bt layer. Topsoils of Lal's Oxic Paleustalf contained in average 52 and 53% sand, Acrisols in our study 51 $\pm$ 10%, and Cambisols 68 $\pm$ 13%. Total topsoil carbon contents were low for both Acrisols (1.42 $\pm$ 0.35 %) and Cambisols 0.96 $\pm$ 0.34%. Phaeozems were found in smaller parts of the upper (Eastern) Rongo watershed. They are of basaltic origin (in contrast to the granitic Acrisols and Cambisols) and would need to be discussed separately; this is beyond the scope of the study as our experiments were confined to the Western part of the watershed. These factors do not act in isolation, but may combine and interact to influence the mechanisms involved in soil erosion, and hence the critical slope length as discussed below.

Cropping or management systems influence soil erosion through their ground or canopy cover provision, which affect hydraulic characteristics (e.g. infiltration rate, flow velocity of overland flow). Generally, as groundcover increases, the resistance to overland flow increases, which leads to lower flow velocity (Liu and Singh, 2004). Hence, critical slope length is expected to increase with increasing soil cover provision due to lengthening of ponding time until runoff is induced. Rogers and Schumm (1991) and Morgan (1995) found that vegetation effect on soil loss is not straightforward, and that plant canopy has shown increasing soil loss rates as vegetation cover thickens under certain experimental conditions depending on how it interacts with the erosion process. In our study, groundcover related positively with soil loss on F2 and F3, and this may be attributed to its spatial distribution at the ground surface which can modify the drop–size distribution of rainfall (Morgan, 2005). In addition, high rainfall events during times of high ground cover (middle and end of season; see Fig. 3 and Fig. S3 in the Appendix) may have overridden the effect of ground cover. Factors facilitating runoff and erosion that are usually associated with cattle grazing are soil compaction (Blake et al., 2018), crusting and removal of cover (Blanco-Canqui and Lal, 2010). We did not find evidence of these despite relatively high stocking rates, probably because of prevailing cut & carry systems.

Slope gradient affects runoff generation and hydraulic characteristics such as velocity of overland flow, and may thus modify the critical slope length. The preeminent importance of slope gradient, more influential than slope length, was evident in our study when comparing different farms with different slopes (Table 3).

High rainfall intensities are generally associated with high runoff and erosion risks due to the high power of detachment and transport forces. The occurrence of high intensity rains especially in periods when crop cover is not dense enough to adequately protect the soil surface may decrease the critical slope length via speeding runoff generation, and consequently aggravate soil erosion. The negative relationship between rainfall and soil loss observed on F1 could be due to the temporal distribution (heavy rain events in the late vegetation period, when the soil was covered, Fig. 3) or rainfall intensity, which determines erosivity. Rainfall intensity in 2016 reached up to > 60 mm h^{-1} and events of 20 mm h^{-1} were not uncommon (data not shown).

Among the numerous pedogenic factors that affect soil loss is high stone contents, which reduces potential water infiltration (de Figueiredo, 1996). In Rongo we found about 20 % vol. in the top- and up to 50 % in the subsoil during our soil survey.

4.2. Designing potential slope length strategies for effective soil conservation

Soil erosion on the studied farms in the Rongo catchment was predominantly driven by slope length, which is inevitably expected to be a key precursor of more severe soil degradation along the landscape particularly, if sustainable conservation measures are not sought. There are numerous soil conservation measures such as grass filter strips, hedgerows or contour ploughing at the plot and landscape level to control soil erosion from agricultural land, and effective conservation measures will help to sustain main crop yield (Tuan et al., 2014). However, there is limited innovation in erosion control process when considering theoretical knowledge on erosion processes and in modelling research (Poesen, 2018). Among the various techniques of soil conservation, preference is given to agronomic measures as they utilise the direct protective role of plant cover in reducing rain drop impact, are less expensive and fit into existing farming systems to maintain plant biodiversity (Morgan, 2005). Such approaches should not be labour intensive and should not require levels of inputs or resources to which targeted farmers have no access.

Strip–cropping offers the advantage of combining row crops and protective or buffer crops in alternate strips aligned on the contour. Eroded sediments from the row crops are trapped within the buffer strip. The difficulty with strip–cropping in mosaic landscapes is that much cropping land will be taken up by the alternate buffer strips to protect valuable crops. Targeting specific positions of the slope, in this case the critical slope length to place the buffer strip can save a considerable amount of land which would otherwise be taken out of production by the buffer strips, and would also save labour and capital input involved in establishing and maintaining the buffer strip. In the landscape, relatively higher soil loss was generated on longer slopes compared to short slope lengths in this study. Although the critical slope length level is likely to be different under alternative settings (as discussed above), the resulting strategic recommendations given below still hold.

Within the same catchment (Fig. 1, LGE plot), Muoni et al. (2019) found that MzBn plus *Calliandra calothyrsus* hedgerows with 5 Mg ha^{-1} leaf mulch amendment (Mul) and *Mucuna pruriens* (Muc) cover crops effectively reduced runoff and soil loss followed over three rainy seasons. This effect was most pronounced at the onset of each cropping season, which was dominated by highly erosive rainfall events. We recommend implementing cash crops, e.g. common beans, maize and groundnut, at the upper end of the slope down to the critical slope length, whereas, legume forage cover crops and mulch, e.g. Muc, and Mul or hedgerows or agroforestry systems, should be implemented as buffer strips beyond the critical slope length (Fig. 5). In the backdrop of land fragmentation and limitation in this region, strip–wise mulching or using Muc as live mulch in strips at strategic landscape positions can be an effective approach to sustainably maximise land area and reduce vulnerability of crops to soil erosion. Existing studies have demonstrated the effectiveness of spatial mulch application arrangements along the slope, i.e. in strips covering only a part of the slope, as being similar to the application over the entire slope. For example, Abrantes

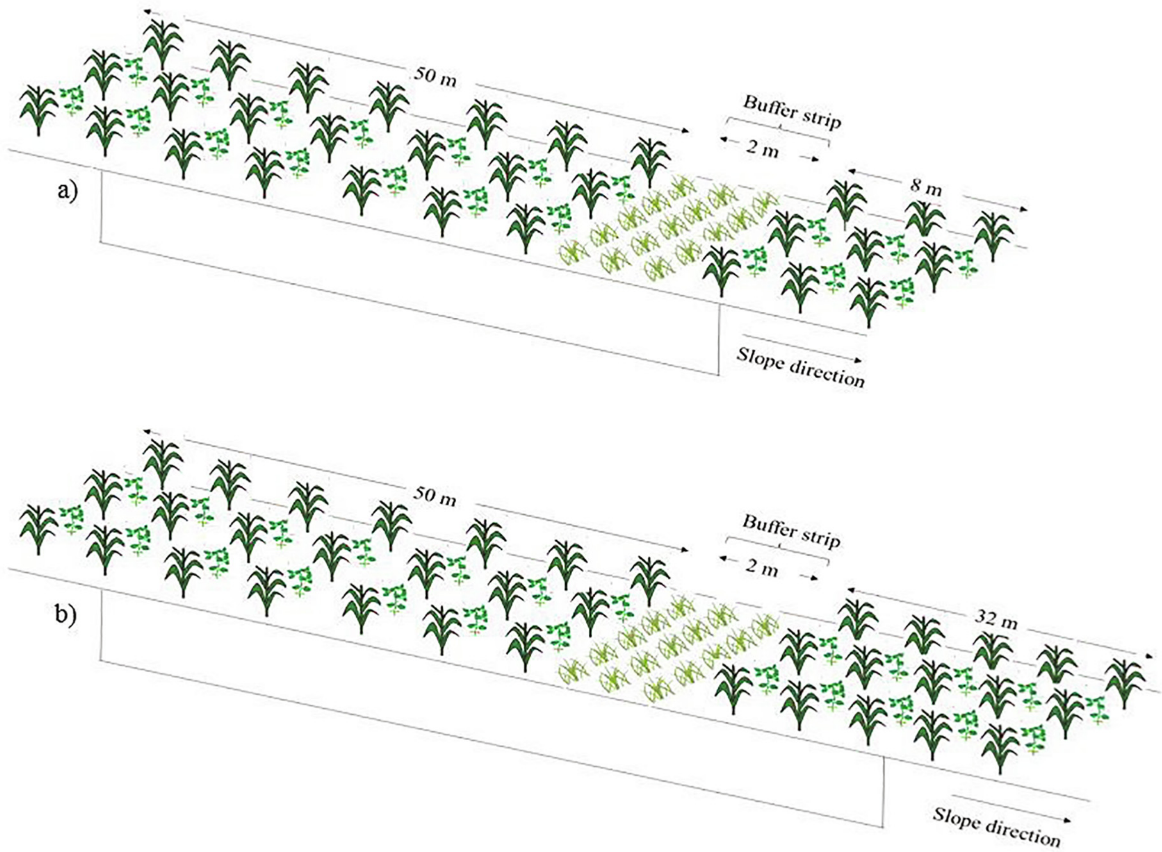

Fig. 5. Schematic diagram showing position of buffer strips at the critical slope length (50 m) on a) 60 and b) 84 m slope length.

et al. (2018) found no significant relationship in runoff and soil loss reduction when rice straw was applied as mulch over the entire flume length compared to 1/3 and 2/3 flume length strips.

The width of the buffer strip may vary depending on the degree of erosion hazard, and is usually 2–4 m (Morgan, 2005). Lal (1997) proposed a revised formula to compute terracing width or width of buffer strip (VI) for conventional till systems as shown in Eq4. An average plot's slope of 12% gives a buffer strip width of 2 m for our recommendation settings.

$$VI = \frac{\%slope}{10} + 0.9 \quad (4)$$

5. Conclusions

At the landscape level, we found that slope length had a major control on soil loss, and hence could be a potential target factor in designing spatially explicit erosion control measures, largely neglected to date. Slope length impact on soil loss was particularly aggravated beyond the critical slope length of 50 m necessitating soil conservation measures to truncate this exponentially degrading effect. It can be concluded that critical slope length is site–specific, nevertheless more generic valid recommendations for soil conservation can be developed.

As discussed the most effective soil protection and erosion control at plot level was provided by maize intercropped with common beans and *Calliandra calothyrsus* hedgerows with mulch (Mul) providing high groundcover. Supporting farmers with *Mucuna* seeds and *Calliandra* seedlings can increase chances of implementation and adoption.

We recommend establishing legume soil erosion conservation measures strip–wise with mulch and *Mucuna* downhill of the critical slope length, and planting legume cash crops and maize above the critical slope length. Such approaches are critical in the backdrop of land fragmentation and labour limitation in the region to sustainably maximise productive land area.

More detailed and extensive work is required to further assess at which slope position and how conservation measures should be best implemented to be most effective in soil fertility management as well as being economically and socially viable.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2020.e00311.

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