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Effect of land terracing on soil physical properties across slope positions and profile depths in medium and high altitude regions of Rwanda

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Although land terracing is promoted as a management practice for effective soil conservation in hilly areas, construction of terraces causes changes in soil properties. This study evaluated the effect of land terracing on some soil physical properties across slope positions and profile depths in medium and high altitudes of eastern and north-eastern Rwanda. Soil samples were collected from top, middle and bottom slopes of four year-old terraced and non-terraced lands. Results showed that soil textures were mainly sandy clay loams. At medium altitude, silt (19.6, 18.6%) and hydraulic conductivity (237.9, 129.8 mm h^{-1}) were significantly ($p < 0.05$) higher in terraced than non-terraced land, while clay (29.2, 27.8%) and total available water content (TAWC) (222.2, 201.7 mm m^{-1}) were higher in non-terraced than terraced land. At the high altitude, hydraulic conductivity (194.3, 124.1 mm h^{-1}) was higher in terraced than non-terraced land, while soil bulk density (1.42, 1.35 g cm^{-3}) and TAWC (251.6, 235.3 mm m^{-1}) were higher in non-terraced than terraced land. Terracing increased silt content and hydraulic conductivity, and slightly decreased clay and water retention capacity. These changes are important in soil water and fertility management, and therefore need to be considered when using terraced lands.

Keywords: soil texture, soil water retention capacity, terracing

Introduction

Soil conservation in hilly and mountainous regions of many countries in Europe, North and South America, Asia and Africa (e.g. Ethiopia, Rwanda and Tanzania) is carried out through construction of terraces (Zuazo et al. 2005; Widomski 2011). The common types of terraces in Rwanda are bench or radical terraces and progressive terraces (Ruganzu et al. 2015). Bench terraces are a series of level or almost level strips running across the slope at vertical intervals, supported by steep banks or risers (Mesfin 2016). During their construction, farmers carefully remove and put aside the topsoil (0–30 cm depth), then work the subsoil (30–70cm) to create the bench surface, after which the topsoil is spread back onto the surface. Grass is then planted on the terrace banks for stabilization (Mesfin 2016; Kagabo 2014). These terraces are constructed on terrain with slopes of up to 55% (Widomski 2011). They are designed principally to reduce soil loss through enhanced retention and infiltration of runoff, promote permanent agriculture on steep slopes, and promote land consolidation and intensive land use (Kagabo 2014).

Progressive terraces are formed by establishing contour bunds with soil or stones in combination with ditches and vegetation as in the *Fanya Juu* terraces of Kenya (Widomski 2011) and develop over time by the natural processes of erosion and sedimentation (Ruganzu et al. 2015). These terraces reduce slope angle and allow runoff from the upper side of the terrace to flow onto a lower portion where it spreads out and infiltrates the soil. The terrace edge is planted with trees and grass to stabilize it and trap sediments (Ruganzu et al. 2015).

Perturbation of soil horizons occurs during construction of terraces, leading to changes in soil physical properties (Ramos et al. 2007). The major changes reported include alteration of particle size distribution of the fine fractions, increase in hydraulic conductivity, and decrease in water retention capacity (Ramos et al. 2007). The degree of change in the soil properties is dependent on the soil types. The major soil types in medium and high altitudes of eastern and north eastern Rwanda are Ferralsols, Lixisols and Acrisols (Verdoodt and Van Ranst 2003). These soils have well developed horizonation which is susceptible to disruption caused by land transformation (Driessen et al. 2001).

The objective of this study was to determine changes in physical properties of soils in terraced lands through comparison with non-terraced lands across slope positions and profile depths in medium and high altitudes of eastern and north eastern Rwanda. Changes in soil properties, depending on their magnitude, could have a significant effect on land management. For example, efficient irrigation practices and fertilizer applications are usually based on specific soil characteristics.

Materials and methods

Study area

The study was done in September 2017 in Rwagamana (medium altitude) and Gicumbi (high altitude) Districts, located in eastern and north eastern Rwanda, respectively. Soils in the medium altitude region (1 502–1 647 m a.s.l.), are mainly Ferralsols/ Lixisols (Verdoodt and Van Ranst 2003). Mean annual rainfall is 950–1 000 mm and the average annual temperature range is 19–30°C (Rwamagana District, 2013). In the high altitude region (1 881−2 130 m a.s.l.), the predominant soils are Alisols/ Acrisols (Verdoodt and Van Ranst 2003). Mean average annual rainfall is 1 200–1 500 mm and the average annual temperature range is 13.2–20.8°C (Gicumbi District 2013). The coordinates and specific soil types of the top, middle and bottom slopes of the study sites are presented in Table 1.

Soil sampling

Soil samples were collected from the top, middle and bottom slopes of four year old terraced and non- terraced lands in both Rwagamana and Gicumbi Districts. For texture determination, the composite samples were collected in a zig-zag pattern using a soil auger, from 0–30, 30–60 and 60–90 cm soil depths, in triplicate. A total of 108 samples composed of 6 samples taken at each of the three soil depths in the three slope positions of the two sites were collected. For bulk density determination, four undisturbed soil samples were collected in duplicates using 5 x 5 cm core rings at each of the four soil depths (0–20, 20–40, 40–60 and 60–80 cm) in the three slope positions of the two sites to give a total of 96 samples. For water holding capacity and hydraulic conductivity determinations, four undisturbed 5 x 5 cm core samples were collected in duplicates from 0–30 and 30–60 cm depths in each of the 3 slope positions to give a total of 48 samples for the two sites.

Soil laboratory analyses

Soil texture was determined using the hydrometer method (Kroetsch and Wang 2006). Percentages of sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm) were used to assign the textural class. For bulk density determination, the undisturbed soil core samples were oven-dried to constant weight at 105 °C for 48 hours. Bulk density was then obtained by dividing the dry weight of each core sample by the volume of the core ring.

Soil water holding capacity was determined by the pressure-plate method (Jury et al. 1991) which consists of an air-tight chamber enclosing a water-saturated, porous ceramic plate connected on its underside to a tube extending through the chamber to the open air. Water retained by the soil at various pressures was measured, from which the respective soil moisture characteristic curves were obtained. Total available water content (TAWC) was determined as the difference between moisture at field capacity, pF2.0 (i.e. 0.1 bar suction), and permanent wilting point, pF4.2 (i.e.15 bar suction). The TAWC was expressed as a percentage on a volume rather than dry-mass basis (Benami and Ofen 1984). The percentage on volume basis was obtained by multiplying the percentage on a mass basis by the relative bulk density (i.e. the soil bulk density divided by the density of water). One percent of water content in the soil is equivalent to 1 cm (or 10 mm) of water per metre depth of soil. The TAWC was calculated using the equation below:

$$\text{TAWC} = \text{FC (\%wt)} - \text{PWP (\%wt)}] \times \text{RBD} \times 10 \times \text{Root zone depth (m)} \quad (1)$$

where TAWC (mm m^{-1} soil depth) is the total available water content, FC (%wt) is the percentage of water content at field capacity, PWP (%wt) is the percentage of water content at permanent wilting point, and RBD is the relative bulk density.

Saturated hydraulic conductivity (Ks) was determined on the undisturbed soil core samples using the constant head method (Klute and Dirksen 1986). A steady flow rate of water at a constant head was passed continuously through the core sample. The water was then collected at the lower end and its volume recorded in a given time period. The Ks (cm^{-1}) was then calculated from Equation 2.

$$\text{Ks} = (Q/A)\times(L/h) \quad (2)$$

where Q (cm^3 h^{-1}) is the steady flow rate of water through the sample (i.e. volume/time), A (cm^2) is the cross-sectional area of the sample, L (cm) is the length of the soil core sample, and h (cm) is the hydraulic constant head between the two ends.

Statistical analysis

The data collected were subject to Bartlett's chi-square test of homogeneity. An analysis of variance was performed using the Statistical Analysis System version 9.2 statistical

Table 1: Coordinates and soil types across slope positions in the study areas

Site location	Slope positions	Slope (%)	Altitude (m)	Coordinates		Soil types
				Latitude	Longitude	
Medium altitude	Top	14–42	1 647	1° 56′ 26″ S	30° 19′ 33″ E	Dystric Regosols/ dystric Leptosols
	Middle	14–27	1 565	1° 56′ 42″ S	30° 19′ 38″ E	Haplic (humic) Ferralsols/ haplic Lixisols
	Bottom	14–27	1 502	1° 56′ 55″ S	30° 19′ 42″ E	Haplic (humic) Ferralsols/ haplic Lixisols
High altitude	Top	11–32	2 130	1° 37′ 52″ S	30° 05′ 01″ E	Humic Alisols/ humic Acrisols
	Middle	11–53	2 061	1° 37′ 56″ S	30° 04′ 31″ E	Humic Alisols/ humic Acrisols
	Bottom	11–32	1 881	1° 37′ 35″ S	30° 04′ 39″ E	Humic Acrisols/ humic (ferralic) Cambisols

Source: GPS Garmin data processed with ArcGIS 10.2 and GIS soil map of Rwanda (Verdoodt and Van Ranst, 2003) software (SAS, 2008). Duncan's Multiple Range Test was performed for means separation. A 5% probability level was used for the significance tests of all statistical analyses (Gomez and Gomez 1984).

Results and discussion

Effect of terracing on soil properties across slope positions and profile depths

Soil texture

Terraced and non-terraced soils in both study areas had sandy clay loam textures except for the middle slope soils of terraced land at the high altitude region, which were sandy loams (Table 2). The soils had varied quantities of sand, silt and clay. At the medium altitude, average contents of sand, silt and clay were 52.5%, 19.1% and 28.5%, respectively. At high altitude, they were 65.3%, 12.9% and 21.8% for the respective fractions (Table 2). At medium altitude, the interaction effect between land terracing and slope position on soil texture was significant ($p < 0.05$) for sand and clay, and non-significant for silt. Clay contents were higher in soils of the top slope (dystric Regosols/dystric Leptosols) than in soils of middle and bottom slopes (haplic (humic) Ferralsols/haplic Lixisols) on both terraced and non-terraced lands (Table 2). Conversely, higher contents of sand were found in soils on the bottom slope compared to those on the top slope of terraced and non-terraced lands (Table 2).

At high altitude, the interaction effect between land terracing and slope position was significant ($p < 0.05$) for sand and non-significant for silt and clay contents. Soils of top and middle slopes (humic Alisols / humic Acrisols) had higher contents of sand than those of the bottom slopes (humic Acrisols / humic (Ferralic) Cambisols) for both terraced and non-terraced lands (Table 2). The observed changes in particle size fractions can be attributed to modification of slope characteristics by human or natural causes (Nelson 2013).

The interaction effect between land terracing and profile depth on soil texture was non-significant in both study areas. The main effect of depth on soil texture was significant ($p < 0.05$) in both study areas; clay contents were relatively higher in the deepest layer (60–90 cm) than in the 30–60 cm and 0–30 cm layers. For silt and sand, higher contents were obtained in surface layers than in sub and deeper layers (Figure 1). At medium altitude, the mean values for clay were 26.9%, 28.5% and 30.1% in the 0–30, 30–60 and 60–90 cm layers, respectively. At high altitude, they were 20.6%, 21.9% and 22.9%, respectively (Figure 1). This increase of clay with depth is probably indicative of illuviation of clay from the surface soils to the lower layers of the profile, resulting from the high amount of rainfall received in the highlands. Coltorti et al. (2019) reported that moderate clay illuviation in buried soils in the Ethiopian highlands was an indication of climatic amelioration and phases of slope stability.

The effect of land terracing on soil texture was significant ($p < 0.05$) for silt and clay and non-significant for sand at medium altitude. The percentage of silt was higher in soils on terraced land (19.6%) than those in non-terraced

Table 2: Interaction effect of land terracing and slope position on soil texture and saturated hydraulic conductivity (Ks) in the study areas (mean ± standard error)

Site location	Type of land	Slope position	Soil types	Soil texture			Textural class*	Ks
				Sand (%)	Silt (%)	Clay (%)		($mm\ h^{-1}$)
Medium altitude	Terraced	Top	Dystric Regosols / dystric Leptosols	49.8 ± 0.3^{c}“	18.4 ± 0.6	31.9 ± 0.7^{a}	SCL	459.3 ± 11.9^{a}
		Middle	Haplic (humic) Ferralsols / haplic Lixisols	49.7 ± 0.3^{c}	22.7 ± 0.5	27.7 ± 0.5^{b}	SCL	219.0 ± 113.9^{b}
		Bottom	Haplic (humic) Ferralsols / haplic Lixisols	58.4 ± 0.4^{a}	17.7 ± 0.6	23.9 ± 0.9^{c}	SCL	35.4 ± 5.4^{d}
	Non-terraced	Top	Dystric Regosols / dystric Leptosols	51.4 ± 0.8^{c}	16.6 ± 0.6	32.4 ± 0.3^{a}	SCL	213.1 ± 117.6^{b}
		Middle	Haplic (humic) Ferralsols / haplic Lixisols	50.7 ± 0.6^{c}	22.2 ± 0.8	27.2 ± 0.6^{b}	SCL	120.1 ± 56.8^{c}
		Bottom	Haplic (humic) Ferralsols / haplic Lixisols	55.1 ± 0.9^{b}	16.9 ± 0.8	27.9 ± 1.4^{b}	SCL	56.2 ± 24.4^{d}
Mean				52.5	19.1	28.5		183.8
N$				54.0	54.0	54.0		24.0
CV# (%)				2.9	8.9	5.8		7.9
High altitude	Terraced	Top	Humic Alisols / humic Acrisols	68.4 ± 0.7^{a}	10.1 ± 0.5	21.5 ± 0.8	SCL	176.8 ± 71.7^{b}
		Middle	Humic Alisols / humic Acrisols	69.1 ± 0.4^{a}	11.2 ± 0.6	19.7 ± 0.6	SL	394.7 ± 29.8^{a}
		Bottom	Humic Acrisols / humic (Ferralic) Cambisols	59.2 ± 0.2^{c}	16.7 ± 0.5	24.1 ± 0.4	SCL	11.3 ± 2.9^{c}
	Non-terraced	Top	Humic Alisols / humic Acrisols	68.3 ± 0.4^{a}	11.0 ± 0.8	20.7 ± 0.9	SCL	193.9 ± 58.8^{b}
		Middle	Humic Alisols / humic Acrisols	66.1 ± 0.4^{b}	12.3 ± 0.2	21.6 ± 0.3	SCL	163.4 ± 71.9^{b}
		Bottom	Humic Acrisols / humic (Ferralic) Cambisols	60.6 ± 0.9^{c}	16.2 ± 0.9	23.2 ± 0.8	SCL	15.1 ± 4.5^{c}
Mean				65.3	12.9	21.8		159.2
N				54.0	54.0	54.0		24.0
CV (%)				2.8	13.0	8.9		13.3

“Different letters in the same column indicate significantly different values at $P < 0.05$; * SCL - Sandy clay loam, SL - Sandy loam; $ N – Number of observations / samples
CV - Coefficient of variation

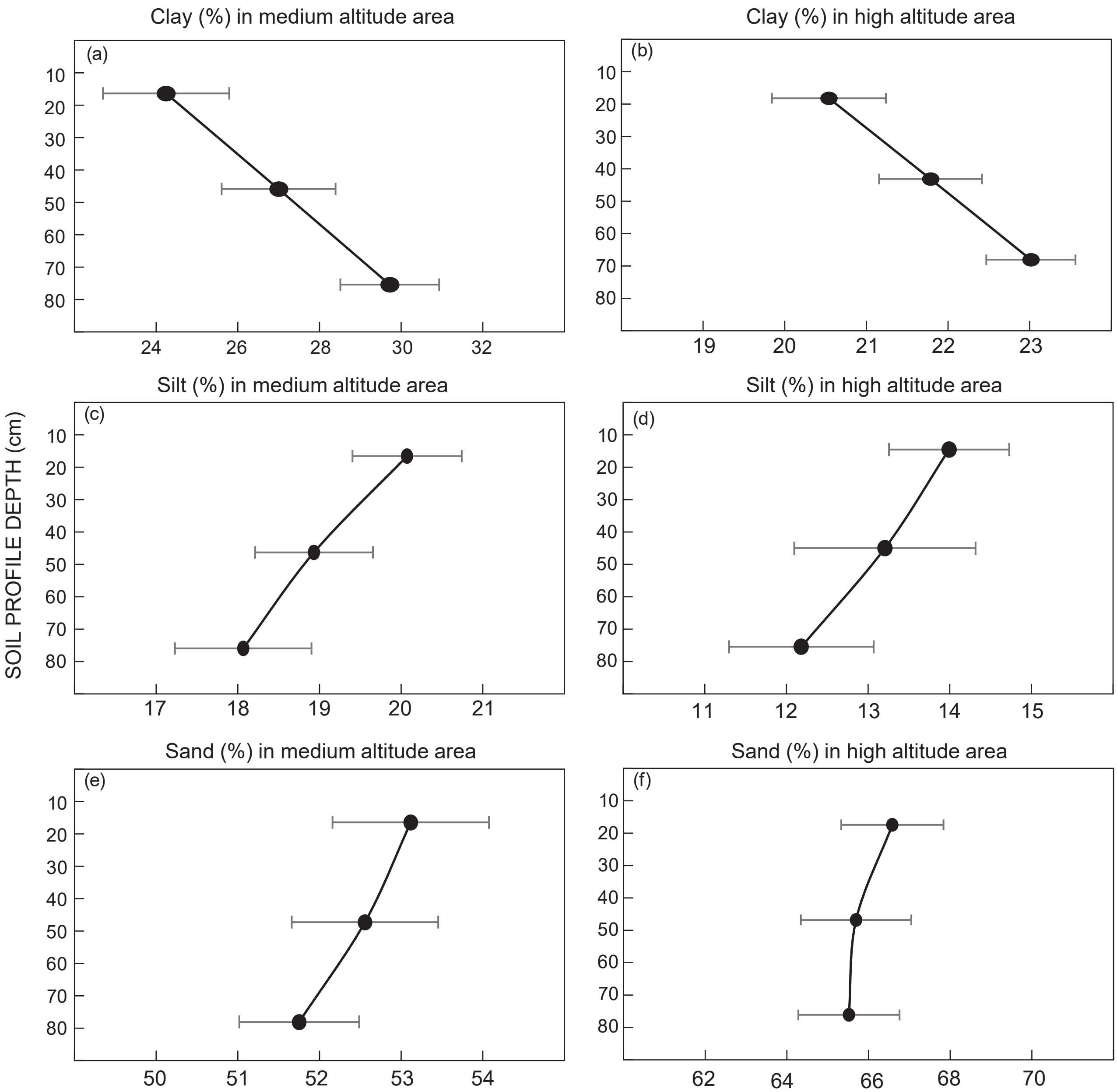

Figure 1: Variation of (a) and (b) clay, (c) and (d) silt, (e) and (f) sand with profile depth at medium and high altitude sites. Error bars represent the standard error.

land (18.6%) while the percentage of clay was higher in non-terraced soils (29.2%) than those in terraced land (27.8%) (Table 3). Thus, land terracing led to slight changes in silt and clay distribution but no changes in the sand fraction. These results are in line with findings of Ramos et al. (2007) who reported changes in the fine particle size distribution of soils that contained more than 60% of coarse particles. At high altitude, the main effect of land terracing on soil texture was non-significant for all soil particle size fractions.

Bulk density

Soil bulk density ranged from 1.33 to 1.57 g cm^{-3} at medium altitude and from 1.20 to 1.66 g cm^{-3} at high altitude (Figure 2). The interaction effect between land terracing and slope position on soil bulk density was significant ($p < 0.05$) in both study areas. At the medium altitude study area (Rwagamana), higher bulk density was found in soils of the middle and bottom slopes whereas at the high altitude (Gicumbi), the highest bulk density was found in soils of the bottom slope followed by those on the middle and top slopes (Figure 2). There was a significant ($p < 0.05$) interaction effect on bulk density between land terracing and soil depth at both study sites. Higher bulk density was found in deeper soil layers (40–60 and 60–80 cm) whereas lower bulk density occurred in the upper layers of 0–20 cm and 20–40 cm for both terraced and non-terraced lands at both medium and high altitudes (Figure 3). This might be due to increase in

Table 3: Effect of terracing on silt, clay, moisture content with suctions of pF0, 2.0 and 4.2, total available water (TAWC) and saturated hydraulic conductivity (Ks) in the study areas (mean ± standard error)

Site location	Type of land	Silt (%)	Clay (%)	pF0 (% water content)	pF2.0 (% water content)	pF4.2 (% water content)	TAWC (mm m^{-1})	Ks (mm h^{-1})
Medium altitude	Terraced	19.6 ± 0.5^{a*}	27.8 ± 0.8^{b}	32.5 ± 2.2^{a}	21.9 ± 0.8^{a}	12.8 ± 0.4^{a}	202.7 ± 6.4^{b}	237.9 ± 62.7^{a}
	Non-terraced	18.6 ± 0.6^{b}	29.2 ± 0.7^{a}	29.8 ± 1.7^{b}	22.3 ± 0.9^{a}	12.8 ± 0.3^{a}	222.2 ± 9.7^{a}	129.8 ± 44.5^{b}
High altitude	Terraced	12.7 ± 0.6^{a}	21.8 ± 0.5^{a}	36.8 ± 3.0^{a}	22.7 ± 1.2^{b}	11.5 ± 0.2^{b}	235.3 ± 13.7^{b}	194.3 ± 52.8^{a}
	Non-terraced	13.2 ± 0.6^{a}	21.8 ± 0.5^{a}	35.0 ± 3.0^{b}	23.5 ± 1.5^{a}	12.0 ± 0.3^{a}	251.0 ± 19.5^{a}	124.1 ± 36.6^{b}

*Different letters in the same column indicate significantly different values at $p < 0.05$

soil porosity associated with soil disturbance caused by soil fauna activity and tillage. The deeper soil layers are relatively free from these disturbances and were also subject to the overburden of soil and increase in finer particles, hence their greater bulk density. This is consistent with findings that soil bulk density often increases with soil depth (Soltanpour and Jourgholami 2013).

Soil water holding capacity

Soil moisture contents at various pF values in the top 60 cm of terraced and non-terraced soils in both study areas are presented in Table 4. Mean TAWCs were 212.4 mm m^{-1} at medium altitude and 243.2 mm m^{-1} at high altitude sites. The results indicate that water availability was high at both study sites (Moore 2001). The interaction effect between land terracing and slope position on TAWC was significant ($p < 0.05$). Higher TAWCs were obtained in top slope soils on non-terraced lands, i.e. 255.7 mm m^{-1} at medium altitude and 335.4 mm m^{-1} at high altitude (Table 4). The interaction effect between land terracing and soil depth on TAWC was non-significant at both study areas. The main effect of profile depths on TAWC was non-significant at the high altitude but significant ($p < 0.05$) at the medium altitude, where a higher TAWC of 221.5 mm m^{-1} was found in the 30–60 cm layer compared to 203.4 mm m^{-1} in the surface layer (0-30 cm) (Figure 4). This was attributed to increased infiltration of water due to increased soil pore spaces created by soil fauna and tillage in the surface soils. The effect of land terracing on TAWC showed significant differences ($p < 0.05$) between terraced and non-terraced lands. The mean values of TAWC were slightly higher in non-terraced land than in terraced land; i.e. 222.2 mm m^{-1} versus 202.7 mm m^{-1} at medium altitude and 251.0mm m^{-1} versus 235.3mm m^{-1} at high altitude (Table 3). Thus land terracing slightly decreased TAWC by 9% and 6% at medium and high altitude sites, respectively. These results show the same trend as findings from north eastern Spain where terracing decreased water retention capacity by up to 45% (Ramos et al. 2007). Dorren and Rey (2004), however, reported that terracing contributes to increasing the soil moisture content through improved infiltration; this was found to be true in this study at pF0 where more water was stored in the terraced than non-terraced soils due to the higher pore space in the terraced land (Table 3).

The entire soil moisture characteristic curves indicated that they were non-linear and showed similar trends for both terraced and non-terraced soils at both medium and high altitude sites (Figure 5). At the medium altitude site, at pF0, soils of terraced land held more water (32.5%) than those of non-terraced land (29.8%), while non-significant differences were found at other pF values, including field capacity (pF2.0) and permanent wilting point (pF4.2) (Table 3). At the high altitude, a similar effect was found at pF0 as soils of terraced land held more water (36.8%) than those on non-terraced land (35.0%). At field capacity (pF2.0) higher water retention capacity was found in soils of non-terraced land (23.5%) than on terraced land (22.7%). A similar trend was obtained at permanent wilting point, with a water content of 12.0% on non-terraced land, compared to 11.5% on terraced land (Table 3). At pF0, higher water storage in terraced soils was attributed to increased pore

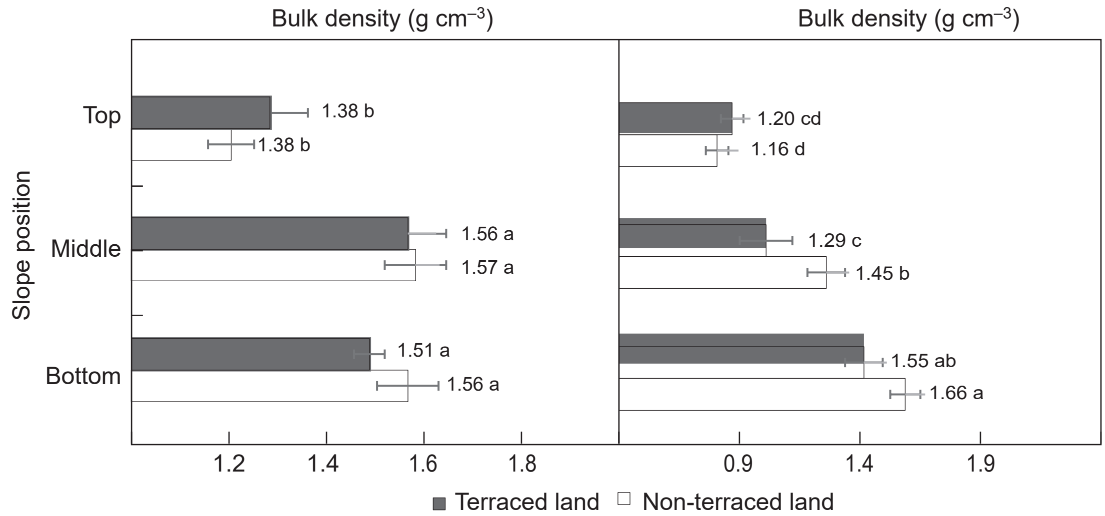

Figure 2: Bulk density of soils on terraced and non-terraced lands across the top, middle and bottom slopes of (a) medium and (b) high altitude areas. Error bars represent the standard error, figures represent the mean values of bulk density, and different letters indicate significantly different values at $p < 0.05$.

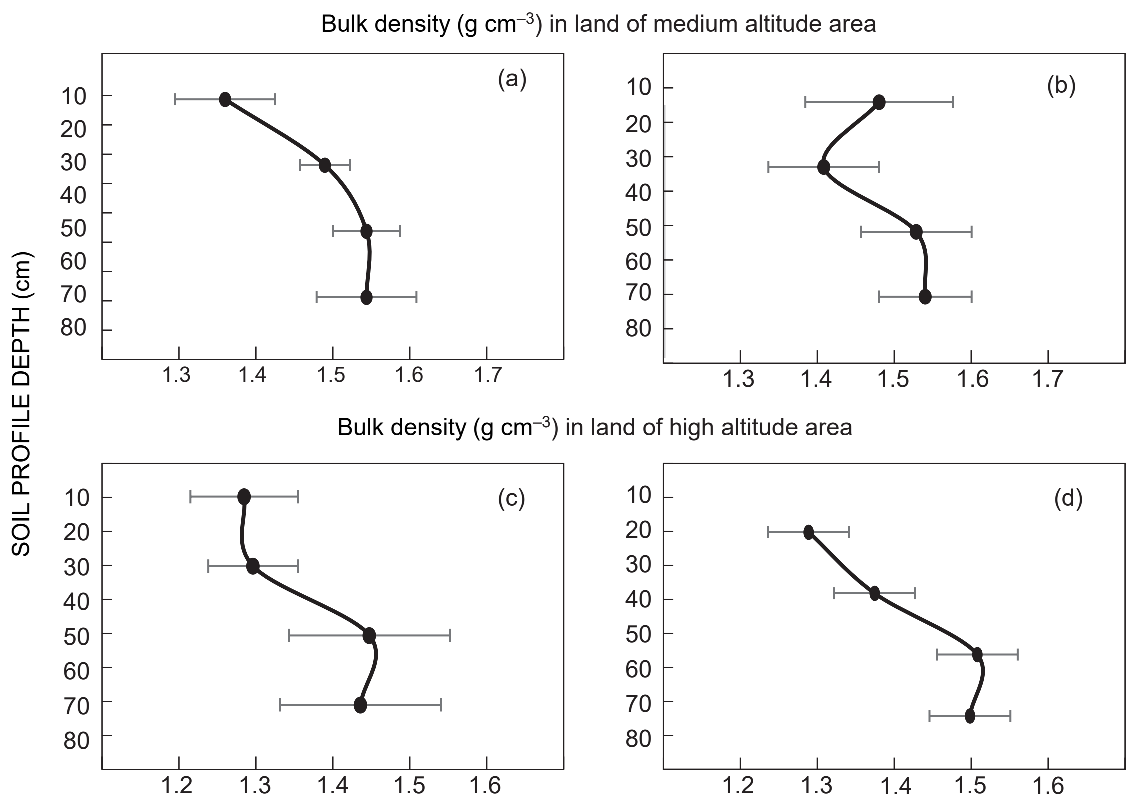

Figure 3: Variation of soil bulk density with profile depth in (a) terraced and (b) non-terraced land of the medium altitude area, and (c) terraced and (d) non-terraced land of the high altitude area. Error bars represent the standard error.

spaces resulting from the terracing work. At field capacity (pF2.0) and permanent wilting point (pF4.2), water retention capacity decreased due to terracing at the high altitude site where soils had high sand content (65.3%).

Saturated hydraulic conductivity

The saturated hydraulic conductivity (Ks) of soils ranged from 35.4 to 459.3 mm h^{-1} at medium altitude and from 11.3 to 394.7 mm h^{-1} at high altitude (Table 2). The

Table 4: Variation of moisture content with suction pF in soils from the top, middle and bottom of terraced and non-terraced lands in the study areas (mean ± standard error)

Site location	Type of land	Slope position	pF0 (% water content)	pF2.0 (% water content)	pF2.3 (% water content)	pF2.5 (% water content)	pF3.7 (% water content)	pF4.2 (% water content)	Available moisture (%)	TAWC* (mm m^{-1} soil)
Medium altitude	Terraced	Top	42.3 ± 0.2^{a}	24.8 ± 0.3	21.8 ± 0.2	20.9 ± 0.2	16.1 ± 0.3	14.1 ± 0.1	10.7 ± 0.2	214.0 ± 6.4^{b}
		Middle	30.2 ± 0.7^{c}	21.0 ± 0.6	19.0 ± 0.4	18.2 ± 0.3	13.8 ± 0.3	12.9 ± 0.2	8.1 ± 0.5	191.9 ± 5.0^{b}
		Bottom	25.0 ± 0.7^{f}	19.7 ± 1.3	16.9 ± 1.1	15.6 ± 0.8	13.2 ± 0.32	11.2 ± 0.5	8.5 ± 1.0	202.1 ± 17.5^{b}
	Non-terraced	Top	35.8 ± 3.2^{b}	25.8 ± 1.0	23.0 ± 0.8	22.1 ± 0.7	15.8 ± 0.4	14.0 ± 0.3	11.8 ± 0.8	255.7 ± 7.4^{a}
		Middle	26.1 ± 1.3^{e}	21.1 ± 0.5	19.1 ± 0.4	18.3 ± 0.4	14.2 ± 0.3	12.6 ± 0.3	8.5 ± 0.7	218.7 ± 13.4^{b}
		Bottom	27.0 ± 1.3^{d}	20.0 ± 0.4	17.3 ± 0.5	16.4 ± 0.5	13.8 ± 0.3	11.8 ± 0.3	8.2 ± 0.3	192.3 ± 10.8^{b}
Mean			31.1	22.1	19.5	18.6	14.5	12.8	9.3	212.4
N$			24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
CV# (%)			1.4	3.8	4.3	4.4	4.9	3.6	**9.6**	**7.9**
High altitude	Terraced	Top	44.5 ± 5.0^{b}	28.0 ± 1.1^{b}	23.6 ± 0.7^{b}	22.3 ± 0.6^{b}	15.4 ± 0.4	12.4 ± 0.3	15.6 ± 0.9^{b}	296.5 ± 11.0^{b}
		Middle	40.7 ± 0.1^{c}	21.1 ± 0.5^{c}	16.9 ± 0.2^{d}	15.6 ± 0.2^{d}	11.8 ± 0.3	10.8 ± 0.1	10.3 ± 0.4^{c}	209.8 ± 4.1^{c}
		Bottom	25.1 ± 0.6^{e}	19.1 ± 0.3^{d}	16.7 ± 0.4^{d}	16.1 ± 0.5^{d}	12.9 ± 0.5	11.3 ± 0.3	7.8 ± 0.2^{e}	199.5 ± 5.2^{c}
	Non-terraced	Top	46.1 ± 3.0^{a}	30.4 ± 0.5^{a}	25.7 ± 0.8^{a}	24.2 ± 0.9^{a}	15.3 ± 0.4	13.0 ± 0.2	17.4 ± 0.6^{a}	335.4 ± 18.7^{a}
		Middle	34.6 ± 2.7^{d}	20.0 ± 0.4^{cd}	15.9 ± 0.1^{d}	14.5 ± 0.1^{e}	11.8 ± 0.3	10.9 ± 0.4	9.0 ± 0.7^{d}	200.4 ± 9.6^{c}
		Bottom	24.3 ± 1.1^{e}	20.2 ± 0.7^{cd}	18.4 ± 0.7^{c}	17.8 ± 0.6^{c}	13.9 ± 0.2	12.2 ± 0.3	8.0 ± 0.5^{de}	217.2 ± 11.0^{c}
Mean			35.9	23.1	19.5	18.4	13.5	11.8	11.3	243.2
N			24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
CV (%)			2.0	3.4	3.6	3.5	5.5	3.7	6.6	6.7

Different letters in the same column indicate significantly different values at $p < 0.05$
* TAWC: total available water content
$ N : number of observations / samples
# CV: coefficient of variation

lower values of Ks indicate that the soils are suitable for irrigation, while the higher Ks values indicate that the soils are too permeable for irrigation (Hazelton & Murphy 2007). The interaction effect between land terracing and slope positions on Ks was significant ($p < 0.05$) in both study areas. At medium altitude, a higher Ks was found in the top slope soils of terraced land (459.3 mm h^{-1}) with lower Ks in soils on the bottom slope of terraced (35.4 mm h^{-1}) and non-terraced (56.2 mm h^{-1}) lands. At high altitude, soils of top and middle slopes on both terraced and non-terraced lands (humic Alisols / humic Acrisols) were more permeable than those on the bottom slopes of both terraced and non-terraced lands (humic Acrisols/ humic (Ferralic) Cambisols) (Table 2).

The interaction effect between land terracing and soil profile depths on Ks was non-significant in high altitude soils and significant ($p < 0.05$) at medium altitude, where soils from the 0-30 cm layer of both terraced and non-terraced lands were more permeable than those from the 30-60 cm layer (Figure 6). This was due to increased infiltration of water in surface soils due to increased soil pore spaces created by soil fauna and tillage.

The effect of terracing on Ks was significant ($p < 0.05$) in both study areas. Higher values of 237.9 mm h^{-1} and 194.3 mm h^{-1} were found in soils of terraced land of medium and high altitudes, respectively, compared to 129.8 mm h^{-1} and 124.1 mm h^{-1} in those of non-terraced land (Table 3). This indicated that soil disturbance by terracing work improved soil permeability due to increasing soil porosity. Ramos et al. (2007) in north eastern Spain also reported increases of hydraulic conductivity due to terracing work.

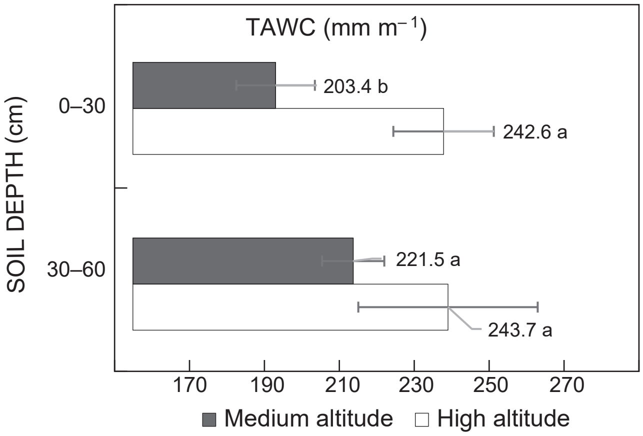

Figure 4: Total available water content (TAWC) in the 0–30 and 30–60 cm soil layers at the medium and high altitude sites. Error bars represent the standard error, figures represent the mean values of TAWC, and different letters indicate significantly different values at p < 0.05.

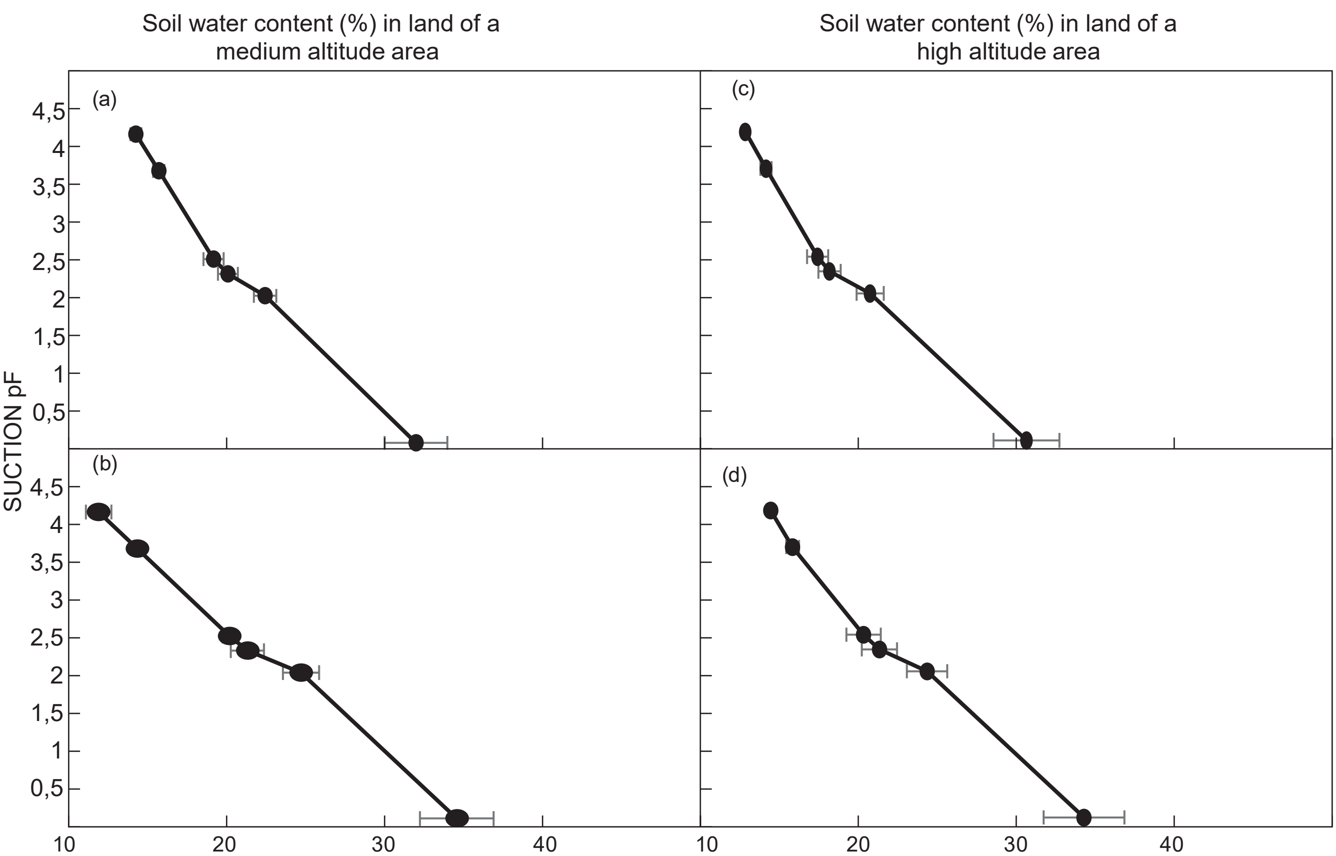

Figure 5: Water retention curves of soils from (a) terraced and (b) non-terraced land of the medium altitude area, and (c) terraced and (d) non-terraced land of the high altitude area. Error bars represent the standard error.

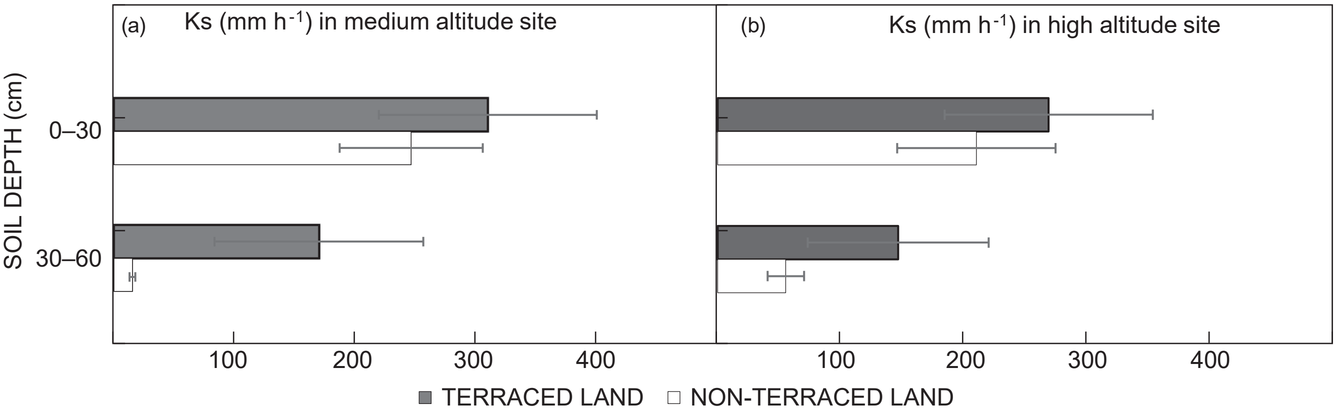

Figure 6: Saturated hydraulic conductivity (Ks) in the 0–30 cm and 30–60 cm soil layers of terraced and non-terraced lands at (a) medium and (b) high altitude areas. Error bars represent standard error.

Conclusion

The objective of this study was to determine the effect of land terracing on some soil physical properties across slope positions and profile depths in medium and high altitude areas of eastern and north eastern Rwanda. The results showed that although terracing caused slight changes in soil particle size distribution, the predominant soil texture remained sandy clay loam. Deeper soil layers had higher clay contents and surface soils had higher silt and sand contents. Higher soil bulk densities were recorded on the bottom and middle slopes of both terraced and non-terraced lands at the medium altitude area and bottom slopes of non-terraced land at the high altitude area. Soil bulk density increased with soil depth with higher values found in deeper soil layers of non-terraced lands at the high altitude site. Higher TAWCs were found in top slope soils of non-terraced lands in both study areas. Sub-soils had higher TAWC at medium altitude. A higher soil Ks was found in top slope soils of terraced lands at medium altitude and in soils on the middle slope at high altitude. Surface soils of terraced lands had higher soil Ks in both study areas. Terracing thus changed soil particle size distribution and improved soil permeability but with a slight reduction in water retention of the surface soils. Land use needs to consider these changes as they can affect soil water movement in terraced lands and potentially influence soil water and fertility management, for example, with regard to water storage capacity and fertilizer leaching from the surface soil layers.

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