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Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands

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Abstract

Soil translocation due to tillage by the ox-drawn ard plough appears to be an important source of colluviation behind stone bunds and lynchets in the Ethiopian highlands. To quantify erosion rates caused by this plough in Ethiopia, painted and numbered rock fragments, 3–5 cm in intermediate diameter, were used as tracers to monitor soil movement on 16 sites, each having a different slope gradient, in the district of Dogu'a Tembien, Tigray Region, Ethiopia. Average tillage depth was 8.1 cm and the net mean downslope displacement distance per tillage operation ranged from 4.7 cm for a 0.03 m m^{-1} slope to 34.4 cm for a field with a gradient of 0.48 m m^{-1}. There was a strong correlation ($R^2 = 0.84$, $P < 0.001$) between slope gradient and downslope displacement. Where present, large rock fragments (>15 cm intermediate diameter) are obstacles to the downslope movement of tilled soil. The unit soil transport rate (Qs) per tillage operation ranged from 4.8 kg m^{-1} on the 0.03 m m^{-1} slope to 38.7 kg m^{-1} on the 0.48 m m^{-1} slope. These values represent the mass of soil deposited by tillage behind 1 m of lynchet or stone bund. During each tillage operation the same mass of soil is also removed from the foot of the upper stone bund or lynchet. For the first tillage operation, before the onset of the rainy season, the tillage transport coefficient (K) was 68 kg m^{-1}. As farmers till 1–4 times per year, annual K values can be assessed to range from 68 to 272 kg m^{-1}. These values are less than those observed for mechanised tillage, which however, is usually conducted on less steep slopes. On average, tillage erosion can be held responsible for half of the sediment deposited behind newly constructed stone bunds in the Tigray highlands. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ard plough; Colluviation; Ethiopia; Soil conservation; Tillage erosion

1. Introduction

Land degradation, desertification and soil erosion are recurrent phenomena in the northern Ethiopian highlands (Hurni, 1990). Erosion rates are partially controlled by soil and water conservation structures, such as lynchets and stone bunds, which result in the development of progressive terraces (Hudson, 1992). Sediment accumulates behind the vegetative barriers of the *daget* (lynchets) and behind stone bunds. These structures act not only as a partial barrier for water-induced erosion, but at the same time form a total barrier to tillage translocation (Turkelboom et al., 1997; Govers et al., 1999). Colluviation occurs in

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the lower part of the field and soil profiles are truncated in the upper part (Nyssen, 1998; Herweg and Ludi, 1999; Nyssen et al., 2000a).

Research on tillage erosion by non-mechanised implements in the third world is rather new, though some measurements have been made for tillage with ox-pulled plough in the Philippines and the Andes (Rymshaw et al., 1998; Thapa et al., 1999; Dercon et al., 1999) and hoe in Rwanda and Thailand (Moeyersons, 1989; Turkelboom et al., 1997, 1999; Lewis, 1992, 1999).

The objectives of this study were: (1) to quantify rates of tillage translocation, erosion and deposition, (2) to examine the controlling factors of tillage erosion in the Ethiopian highlands, and (3) to assess the relative contributions of water and tillage erosion processes to the total amount of sediment deposited behind soil conservation structures. A field experiment was set up and the displacements of tracers were measured after the topsoil was ploughed by the ard or single-tined plough (*mahrasha* in Tigrinya, *maresha* in Amharic) in the village of Harena, Tigray.

2. Materials and methods

2.1. The study area

Hagere Selam, market centre of the Dogu'a Tembien district, is situated at an altitude of 2650 m, about 50 km west of Makalle, Tigray's regional capital (Fig. 1). In this region, Mesozoic sediments are capped by the Tertiary Ashange basalt flows, which include silicified lacustrine deposits. The numerous subhorizontal layers give rise to a stepped landscape of cliff-edged tabular structures. The modal slope gradient is 0.1 m m^{-1} (Nyssen, 1995).

The major rainy season extends from June to September with about 700 mm of precipitation. It is preceded by 3 months of dispersed rain. From November to February, the weather is usually almost completely dry.

On the basaltic rocks one finds a typical Luvisol–Regosol–Cambisol–Vertisol catena. Vertisols are only found on footslopes. The lower tracts of the valleys, on limestone, have Calcisols, other calcaric soils and

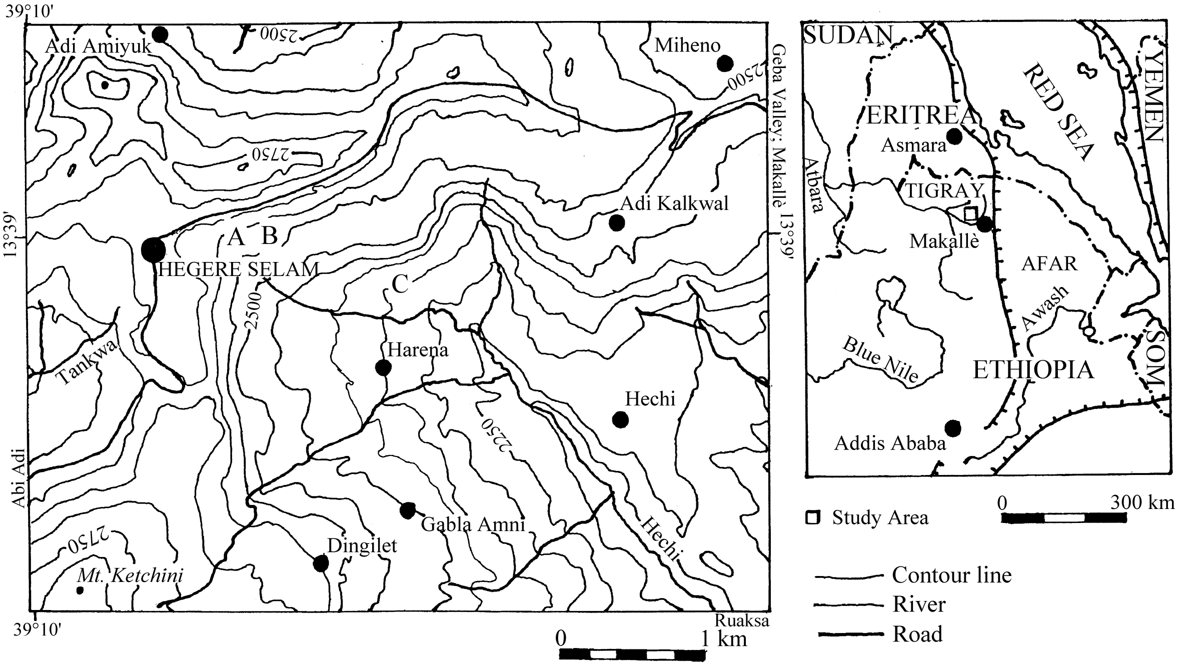

Fig. 1. The study area, Dogu'a Tembien in the Tigray highlands. A, B and C indicate the selected slopes where the experiments were conducted.

Fig. 2. Tillage by *maresha* (experiment C6, Gra Arho, Harena, March 1999). The farmer inclines the steering stick to give it a position that is perpendicular to the soil surface. On steep slopes, this results in throwing all soil to the lower side of the furrow during every tillage pass.

some Vertisols. The combined physical, geological and meteorological conditions of the area are ideal for the formation of smectitic clays (Nyssen et al., 2000b).

The agricultural system in the northern Ethiopian highlands has been described as ‘‘grain-plough complex’’ (Westphal, 1975). The main crops are barley (*Hordeum vulgare* L.), wheat (*Triticum* sp.) and tef (*Eragrostis tef*), an endemic cereal crop. In spite of a generally low soil erodibility, reflecting high clay and rock fragment contents, the steep slopes induce much soil erosion.

Grepperud (1996) found a positive relationship between degree of soil erosion and livestock and population pressure, but stressed that it ‘‘would probably not have been identified if substantial innovation had occurred in Ethiopia’’. Agricultural techniques have, however, stagnated for centuries. Investment in agriculture was mostly oriented towards export crops like coffee (*Coffea arabica* L.), grown in southern Ethiopia. Therefore, there was limited agricultural investment in the highlands, where subsistence production dominates (Ståhl, 1990; Mulugetta, 1992). Until the late 1970s, share-cropping prevented the farmers from investing in their fields. To increase agricultural production, most of the trees and shrubs between the fields and on steep slopes have been

Fig. 3. The wedge-shaped metal share, flanked by two wooden ears, which spread the tilled soil.

Table 1
Characteristics of the sites in Dogu'a Tembien, Ethiopia, where tillage experiments were carried out in 1999

Slope	Site	Lithology	Texture[a]	Slope[b]	Bd[c]	Soil moisture[d]	Rock fragment cover		Number of tracers				
							Gravel[e]	Total[f]	Total	n_1[g]	n_2[h]	n_3[i]	Recovery rate[j]
A	A1	Basaltic colluvium	Clay loam	0.1	1170	0.13	21.0	60.9	80	33	47	38	80.9
	A2		Clay loam	0.2	1290	0.20	32.8	53.4	79	26	53	50	94.3
	A3		Silty clay loam	0.31	1110	0.20	27.6	62.7	79	45	34	30	88.2
	A4		Clay loam	0.155	1250	0.17	48.1	63.9	80	32	48	45	93.8
	A5		Silty clay loam	0.26	1090	0.14	23.7	62.2	80	53	27	24	88.9
B	B1	Basaltic and silicified rock colluvium	Clay loam	0.03	890	0.14	2.2	22.1	80	19	61	57	93.4
	B2		Clay loam	0.06	1210	0.14	8.2	37.3	80	27	53	45	84.9
	B3		Loam	0.35	1050	0.13	42.3	79.2	80	8	72	70	97.2
	B4		Sandy loam	0.48	1100	0.13	36.2	50.0	77	16	61	60	98.4
	B5		Sandy loam	0.42	1100	0.13	30.5	73.4	80	30	50	49	98.0
C	C1	Limestone	Clay loam	0.07	1180	0.06	15.3	31.5	78	41	37	35	94.6
	C2		Loam	0.03	1340	0.02	25.2	36.2	78	42	36	36	100.0
	C3		Loam	0.09	1090	0.06	22.1	45.6	80	43	37	29	78.4
	C4		Loam	0.15	1250	0.07	57.7	70.8	80	46	34	34	100.0
	C5		Loam	0.24	1070	0.09	54.7	70.1	80	28	52	50	96.2
	C6		Loam	0.19	1090	0.11	43.0	54.1	75	42	33	30	90.9

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[a] Texture of plough layer.

[b] Slope gradient (m m^{-1}).

[c] Dry bulk density (kg m^{-3}).

[d] Volumetric soil moisture content (m^3 m^{-3}).

[e] Rock fragment cover (% of surface area) by gravel (0.5–5 cm intermediate diameter).

[f] Total rock fragment cover (>5 cm).

[g] Number of tracers used for measuring tillage depth.

[h] Number of tracers used for measuring soil movement.

[i] Number of translocation observations.

[j] Recovery rate in % (n_3/n_2).

cleared during the 19th and 20th centuries, increasing runoff and soil erosion. Since 1990, soil and water conservation has been a high priority in Dogu'a Tembien (Nyssen, 1998). Grazing and woodcutting are prevented on many steep slopes, and the communities have constructed stone bunds on the contour in order to obtain progressive terraces.

2.2. *The Ethiopian ard or maresha*

The ard-type of plough was first described in the poems of Hesiod, in approximately 700 BC (Frazer, 1984). Goe (1989) and Girma et al. (1997) reviewed the characteristics and the use of these ploughs, with a focus on Ethiopia. The Ethiopian ard or *maresha* is a wooden plough, pulled by two oxen (Fig. 2). Inserted in a hole at the end of the 2.2–2.5 m long beam is a steering stick with a wedge-shaped metal share, which penetrates the soil (Fig. 3). Two wooden "ears" located on either side of the beam spread the tilled soil. Having studied tillage operations from the point of view of draught necessary to pull the implement, Goe (1999) concluded that "the design and construction of the *maresha* allows it to be used equally well for tillage operations on plots having minimal or high stone cover which may be located on flat or gentle sloping land, or on steep hillsides". It is well adapted to ploughing soil with vertic properties because it breaks up hard, dried topsoil.

The number of tillage operations per year ranges from one for most leguminous crops to four for tef. This study concerns the first tillage operation, before the onset of the minor spring rains. Information provided by local farmers and Gete (1999) indicates that subsequent ploughings are deeper, except for the last tillage operation, which is done after broadcast sowing.

In Tigray, particularly since the widespread introduction of stone bunds in the late 1980s, ploughing is parallel to the contour. The first furrow is made at the lower end of the field, and the oxen move upslope for each subsequent furrow. The initial furrow is never made at the top of the field because it is more difficult for the oxen. In that case, they spontaneously walk too far downslope when turning and additional efforts are needed to bring them up to the position of the next furrow.

2.3. *Experimental sites*

Three representative slopes were chosen in the district of Dogu'a Tembien, Tigray Region (slope A, B and C, Fig. 1). On each slope, we selected 5–6 sites with a range of representative slope gradients (Table 1). The first slope (A) is on the footslope of a basalt cliff, and is covered by basaltic colluvium, with a very variable content of often large rock fragments (up to 25 cm intermediate diameter). Clay content of the plough layer of all these sites is over 300 g kg^{-1} and sand content generally below 300 g kg^{-1}. The second slope (B) is also on the footslope of the basalt cliff, it also consists of basaltic colluvium but with a large content of silicified materials originating from

Fig. 4. Installing tracers for experiment C4. After measurement of their three-dimensional position, the tracers are covered by a thin, slightly compacted layer of soil, and another row of tracers is installed. The thin sticks serve as a guide to put the tracers in a vertical position above those of the previous rows. The exposure of the base of the stone bund (in the upper part of the photo) indicates the magnitude of soil profile truncation just downslope of it.

Tertiary lake deposits. These Regosols and Cambisols are lighter and more easily tilled (<300 g kg^{-1} clay, >300 g kg^{-1} sand). A third series of measurements were made on the footslope of a sand- and limestone cliff (slope C), situated some 400 m lower than the other two slopes. These calcaric soils have a very uniform loamy texture.

2.4. Experimental methods

Tillage experiments were conducted on 16 sites (Table 1). Rock fragments, 3–5 cm in intermediate diameter, were taken from nearby fields, painted and numbered. At each site, 80 of such tracers were used. It was assumed that the coarse fraction of the plough layer and the fine earth fraction "evidence similar relationship between translocation distance and slope" (Quine et al., 1999a). Elements of the coarse fraction, used as tracers, were thus installed at different depths in a 2 m long, narrow trench extending directly downslope, perpendicular to tillage direction. The three-dimensional position of each tracer was measured by a laser theodolite before and after tillage (Fig. 4). The recovery rate of the tracers after tillage ranged between 78.4 and 100% (Table 1).

Measurement of the depth of the deepest tracers which moved and of the upper tracers which remained in place after tillage allowed the average depth of the tilled soil layer to be calculated (Turkelboom et al., 1997). Tillage depth was expressed as the depth below the unploughed, compacted soil. Soil samples were taken from the unploughed topsoil by 100 cm^3 core sampling rings for measurement of bulk density. Moisture content was determined by weighing topsoil samples before and after oven drying at 105°C. Rock fragment cover was determined by the point-count method (Poesen et al., 1998), superposing a grid on slides taken vertically on each site before the experiments were carried out.

2.5. Measurement of volumes of recent colluvium

Volumes of sediment deposited behind stone bunds were measured on a vertical soil cross-section, perpendicular to the contour. This cross-section was made in an area, where new stone bunds had been built in

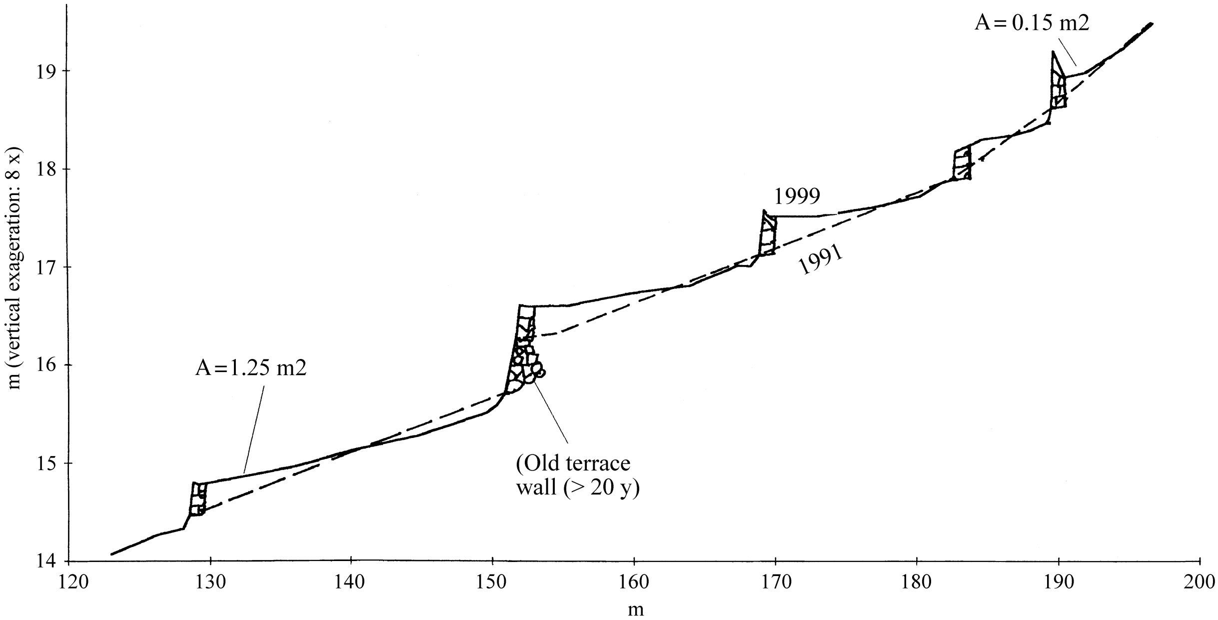

Fig. 5. Colluviation and soil profile truncation after the construction of stone bunds in fields 2 km east of Hagere Selam. The present-day surface (February 1999; full line) results from the establishment of stone bunds in 1991. The original surface (dashed line) has been partially covered by colluvium and partially truncated (topographical survey by theodolite, February 1999). **A** equals to the cross-sectional area comprised between the old and the new soil surface.

Table 2
Results of experiments for the measurement of tillage erosion rates in the northern Ethiopian highlands

Experiment	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5	C6
Slope (m m^{-1})	0.1	0.2	0.31	0.155	0.26	0.03	0.06	0.35	0.48	0.42	0.07	0.03	0.09	0.15	0.24	0.19
Net mean downslope displacement, d (m)[a]	0.10 (±0.10)	0.14 (±0.10)	0.17 (±0.17)	0.19 (±0.15)	0.14 (±0.13)	0.05 (±0.07)	0.07 (±0.11)	0.17 (±0.13)	0.34 (±0.31)	0.29 (±0.21)	0.08 (±0.09)	0.07 (±0.09)	0.08 (±0.08)	0.09 (±0.10)	0.17 (±0.13)	0.10 (±0.13)
Mean tillage depth, D (m)[a]	0.10 (±0.03)	0.10 (±0.03)	0.06 (±0.03)	0.08 (±0.04)	0.05 (±0.02)	0.10 (±0.03)	0.09 (±0.02)	0.11 (±0.03)	0.10 (±0.03)	0.08 (±0.03)	0.06 (±0.03)	0.06 (±0.03)	0.08 (±0.03)	0.06 (±0.03)	0.09 (±0.02)	0.07 (±0.03)
Unit soil transport rate, Qs (kg m^{-1})	11.5	16.7	10.8	17.8	8.3	5.4	7.3	21.8	38.7	27.4	5.3	4.8	6.9	6.5	16.6	7.4
Volumetric unit soil transport rate (m^{3} m^{-1})	0.010	0.015	0.009	0.016	0.007	0.005	0.006	0.019	0.034	0.024	0.005	0.004	0.006	0.006	0.015	0.007
Tillage speed (km h^{-1})	0.9	1.1	0.7	1.4	0.9	1.0	0.8	1.5	1.0	1.1	1.0	1.1	1.4	1.5	1.0	1.3
Number of observations	38	50	30	45	24	57	45	70	60	49	35	36	29	34	50	30
Number of tracers upslope	4	1	1	2	0	11	11	1	0	0	4	7	5	5	1	2
Number of tracers downslope	34	49	29	43	24	46	34	69	60	49	31	29	24	29	49	28

[a] Standard deviation between brackets.

1991. A 0.5–1.5 m deep trench was dug straight upslope, perpendicular to the stone bunds. The position of the soil surface was measured by a laser theodolite. The thickness of the colluvium deposited since stone bund building was also measured. The feet of the stone bunds were considered to correspond to the initial position of the field surface. This allowed the reconstruction of the position of the original soil surface (Fig. 5). Unbalanced cross-sections of colluviation and soil profile truncation should not surprise since soil transported by runoff from more upslope is also deposited behind the stone bunds.

2.6. Statistical methods

The degree of association between variables was measured by linear regression and calculation of the Pearson correlation coefficient R. Levels of significance (P) for these correlations were obtained by F-tests based on analyses of variance (Beguin, 1979; Waltham, 1994).

3. Results and discussion

3.1. Soil moisture content

At the time of the experiment (March 1999), the soil moisture content on the basaltic slope A ranged from 0.13 to 0.2 $m^3\ m^{-3}$ (Table 1). The farmers considered this soil moisture content exceptionally high. March normally terminates a 6 months long dry season, but there were exceptional rains (48 mm) in January 1999, and the previous rainy season was also very wet. The moisture content of the ploughed layer of slope B varied between 0.13 and 0.14 $m^3\ m^{-3}$. The moisture content of the tilled horizon of the loamy calcaric soils of slope C was less (0.02–0.11 $m^3\ m^{-3}$). No significant relationship was found between volumetric soil moisture content and the displacement distances of the tracers.

3.2. Tillage depth

Farmers can control tillage depth by changing the angle of the plough point (Fleur, 1987), by varying the length of the leather strap which links the beam to the yoke, or in some cases, by changing the metal point or even by shifting to a bent beam. Tillage depth seems only to depend on these characteristics of the plough and on the downward pressure which the farmer exerts on it (Goe, 1990), since no significant correlation was found with soil texture or rock fragment cover. No correlation was found either between tillage depth and tillage speed. The latter is positively, but moderately correlated with gravel cover (0.5–5 cm across) ($R^2 = 0.30$) and negatively with clay content ($R^2 = 0.25$).

Mean tillage depth, measured vertically, varies between 5.4 ± 2.3 cm and 11.0 ± 2.6 cm and is not dependent on slope gradient ($R^2 = 0.03$) (Tables 2 and 3). Average tillage depth of the first ploughing in our study area was 8.1 cm (320 measurements). Other authors have measured average tillage depths by *maresha* of 7 cm (Fleur, 1987), 6.8 cm (Hunting, 1976). Goe (1999) measured plough furrows depths of 10.1–15.3 cm, whereas Gete (1999) measured 10.1–12.5 cm.

Table 3
Correlations between slope gradient and downslope displacement, tillage depth and unit soil transport rate

Correlation (R^2) between slope gradient and	All	Slope A (basaltic colluvium)	Slope B (basaltic and silicified colluvium)	Slope C (calcaric colluvium)
Net mean downslope displacement	0.84[***]	0.17[a]	0.93[**]	0.73[*]
Mean tillage depth	0.03[a]	0.68[****]	0.00[a]	0.36[a]
Unit soil transport rate per tillage operation	0.73[***]	0.19[a]	0.94[**]	0.67[*]
Number of experiments	16	5	5	6

[a] Not significant.

[*] Significant at 5% probability level.

[**] Significant at 1% probability level.

[***] Significant at 0.1% probability level.

[****] Significant at 10% probability level.

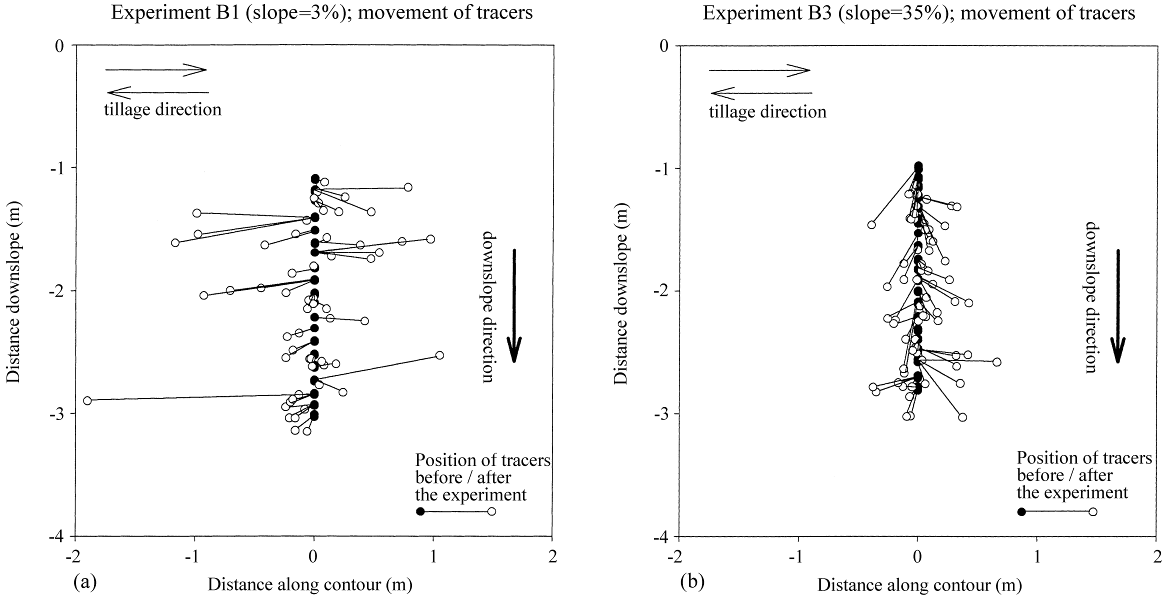

Fig. 6. Displacements of tracers for (a) experiment B1 and (b) experiment B3. The displacements along the contour decrease with the increase of slope steepness. As ploughing is on the contour and alternatively in either direction, the sum of all displacements along the contour can be considered equal to 0.

3.3. Downslope displacement

Displacements parallel to the contour decrease with increasing slope steepness (Fig. 6a and b). Since tillage is on the contour, and as half of the tillage passes are to the left and half to the right, the sum of all displacements is equal to 0. Therefore, only the up- and downslope components of the tillage translocation will be considered here.

Although it is often assumed that the soil is thrown to both sides of the furrow with an ard (Huffnagel, 1961; Westphal, 1975), our measurements showed that on slopes steeper than 0.15 m m^{-1}, virtually all soil is thrown to the lower side of the furrow as indicated by the number of tracers moved up- and downslope (Table 2). When ploughing sloping land, the farmer always walks at the lower side of the ard, inclining it so as to adopt a position that is perpendicular to the soil surface (Fig. 2). The plough-point and the ears are thus also inclined and direct most of the tilled soil to the lower side of the furrow.

The net mean downslope displacement (d) was calculated as the average of all tracer movements, positive values being given to downslope movements and negative to upslope movements. The net mean downslope displacement (Fig. 7) ranged from 4.7 cm for a 0.03 m m^{-1} slope to 34.4 cm for a very steep field with a slope of 0.48 m m^{-1} on which even walking leads to soil displacements. On slopes steeper than 0.15 m m^{-1} individual tracers moved as far as 87 cm downslope. Maximum upslope movement of an individual tracer was 17.8 cm on a slope with a gradient of 0.03 m m^{-1}. These extreme displacements correspond to strong upliftings of the plough by the farmer when it stuck behind a rock or in weeds.

In the fields on basaltic colluvium (Table 3, slope A), there is a poor correlation between slope gradient and downslope displacement, but a strong negative relationship ($R^2 = 0.67, P = 0.08$) between large rock (>15 cm intermediate diameter) cover and downslope movement. Large rock fragments (up to 5 m^{-2}) are obstacles to the downslope movement of tilled soil. Their variable presence (i.e., not correlated to slope gradient) on the sites of slope A explains the poor correlation between slope gradient and downslope displacement.

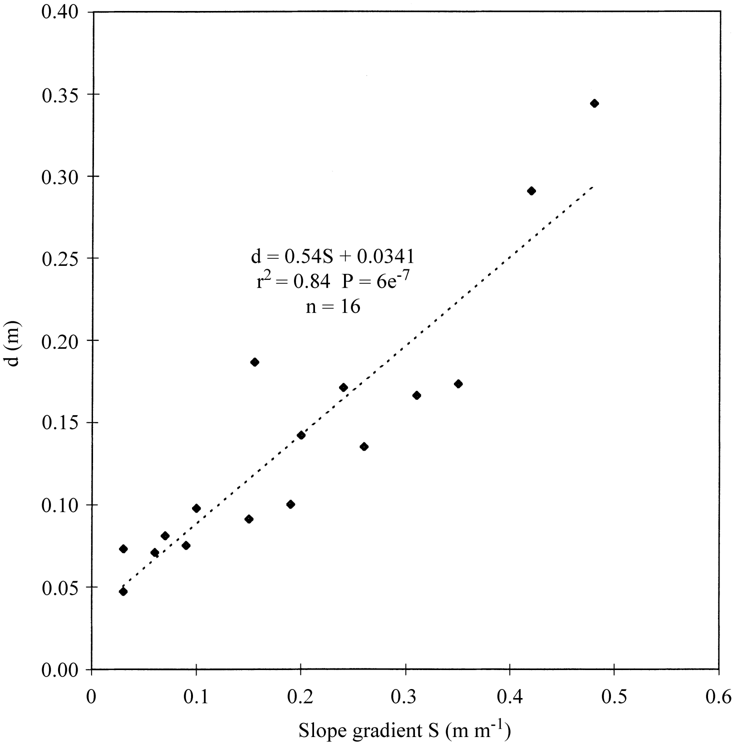

Fig. 7. Net mean downslope component of tracer displacements (*d*) vs. slope gradient (*S*).

Nevertheless, the overall correlation is strong ($R^2 = 0.84$, $P = 0.001$) for the 16 experiments (Fig. 7 and Table 3).

3.4. Assessment of the unit soil transport rate due to the first tillage operation

The unit soil transport rate (soil flux) was estimated, using the equation applicable to contour ploughing (Poesen et al., 1997):

$$\mathrm{Qs} = d\,D\,\mathrm{Bd} \qquad (1)$$

where Qs is the unit soil transport rate (kg m^{-1}), *d* the net mean downslope component of all tracer displacements (m), in the direction of the steepest slope, measured horizontally, *D* the mean tillage depth (m), measured vertically, and Bd is the dry soil bulk density (kg m^{-3}); assuming that *d* approaches the mean downslope displacement distance of the entire soil mass in the plough layer (Quine et al., 1999a). Bulk density was measured once for each experiment (Table 1), to give an average value for each slope. As there was no significant difference between the values of average bulk density for the three slopes, it was preferred to use the mean bulk density of the 16 samples (1142 kg m^{-3}) in all calculations.

Qs ranged from 4.8 kg m^{-1} on a 0.03 m m^{-1} slope to 38.7 kg m^{-1} on the 0.48 m m^{-1} slope (Fig. 8). The values obtained for Qs correspond to the mass of soil that is deposited behind 1 m of grass strip or stone bund after one tillage operation. The same soil mass is also removed from the foot of the upper soil conservation structure. The correlation coefficient between Qs and slope gradient (*S*) is 0.73 ($P < 0.001$) (Table 3 and Fig. 8).

3.5. Long-term unit soil transport rates and colluviation behind soil conservation structures

The volumes of soil deposited behind stone bunds (Fig. 5) ranged from 0.15 m^3 m^{-1} on a slope of 0.12 m m^{-1} to 1.25 m^3 m^{-1} on a 0.05 m m^{-1} slope in 8 years, or 0.02–0.16 m^3 m^{-1} per year. On the same slopes, yearly unit soil transport rates resulting from two to

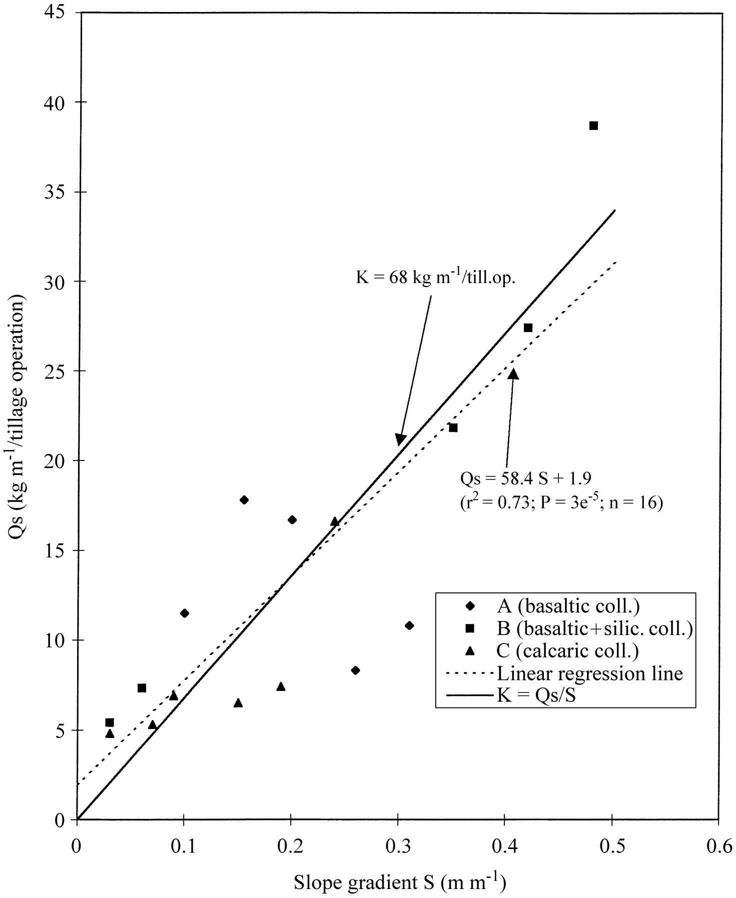

Fig. 8. Unit soil transport rate per tillage operation (Qs) vs. slope gradient (*S*) and corresponding tillage transport coefficient (*K*).

four tillage operations can be tentatively assessed to range from 0.01 to 0.08 $m^3\ m^{-1}$ per year (Table 2). On average, tillage translocation can thus be held responsible for half of the sediment deposited behind the stone bunds. On the steepest slopes, however, the volumes of soil trapped behind each stone bund are low, because the available volume for storage is less. Here, the unit soil transport rate due to tillage is also greater than the average. On steep slopes, tillage translocation contributes thus largely to the rapid formation of terraces behind stone bunds.

3.6. The tillage transport coefficient

In this diffusion-type geomorphological process of soil displacement (Kirkby, 1971), the proportionality coefficient relating unit soil transport rate Qs to the slope gradient *S* is called the tillage transport coefficient (Govers et al., 1994):

$$K=\frac{\mathrm{Qs}}{S} \qquad (2)$$

where $S=\Delta h/\Delta x$ (increase in elevation per horizontal distance unit).

For the first tillage operation, before the onset of the rains, the tillage transport coefficient is 68 kg m^{-1} (Fig. 8). Over the whole year, the tillage transport coefficient might therefore be up to four times higher (272 kg m^{-1} per year), as tef needs four tillage operations. The value of this tentative assessment is comparable to those obtained in the Andes (150–250 kg m^{-1} per year) where a very similar implement is used (Dercon et al., 1999), but is much less than those for tillage with mechanised implements in Europe (Quine et al., 1999b).

4. Conclusions

Soil translocation through tillage by the *maresha* contributes to colluviation behind soil and water conservation structures on the Ethiopian highlands. Average tillage depth is 8.1 cm, but net mean downslope displacement is important, especially on steep slopes where the *maresha* throws all the tilled soil to the lower side of the furrow. The main controlling factor of the unit soil transport rate Qs is slope gradient. Where present, large rock fragments (>15 cm intermediate diameter) on the field surface are obstacles to the downslope movement of tilled soil. On average, tillage erosion can be held responsible for half of the sediment deposited behind newly constructed stone bunds. The tillage transport coefficient *K* is less than those observed for mechanised tillage in Europe, but the average slopes tilled by *maresha* are much steeper than those ploughed by tractors.

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