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Effects of land use and land cover on sheet and rill erosion rates in the Tigray highlands, Ethiopia

by

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with 5 figures, 9 tables and 1 appendix

Summary. Sheet and rill erosion rates have been well studied in rain-rich central and south Ethiopia. We conducted runoff plot experiments in the semi-arid north Ethiopian Tigray highlands to investigate whether erosion rates are within the same order of magnitude, to measure the effects of various land uses and covers, and to examine the application of the (Revised) Universal Soil Loss Equation (RUSLE) to the Ethiopian highlands. Average soil loss rate by sheet and rill erosion was 9.7 (± 7.8) Mg ha^{-1} y^{-1} (42 plot-years), with 3.5 Mg ha^{-1} y^{-1} in exclosures and forest, and 17.4 Mg ha^{-1} y^{-1} in rangeland. Especially on arable land, the measured rate (9.9 Mg ha^{-1} y^{-1}) was well below the average erosion rate elsewhere in Ethiopia (42 Mg ha^{-1} y^{-1}), which is attributed to (1) precipitation depth and total rain intensity, which are lower in north Ethiopia, (2) the widespread use of stone bunds, which decrease runoff length and velocity, and (3) often high rock fragment cover at the soil surface in arable land. The cover-management C-factor of RUSLE for tef (*Eragrostis tef*) was lower than in central Ethiopia (C = 0.07 against 0.25), probably due to earlier sowing than in the rain-rich regions of Ethiopia. Further values of C in the study area were 0.21 for arable land under wheat and barley; 0.42 for degraded rangeland, and 0.004 for forest and exclosures. Exclosures and forests also trapped upslope eroded sediment.

Introduction

Several runoff plot studies have been conducted on sheet and rill erosion rates in semi-arid mountain areas. Some studies have used rainfall simulators (HARDEN 1988, PUIDEFABREGAS 2005) but many were carried out under natural rainfall conditions (e. g. LUNDGREN 1980, RYDGREN 1988, ARHONDITSIS et al. 2000, LECHMERE-OERTEL 2003, FRANCIA-MARTINEZ et al. 2006, FLESKENS & STROOSNIJDER 2007, KOULOURI & GIOURGA 2007).

Results of runoff plot studies under natural rainfall conditions in semi-arid mountain areas are very variable, as shown by FLESKENS & STROOSNIJDER's (2007) review who observed that different studies have reported results on sheet and rill erosion rates with a 10,000-fold variation. In addition, we may point to 0.4–1 Mg ha^{-1} yr^{-1} on 0.03–0.1 m m^{-1} slopes with farmland in Lesotho (RYDGREN 1988) or less than 0.1 Mg ha^{-1} yr^{-1} in forest and 0.01 mg ha^{-1} yr^{-1} on agricultural land on 10°–25° slopes

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Fig. 1. Rill development in steep arable land without stone bunds near Korar, Dogu'a Tembien, Tigray (September 2005). Length of rills is approximately 100 m. Such views are becoming rare since most of the arable land has now been treated with stone bunds. Photo G. Verstraeten.

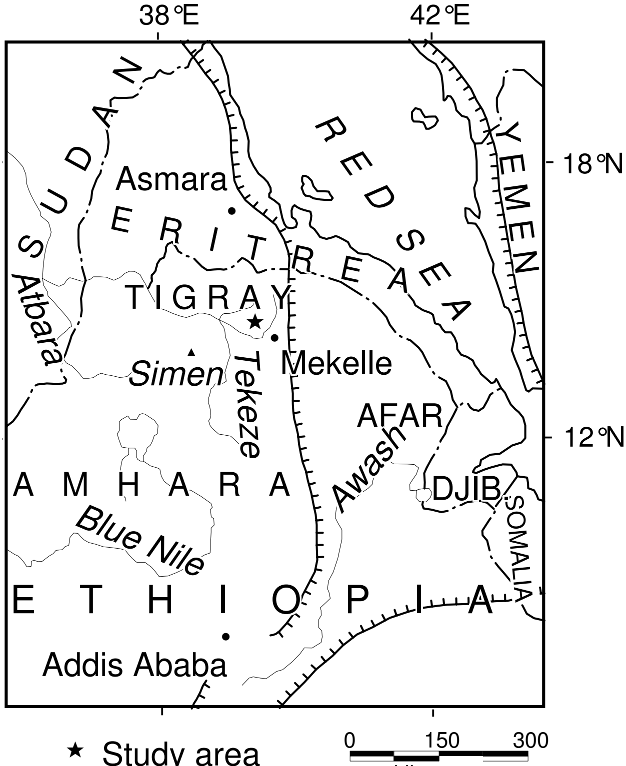

Fig. 2. Location of the study area (May Zegzeg).

in the Usambara mountains in Tanzania (Lundgren 1980). The latter low rates were attributed to good land management including surface mulching and absence of extreme events during the monitoring period.

Most research on soil erosion by water in Ethiopia deals with sheet and rill erosion (fig. 1). Hurni (1975, 1978, 1979) studied thoroughly the Jinbar valley (3,200–4,000 m a. s. l.) in the Simen Mountains (fig. 2) and estimated long-term soil loss rates of 14.5 ± 2.1 cm, or 950 ± 200 Mg ha^{-1} over a cultivation period of 20–200 years. Given the dominance of Andosols in the Simen mountains, (Hurni 1979) measured low soil bulk densities. Due to elevation and to the proximity of the climatic limit of barley cultivation, deforestation here has started much later than in most other parts of the highlands (Hurni 1982). The variability in soil loss depth is correlated with slope aspect and probably with the age of deforestation (Hurni 1975, 1978).

In north Ethiopia, soil loss by water erosion occurs mainly at the beginning of the main summer rainy season (*kremt* – June to September). In those regions where spring rains (*belg* – February to May) are sufficient for cultivation, crops have been harvested and the land ploughed again before the upcoming kremt (Mulugeta 1988). At the beginning of the summer rains, the fields have undergone at least two tillage operations, are bare and offer less resistance to splash and runoff erosion (Virgo & Munro 1978). With the advance of the rainy season, soil loss decreases, as it is negatively correlated to crop cover (Mulugeta 1988). We observed however in the semi-arid Tigray region that substantial runoff only occurred more than one month after the beginning of the kremt rains. The same was observed in the humid Simen highlands (Hurni 1979). In the beginning of the rainy season, most rain infiltrated quickly into the dry, tilled fields. Furthermore, on Vertisols, which are well represented in Ethiopia (Kanwar & Virmani 1986, Deckers 1993), the first rains are well absorbed by the soil, in deep shrinkage cracks. After absorbing some moisture, the soil starts swelling, the cracks close, the soil becomes less permeable and generates important runoff (Bauduin & Dubreuil 1973, Tewodros et al. 2009).

Expectedly, soil loss on experimental plots in Ethiopia was shown to be positively correlated to runoff volume (Feleke 1987, Sonneveld 2001).

At farm plot level, the Universal Soil Loss Equation (USLE – Wischmeier & Smith 1978) is the most commonly used model in Ethiopia for sheet and rill erosion prediction. In addition, single factors of the model are often used as a measure in particular studies. From his research and from data collected in the Soil Conservation Research Programme (SCRP) stations, Hurni (1985) adapted the USLE to Ethiopian conditions for use by development agents in the field of soil and water conservation (SWC). Due to the large difference between its minimum and maximum values, the cover-management (C) factor has outstanding importance and small mistakes in the analysis of land cover can easily result in large over- or under-estimations of soil loss rates. In their USLE application to a Kenyan catchment, Mati et al. (2000) reported limitations in determining reliable model parameters. The model calibration for Ethiopia has been used in various studies (see for instance Helldén 1987, Eweg & Van Lammeren 1996, Nyssen 1997, Desta et al. 2005) and it appears necessary to check it against more recent developments of the model, as incorporated in the Revised USLE (RUSLE) (Renard et al. 1997), for instance.

Measurements of sheet and rill erosion rates were conducted in the north Ethiopian Tigray highlands to contrast it with existing data for central, east and south

Fig. 3. Sediment collecting trench in the rangeland of Luqmuts at the end of the rainy season.

Ethiopia (Hurni 1985, 1990, Keefeni 1992, Herweg & Ludi 1999, SCRP 2000). The composition of the runoff plot set was representative for the major types of land use in the catchment: arable land (fig. 1), rangeland (fig. 3), exclosure and forest.

The objectives of this paper are (1) to check whether soil loss rates by sheet and rill erosion at farm plot scale in the north Ethiopian highlands are within the same order of magnitude as the rates observed in central, east and south Ethiopia, (2) to measure the effects of various land uses and covers, and (3) to discuss the application of the (Revised) Universal Soil Loss Equation ((R)USLE) to the Ethiopian highlands.

2 *Materials and methods*

2.1 *Study area*

The May Zegzeg catchment nearby Hagere Selam (13°40′N, 39°10′E), located about 50 km west of Mekelle (fig. 2), was selected for this study as it presents high elevations (> 2,000 m a. s. l.) and a subhorizontal structural relief, typical for the north Ethiopian highlands. The Atbara-Tekeze river system drains the waters of the study area to the Nile.

The main rainy season (> 80 % of total rainfall) extends from June to September but is preceded by three months of dispersed less intense rains. Average yearly precipitation is 774 mm; fig. 4 shows that 1998 and 2005 were rainy years whereas 2002–2004 were below average. For the purpose of this research, the study area was equipped with 15 rain gauges. Field measurements showed that precipitation is highest nearby cliffs and other eminent slopes, perpendicular to the main valleys which are preferred flow paths for the air masses. High rain erosivity is due to large drop sizes at this altitude (Nyssen et al. 2005).

The local geology comprises subhorizontal series of alternating hard and soft Antalo limestone layers, some 400 m thick, overlain by Amba Aradam sandstone

(Hutchinson & Engels 1970). Two series of Tertiary lava flows, separated by silicified lacustrine deposits, bury these Mesozoic sedimentary rocks (Arkin et al. 1971, Merla et al. 1979).

Erosion, in response to the Miocene and Plio-Pleistocene tectonic uplifts (order of 2,500 m), resulted in the formation of tabular, stepped landforms, reflecting the subhorizontal geological structure. The uppermost levels of the landscape at about 2,700–2,800 m a. s. l. are formed in the basalt series. Other structural levels correspond to the top of the Amba Aradam sandstone and to the top of hard layers within the Antalo limestone.

Major soil types (World Reference Base for Soil Resources; (IUSS Working Group WRB 2006)) in the study area are Regosols, Vertisols and Cambisols, with clay to loam texture (Nyssen et al. 2008a).

Permanent cropped fields are the dominant land use type, covering around 65 % of the study area. The agricultural system in the north Ethiopian highlands has been characterised as a 'grain-plough complex' (Westphal 1975). The main crops are barley (*Hordeum vulgare* L.) and wheat (*Triticum* sp.) which are sometimes sown as a mixture, locally called *hanfets.* Tef (*Eragrostis tef*), an endemic cereal crop (Ruskin 1999, Deckers et al. 2001, Brink & Belay 2006), and various species of grain legumes are also important parts of the crop rotation (Nyssen et al. 2008a). Soil tillage is carried out with ox-drawn single tined ard ploughs or *mahrasha* (Nyssen et al. 2000, Solomon et al. 2006) which till the topsoil to a depth of 8 to 15 cm. After broadcast sowing on a flat seedbed, the soil is reworked slightly by ploughing, except for tef which is sown on the surface of the prepared soil. After harvest, stubble grazing is widespread; in recent years, zero grazing on arable land has been promoted (Nyssen et al. 2009). Besides small remnant forests, steep slopes (i. e. > 0.3 m m^{-1}) are mainly under rangeland, typically with a grass and herb cover of maximum 40 % at the end of the rainy season (down to nearly nil in April) and a tree and shrub (*Acacia* sp., *Dodoneae angustifolia*, *Euclea schimperi*) canopy cover of maximum 20 %. Parts of

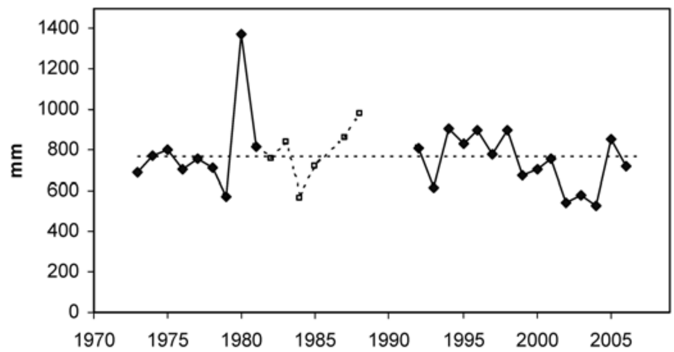

Fig. 4. Annual precipitation in Hagere Selam. Annual average is 762 (± 171) mm. Source: National Meteorological Agency (www.ethiomet.gov.et), except 1992–1994: Dogu'a Tembien Agricultural Office. Missing data correspond to the period of civil war and the years thereafter. A tentative reconstruction of yearly rainfall for 1982–1988 was done through correlation with the 50-km away Mekelle station; for 1989–1991, rainfall data are also missing for Mekelle.

these rangelands have been set aside recently to allow vegetation recovery (exclosures) (Descheemaeker et al. 2006a, 2006b, Nyssen et al. 2008b, Aerts et al. 2009).

2.2 *Sediment collecting trenches located in non-arable land*

Four 12-m long sediment collecting trenches (Moeyersons 1990) were dug early 1999 on the steep slope in Luqmuts-Hechi (table 1; fig. 5, sites 5 to 8), under different types of land use (forest, rangeland, exclosure), in order to measure soil loss from the slope. Trenches were 1 m wide × 1 m deep in rangeland, and 0.5 m × 0.5 m in exclosures and forest (fig. 3). Areas draining to these collecting trenches, measured in the field by theodolite, ranged between 0.03 and 0.39 ha, including 0 to 64 % arable land, situated on the upslope plateau. The overall slope gradient (macroslope) of the steep hillslope sections is around 0.4–0.5 m m^{-1}, whereas that of the arable land is some 0.05 m m^{-1}. The volumes of the trenches that were not filled with sediment were measured after the rainy season in 1999, 2000, 2001 and 2005, and bulk density of the deposited sediment determined. This allowed calculation of the volume and mass of the deposited sediment in 1999, 2000, 2001, as well as an average for 1999 to 2005 (total volume of deposited sediment divided by six years). In this way, soil loss meas-

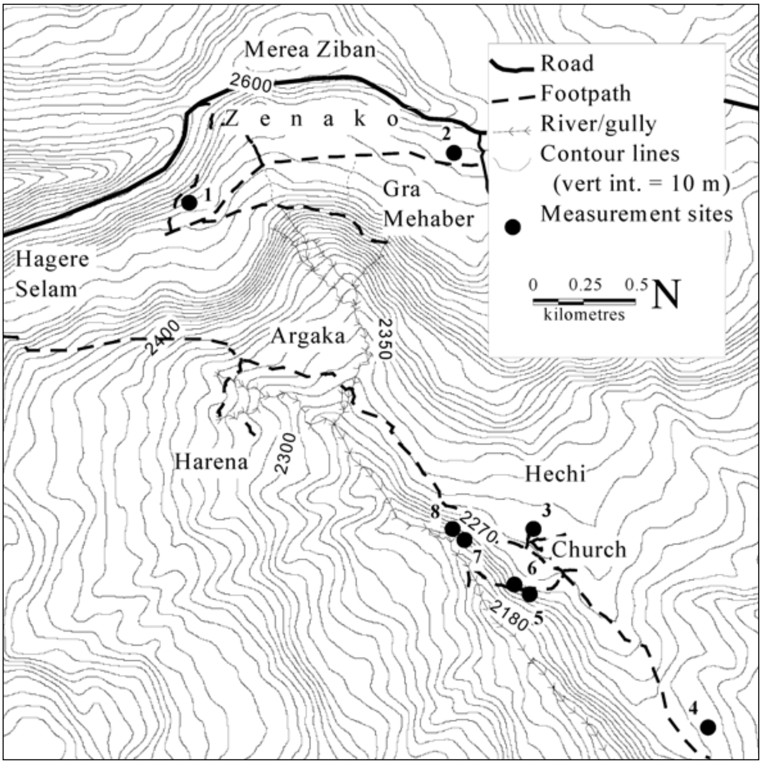

Fig. 5. Location map of sheet and rill erosion measurement sites: 1 Zenako, 2 Gra Mehaber, 3 Shikha, 4 Awhi Grat, 5 Luqmuts rangeland, 6 and 7 Luqmuts forest, 8 Luqmuts exclosure.

urements from a slope, with natural, rather than confined boundaries, best reflect the actual processes (Evans 1995). Boix-Fayos et al. (2006) have shown that there is great variation between measurement results on runoff plots at different sites, which are related to “lack of harmony between methodological conditions and the processes operating in the environment at different scales”. Hence, utmost care has been taken to avoid over- and underestimations during the measurements. In particular, when measuring the unfilled volume of the trenches, small collapsed volumes at the edges of the trenches could be taken into account.

2.3 *Bounded runoff plots in arable land*

In addition, four experimental sites with 14–37-m long bounded runoff plots (table 2), representative for the present-day conditions of arable land, including stone bunds with horizontal intervals of 15–40 m, were established in farmers’ fields. Each runoff plot was laterally separated from the adjacent land by a soil bund 30 cm wide and 15 cm high. The stone bunds or lynchets, which were present at the upper side of all runoff plots, were strengthened. Lateral evacuation of runoff was organised to prevent any overland flow run-on from entering into the plots. The landholder of each experimental site was asked to manage his land similarly to neighbouring land. Ploughing was along the contour. The eroded soil was trapped in 1 m wide and 1.5 m deep collecting trenches lined by masonry. A measurement problem resulted from the fact that a 20–30 cm wide strip along the edge of the trench remained unploughed; it was estimated that half of the soil moved by tillage translocation (Nyssen et al. 2000) was trapped in this strip, instead of rolling into the collecting trench. The volume of sediment trapped in the collecting trenches was measured between the moment of disappearance of runoff water in the trenches by infiltration and/or evaporation and the moment of sediment cracking. The thickness of the deposited sediment was obtained by inserting a metal peg in the sediment until it reached installed embedded flat stones at the bottom of the trench (Moeyersons 1990). Core samples were taken with Kopecki rings, 100 cm^3 steel cylinders driven in the sediment using a ring holder. The oversized parts of the samples in the carefully dug out rings were trimmed, after which the samples were dried at 105 °C and weighed, which allowed calculation of the dry sediment bulk density. The estimated mass of soil which entered into the collecting trenches by tillage translocation (calculated using empirical relations with slope gradient, developed from the results of field experiments by Nyssen et al. (2000) was deduced from the total mass of sediment deposited in the trenches, in order to obtain soil loss by sheet and rill erosion only. As the lateral soil bunds occupied at most 6 % of the runoff plot area and were covered with high stone density and weeds, it was assumed that they would not lead to an overestimation of soil loss. All collecting trenches were built by masonry and measurements were carried out successfully in 1999, 2000 and 2001. All data were expressed in terms of soil flux and soil loss rate. Soil flux, the mass of sediment transported yearly through a length unit on contour, was calculated by dividing total dry sediment mass by the bottom width of the plot whereas soil loss rate was obtained by dividing sediment mass by the plot areas.

Table 1. Characteristics of the open plots in Luqmuts-Hechi.

Site and land use	Soil type[a]	Sand %	Silt %	Clay %	SOM[b] %	R_C[c] %	K[d] on steep hillslope section	K[d, e] on plateau	SG[f] mm^{-1}	Slope length[g]	Drain. area (ha)	% plateau with arable land	Vegetation cover of the steep hillslope section
5 Rangeland	Calcaric Regosol	53	18	29	1.7	50	0.002	–	0.33	28	0.037	0	Sparse short grass, few small shrubs, > 50 % bare soil and rock
6 Forest	Haplic Phaeozem	16	68	17	5.8	2	0.032	–	0.49	40	0.030	0	Continuous forest cover
7 Forest	Haplic Phaeozem	20	65	16	5.8	2	0.017	0.042	0.42	157	0.20	35	Sub-continuous forest cover
8 Exclosure	Cumuli-cari-humic Regosol	56	19	25	2.5	50	0.002	0.042	0.42	210	0.39	64	Continuous grass cover; 30 % shrub cover

Soil characteristics relate to the upper 10 cm of the soil profile.

[a] According to IUSS Working Group WRB (2006);
[b] Soil organic matter content = 1.7 organic carbon content;
[c] Rock fragment cover;
[d] Soil erodibility factor (eq. 1), adjusted for rock fragment cover (eq. 4), in $Mg\ h\ MJ^{-1}\ mm^{-1}$;
[e] Arable land on Protoverti-calcaric Cambisol;
[f] Slope gradient – if present, arable land in plateau situation is not included in slope gradient calculation;
[g] Horizontal projection.

Table 2. Characteristics of the bounded runoff plots on arable land.

Runoff plot	Soil type[a]	Sand %	Silt %	Clay %	SOM[b] %	R_C[c] %	K[e]	SG[f] (mm^{-1})	Length[g] (m)	Width (m)	Area (m^2)	Successive crops	Till[h]
1 Zenako	Cumuli-haplic Regosol	28	34	38	1.6	22	0.009	0.28	18.3	4.1	75.2	Tef, lentil, wheat	2
2a Gra Mehaber	Vertic Cambisol[i]	13	31	56	1.9	9	0.022	0.09	27.6	4.8	132.3	Tef, *hanfets*[j], tef	2.7
2b Gra Mehaber	Vertic Cambisol	13	31	56	1.9	9	0.022	0.10	25.9	4.7	121.9	Tef, *hanfets*, tef	2.7
3 Shikha	Epistagnic Vertisol	10	49	41	1.9	3	0.036	0.06	36.6	7.4	270.7	Wheat, wheat, –	2
4 Awhi Grat	Calcaric Cambisol	15	58	28	1.8	29[d]	0.019	0.10	14.7	7.5	110.5	Wheat, *hanfets*, lentil	2

Soil characteristics relate to the upper 10 cm of the soil profile.

[a] According to IUSS Working Group WRB (2006);
[b] Soil organic matter content = 1.7* organic carbon content;
[c] Rock fragment cover;
[d] Continuous limestone at 5–30 cm depth;
[e] RUSLE's soil erodibility factor (eq. 1), adjusted for rock fragment cover (eq. 4), in Mg h MJ^{-1} mm^{-1};
[f] Slope gradient;
[g] Horizontal projection;
[h] Average number of tillage operations per year;
[i] At this site, the experiment was replicated twice and average of the values measured was used in further analysis;
[j] Barley and wheat sown together.

2.4 *Measurement of explanatory variables*

A mixed soil sample was taken in every plot, at a depth of 0–10 cm. Organic carbon was measured by the Walkley-Black method (Allisons 1965) and soil texture by sieve-pipette method. Soil texture classes were determined as recommended for (R)USLE (Renard et al. 1997): clay < 0.002 mm < silt and very fine sand < 0.1 mm < sand < 2 mm. The following equation allows calculating the values of the soil erodibility factor K (Renard et al. 1997):

$$K = [2.1\ M^{1.14}\ (10^{-4})(12\text{-}a) + 3.25\ (b\text{-}2) + 2.5\ (c\text{-}3)] \times 0.1317/100 \quad (1)$$

where: K = erodibility factor in RUSLE, in Mg h MJ^{-1} mm^{-1},

$$M = \text{particle size parameter} = (\%\ \text{silt and very fine sand}) \times (100 - \%\ \text{clay}), \quad (2)$$

a = percentage of organic matter,
b = soil structure code, ranging between 1 (very fine granular) and 4 (blocky, platy or massive), with default value 2,
c = permeability class, ranging between 1 (rapid) and 6 (very slow), with default value 3,
0.1317 = proportionality between the metric and the American (p.f.s.) system (Renard et al. 1997).

For soil structure, the mineralogical composition has been used in a qualitative way in this equation: on a scale from 1 to 4, representing the influence of soil structure on erodibility, a value of 1 (less erodible) was attributed to smectic soils and a value of 2 (default value proposed by Wischmeier & Smith (1978)) to the other soils. Note the ambivalent character of smectite-dominated clays with respect to soil erodibility: on the one hand, they are less erodible due to their microstructure, on the other, with respect to runoff, these clays provide two contrasting situations: (1) when dry, the soils form strong aggregates and deep cracks, which enhances infiltration, but (2) when wet, the clays swell, the cracks close up, permeability becomes low and runoff volumes are important, which increases the wash potential. Furthermore when dry the cracks may serve as preferential pathways and enhance tunnelling and gully erosion.

The rock fragment cover at the soil surface (R_C) was measured in the field by the point-count method. At regular distances under a tape metre, randomly rolled out in different parts of the plot, presence or absence of a rock fragment was recorded. Four hundred observations were made in each runoff plot. R_C was calculated as:

$$R_C(\%) = 100\ n_p/n_t \quad (3)$$

where: n_p = number of observations with a rock fragment present;
n_t = total number of observations.

Rock fragments at the soil surface reduce the effect of splash as well as runoff rates and overland flow velocity (Poesen et al. 1994). They have a similar effect as the permanent presence of litter (Römkens 1985). This reduction of the erosion risk can be translated by an adjustment of the K-factor (Arnoldus 1977, Wischmeier & Smith 1978). Poesen et al. (1994) presented a multiplicative factor allowing the calculation of this adjustment of K (eq. 1) taking into account rock fragment cover:

$$\delta = e^{-0.04\,(Rc-10)} \qquad (4)$$

where: δ = multiplicative factor for relative interrill and rill sediment yield;
R_c = rock fragment cover (in %).

2.5 *Calibration of the (R)USLE's cover-management C-factor*

The soil loss rate measurements from our runoff plots allowed calibrating the C-factor for the study area:

$$A = R\ K\ S\ L\ C\ P \qquad \text{(Renard et al. 1997)} \qquad (5)$$

with: A: yearly soil loss rate, in Mg ha^{-1} y^{-1};
R: annual rain erosivity, in MJ mm ha^{-1} h^{-1} y^{-1};
K: soil erodibility, in Mg h MJ^{-1} mm^{-1};
S: slope steepness factor, dimensionless;
L: slope length factor, dimensionless;
C: cover-management factor, dimensionless;
P: supporting practices, dimensionless;

thus

$$C = A\ (R\ K\ S\ L\ P)^{-1} \qquad (6)$$

A was calculated from the recorded soil loss rates at the various experimental sites. K was computed from soil data (eq. 1), taking into account rock fragment cover, as indicated in eq. (4). R was computed from precipitation data at the nearest rain gauge, using

$$R = 5.5\ Pr - 47 \qquad \text{(adapted from Hurni 1985)} \qquad (7)$$

where Pr = annual precipitation in mm.

For S, the most recently developed equation, taking into account steep slopes, was used:

$$S = -1.5 + 17/(1 + e^{(2.3-6.1\ \sin\theta)}) \qquad \text{(Nearing 1997)} \qquad (8)$$

where θ = slope angle.

The slope length factor L was obtained applying

$$L = (\lambda/22.13)^m \qquad \text{(eq. 4–1 in Renard et al. 1997)} \qquad (9)$$

where L = slope length factor (dimensionless);

λ = slope length (horizontal projection, in m);
m = slope length exponent, in our case under the condition of small rill : interrill ratio.

The values for m, corresponding to slope gradients of our runoff plots, were taken from Renard et al. (1997, table 4.5).

Since our control runoff plots were bounded at the upper side and no SWC structures were present within these plots, the only support practice was contour ploughing, for which, under the condition of low (5–7.5 cm) ridges, average P is 0.9 (Renard et al. 1997: fig. 6.2).

Table 3. Soil loss rates and soil flux on bounded plots in arable land (Average 1999–2001) (n = 3).

Plot[a]	Soil loss rate[b] (Mg ha^{-1} y^{-1}) (range)	Soil flux[c] (kg m^{-1} y^{-1})			Soil loss rate (Mg ha^{-1} y^{-1}) by sheet and rill erosion
		Total	Due to tillage erosion	By sheet and rill erosion[d]	
1	7.7 (2.4–11.5)	14.3	9.2	5.1	2.8
2[e]	9.4 (2.3–17.4)	25.3	7.6	18.6	6.9
3[f]	8.4 (7.1–9.8)	30.8	3.6	27.2	7.4
4	27.9 (5.6–50.0)	41.0	7.8	33.2	22.6
Average	13.4	27.9	7.1	21.0	9.9

[a] See table 2;
[b] Due to sheet, rill and tillage erosion;
[c] Mass of sediment transported through a length unit on contour;
[d] After subtraction of estimated volumes of sediment deposited in the collecting trenches by tillage erosion;
[e] Average of the two plots;
[f] n = 2.

3 *Results*

3.1 *Soil loss rates*

As the composition of the runoff plot set was similar to that of the catchment in terms of land use, soil types and slope gradients (Nyssen et al. 2008a), a representative arithmetic average soil loss rate by sheet and rill erosion for all the experimental sites could be calculated at 9.7 (± 7.8) Mg ha^{-1} y^{-1} (42 plot-years). Among the plots on arable land (table 3), important variability was observed, with soil loss rates due to sheet and rill erosion ranging between 2.8 and 22.6 Mg ha^{-1} y^{-1}.

For the collector trenches on non-arable land, table 4 shows not only much higher soil loss rates from strongly degraded rangeland in comparison to forest or exclosure, but also a greater yearly variability.

A clear difference in soil loss rates by sheet and rill erosion for different land use categories was found (table 5), whereby rangeland yielded around 5 times more sediment than exclosures situated in the same landscape position (17.4 against 3.5 Mg ha^{-1} y^{-1}). Comparison of soil flux rates for the different land use categories was difficult because plots under exclosure/forest were generally an order of magnitude larger than the others, which made conversion between soil loss rates and soil flux delicate. With 9.9 Mg ha^{-1} y^{-1}, soil loss on arable land held an intermediate position between that in rangeland and in exclosures.

3.2 *The cover-management C-factor in north Ethiopia*

Integration of the explanatory variables in the RUSLE (using the metric units recommended by Renard et al. (1997) allowed to calculate the C cover-management factor for the major land use and cover categories. The C values obtained (table 6) confirmed the high sensitivity of degraded rangeland to sheet and rill erosion (C = 0.42); the good protection offered by forest (C = 0.004 or two orders of magnitude smaller than C for degraded rangeland); and the intermediate situation of arable land (C = 0.14), with an unexpected low value for tef (C = 0.07), showing its effectiveness in protecting soil from sheet and rill erosion in the study area.

3.3 *The sediment trapping capacity of exclosures*

Our data also suggest that forest and exclosure with a good soil cover by grass and shrubs have a high sediment trapping capacity, even on steep slopes. Although sediment from the arable land on the plateau entered the exclosure or forest (sites 7 and 8), sediment deposition in the collecting trenches below the exclosure was low. It was even smaller than at site 6, where the whole drainage area was under closed forest. This high sediment trapping capacity of exclosures was confirmed by a comparison of estimated soil loss rates from the arable land in the upper part of the drainage areas, with sediment volumes deposited in collecting trenches 7 and 8 (table 7). Estimated sediment deposition rates in the exclosures ranged between 0.3 mm y^{-1} for site 7, with only a small drainage area on the plateau, and 1.1 mm y^{-1} in an exclosure with a larger drainage area in arable land. Augerings in the upper third of the exclosure, where most sediment deposition takes place, indicated that the thickness of sediment deposited since the area became an exclosure some 15 y earlier, would be around 24 cm (n = 4).

4 *Discussion*

4.1 *Impact of land use on sheet and rill erosion rates*

Relatively high soil loss rates due to sheet and rill erosion in runoff plot 4 were due to conditions favouring high runoff, i. e. bedrock at a depth of 5–30 cm. Although plot 1 was steep (0.28 m m^{-1}), its sandy and stony characteristics induced high infiltration rates, which led to small volumes of runoff and soil loss. In the areas around plots 2 and 3, on Vertic Cambisol and Vertisol, more important runoff, including rill formation, could be observed during the month of August.

Despite the low soil erodibility of the outcropping saprolite in the study area (table 1), the rangelands suffered much more from soil erosion than forests or exclo-

Table 4. Soil loss and soil flux rates (1999–2005) due to sheet and rill erosion as measured in sediment collector trenches located in non-arable land in Hechi-Luqmuts.

Site and land use	Soil loss rate (Mg ha^{-1} y^{-1})		Soil flux (kg m^{-1} y^{-1})	
	Average	(range)	Average	(range)
5 Rangeland	17.4	(6.0–28.2)	54	(19–88)
6 Forest	8.5	(4.8–10.9)	21	(12–27)
7 Forest	1.4	(0.3–1.8)	25	(5–31)
8 Exclosure	0.7	(0.3–0.7)	22	(10–25)

Table 5. Soil loss rates by sheet and rill erosion for different land use categories.

	Average yearly soil loss rate (Mg ha^{-1} y^{-1}) (± st.dev.)	Average yearly soil flux (kg m^{-1} y^{-1}) (± st.dev.)	Number of plot-years
Exclosure or forest without stone bunds ($0.4 < SG < 0.5$ m m^{-1})	3.5 (± 4.5)	23 (± 2)	21
Rangeland without stone bunds ($0.3 < SG < 0.4$ m m^{-1})	17.4	54	7
Arable land with broad-spaced stone bunds ($SG < 0.3$ m m^{-1})	9.9 (± 13.2)	21 (± 24)	14

SG = slope gradient.

sures (table 4). The relatively high soil loss rate from rangeland in our study area is attributed to the large runoff coefficients from overgrazed areas having a discontinuous grass mat, and to the fact that only rangeland situated on a steep slope was taken into account in contrast to the situation in central Ethiopia where rangelands have often a continuous grass mat.

HURNI (1985, 1990) estimated average soil loss rates by sheet and rill erosion on slopes in the Ethiopian highlands at 5 Mg ha^{-1} y^{-1} for grazing land, 1 Mg ha^{-1} y^{-1} for forest and 42 Mg ha^{-1} y^{-1} for arable land. Soil loss rates from arable land in the study area were in the lower half of the range of values measured in the SCRP's runoff plots

Table 6. Calculated values of USLE's C-factor for representative land uses in the study area using soil loss data, and comparison with average C-values calculated for the central and eastern Ethiopian Highlands by HURNI (1985).

	Average[a]	st. dev.	n	(HURNI 1985)
tef	0.07**	0.08	5	*0.25*
wheat and barley	0.21[ns]	0.25	7	*0.15*
all arable land	0.14[ns]	0.19	14	*0.10–0.25*
rangeland[b]	0.42**	0.22	7	*0.05*
forest	0.004***	0.003	21	*0.001*

[a] average value of USLE's C-factor in the study area, with level of significance for the deviation from values suggested by HURNI (1985);
[b] degraded (< 50 % vegetation cover) in this study, good vegetation cover in sites studied by HURNI (1985);
** significant at 0.01 level;
*** significant at 0.001 level;
[ns] not significant.

Table 7. Estimation of sediment trapping capacity of exclosures on steep slopes (0.6 m m^{-1}), based on a comparison between sediment entering over the upper cliff and sediment trapped in collecting trenches

Site Catchment of collecting trench No.	7	8
A. Soil loss rate in the upper arable land[a] (Mg ha^{-1} y^{-1})	8.4	8.4
B. Area of arable land within drainage area of collecting trench (ha)	0.07	0.25
C. Area of exclosure within drainage area of collecting trench (ha)	0.13	0.14
D. Sediment entering the exclosure (A x B) (kg y^{-1})	588	2100
E. Sediment leaving the exclosure[b] (kg y^{-1})	204	240
F. Sediment deposited in the exclosure (D–E) (kg y^{-1})	384	1860
G. Net sediment deposition rate within exclosure (F/C) (Mg ha^{-1} y^{-1})	3.0	13.3
Sediment deposition rate within exclosure (mm y^{-1})	**0.3**	**1.1**

Average values for the period 1999–2001 have been used.

[a] Rate of soil loss by sheet and rill erosion, as measured in the nearby runoff plot No. 3;
[b] as measured in the collecting trench at the lower side of the exclosure.

under similar agroclimatic conditions (moist mid-altitude agro-ecological belt) (Herweg & Stillhardt 1999).

These below Ethiopian average values of sheet and rill erosion from arable land are most probably related to (1) on average higher rock fragment cover in the fields, and (2) yearly precipitation depth and total rain intensity, which are lower in the study area compared to most of the SCRP stations on which Hurni's estimates were based. Soil types are also different: Regosols and Cambisols are dominant in Tigray against Vertisols, Luvisols, Nitisols and Chromic Cambisols in central Ethiopia.

Experts, visiting the experimental sites, were often astonished to see that even at the end of the rainy season important sections of the collecting trenches were still nearly empty. The fact that all areas around the experimental site are treated with stone bunds (horizontal interval: 15–40 m) made that runoff plot length was representative for real runoff length.

Finally, during field visits, the question was raised if the number of tillage operations in our runoff plots was representative for the study area. Though the farmers were instructed to manage the runoff plots in the same way as other land in the area, they might have decreased the number of tillage operations, given the complexity of ploughing runoff plots and in the knowledge that a certain income from plot rent by the research team was guaranteed. In order to check this, randomly selected plots in Zenako and Argak' a were monitored weekly in 2001, and the number of tillage operations and type of crop sown were noted (table 8). It effectively seemed that, on average, our experimental plots were tilled one time less than other plots, which points to some error in our methodology.

In a previous assessment of soil loss rates by sheet and rill erosion in the study area on 24 sites, representing well soil, slope and land use conditions of the study area (Nyssen 1997), using USLE (Wischmeier & Smith 1978), an overall average value of 11.2 Mg ha^{-1} y^{-1} was found, which is slightly above the average measured soil loss rate by sheet and rill erosion in this study (9.7 Mg ha^{-1} y^{-1}). In that application of the USLE, above average soil loss rates were also forecasted for degraded rangeland on steep slopes.

Table 8. Average number of tillage operations for each crop type on runoff plots and on randomly selected fields.

Crop type	On runoff plots	On randomly selected fields
Tef	2.7 (3[a])	4 (1[b])
Wheat	2 (4)	3 (3)
Hanfets	2 (2)	3 (3)
Lentil	1.5 (2)	1 (1)

Between brackets:
[a] number of plot-years observed;
[b] number of observed plots.

4.2 *The cover-management C-factor*

We could not find any significant correlation between soil loss rates or soil flux on the one hand and single quantitative variables (precipitation depth in the nearest rain gauge, soil erodibility, rock fragment cover, slope gradient), neither for all sites together, nor for the runoff plots on arable land only. Integration of these variables in the RUSLE allowed calculating values for the C cover-management factor (table 6), which confirmed the high sensitivity of degraded rangeland to sheet and rill erosion, the good protection offered by forest, and the intermediate situation of arable land. A comparison to C values in other semi-arid mountainous areas (table 9) tends to indicate that our C values for forest and rangeland are in accordance with what was measured on numerous runoff plots in southern Spain (DGCONA 2002), and through use of empirical handbook procedures in Tunisia and Southern France (Haemers 1987, Van Hees et al. 1987, De Jong 1994). In the Cape Fynbos, Van Rompaey et al. (2001) assessed C values at an order of magnitude smaller than ours. On arable land however, C values for Spain and Tunisia were larger than those measured in Tigray.

However, our data did not confirm the small C-factor for degraded rangeland, as used in the adjustment of the USLE to Ethiopian conditions (Hurni 1985). Mostly, the experimental sites used by Hurni (1985) had still a good cover by short grasses, whereas overgrazing, as is the case in the study area, leads not only to poor grass cover but also to compaction and high runoff coefficients (Mwendera & Saleem 1997a, 1997b, Mwendera et al. 1997, Girma et al. 2002, Descheemaeker et al. 2006c).

With respect to the different crops (tef or wheat and barley), we obtained an unexpected small C value for tef, which is generally thought to protect arable land poorly against sheet and rill erosion particularly in high rainfall areas where it is sown later than other crops and because it requires numerous tillage operations to prepare a very fine seedbed (El Swaify & Hurni 1996). The small soil loss rates on tef fields in Tigray result from some environmental conditions and agricultural practices that are different from central Ethiopia. The short duration of the rainy season in Tigray leads to tef sowing soon after the initiation of the season, whereas in rain-rich central and east Ethiopia tef is sown only after about 2–3 months of rainy season and soil remains bare long into the rainy season. In the study area, the need to sow early allows only three to four tillage operations for tef, although the farmers generally claim that tef needs more, four up to six, tillage operations. In addition, most runoff occurs in the second half of the rainy season, after soil saturation (Vanmaercke et al. 2008, Tewodros et al. 2009); at that time, tef has started to grow and protects against sheet erosion. Once established, this grass-like crop offers a better soil cover and denser root system than other crops (Kleeberg & Richter 2002) and hence has good value for erosion control (Narayanan & Dabadghao 1972, Ruskin 1999, Brink & Belay 2006), to the point that Eragrostis species are sometimes presented as a valid alternative for vetiver grass (Borlaug et al. 1993). Especially the root mat increases the resistance to rill erosion dramatically (Gyssels et al. 2005, De Baets et al. 2006).

Table 9. C values measured in semi-arid mountains.

Region	Arable land	Degraded rangeland (< 50 % veg.cover)	Forest		Methodology	Reference
Murcia (Spain)	0.45	0.35	> 66 % tree cover	0.014	Runoff plots	(DGCONA 2002)
Ardèche (France)	–	0.18	50–80 % tree cover > 80 % tree cover	0.048 0.005	Field survey using empirical handbook procedures	(Haemers 1987, De Jong 1994)
Cape (South Africa)	–	–	Fynbos, *Pinus* plantations	0.0003	Field survey using empirical handbook procedures	(Van Rompaey et al. 2001)
North Tunisia	0.40–0.60	–	Dense forest	0.003	Field survey using empirical handbook procedures	(Van Hees et al. 1987)
Tigray (Ethiopia)	0.14	0.42		0.004	Runoff plots	This study

4.3 *Sediment trapping in exclosures*

Augerings as well as the establishment of sediment budgets (table 7) for micro-catchments (with arable land on the upper flats and exclosures on the steep slopes) showed the high capacity of densely grown exclosures to trap upslope eroded sediment. Average deposition rates were estimated around 1 mm y^{-1} with values up to 16 mm y^{-1} at the upper side of the exclosures, which is in accordance with observations by (Descheemaeker et al. 2006a) in a nearby area (averages of 2.2 to 10.2 mm y^{-1}). Similar findings have been reported from Rwanda (Moeyersons 2004). As also stated by (Descheemaeker et al. 2006a), sediment trapping is, besides functions of biomass production, biodiversity, carbon sequestration, water storage and runoff decrease, a good reason for the maintenance and extension of this land management system on steep slopes.

4.4 *Use of the Universal Soil Loss Equation in Ethiopia*

For an appropriate use of the USLE in Ethiopia, we suggest for several factors to revert to the equations developed for the (R)USLE (eq. 5). An overview table with state of the art for the use of RUSLE in Ethiopia is presented in Appendix A.

The soil erodibility factor K can be assessed from soil textural data, organic matter content, and rock fragment cover (eq. (1) and (4)). We do not recommend to include the often-occurring rock fragment cover (Nyssen et al. 2002) in the management factor P but rather as a correction factor for K.

For the R-factor (rain erosivity), the Ethiopia-specific equation (7) may be used, bearing in mind that additional studies, taking into account above average drop sizes in the Ethiopian highlands, should be carried out (Nyssen et al. 2005). Here, we must also consider that RUSLE works with R values that are an order of magnitude larger than in USLE and K values that are an order of magnitude smaller.

The slope steepness factor (S) is calculated with eq. (8). For the slope length L factor, rather than eq. (9), complex with its incorporation of slope gradient and rill:interrill ratios, we suggest the use of the equation prepared from Hurni's (1985) dataset, the results of which are very near to those of eq. (9) (average difference of 4 %):

$$L = 0.232\,\gamma^{0.48} \qquad (5\text{ m} \le \gamma \le 320\text{ m}) \qquad \text{(after Hurni 1985)} \qquad (10)$$

with γ = slope length (horizontal projection, in m).

The use of equations for L requires caution, since "slope length is the factor that involves the most judgement, and length determinations made by users vary greatly" (Renard et al. 1997). In Ethiopian highland conditions, due to the presence of numerous stone bunds, stoil bunds and plot boundaries, this runoff length is generally longer than one single farm plot and shorter than the whole slope, from ridge to thalweg.

Cover-management C values have been discussed in section 4.2.

The P factor (dimensionless) relates to supporting practices and indicates reduced soil erosion potential due to farming practices and conservation measures. Sub-factors yield one composite P-value (Foster & Highfill 1983) for a conservation system, in our case:

$$P = P_C \times P_N \times P_M \quad (11)$$

Where: P_C = Sub-factor for ploughing and cropping practices;

P_N = Sub-factor for conservation structures;

P_M = Sub-factor for *in situ* conservation practices.

Suggested values for these subfactors, taken from our field studies, are presented in Appendix A.

5 *Conclusions*

Our average measured soil loss rate by sheet and rill erosion on arable land of 9.9 Mg ha^{-1} y^{-1} is below the Ethiopian average proposed by HURNI (1990), i. e. 42 Mg ha^{-1} y^{-1}. This is essentially related to less rain in comparison to the central Ethiopian highlands and to the high surface rock fragment cover in half of the measurement sites.

Given that a fair correspondence was found between soil loss measurements from runoff plots and collecting trenches on the one hand, and the results of an earlier application of the RUSLE (NYSSEN 1997), values for the C cover-management factor of this equation were calculated. Relatively high soil loss rates measured in the collecting trench on rangeland, resulted in a rather high C factor for this type of land use (C = 0.42), which is explained by the generally very degraded (overgrazed and compacted) situation of rangeland in the study area. Mean C factor for arable land is 0.14 and for forest 0.004. Both are within the range of values found elsewhere in Ethiopia. A C-value of 0.07 was found for tef. This small value is related to relatively early sowing of tef and thus a smaller number of tillage operations in Tigray as compared to central Ethiopia; crop soil cover will also be good when intense rainfall occurs.

Results of this research and data from the literature allowed presenting a guide (Appendix A) for the application of RUSLE to the Ethiopian highlands.

Finally, a comparison between the estimated sediment mass entering at the top of exclosures and the mass collected at its lower side showed the important sediment trapping capacity of the dense grass and shrubs growing there.

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APPENDIX A. The Revised Universal Soil Loss Equation (RUSLE) – adapted for field assessments in Ethiopia

Equation: **annual soil loss rate A** = R × K × S × L × C × P ($Mg\ ha^{-1}\ y^{-1}$)

1. **R: annual rain erosivity** ($MJ\ mm\ ha^{-1}\ h^{-1}\ y^{-1}$)

$R = 5.5\ Pr - 47$

Pr = annual precipitation (mm)

2. **K: soil erodibility** ($Mg\ h\ MJ^{-1}\ mm^{-1}$), including effects of rock fragment cover

$K = [2.1\ M^{1.14}\ (10^{-4})\ (12-a) + 3.25\ (b-2) + 2.5\ (c-3)] * e^{-0.04\ (d-10)} * 0.001317$

M = particle size parameter = (% silt and very fine sand) * (100 – % clay)
a = percentage of organic matter
b = soil structure code, ranging between 1 (very fine granular) and 4 (blocky, platy or massive), with default value 2
c = permeability class, ranging between 1 (rapid) and 6 (very slow), with default value 3
d = stone (rock fragment) cover (in %)

3. **S: slope steepness factor** (dimensionless)

$S = -1.5 + 17/(1 + e^{(2.3-6.1\ \sin\theta)})$

θ = slope angle (°)

4. **L: slope length factor** (dimensionless)

$L = 0.232\ \lambda^{0.48} \qquad (5\ m \leq \lambda \leq 320\ m)$

λ = slope length (horizontal projection, in m)

5. **C: cover-management factor** (dimensionless)

Dense forest	0.001	Degraded rangeland (< 50 % vegetation cover)	0.42	Badlands hard	0.05
Dryland forest; exclosure	0.004			Badlands soft	0.40
Dense grass	0.01	Degraded grass	0.05		
Sorghum, maize	0.10	Tef (in high rainfall areas)	0.25	Fallow hard	0.05
Cereals, pulses	0.15	Tef (in semi-arid areas)	0.07	Fallow ploughed	0.60

6. **P: supporting practices** (dimensionless)
$P = P_C . P_N . P_M$ (on arable land); $P = P_N$ (on other land)

Ploughing and cropping practices	P_C	Conservation structures	P_N	In situ conservation practices	P_M
Ploughing up and down	1	No conservation structures	1	Stubble grazing; no mulching	1
Ploughing along the contour	0.9	Stone bund (average condition; smaller value for new s. b. and larger for older s. b.)	0.3	Applying mulch	0.6
Strip cropping	0.8	Grass strip (1 m wide; slope ≤ 0.1 m m^{-1})	0.4	Zero grazing	0.8
Intercropping	0.8	Grass strip (1 m wide; slope > 0.2 m m^{-1})	0.8		
Dense intercropping	0.7				

Source: Renard et al. (1997). Adaptations: R correlation by Hurni (1985): K adjustment for rock fragment cover by Poesen et al. (1994); L correlation by Hurni (1985); C values by Hurni (1985) and Nyssen et al. (this study); P model by Nyssen et al. (this study); P values by Hurni (1985), Nyssen (2001), Desta et al. (2005), and Nyssen et al. (2007, this study). Limitations as mentioned in section 4.4 of the article.