

The Trap Efficiency for Sediment and Carbon in Exclosures on Steep Slopes. A Case Study from the Tembien highlands, Tigray, Ethiopia

Jozef Naudts^{a,b}, Karen De Geyndt^a, Jan Nyssen^{c,d}, Jozef Deckers^a,
Mitiku Haile^d, Jan Moeyersons^e, Jean Poesen^c

^a Institute for Land and Water Management, K.U.Leuven, Vital Decosterstraat 102, B-3000 Leuven, B.

^c Laboratory for Experimental Geomorphology, K.U.Leuven, Redingenstraat 16, B-3000 Leuven, Belg.

^d Mekelle University, PO Box 231, Mekelle, Ethiopia; jef_naudts@hotmail.com,

^e Royal Museum for Central Africa, B-3080 Tervuren, Belgium; jmoeyersons@africamuseum.be

Abstract

In an attempt to reverse land degradation, exclosures have been set up in many places across the highlands of Tigray, northern Ethiopia, to control soil erosion and to improve biomass productivity. Local farmers are entitled –under certain conditions- to use some of the resources found in the closed lands (by cutting grass, taking wood, etc.). In this way exclosures constitute a valuable alternative for the local communities, notwithstanding the high land pressure in this part of the Ethiopian Highlands.

Land management and consequences for soil erosion and sediment accumulation were studied during a field survey near the village of Hechi, in the Tembien highlands (northern Ethiopia). Land-use changes over the last 40 y were analysed and different soil profiles were described, both in a flat topographical position and on a steep slope (slope gradient of 0.4 – 0.6 m m⁻¹). The research included soil profiles under overgrazed rangeland, cropland, recently closed area (15 years) and under dense natural vegetation, which has been protected as a result of its very strict religious status.

In the 202 ha large study area, the area covered by forests strongly decreased, from 10 to 4 % between 1963 and 1994. As a consequence of the exclosure policy, which started during the 1980s, it increased again to 6 % in 2000.

Physical and chemical analysis of the soil profiles show that deforestation on steep slopes and cultivation of the cropland of the flat areas had caused much soil loss. In a dense, natural forest on the steep slope, some 1.4 m of sediment was found to be accumulated in the soil profile. In a more recent exclosure, 40 cm of sediment has accumulated since the closure of the area (15 years ago). This sediment has an average organic carbon content of 4.1 % of the soil weight. In the flat area there was more erosion and less soil development in the cropland than in a comparable setting in a protected churchyard.

The ‘exclosure’ land management practice brings soil erosion in degraded areas to a standstill. Besides improved infiltration, less runoff, improved biomass and biodiversity, this technique brings about the accumulation of large amounts of carbon-rich colluvial material, even on steep slopes, and allows thus for a relatively fast regeneration of soil productivity in these areas.

Keywords: Exclosure, Land degradation, Soil erosion, Soil accumulation, Carbon sequestration, Ethiopia

Résumé

En vue de lutter contre la dégradation du sol dans les hautes terres du Tigré en Ethiopie septentrionale, environ 8 % des terres dans cette région a été mises en défens. Le contrôle de l'érosion et une augmentation de la production en biomasse sont visés. Les paysans locaux peuvent utiliser une partie des ressources de ces terrains en défens (en coupant

de l'herbe, en ramassant du bois etc.). Ainsi, les bois en défens amortissent partiellement la pression humaine sur les terres et forment une alternative valable pour les communautés locales. Une mission sur le terrain a permis d'étudier les effets des mises en défens sur l'érosion du sol dans les alentours du village d'Hechi, sur les hautes terres du Tembien, dans le Nord de l'Ethiopie. Cette étude comprend une analyse des changements d'utilisation des terres durant les derniers quarante ans, ainsi que la description de plusieurs profils pédologiques, dont certains sont localisés sur une pente raide ($0.4 - 0.6 \text{ m m}^{-1}$) et d'autres sur un terrain plat. Les différents profils se trouvent dans des terrains surpâturés, des parcelles cultivées, un terrain en défens depuis quinze ans et une petite forêt d'église à végétation culminante.

La région d'étude est large de 202 ha. Le pourcentage de sa superficie sous forêt diminuait entre 1963 et 1994 de 10 % à 4 % mais remontait ensuite jusqu'à 6 % en 2000. Cette augmentation est la conséquence de la mise en défens de plusieurs terrains.

L'analyse physique et chimique des profils pédologiques montrent les effets érosifs de la déforestation. Sur la pente raide, 1,4 m de sédiments ont été accumulés sous une forêt dense. Dans un autre terrain sur la pente, mis en défens avant 15 ans, il y a eu une accumulation de 40 cm de dépôts avec un taux moyen de carbone organique de 4.1 % du poids du sol. Dans les champs cultivés sur terrain subhorizontal, l'érosion est plus prononcée et la vitesse de pédogénèse en retard en rapport au terrain protégé autour de l'église.

La pratique des terrains en défens peut arrêter complètement l'érosion dans une région dégradée. En même temps elle améliore la capacité d'infiltration du sol, réduit le ruissellement, augmente la biomasse et la biodiversité. Mais la technique occasionne surtout une accumulation d'importants volumes de colluvions riches en carbone, même sur des pentes très raides et sur terrains dégradés. Ainsi, elle assure une restauration accélérée de la productivité du sol.

Mots-clés: Mises en défens, Dégradation des terres, Erosion du sol, Accumulation de sol, Séquestration du carbone, Ethiopie

1. Introduction

Land degradation, desertification and soil erosion are recurrent phenomena in the northern Ethiopian highlands (Hurni, 1990). In recent decades, the local communities of these regions have been encouraged by the local government and by a local NGO (REST, the Relief Society of Tigray) to fight these phenomena. Hence, different soil conservation techniques such as stone bunds (built in order to obtain progressive terraces) have been introduced.

One of these soil conservation techniques which proves to be especially efficient, is the 'exclosure' or 'hillside closure' land management practice, estimated to cover nowadays 8 % of the highlands in Tigray (Nyssen, 2001). Although cattle are not allowed to enter these closed areas, local farmers are entitled –under certain conditions- to use some of the resources found in these closed lands. In some of these areas local people are for example allowed to hay grasses, but only during one day of the year. In some other places, which are considered to be 'holy forests' –protected by a very strong religious status-, cutting of trees is only allowed for construction and restoration works in the local church building. Sometimes, only certain groups within the local society (widows or war veterans for example) are given the permission to take wood and branches out of the closed areas. In most places, local guards have been installed in order to control these regulations (Naudts, 2002).

The objective of this research was to study in detail the interactions between land use, soil formation and soil erosion for a selected catchment in the highlands of northern Ethiopia. This article focuses on the results of one part of the research: the study of soil erosion and accumulation of sediment and organic carbon in two closed areas near the village of Hechi.

2. Materials and Methods

2.1 Presentation of the study area

The mountainous Dogua Tembien (Tembien highlands) district, located in the central part of Tigray (figure 1), was selected as research area for this study, since its elevation (1800 – 2800 m) and morphology are typical for the northern part of the Ethiopian highlands. Hagera Selam, the main town of the district, is situated at an altitude of 2650 m, on the road from Mekelle to Adua. The population of the district is mainly rural and population density reaches about 90 inhabitants km². Since 1990, soil and water conservation has been a high priority in the Tembien highlands (Nyssen, 1998).

In this region, Mesozoic sedimentary rock (Amba Aradam sandstone and Antalo limestone) is capped by Tertiary Ashange basaltic flows, which include silicified lacustrine deposits. The numerous subhorizontal layers give rise to a stepped landscape of cliffed tabular structures. On the basaltic rocks, one finds a typical Luvisol-Regosol-Cambisol-Vertisol catena.

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. The agricultural system in this part of the northern Ethiopian highlands has been described as a “grain-plough complex” (Westphal, 1975). The main crops are wheat (*Triticum sp.*), barley (*Hordeum vulgare*) and tef (*Eragrostis tef*), an endemic

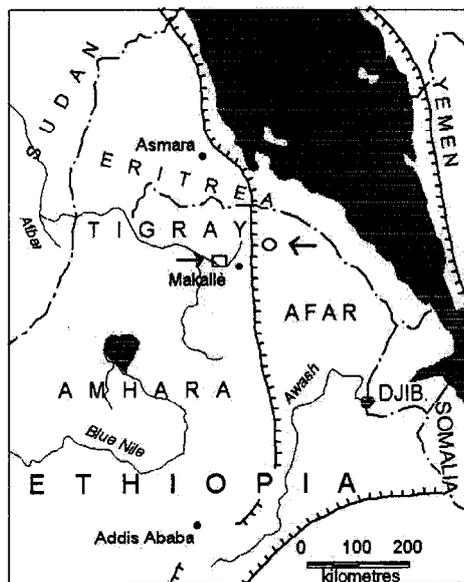


Figure 1: Localisation of the study area. The study area is indicated by the little rectangle, the Dessa state forest by the little oval.

cereal crop. In spite of a generally low soil erodibility, reflecting high clay and rock fragment contents, the croplands situated on sometimes steep slopes induce much soil erosion (Nyssen *et al.*, 2000).

After a preliminary comparison of the lithology, geomorphology, soils and land use of twelve catchments on the Tembien highlands, the Zenako-Argaka catchment was found to be the most representative, and selected for this study. Soil catenas on both dominant lithologies (basalt and limestone) show in general a clear correspondence between geomorphology, parent material and soils.

Part of the village of Hechi was included in the study area, in view of the presence of two areas which still hold a semi-natural vegetation: a park (churchyard) around the local church, and the Luqmut slope forest. Special attention was given to the analysis of soil

erosion (assessment of historical soil loss) and accumulation of eroded material in the surroundings of this village, where different types of land use (cropland, rangeland, exclosures and semi-natural forest) can be found in the same topographical positions. The total surface area of the selected catchment area is 202 ha.

In order to compare the findings of this study to other similar situations of forested slopes in northern Ethiopia, the observations were complemented by observations made along a transect in the Dessa state forest, located in the eastern part of the Tigray region (May 2002).

2.2 Soil survey and land-use inventory for a selected catchment

Data on the soils and the land use within the selected catchment were recorded during a three month field survey (summer 2000). After a preliminary prospection, including the description of twelve soil profiles in gully walls, augerings were carried out throughout the catchment, with an approximate density of one augering ha⁻¹. Representative augering sites were selected as much as possible in the middle of a field where soil profiles were expected to be less disturbed by erosion or deposition. Physical and morphological characteristics of all horizons were recorded. Based on these data, on the geomorphology of the site, and on information from nearby soil profiles, the augered soils were classified, using the World Reference Base (WRB) for Soil Resources (FAO *et al.*, 1998).

A land-use inventory of the 208 ha large study catchment was made using a GPS-navigation system (accuracy \pm 4 m). The exact location of each augering site as well as the data on the land use were brought together and analysed in a Mapinfo GIS-environment, using a Digital Terrain Model (DTM).

2.3 Historical changes in land use

In order to relate historical changes in land use to soil formation and soil erosion processes, stereoscopic Aerial Photo Interpretation (API) and the technique of semi-structured group interview sessions (Hinton & Young, 1999) were used. The land cover as seen from a pair of aerial photographs of December 1963 (EMA, 1963) was compared to that found on aerial photographs of February 1994 (EMA, 1994), and to present-day land use.

2.4 Description of selected soil profiles

In order to study in more detail the impact of area closure on soil erosion and sediment accumulation, two soil / land use transects were investigated in the village of Hechi: a soil chronosequence (i.e. a sequence of soil profiles in which the major factor of differentiation are different types of land use that have been succeeding to each other through time) in the surroundings of the Luqmut forest, on a slope of 0.4 – 0.6 m m⁻¹ (3 profiles and 5 augerings), and another transect (land-use sequence) in a flat topographical position around the churchyard and church forest of the village (1 profile and 8 augerings).

The location of the soil profile pits was based on the information collected from preliminary augerings. Morphological soil characteristics were interpreted and recorded according to Ethiopia-specific guidelines (De Pauw, 1985), which are based on the FAO guidelines for soil description. All horizons of 10 soil profile pits, representing the most common soil types in the study area, were sampled for further laboratory analysis.

2.5 Physical and chemical soil analysis

For each of the soil samples grain size was analysed by the sieve-pipette method (Gee & Bauder, 1986), organic C by Walkley-Black method (Allisons, 1965), total nitrogen content by the Kjeldahl method (Avery & Bascomb, 1982). The Cation Exchange Capacity (CEC) was determined by ammonium acetate extraction and measurement by spectrophotometer;

exchangeable bases (Ca, K, Mg) were measured in the first CEC percolate, K with flame spectrophotometer, Ca and Mg by atomic adsorption spectrophotometry. Available P was determined by the Bray II extraction method. CaCO₃ content was obtained through reaction with HCl (15 %). All the analyses were realised at the laboratories of the 'Soil Service of Belgium' at Heverlee, Belgium.

2.6 Assessment of soil loss and sediment accumulation by comparison of horizons

Comparisons of soil profiles under cropland or rangeland with nearby profiles in the same landscape position, but under a semi-natural vegetation or in an closed area, allow calculations of the rates of soil loss and sediment accumulation. Morphological description and chemical analyses of the profiles were used to identify corresponding horizons, and hence to contrast soil erosion versus sediment accumulation.

3. Results and Discussion

3.1 Historical changes in land use

	1963		1994		2000	
	ha	%	ha	%	ha	%
Cropland	87	41	109	53	109	53
Fallow	23	11	12	6	11	5
		52		58		58
Overgrazed rangeland	33	16	41	20	38	18
Shrubland	45	22	37	18	38	18
Forest	21	10	8	4	12	6
TOTAL	208	100	208	100	208	100

Table 1: Land-use evolution in the selected catchment between 1963 and 2000.

Throughout the studied period, cropland has occupied more than half of the studied catchment, increasing by 6 % in 37 years time. Increase of the surface of cropland was mainly at the expense of shrubland. The relative area of fallow land within the arable land was reduced from 21 to 9 %. As a result of the high pressure on the land, the practice of leaving land fallow is abandoned more and more. The area of the overgrazed rangeland increased by 4 % from 1963 to 1994, after which it slightly decreased. Non-arable shrubland with sparse vegetation also decreased by 4 %, and then increased slightly. The area covered by forests strongly decreased, from 10 to 4 % between 1963 and 1994. Due to enclosure policy, it increased again to 6 % in 2000.

3.2 Estimation of soil loss on cropland in the surroundings of the churchyard of Hechi

In Hechi's churchyard no agricultural activity or haymaking are allowed. Neither is woodcutting, except for construction and reparation works in the church building. Besides gardening activities (plantation of exotic flowering shrubs), the area is relatively undisturbed. In the outer circle, large trees are also growing: *Olea europaea* ssp. *africana*, *Juniperus procera*, *Euphorbia* sp. In this park-like area, which holds a closed vegetation cover and where the soil is expected to be very similar to the one of the church forest *sensu stricto*, we were allowed to auger, which allowed us to compare soil profiles with the surrounding cropland. The whole site (including churchyard and surrounding cropland) is located on slopes $< 0.05 \text{ m m}^{-1}$, and relatively deep soils were expected. The soil type, analysed in a nearby profile pit (P 8 in figure 2), is a Protoverti-calcaric Cambisol (Humic), with a dark

cambic horizon with some vertic properties, reaching to a depth of 40 cm, where it presents a neat boundary with the weathering limestone parent material. We augered for this boundary at three places in the churchyard (K 10, K 11 and K 13) and one in edaphic grassland (K 15) and found it at a depth of 90 – 120 cm (average: 110 cm). Comparison with augerings in the surrounding, gently sloping cropland (K 8, K9, K14 and K 16) indicate an average historical soil loss of 31 ± 18 cm.

This relative high soil loss for the cropland can be attributed mainly to tillage erosion. Nyssen *et al.* (2000) measured unit soil transport rates on cropland in Dogua Tembien which vary between 4.8 and 7.2 kg m^{-1} for slope gradients between 0.03 and 0.06 m m^{-1} . These values represent the mass of soil deposited during each tillage operation behind 1 m of lynchet or

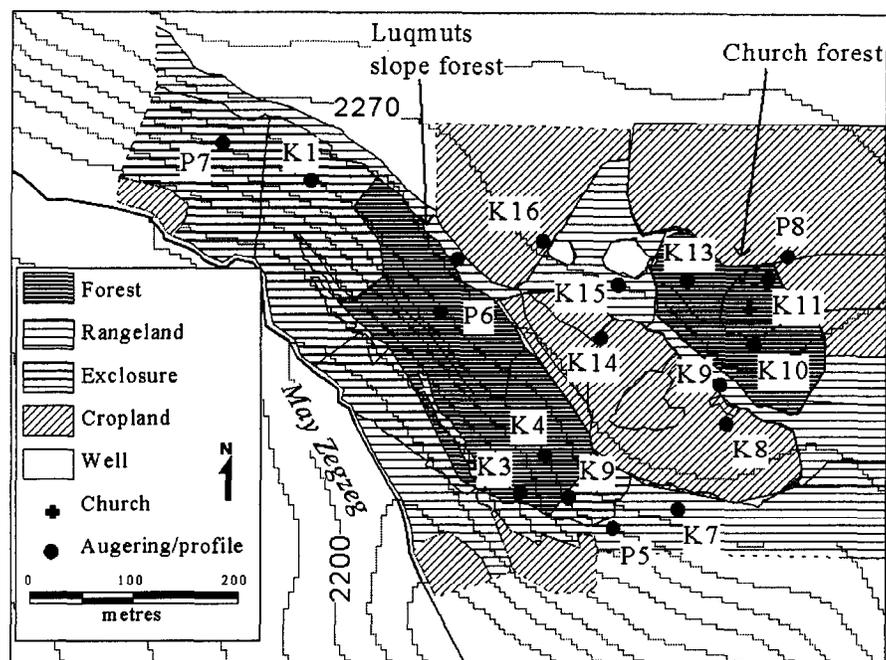


Figure 2: Situation of the soil profile pits and augering sites for the two soil / land use studies in Hechi

stone bund. As farmers till 2 to 4 times per year, values for the annual tillage transport coefficient in this area can be assessed to range from 9.6 to 28.8 kg m^{-1} .

3.3 Accumulation of eroded material in closed areas: the Luqmuts slope forest

The Luqmuts ‘exclosure’ forest is situated on a limestone cliff (overall slope gradient $0.4 - 0.6 \text{ m m}^{-1}$), immediately downslope from the cropland surrounding Hechi’s churchyard, where estimations for soil loss were made. On this slope, three different situations of land use can be found in a similar topographical position. In the middle, there is a dense natural forest (area A in figure 3), which is nowadays considered as a ‘holy forest’; protected by a very strong religious status. Interviews with local people show however that there used to be some woodcutting and occasional grazing in the forest during recent decades, especially during the civil war (1979 - 1989). Although it is most likely that some scattered trees are thus the only remnants of the indigenous ‘climax’ vegetation, one finds enough evidence to presume that this area has always been covered with a nearly complete vegetation deck, and benefited from a *de facto* ‘closed’ status because of its religious protection. Dominant woody species in this area are: *Carissa edulis*, *Acacia etbaica*, *Euclea racemosa*, *Dodonaea angustifolia*, *Ficus glumosa*, *Ficus sur*, *Maytenus senegalensis*, *Pterolobium stellatum*, *Rhus natalensis* and *Rhus vulgaris*.

To the south-east of this dense forest, the slope is used as rangeland (B in figure 3). All trees have disappeared and the vegetation consists only of those species that resist best to livestock: *Aloe* sp., *Opuntia ficus-indica*, *Rumex nervosus*, *Echinops* sp., as well as locally very short grass (*Cynodon dactylon*). Limestone parent rock and sapprolite outcrop here in many places.

The area north-west of the densely forested area (C in figure 3) has been used as rangeland until it was closed some 15 years ago, although the area has never been completely overgrazed and has always supported a scarce vegetation. The woody species which are



Figure 3: Chronosequence of three different land-use situations around the Luqmut's slope forest.
 A = dense, natural forest, B = overgrazed rangeland, C = enclosure since 15 years.
 The tree cluster on the plateau is Hechi church forest. (Photo: B. Muys)

encountered here (including *Acacia etbaica*, *Becium grandiflorum*, *Dodonea angustifolia*, *Euclea racemosa* and *Grewia* sp.) indicate an important rise in biodiversity and biomass production since the closure of the area.

Taking into account (1) the presence of remnant trees at the margins of the rangeland, and especially in cropland more to the south south-east of the Luqmut's forest and (2) the fact that slopes have been deforested later than the flat land, as indicated by the preferential location of remnant forests on steep slopes, it is hypothesised that, before human intervention, the whole Luqmut's slope was under the same land use, i.e. forest. In that case, a chronosequence, i.e. land-use types that succeed to each other through time but are also present as a spatial succession, allows to assess the impact of land-use changes on soil. In each of the above described areas (A, B and C in figure 3) a soil profile pit was dug and additional augerings have been made. Care was taken to realise the 3 profiles and 5 augerings in the same topographical position, on a narrow structural flat within the slope with a local slope gradient of 0.1 - 0.15 m m⁻¹. Morphological descriptions and chemical analyses of the profiles were used to find corresponding horizons, and hence for making assessment of soil erosion and sediment accumulation.

The soil profile encountered in the dense natural forest (P 6 in figure 2) was keyed out as a Calcari-luvic Phaeozem. It bears a mulch layer and a 2-cm thick organic horizon at its surface. These two horizons overly two layers of colluvial material. A clear layering was found in these layers, allowing the conclusion that they developed on sediment material. Near the bottom of the profile, a limestone sapprolite was found.

In the upper layer of colluvial material, a mollic horizon (Bw in figure 4) is present: blocky structure, 10 YR 3/1, 3.8 % organic C, high base saturation, no secondary carbonates and a thickness of 37 cm. The presence of this mollic horizon and high base saturation allows classifying the soil as a Phaeozem. Typical properties of the underlying Bt horizon are its high clay (45 %) and organic C (3.8 %) content. Since a clay jump is present, the horizon was qualified as "Luvic". It is presumed that this argic horizon is due to the deposition of different sediment layers. In the lower limestone sapprolite, no diagnostic horizons are present.

Despite the steep overall slope, huge amounts of sediment have been accumulating here, and a deep soil (total depth of A and B horizons: 1.4 m) has developed. As mentioned before, the sediment has an average organic carbon content of 3.8 % of the soil weight. This "trap efficiency" for organic carbon-rich colluvial material is explained by the deep rooting trees, which fix the soil on the slope, and by canopy cover and surface mulch which protect the slope from water erosion.

The profile under overgrazed rangeland (P 5 in figure 2) was classified as a Calcaric Regosol. The outcropping material corresponds to the limestone sapprolite. All original soil layers have been eroded in this area, and there has not been any accumulation of sediment. Variations in texture and rock fragment content, which were encountered here, correspond probably to very rapid vertical changes within the Antalo limestone (Russo *et al.*, 1999).

In the area which has been exclosed before 15 years (area C in figure 3), accumulation of upslope eroded material and of organic matter produced by the fastly recovering vegetation have resulted in the presence of a 40-cm thick Cumulicalcari-Humic Regosol (P 7 in figure 2). This sediment has an average organic carbon content of 4.1 % of the soil weight. Under this Regosol a Calcaric Cambisol was found, corresponding to the Calcaric Regosol found in the overgrazed rangeland.

Comparison between moisture contents in the topsoil of the three profiles indicated better infiltration and water availability in the dense natural forest and the 15-year old exclosure than under overgrazed rangeland.

	Forest (P6) III C1, depth: 130 cm	Rangeland (P5) C1, depth: 0 cm	Exclosure (P7) III Bw, depth: 75 cm
Soil type	Calcaric Regosol buried under Luvic Phaeozem	Calcaric Regosol	Calcaric Cambisol buried under Cumulicalcari-Humic Regosol
PH (H ₂ O)	8.1	7.8	8
O. C. (%)	1.1	1.0	0.4
N tot. (%)	0.07	0.07	0.06
CaCO ₃ (%)	42.4	19.1	61.2
Pav. (ppm)	9	0	0
K (meq/100g soil)	0.3	0.2	0
Ca (meq/100g soil)	19.5	14.1	15.9
Mg (meq/100g soil)	5.2	0.6	0.2
CEC (meq/100g soil)	15.1	9.7	5.9
Base sat. (%)	100	100	100
Sand (> 0.05 mm) (%)	38	59	38
Silt (0.002-0.05 mm) (%)	49	12	37
Clay (< 0.002 mm) (%)	13	29	26

Table 2: Characteristics of comparable horizons in the three soil profiles around the Luqmut's slope forest

The best correspondence between horizons in the three profiles was found for the upper part of the sapprolite (table 2, figure 4), which is buried under deposited material in the forest and under exclosure. Chemical characteristics of the sapprolite in the three profiles are similar. K, Ca and Mg have higher concentrations under the forest soil, which is probably the

consequence of higher nutrient inputs from leaf debris and less leaching losses (White, 1997). A large variability in soil texture among the profiles should not surprise, since the sapprolite is merely a reflection of the parent limestone, which has rapid vertical changes in rock type.

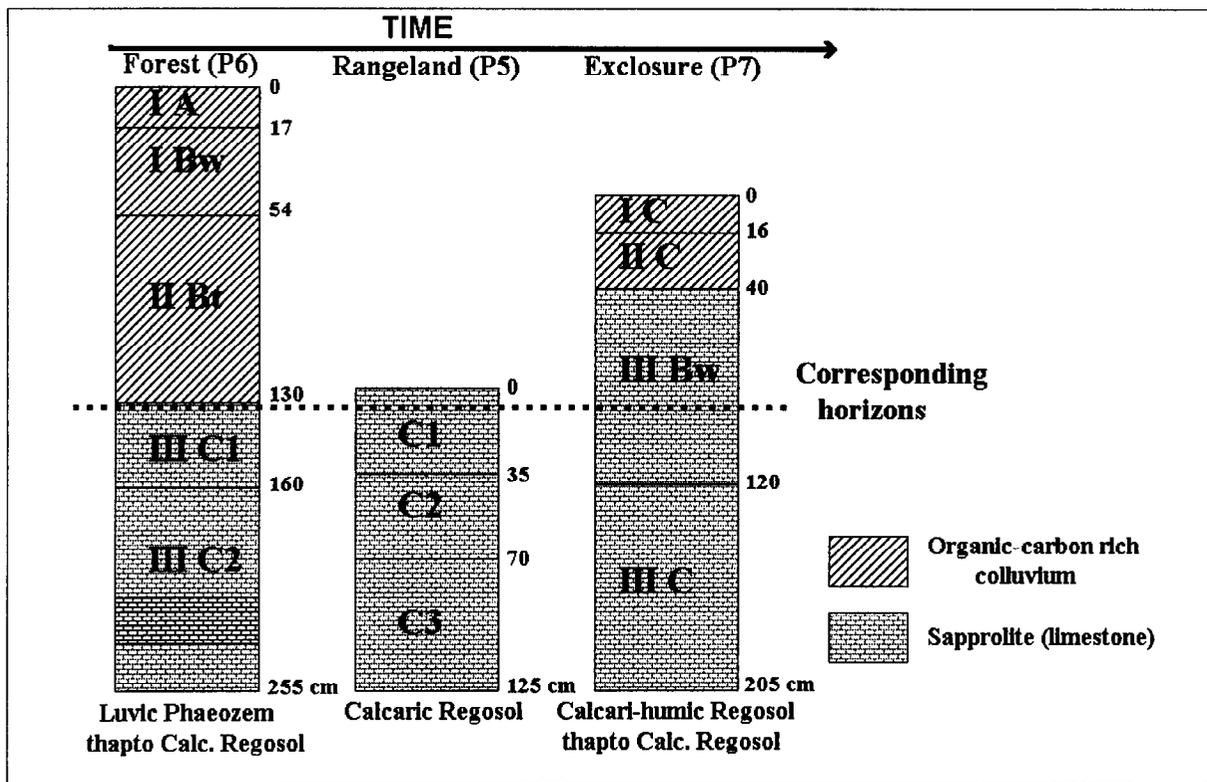


Figure 4: Evolution of soil profiles as a result of land-use changes

It is expected that the original soil of the Luqmut's slope forest would be comparable to the soil actually found in the Dessa slope forest, situated in similar topographical and lithological position (although the eastern part of the Tigray region receives less rainfall), but without any cropland nearby. It appeared from ten augerings in two localities and from observations along roadcuts that in most places in the Dessa slope forest only a shallow profile (10 - 40 cm) developed on *in situ* weathering limestone material. In one locality at a slope break, however, a dark humic horizon developed in fine accumulations. In the vicinity humic rich gully infills have been found under the Dessa forest, pointing to early openings and to local erosion phenomena.

These observations in the Dessa slope forest give evidence for the hypothesis that the original soil of the Luqmut's forest was rather thin. This allows us to conclude that 1.4 m of organic carbon-rich sediment has eroded from the cropland upslope in the village of Hechi, and that this sediment has been transported and accumulated in the Luqmut's slope forest. Augerings in other places along the slope (K 1, K 3, K 4, K 7 and K 9 in figure 2) showed a sediment accumulation of 93 ± 18 cm.

In the overgrazed rangeland, it should be expected that not only the original, shallow soil has eroded but also (an unknown) part of the sapprolite, as well as a certain thickness of sediment, which was accumulated in the original slope forest after agriculture started on the plateau above the slope, but eroded again after deforestation of the steep slope. Starting from this situation, up to 40 cm of sediment was accumulated over the last 15 years in the recent exclosure, which is another indication for the strong degradation of the cropland upslope of the Luqmut's forest area, and for the 'trap efficiency' of closed areas.

4. Conclusions

The 'exclosure' land management practice is very effective in bringing soil erosion in degraded areas to a standstill. Besides improved infiltration, less runoff, improved biomass production and a rise in biodiversity, this technique brings about the accumulation of large amounts of organic carbon-rich colluvial material, even on steep slopes, and allows thus for a relative fast regeneration of soil productivity in these areas. The high capacity for sediment deposition in the closed areas, together with the improved infiltration, has also important off-site effects: increased ground water recharge, decreased flooding in downstream areas and decreased reservoir siltation. In this way exclosures constitute a valuable alternative for the local communities of the northern Ethiopian highlands.

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