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SOILS AND LAND USE IN THE TIGRAY HIGHLANDS (NORTHERN ETHIOPIA)

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ABSTRACT

Land use in a 208 ha representative catchment in the Tigray Highlands, Dogu'a Tembien district in Northern Ethiopia was studied in relation to soil geography. Typical soils are Vertisols, Vertic Cambisols, Cumulic Regosols, Calcaric Regosols and Phaeozems. Patterns of land use vary greatly within the catchment and results from χ^2-tests showed strong associations ($p < 0{\cdot}001$) between soil type and land use and crop production system. There is a strong association between cropland and colluvium high in basaltic content because the most fertile soils, such as Vertisols and Vertic Cambisols, have developed on this material. Preference is for autochthonous soils on *in situ* parent material, irrespective of the rock type, to be put under rangeland. Land use by smallholders in Dogu'a Tembien appears to be the result primarily of the interaction between environmental and social factors. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: soil geography; Tigray; land capability; crop rotation; permanent upland farming system; Ethiopia

INTRODUCTION

Limited agricultural intensification in Ethiopia combined with a population growth rate of 2·7 per cent y^{-1} for the period 1975–2002 (UNDP, 2004) has resulted in increased pressure on the natural resources of the Ethiopian Highlands, leading to land degradation. The sustainability of traditional agricultural systems is threatened, not only by soil degradation but also by a decline in the natural vegetation (Gryseels, 1988; Zeleke *et al*., 1999).

A regional scale (1:250 000) soil survey in part of Tigray is reported in the Tigray Rural Development Study (HTS, 1976). In a large area west of Mekelle, soils vary primarily according to parent material. The Hagere Selam uplands are one distinct physiographic unit in this study with such dominant soils as Vertic and Dystric Cambisols on the footslopes and plateaux and Leptosols on steep slopes. However, the understanding of soils and their spatial associations in the Tigray Highlands is limited. Most of the land around Hagere Selam was considered as suitable for rain-fed crops, but only with intensive conservation measures.

Land cover is defined as the biophysical cover of the earth's surface, while the concept of land use is a broader concept including land management (Di Gregorio and Jansen, 1998). Goebel and Odenyo (1984) describe the dominant land use in Dogu'a Tembien as intensive rain-fed peasant cultivation of cereals and pulses, and the major land cover, besides cropland, as scattered scrub and grass vegetation as well as much bare rock. Factors influencing land use are discussed by Ståhl (1974) and Reid *et al.* (2000) for the Ethiopian Highlands and more generally by

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Blaikie (1985). This paper addresses issues which have been generally overlooked in previous studies and focuses on (1) major differences in soil types, their location and suitability and (2) how soil distributions in Dogu'a Tembien influence land-use decisions by smallholders.

MATERIALS AND METHODS

Study Area

Geology and geomorphology

The May Zegzeg catchment near Hagere Selam (13°40′N, 39°10′E), located *ca* 50 km west of Mekelle (Figure 1), was selected for this study as it is typical in terms of high elevation and geology. The local geology comprises a subhorizontal series of alternating hard and soft Antalo limestones, some 400 m thick, overlain by Amba Aradam sandstone. Two series of Tertiary lava flows, separated by silicified lacustrine deposits, bury these Mesozoic sedimentary rocks. Erosion in response to Miocene and Plio-Pleistocene tectonic uplifts, of the order of 2500 m, has resulted in the formation of tabular, stepped landforms. The highest areas at 2700–2800 m a.s.l. are underlain by 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 (Nyssen *et al*., 2002a).

Climate

The average yearly precipitation is 778 mm and the main rainy season (>80 per cent of total rainfall) is from June to September. High rainfall erosivity is due to large drop size (Nyssen *et al*., 2005). Seasonal droughts, as well as important annual variability in rainfall, influence land-use decisions. Monthly average minimum temperatures range from 4 to 6°C and maxima from 20 to 22°C. Variation is less during the rainy season due to cloud cover.

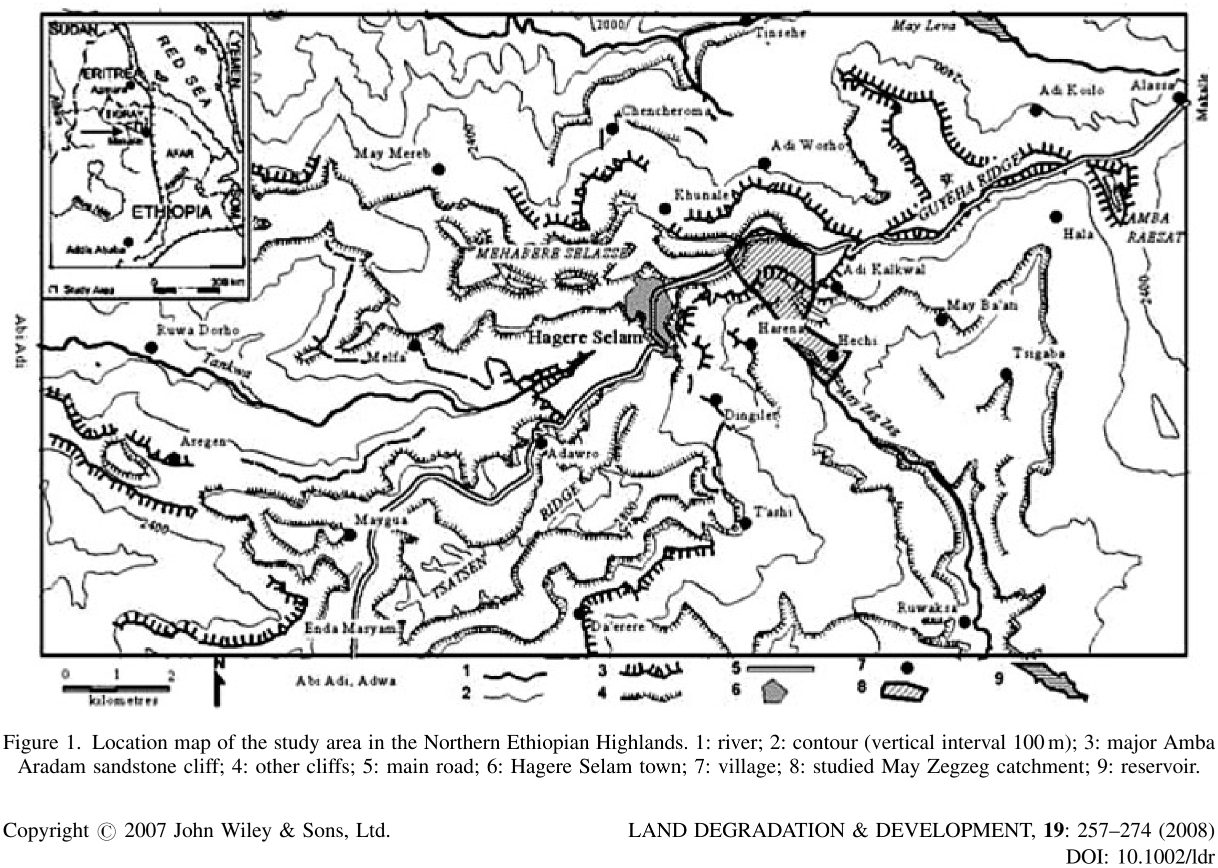

Figure 1. Location map of the study area in the Northern Ethiopian Highlands. 1: river; 2: contour (vertical interval 100 m); 3: major Amba Aradam sandstone cliff; 4: other cliffs; 5: main road; 6: Hagere Selam town; 7: village; 8: studied May Zegzeg catchment; 9: reservoir.

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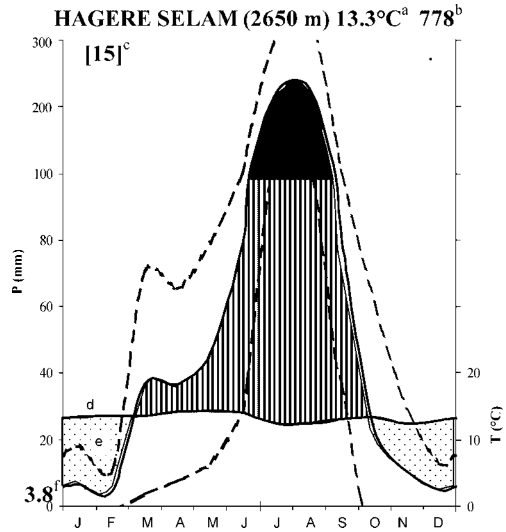

Figure 2. Ombrothermic diagram for Hagere Selam. Monthly precipitation (P) is indicated with $\pm 1\sigma$. The lower dashed line stands for 84 per cent probability of exceedance of average monthly rain. Note change in y-axis scale above 100 mm; a: mean temperature; b: mean yearly rain; c: number of rain observation years; d: mean monthly temperature; e: month where $P < 2T$; f: lowest monthly minimum temperature. Precipitation and temperature data from National Meteorological Services Agency (1973–1982 and 1996–2000).

Rainfall seems sufficient for agriculture from March (Figure 2), but it is uncertain till June. For the Hagere Selam uplands, the average growing period for agricultural production (LGP) is 162 days (Goebel and Odenyo, 1984).

The Farming System

Agriculture in Dogu'a Tembien consists exclusively of small-scale family farms. Since the 1980s a land tenure regime has been introduced which has led to broad equality in size of landholdings (Hendrie, 1999). On average, the families in the study area use two or three parcels of cropland, with a combined area of between 0·5 ha (Gebremedhin, 2004) and 0·75 ha (Naudts, 2002). Grassland, rangeland and exclosures are communally owned.

The most cultivated crops in the Dogu'a Tembien district (Table I) include common cereals like barley (*Hordeum vulgare*) and wheat (*Triticum* sp.), as well as **tef** (*Eragrostis* ***tef***), a cereal with very fine grains endemic to Ethiopia. Barley and wheat are sometimes sown together in a mixture called **hanfets** to reduce the risk of crop failure. Grass pea (*Lathyrus sativus*) and horse bean (*Vicia faba*) are also important crops. Some fields are under lentil (*Lens culinaris*) or linseed (*Linum usitatissimum*). In the lower parts of the study area, we also found maize (*Zea mays*). In addition, most households manage a small garden near their homestead for vegetables. The concept of a 'crop production' system (Beets, 1978; Devienne and Wybrecht, 2002) was used during our survey for analysing arable land use. Three major crop production systems were identified in the study area (Table II). The upland farming system (Ruthenberg, 1980) in the Tembien Highlands has clearly demarcated fields and a rotation intensity of 0·91, that is the ratio of cropped area/(cropped + fallow).

Livestock are mainly cattle, especially oxen, sheep, goats, donkeys and mules. An average family in the Tembien Highlands owns one or two oxen, five to six goats or sheep and sometimes a donkey. 'Livestock keeping is part of the permanent upland system' (Ruthenberg, 1980). Since no forage crops are grown, livestock are allowed on all land where not forbidden. Fallow land and harvested cropland are also used for grazing. In a bid to protect the most endangered areas such as steep slopes, they are increasingly converted into exclosures, i.e. land under strict management, often by the community, where grazing is prohibited, woodcutting sometimes allowed under strict regulations and yearly grass cutting organised (Descheemaeker *et al.*, 2006). Regulations imposed by the local communities to set aside wetland areas for grazing during the dry season are important for determining rangeland condition. Hay for livestock is of lesser importance than free grazing.

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Table I. Crop requirements

	Wheat (*Triticum* sp.)	Barley (*H. vulgare*)	**Tef** (*E.* ***tef***)	Horse bean (*V. faba*)	Grass pea (*L. sativus*)	Lentil (*L. culinaris*	Linseed (*L. usitatissimum*)
Average yield estimations (kg ha^{-1})							
Ethiopia[a]	760	860	610	960		610	520
Vertisol areas[b]	870	970	620		610		
Dogu'a Tembien[c]	700	850	425				
Crop requirements[d]							
Growing period	Rapid maturation period, coinciding with rapid decline in rainfall at the end of the rainy season		90–110 days	Very variable, depending on cultivars			6–7 months
Moisture requirements		Importance of even distribution of rainfall	Needs soils with good moisture retention		Drought resistant, can be sown late		
Waterlogging	Tolerant to short periods	Intolerant to water logging	Tolerant in early vegetative stage		Tolerant		Intolerant
Nutrient status and retention	Landraces have low fertility requirement	Moderate requirements	Needs fertile soil; good after legumes	Good response to P and K on infertile soils	Can be grown on soils with few inherent nutrients	High Mo requirement	Prefers slightly alkaline soils
Rooting depth	50–60 cm	1–2 m	10 cm				
Toxicities	Intolerant to high levels of Na, Mg and Fe; moderately tolerant to salinity and $CaCO_3$	Intolerant to high levels of Al; reasonably tolerant to salinity and alkalinity	Wide range of pH tolerance, not known to suffer from toxicities			Tolerates moderate alkalinity	
Pests and diseases	Late sowing (especially on Vertisols) avoids pests and diseases	High humidity increases hazard; barley fly endemic to Tigray	**Tef** rust if high humidity and temperatures; barley fly	Root rot if high humidity and temperatures			
Other hazards	Strong wind		Water erosion				

Most data from FAO and UNDP (1983). For more details, see Naudts (2001).
[a]According to Westphal (1975).
[b]In the Ethiopian Highlands, under traditional management, according to Brusselmans and Van Muysen (1995).
[c]Without fertiliser, according to official data (DTWA, 2000).
[d]Of local landraces; all reviewed crops present chilling tolerance.
[e] Only toxicities bound to occur in the study area are mentioned.

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Table II. Cropping systems in the May Zegzeg watershed

	Cropping system	Crop rotation
CB	Cereals–beans	Wheat, barley or **hanfets** Horse beans
TG	**Tef**–grass pea–cereals	**Tef** Grass pea Wheat, barley or **hanfets**
FL	‘Flexible’	Wheat, barley or **hanfets** Lentils, grass pea, linseed or fallow If early rains (Feb.–Mar.): maize or sorghum

Note: crop rotations are not very rigid: observation of previous years’ crop yield, antecedent rainfall and opportunity are very important in farmers’ decisions.

Soil Survey and Classification

Profile descriptions

Fieldwork was conducted in the summer of 2000. Morphological soil characteristics were interpreted and recorded according to Ethiopia-specific guidelines (De Pauw, 1985) which are based on the FAO guidelines for soil profile description. All horizons from ten representative soil profile pits were sampled for laboratory analysis.

Augering

Augering was carried out throughout the catchment, with an approximate density of inspection of 1 ha^{-1}. Representative sites were selected as far as possible in the middle of terraced fields where soil profiles were expected to be less subject to erosion or deposition. The location of each augering site was determined by GPS and then physical and morphological characteristics of all horizons were recorded. As a result augered soils were cross-referred to soil profile pits and thus classified.

Laboratory analysis

Grain size was analysed by the sieve and pipette method (Gee and Bauder, 1986), organic C by the Walkley–Black method (Allison, 1965) and total nitrogen by the Kjeldahl method (Avery and Bascomb, 1982). The cation exchange capacity was determined by ammonium acetate extraction and measured by spectrophotometer; exchangeable bases (Ca, K, Mg) were measured in the CEC filtrate, K with flame spectrophotometer and Ca and Mg by atomic adsorption. Available P was determined by the Bray II extraction method. $CaCO_3$ content was obtained through reaction with HCl (15 per cent). All analyses were made at the ‘Bodemkundige Dienst van België’, Heverlee, Belgium.

Soil classification and mapping

Soils were classified according to the World Reference Base (WRB) (FAO *et al*., 1998), with the addition of qualifiers. The soils were also mapped according to a farmers’ classification system and correlated with WRB. Augering sites and soil profile pits were located on a topographic map with a contour interval of 10 m. In addition, boundaries between soil units as observed in the field and in gully banks were registered by GPS and mapped. The delimitation of soil units on the map was done through interpolation, taking into account geomorphology, parent material and topography.

Land-Use Analysis

Inventory and quantitative evaluation

A land-use inventory was completed for the catchment (Naudts, 2001) with the aid of a GPS navigation system and a digital terrain model (Nyssen, 1995). Because of the small plot sizes (generally $<0{\cdot}25$ ha), it proved impossible to

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delimit each parcel and that is why we identified and measured groups of parcels which were under the same crop. Land characteristics were also recorded: slope angle, vegetation and rock fragment cover and ground water depth.

Interview methods

Semi-structured group interviews (Young and Hinton, 1996) were used to collect information on the land-use systems in the study area. Three interview sessions were organised with the help of an interpreter, familiar with local agricultural practices. Each group consisted of four farmers of different ages. Questions inviting 'yes' or 'no' answers were avoided and instead questions were always asked in an explicit way, often by pointing to land to clarify the meaning of the question.

Statistical Analysis

Independence versus association between variables was tested by χ^2-tests. In case of association, the combinations with a larger absolute value of the residual ε_{ij} indicate those classes of criteria that are responsible for the association observed between the variables (Diem, 1963; Beguin, 1979).

RESULTS AND DISCUSSION

Soils

Representative soil profiles

Six representative soil profiles are discussed here: a Pellic Vertisol, a Vertic Cambisol, a Cumuliskeletic Regosol, a Cumulicalcaric Regosol, a Calcaric Regosol and a Haplic Phaeozem. Full details of all soil profile and augering descriptions have been reported by De Geyndt (2001).

Grumi-pellic Vertisol (*Eutric*). This profile [Figure 3, (1)] is situated on a flat area, on fine basaltic colluvium, overlying *in situ* silicified limestone, under grazing, on top of the lower basalt cliff. A 60 cm thick vertic horizon is present, consisting of heavy clay with wedge-shaped structural elements and slickensides. The vertic horizon has a massive structure, hard consistency under dry circumstances and a Munsell value of 10 YR 1·7/1 (black) when moist. Polygonal structures can be distinguished at the surface. A base saturation of 55 per cent justifies the qualifier 'Eutric'. The volumetric rock fragment content is much higher in the plough layer (20 per cent) than in the vertic horizon (1–5 per cent), due to argillipedoturbation (Nyssen *et al*., 2000a; Moeyersons *et al*., 2006).

Verti-Humic Cambisol. This soil [Figure 3, (2)] on a 0·1 mm^{-1} slope, developed on basalt rich colluvium, overlies other colluvium dominated by silicified limestone. There is a high volumetric rock fragment content (50 per cent) due to its position in a plan concavity. Hence vertic movements are constrained and a Vertisol could not develop here. Some vertic properties could be observed, such as small cracks, high clay content and some slickensides. The qualifier 'Humic' was added since the upper soil horizons contain >2·3 per cent organic C.

Humi-Cumuliskeletic Regosol. This profile was observed on a 0·33 m m^{-1} debris slope at the base of a basalt cliff [Figure 3, (3)]. This soil is constantly rejuvenated and no diagnostic horizons can develop due to deposition of new sediment. Texture of the different layers varies between light clay and loam. Soil structure is poorly developed. In most horizons/layers, volumetric rock fragment content is >40 per cent. Organic C content is >1 per cent throughout the soil profile. The prefix Cumuli—refers to a soil 'having a repetitive accumulation of soil material of 50 cm or more in the surface or A horizon' (FAO *et al*., 1998).

Humi-Cumulicalcaric Regosol. This soil profile [Figure 3, (4)] on the footslope of the limestone cliff is on long established cropland, as indicated by an ancient agricultural terrace (Nyssen *et al*., 2000b). Soil eroded upslope accumulated in and behind a wide grass strip. The soil consists of an accumulation of recent sediment with a high $CaCO_3$ content (35 per cent) and 2 per cent organic C.

Calcaric Regosol. This profile in overgrazed rangeland is located on a steep limestone slope [Figure 4, (P5)] which is subject to intense soil erosion. It has been eroded to the saprolite and shows no diagnostic horizons. Variations in texture and rock fragments correspond to very rapid vertical lithological variability within the Antalo limestone (Russo *et al*., 1999).

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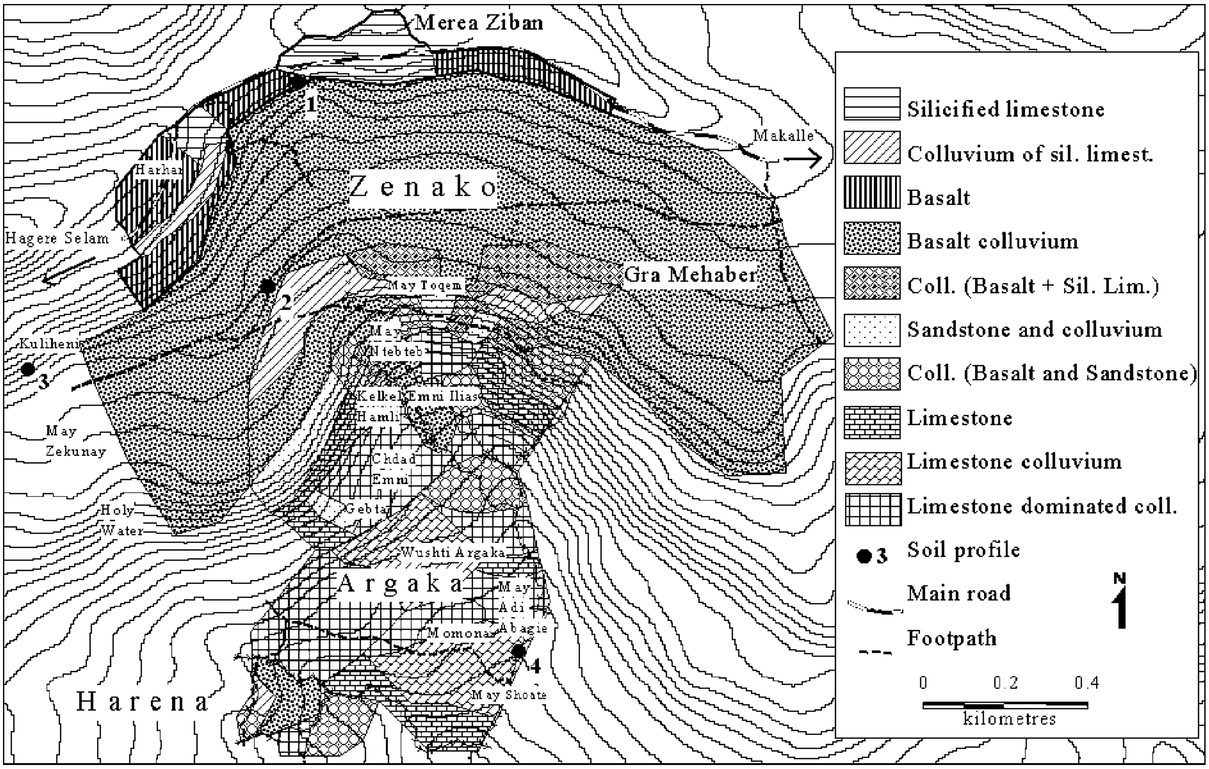

Figure 3. Parent material and location of the analysed soil profiles in the study catchment.

Calcari-Luvic Phaeozem. Located in the remnant Luqmuts Forest [Figure 4, (P6)], this profile represents forest soils on steep slopes before deforestation. It has a mulch layer and a 2 cm thick surface organic horizon. These overlie two different slope deposits formed after the deforestation of the structural flat above (Descheemaeker *et al*., 2006). This colluvium overlies limestone saprolite. In the upper layer, a brownish black (10 YR 3/1) mollic horizon is present with a blocky structure, 3·8 per cent organic C content, a high base saturation and no secondary carbonates. The presence of this mollic horizon and the high base saturation means this soil is a Phaeozem. Typical

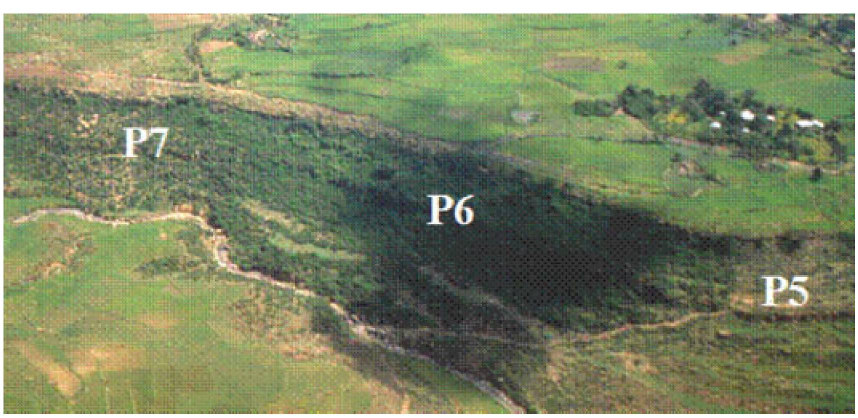

Figure 4. The impact of land use and vegetation on soil type at Luqmuts. Forest on Phaeozem (P6), exclosure on Cumulihumic Regosol (P7), rangeland on Regosol (P5). The tree cluster on the structural flat is Hechi Church Forest; to the left of it is cropland. Photo B. Muys, September 2001. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

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properties of the underlying Bt horizon are its high clay content (45 per cent) and organic C (3·8 per cent) content. The abrupt textural change justifies the qualifier Luvic. It is not clear whether this argic horizon is due to the deposition of different sediment layers or to pedogenetic processes. In the lower limestone saprolite, no diagnostic horizons are present. Despite the steep slope (0·6 mm^{-1}), a deep soil (total depth of A and B horizons: 1·4 m) has developed.

Spatial distribution of soil types (Table III)

The influence of parent material on soils is particularly marked when such material is of recent origin as is the case in the study region (Nyssen *et al*., 2002a; Moeyersons *et al*., 2006). The sediment deposited as colluvium covers older soils. Young soils in our study area are generally (Cumulic) Regosols, Cambisols as well as Leptosols which are found on the different lithologies within the study area. Other soil types are better correlated with specific parent materials, Vertisols on basalt, Calcisols on limestone and Luvisols on silicified limestone. In the upper Zenako area (Figure 3), basalt colluvium often overlies colluvium of silicified limestone. On plan convexities, the basalt colluvium is very thin or absent, resulting in outcropping of silicified limestone colluvium. In such areas of Vertisols, pockets of Haplic Luvisols have developed. It should be stressed that these are not comparable to the Luvisols which are commonly found in the upper part of the 'red–black soil catena' (Driesen *et al*., 2001), and which are present in neighbouring areas but not within the study catchment. Correlations between parent material and soils are not always valid as demonstrated by the particular case of Vertisols and other vertic soils in limestone areas.

In addition, human impact in the study area is an important explanatory factor of soil variability. Cereal growing, as well as stubble grazing by cattle and collection of dung for fuel leads to decreased soil fertility. Other major human activities leading to greater spatial variability of soils are the removal of natural forest vegetation, followed by water erosion as well as tillage erosion. These processes result in frequent outcrops of saprolite (Regosols) which are very different from the soils under (original) forest cover, such as Phaeozems. On the other hand, human decisions such as the exclosure policy rapidly lead to the formation of humus-rich topsoil (Descheemaeker *et al*., 2006).

Soil catenas

The topography results in a sequence of soils along slopes (catenas) as a consequence of sequential change in infiltration, surface runoff and transportation of soil material.

Along slopes on basalt, sequences of Leptosols, Skeletic Regosols, Cumuli(skeletic) Regosols, Vertic Cambisols and Vertisols are typical (Figure 5). In the limestone area, there is more lateral variation, but the following sequence is common: Leptosols on cliffs, Calcaric Regosols/Cambisols on the steeper slopes, Cumulicalcaric Regosols on the footslopes (Figure 6) with Calcisols on the flattest areas and Fluvisols on river terraces.

General characteristics of the footslopes of both major lithologies are sediment deposition, higher infiltration rates leading sometimes to a perched water-table expressed in stagnogley properties and precipitation of dissolved minerals which, depending on the type of minerals, will lead to Calcisols or to a recombination into smectites and formation of Vertisols. Typical for all soils on steep slopes is high rock fragment content: Leptosols on cliffs, Skeletic Regosols in eroded areas below these and Cumuliskeletic Regosols on upper colluvial slopes. The distribution and effects of rock fragments in the topsoils of the study area have been discussed elsewhere (Nyssen *et al*., 2001, 2002b, 2006; Moeyersons *et al*., 2006). The distribution of soils parallels the contour pattern (Figure 7). Some downslope oriented soil patterns result from the redistribution of basaltic material by hillslope processes.

Indigenous soil classification

Knowledge and use of local soil classification systems are important for efficient communication between farmers, researchers and development agents. Soil colour, texture and workability are important criteria for farmers. Colour and texture often reflect parent material. The farmers use local soil classification systems to aid choice of soil fertility strategies (Corbeels *et al*., 2000). Studies of local classification systems in Tigray (Mitiku, 1996; Tsegay,

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Table III. Area and locational characteristics of the soils types in the study catchment (soil types added between brackets are associated with the dominant soil type)

Soil type	Symbol	Position on slope	Parent material	Land use	Area (per cent)
Vertisols		Footslope	Basalt (limestone)	Grassland, cropland	20·4
Pellic Vertisol	PeVe	Footslope	Basalt	Grassland	3·3
Pellic Vertisol (VeCa)	PeVe (VeCa)	Footslope	Basalt	Cropland, grassland	16·5
Epistagnic Vertisol	EpstVe	Footslope	Limestone	Grassland	0·6
Fluvisols		River terraces		Rangeland (cropland)	0·4
Haplic Fluvisol	HaFl	River terraces		Rangeland (cropland)	0·4
Leptosols		Cliff	Various	Close to none	7·3
Lithic Leptosol	LiLe	cliff	Various	Close to none	5·7
Lithic Leptosol (HaRe)	LiLe (HaRe)	Cliff	Sandstone	Close to none	1·3
Hyperskeletic Leptosol	HyskLe	Various	Sandstone, basalt	Rangeland	0·3
Regosols		Mostly steep	Various	No cropland	8
Skeletic Regosol	SkRe	Steep slopes	Basalt	Unused or rangeland	2·6
Stagnic Regosol	StRe	Flat areas	Basalt	Grassland	1·9
Calcaric Regosol	CaRe	Eroded parts of foot/backslope	Limestone	Rangeland	1·8
Haplic Regosol	HaRe	Steep slope	Silicified limestone	Rangeland	0·9
Haplic Regosol (HaCam)	HaRe (HaCam)	Steep slope		Rangeland	0·8
Cumulic Regosols		Various	Various	Various	41·8
Cumulihaplic Regosol	CuhaRe	Backslope	All, except limestone	Cropland	16·5
Cumulicalcaric Regosol	CucaRe	Back- and footslope	Limestone	Cropland	14·8
Cumulicalcaric Regosol (CaRe)	CucaRe (CaRe)	Deposition/erosion areas on footslope	Limestone	Cropland, Rangeland	1·0
Cumuliskeletic Regosol	CuskRe	Backslope	Basalt (sandstone)	Cropland (exclosure)	6·7
Cumulihaplic Regosol (CuskRe)	CuhaRe (CuskRe)	Backslope	Basalt (sandstone)	Cropland (exclosure)	1·6
Cumulihaplic Regosol (CuhaCam)	CuhaRe (CuhaCm)	Steep slope	Basalt, sandstone	Rangeland	0·9
Cumuliskeletic Regosol (HyskLe)	CuskRe (HyskLe)	Debris slope	Basalt	Close to none	0·3
Cambisols		Various	Various	Mostly cropland	17·1
Vertic Cambisol	VeCam	Footslope	Basalt	Cropland	7·7
Calcaric Cambisol	CaCam	Eroded parts of foot/backslope	Limestone	Cropland	2·4
Calcaric Cambisol (CucaRe)	CaCam (CucaRe)	Eros./depos. areas on foot/backslope	Limestone	Cropland	1·1
Haplic Cambisol	HaCam	Backslope	Basalt	Cropland	2·8
(Proto)verti-Calcaric Cambisol	VecaCam	Footslope	Limestone	Cropland, grassland, exclosure	1·9
Cumulihaplic Cambisol (CuskRe)	CuhaCam (CuskRe)	Steep slope	Sandstone	Exclosure	1·6
Calcisols		Footslope	Limestone	Crop- and rangeland	1·4
Haplic Calcisol	HaCal	Footslope	Limestone	Crop- and rangeland	1·2
Hypercalcic Calcisol	HycaCal	Footslope	Limestone	Crop- and rangeland	0·2
Phaeozems		Steep slope	Limestone	Dense vegetation	2·4
Calcaric Phaeozem	CaPh	Steep slope	Limestone	Dense vegetation	2·4
Luvisols		Footslope	Sil. limest.	Cropland	1·7
Haplic Luvisol	HaLu	Footslope	Sil. limest.	Cropland	1·7

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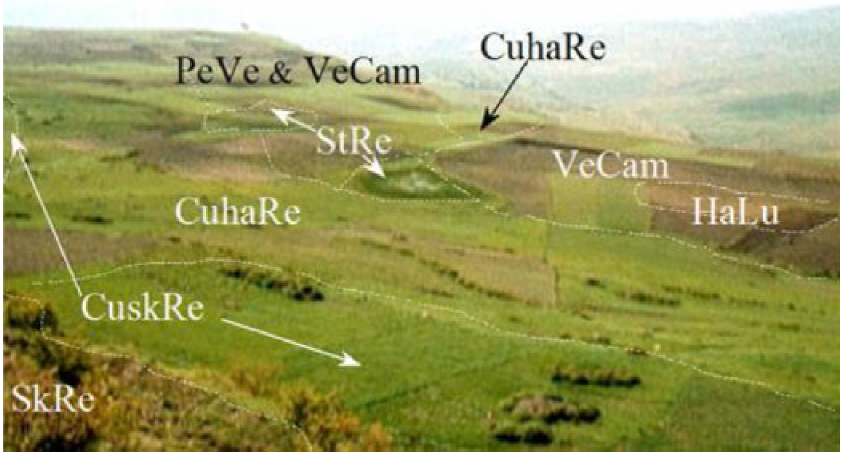

Figure 5. Soil catena on basalt (Zenako area, looking downslope and south). Soil acronyms as in Table III. Rangeland on Skeletic Regosol; grassland on Stagnic Regosol. The photograph was taken in August 2000; on Vertisol and Vertic Cambisol, the crop is only emerging, beans and grains on Cumulic Regosols have already a good stand. Note also the presence of stone heaps or **zala** on Cumuliskeletic Regosols. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

1996; Mitiku *et al*., 1999) and Southern Ethiopia have been made (Kelsa, 1999). The local soil classification system in the study area is similar to the one described by Mitiku (1996) (Table IV).

From experience gained during this research, it became clear that the use of indigenous soil classification needs joint observations with farmers when augering or describing soil profiles. General discussions, even in the field, are not sufficient. A soil map of the catchment using the local classification was prepared by De Geyndt (2001). The local soil classification could not simply be transferred, even for agricultural extension work. For instance, differences between Luvisols on weathered silicified limestone and Calcaric Regosols (both '**Baekhel**') are too important for both soil types being considered as one for agronomic purposes. The same holds true for most of the other local soil groups. Also, the local soil classification includes variations between different villages.

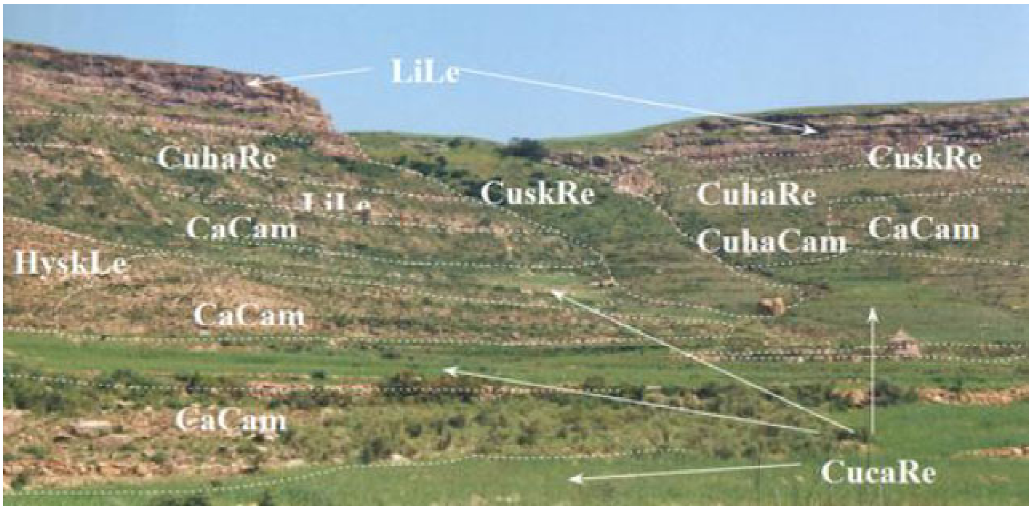

Figure 6. Soil distribution in the lower sandstone–limestone area, looking North. Soil acronyms as in Table III. Calcaric Cambisol is generally under rangeland and Cumulicalcaric Regosol under cropland. The upper Lithic Leptosol is the sandstone cliff, lower Lithic Leptosol the limestone cliff. The downslope oriented Cumuliskeletic Regosol in the middle is on different parent material, that is a debris flow composed of basaltic colluvium (Moeyersons *et al*., 2006). This figure is available in colour online at www.interscience.wiley.com/journal/ldr

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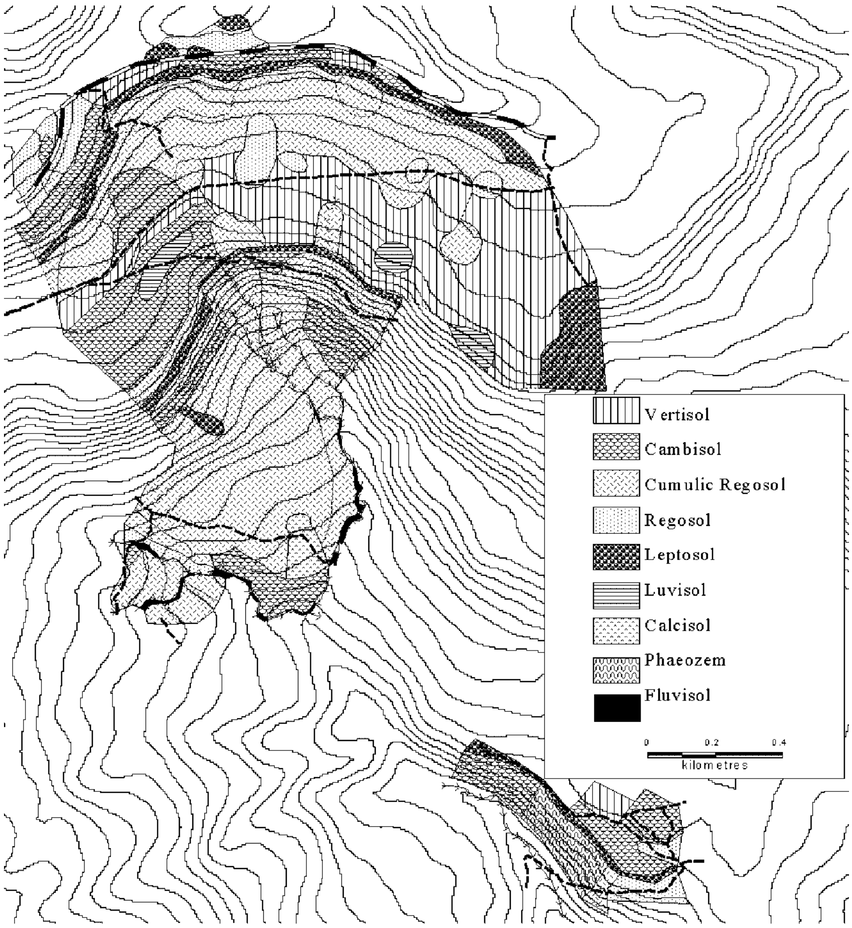

Figure 7. Simplified soil map of the May Zegzeg catchment, based on the detailed map produced by De Geyndt (2001).

Table IV. Traditional soil classification in the Hagere Selam area

Name	Mitiku (1996)	Characteristics	Correspondence (WRB)
Walka	**Walka**	Black heavy clay, cracks in the dry season, waterlogging in the rainy season	Vertisol, Vertic Cambisol
Baekhel	**Baekhel 2**	Light soils, light coloured. In the study area: soils on silicified limestone; young soils on limestone	Calcaric Regosol and Cambisol; Luvisol on silicified limestone
Andel (='mixed')	**Baekhel 1**	Loamy texture, higher organic matter content than **Baekhel**; (dark) brown coloured	Cumulicalcaric Regosol, Cumuliskeletic Regosol, Phaeozem
Kayeh	**Mekayto**	Red soils, include colluvium from the sandstone cliff and old soils on basalt *in situ*	Skeletic Regosol and Luvisol on basalt; Cumulihaplic Regosol and Hyperskeletic Leptosol on red sandstone

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Table V. Land use in the selected catchment in 2000

Functional land-use group	Land-use class	Land utilisation	Area (ha)	Per cent
Agriculture/cropland		Crop production system	135·7	65·7
	Rain-fed crop production	Cereals–beans	39·7	19·2
		Tef–grass pea–cereals	62·1	30·1
		Flexible crop production system	30·1	14·6
	Fallow land		3·4	1·6
	Irrigated fields	Intensive maize and vegetable production	0·4	0·2
Agriculture/non arable land			41·3	20·0
	Rangeland		41·1	19·9
	Grassland, grassed waterways		0·2	0·1
Protected			21·6	10·5
	Religious protection	Church forest and park	1·7	0·8
	Exclosures (including semi-natural forest)		19·8	9·6
Support			4·4	2·1
	Transport	Road and road bank	2·8	1·4
	Water related structures	Gully and river banks	1·2	0·6
		Water ponds	0·2	0·1
	Housing	Farms	0·3	0·1
Unused			3·6	1·7
	Degraded areas	Badlands	0·5	0·2
		Quarry	0·8	0·4
	Bare Rock		2·3	1·1
Total			206·6	100·0

Land Use

Land-use systems

Land use was classified into different functional land-use groups and land-use classes (Table V; Figure 8). Rain-fed crop production accounts for the largest area in the catchment. The important crop production systems in the catchment are **tef**–grass pea–cereals, cereals–horse beans and a very flexible crop production system in the lower part of the catchment including a variety of crops with the notable exception of beans (Table II).

The irrigated gardens class includes river terraces with simple irrigation canals which were developed in 1999 as a result of the greater availability of water following the conversion of slopes from rangeland to exclosures.

Rangeland and grasslands were defined following the guidelines of FAO (1988) with rangeland taken as areas that are grazed by livestock during at least one period of the year. All rangeland in the catchment is held by local village communities and often some management restrictions exist. Rangeland is used not only for grazing livestock, but also for fuelwood gathering. Grasslands are defined in this study as areas that have as their main function the production of grass for use as fodder at the homestead.

The protected areas can be divided into two classes: (1) land which is protected for religious reasons and (2) the other exclosures. In the catchment, only the church park and church forest of Hechi belong to the former class. Exclosures should also be seen as a compound land utilisation type and their main function is to protect natural resources, vegetation, soil and water. Besides, the community also harvests grass and wood out of most exclosures or intends to do so.

Soils and land use

Spatial patterns of land use vary greatly within the catchment. As expected soil, associations are associated with topography and landforms (Gobin *et al*., 2000; Deckers, 2002). The Cumulic Regosols in the upper part of the Gra

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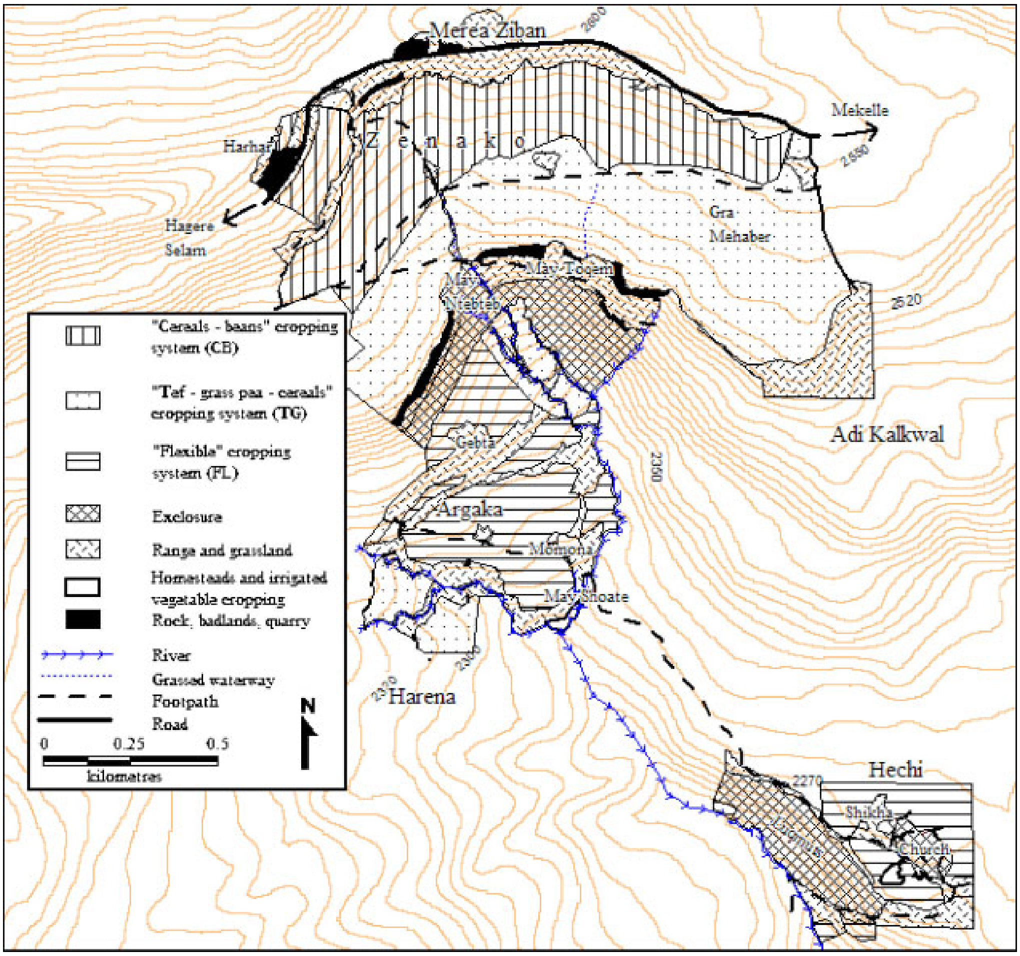

Figure 8. Land cover (2000) and cropping systems in the study catchment. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

Mehaber and Zenako areas (Figure 8), as developed on colluvium below a steep basalt slope, are used as cropland. These areas are planted following the cereals–beans crop production system (Figure 5).

The lower part of the structural flat above the Amba Aradam sandstone cliff (Figure 8) has Vertic Cambisols and Vertisols on basaltic colluvium and colluvium of silicified limestone. This area is flat to gently rolling, with slope gradients up to 0·1 mm^{-1}, and is almost exclusively used as cropland, except for the vast degraded rangeland near the village of Adi Kalkwal and some grassed waterways. Crops in this area are sown late, usually in early- to mid-August (Figure 5). The crop production system in this area is **tef**–grass pea–cereals. Close to the Amba Aradam Sandstone cliff, several fields with incipient gully erosion are left fallow or are abandoned.

The Argaka area (Figure 8) is located below the sandstone and limestone cliff. The larger part of the steep slopes has been gradually converted between 1990 and 1999 from rangeland into exclosures. The parent material on the foot and backslopes of this area is mostly limestone and sandstone colluvium, locally mixed. An important area of basaltic colluvium extends below the sandstone cliff from the May Ntebteb concavity. The Cumuliskeletic Regosols on the lower part are used for cropping. The adjacent limestone areas are marginal fields or degraded rangelands, sometimes converted into exclosures. The relationship between lithology and the complex land-use distribution is further illustrated by the presence of cropland in places where fertile sand or limestone colluvium was deposited by sheetwash (Cumulicalcaric Regosols, Figure 6). Degraded rangeland is found in places where

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limestone outcrops. Crops in the Argaka area are sown in the first half of July. The crop production system alternates between wheat or barley and leguminous crops such as lentils or grass peas, or sometimes leaving the plot fallow for 1 year. When rains start early, many farmers plant sorghum or maize.

The village of Harena and the larger part of its cropland are located on a 2 km long ancient landslide (Nyssen *et al*., 2002a); Cumulic Regosols developed on this basaltic and sandstone material. A small part of this landslide lobe was included in the study area; it shows a land-use pattern similar to the Zenako area which is situated 250 m higher. Crop production in this area also follows the **tef**–grass pea–cereal system.

The study area in Hechi, located around the church, about 1·5 km to the south east of the Argaka area, consists of a structural flat with farmland and a church forest as well as the adjacent Luqmuts forest on steep slopes (dominantly on Phaeozems). The lithology in this area is limestone and limestone colluvium. On the Cambisols around the church (Figure 4), a flexible crop production system as in Argaka is followed.

Statistical analyses by χ^2-tests show clear associations ($p < 0{\cdot}001$) between soil type and parent material on the one hand and land-use class and crop production system on the other, as also shown in Nigeria by Gobin *et al.* (2000). The strong association (Table VI) between cropland and basaltic colluvium is due to the fact that the most fertile soils, such as Vertisols and Vertic Cambisols, have developed on this material. Soils on parent material *in situ*, irrespective of the rock type, are preferably put under rangeland. Some cropland is also found on limestone colluvium. Exclosures are mostly found on limestone, 'pure' limestone colluvium and colluvium of basalt and sandstone, that is those parent materials which are dominant on steep slopes.

The contrast between the preferred locations for cropland and rangeland is also very apparent when soil types are considered (Table VIb). Exclosures are found on Calcaric Cambisols, Calcaric Phaeozems and on Haplic Regosols. The geographical distribution of exclosures and protected areas is explained by their topographical position and erosion hazard and is not directly correlated to soil type. However their protected status has been an important factor for soil development and/or conservation (Descheemaeker *et al*., 2006). Large areas of rangeland are found on Leptosols, infertile Calcaric Regosols and on Haplic Cambisols and Regosols. In contrast cropland (Table VIb) is mainly found on Cumulihaplic Regosols, Pellic Vertisols and Vertic Cambisols.

Within the land-use class 'rain-fed agriculture' we also find a strong association ($p < 0{\cdot}001$) between the different crop production systems and soil types (Table VIc). The crop production system including horse beans (CB) is found exclusively in the upper part of the catchment on Cumulihaplic and (Cumuli)skeletic Regosols developed on basaltic parent material. Farmers stated that they would never grow horse beans anywhere else in the catchment. This crop is probably not grown in areas with a high moisture retention capacity because of its susceptibility to root rot (*Slerotium rolfsii*) (FAO and UNDP, 1983). Observations by the authors throughout the Ethiopian Highlands show furthermore that horse beans are more adapted to higher altitudes.

The production system TG that includes crops that are sown late in the rainy season, **tef** and grass pea, is mostly found on Pellic Vertisols and on the associated Vertic Cambisols. These are soils that have good moisture holding capacities. **Tef** growth is best towards the end of the rainy season on the residual moisture stored in the soil (FAO and UNDP, 1983).

The flexible crop production system FL where all crops except horse beans may appear in the rotation, is well suited to lime-rich soils. A difference was found between the distribution of wheat and barley over the different soil types. Wheat is grown throughout the catchment. Barley is mainly grown on Regosols in the Zenako and Argaka areas under the form of **hanfets**, the mixture of both grains. Barley is never sown on Pelli-grumic Vertisols and Vertic Cambisols, and neither is **hanfets**. One explanation for this is that barley is deep rooted compared to wheat and cannot tolerate waterlogging (FAO and UNDP, 1983).

Lentils and flax should be considered as marginal crops. Farmers often sow these crops instead of leaving their land fallow. For this reason, small areas of lentils are found in all crop production systems and different soil types. Some marginal fields on steep slopes are also used for lentils and linseed, often on Lithic or Hyperskeletic Leptosols.

Crop rotation

In the crop production systems of the area, generally, 1 or 2 successive years of cereals are alternated with 1 year of legumes (horse beans, grass peas or lentils). Block rotation is common, that is adjacent farmers in a certain areas

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Table VI. Residuals of χ^2-tests on the association (a) between parent material and land-use class ($n = 376$), (b) between soil type and land-use class ($n = 378$), (c) between soil type and crop type ($n = 123$)

a	Cropland	Rangeland	Exclosures
Basalt	−1·4	**3·5**	−1·4
Silicified limestone	−1·5	**3·3**	−0·9
Sandstone (+ sandstone coll.)	**−2·7**	**4·7**	0·3
Limestone	**−2·6**	1·9	**3·8**
Colluvium basalt	**3·5**	**−4·1**	**−3·2**
Coll. silicified limestone	1·2	−1·3	−1·3
Coll. (bas. + si. lim.)	0·8	−0·5	−1·4
Coll. (bas. + sandst.)	−0·7	−0·6	**2·7**
Coll. limestone	**−2·2**	1·2	**3·9**
Limestone dominated coll.	−0·3	0·3	0·3

b	Cropland	Rangeland	Exclosures
Calcisols	0·6	−0·4	−0·9
(Verti)calcaric Cambisols	**−3·0**	0·0	**7·5**
Vertic Cambisols	1·2	−1·9	−0·3
(Cumuli)haplic Cambisols	−1·5	**3·4**	−1·1
Leptosols	**−3·3**	**6·9**	−1·2
Haplic Luvisols	1·1	−1·3	−0·9
Calcaric Phaeozems	**−2·3**	−1·3	**7·5**
Calcaric Regosols	−1·3	**2·3**	0·0
Haplic Regosols	**−2·3**	**2·6**	**2·2**
Stagnic Regosols	1·0	−1·2	−0·9
Skeletic Regosols	−0·2	1·1	−1·1
Cumulicalcaric Regosols	−0·3	1·2	−0·9
Cumulihaplic Regosols	**2·2**	**−3·0**	−1·2
Cumuliskeletic Regosols	0·7	−1·8	0·8
Pellic Vertisols (often in association with Vertic Cambisols)	**2·3**	**−2·0**	**−2·8**

c	**Tef**–grass pea–cereals	Cereals–beans	Flexible
Calcisols	−0·7	−1·1	**2·4**
Calcaric Cambisols	−1·0	−0·8	**2·5**
Haplic Cambisols	−0·4	1·1	−0·8
Vertic Cambisols	0·7	−0·6	−0·4
Pellic Vertisols (often in association with Vertic Cambisols)	**3·6**	**−2·4**	**−2·6**
Haplic Luvisols	1·1	−0·8	−0·6
Stagnic Regosols	0·0	0·5	−0·6
Skeletic Regosols	−1·2	**2·1**	−0·8
Cumulicalcaric Regosols	**−2·2**	**−2·6**	**6·6**
Cumulihaplic Regosols	−1·3	**3·6**	**−2·4**
Cumuliskeletic Regosols	−0·8	**2·2**	−1·4

The larger the absolute values (bold) of the residuals (ε), the stronger the (positive or negative) association between classes of criteria. Zero values correspond to a perfect match between observed and expected frequencies.

through consultation follow the same crop rotation scheme. Typically such blocks include 10–20 parcels with a total area of 4–7 ha. The creation of larger areas under the same rotation crop facilitates stubble grazing after harvesting. On fertile soils, cereals are grown for several successive years, without rotation with any leguminous crop or fallow. Generally the crop rotation schemes are not very rigid; they often depend on non-edaphic factors such as seed price or availability, climatic conditions, advance of preparatory work for sowing or availability of labour that is necessary for weeding **tef**. Moreover, higher valued cereals are preferred above leguminous crops.

Small patches of fallow land, grazed by livestock, are found on very diverse soil types throughout the arable land of the catchment. Some fields have been under fallow for many years and are abandoned; the landholder is usually

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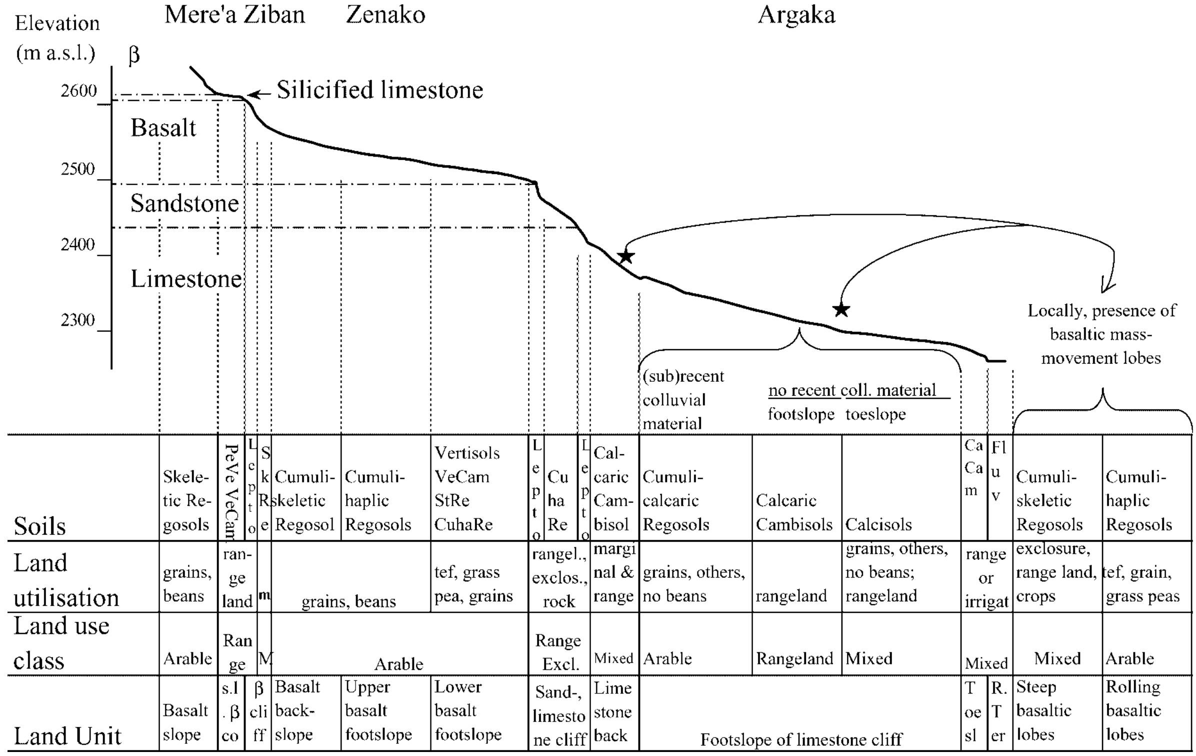

Figure 9. Major land units in the study area (β = basalt; m = marginal land, fallow, lentils, patches of rangeland; M = mixed land use; Toesl. = toeslope; R. Ter. = river terrace; soil acronyms as in Table III).

not living in the village, or is not interested anymore in farming. However most fallow parcels are characterised by maintained stone bunds; here, fallow is part of the crop production system. There is a trend towards abandoning fallowing. The abandonment of fallowing is related to land scarcity and the concomitant need to increase cereal production. Consequently, pressure on land is increasing. The cultivation of legume crops is more and more spaced within crop rotation schemes. Such shortening of the crop rotation schemes results in a decrease in crop productivity, and unless the level of organic and mineral fertiliser input is increased, will cause further depletion of soil nutrient reserves (Corbeels *et al*., 2000). On marginal lands, farmers are reluctant about growing no crops at all on a field and rather grow lentils or linseed when they want to restore soil fertility. Rather than a simple abandonment of fallowing, this is a balanced intensification of the crop production system.

CONCLUSIONS

The structural geology and lithology control the relief which in turn conditions the distribution of soils in Dogu'a Tembien (Figure 9). Lithology and position on the slope largely determine the spatial distribution of soils and land use. The soil distribution with its dominance of Regosols, Cambisols and Leptosols is the result of active geomorphic processes. Young soils are dominant in the study area due to active erosion processes. Old soils include Phaeozems under forest on steep limestone slopes, Vertisols, generally on footslopes on basalt colluvium and Calcisols on limestone footslopes. Catenas on both dominant lithologies (basalt and limestone) show in general a clear correspondence between geomorphology, parent material and soils.

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The permanent upland cultivation system in Dogu'a Tembien is best described as a grain plough-complex with cropping organised according to different soils within a catena. Cereals are the prevailing crops; crop production systems are directed towards maximisation of yields. Crop choice depends largely on the soil characteristics. **Tef** is grown on soils with good soil moisture retention characteristics, especially on Vertisols and Vertic Cambisols. Wheat and barley have a different spatial distribution due to their differences in rooting depth; deep-rooted barley cannot resist waterlogging which may occur in Vertisols. The distribution of grass pea, lentil and linseed can to a large extent not be explained by their specific requirements, but rather by the fact that they were introduced into the crop production system to replace fallow. Farmers have a good insight into the soil characteristics of their land and will only grow crops where conditions are favourable. As far as land-use and crop production systems decisions are concerned, this study contradicts Wilson (1977), who states that 'present land use in the Tigray Highlands is (...) almost completely unrelated to land capability'.

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