Catena xxx (2008) xxx-xxx

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia

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ARTICLE INFO

Available online xxxx

Keywords:
Soilscape
Ethiopia
Soil map
Landscape
Catena
Pedogeography

ABSTRACT

Though knowledge about the distribution and properties of soils is a key issue to support sustainable land management, existing knowledge of the soils in Tigray (Northern Ethiopian Highlands) is limited to either maps with a small scale or with a small scope. The goal of this study is to establish a model that explains the spatial soil variability found in the May-Leiba catchment, and to open the scope for extrapolating this information to the surrounding basalt-dominated uplands. A semi-detailed (scale: 1/40 000) soil survey was conducted in the catchment. Profile pits were described and subjected to physico-chemical analysis, and augerings were conducted. This information was combined with information from aerial photographs and geological and geomorphologic observations. The main driving factors that define the variability in soil types found were: 1) geology, through soil parent material and the occurrence of harder layers, often acting as aquitards or aquicludes; 2) different types of mass movements that occupy large areas of the catchment; and 3) severe human-induced soil erosion and deposition. These factors lead to "red-black" Skeletic Cambisol–Pellic Vertisol catenas on basalt and Calcaric Regosol–Colluvic Calcaric Cambisols–Calcaric Vertisol catenas on limestone. The driving factors can be derived from aerial photographs. This creates the possibility to extrapolate information and predict the soil distribution in nearby regions with a comparable geology. A model was elaborated, which enables the user to predict soil types, using topography, geomorphology, geology and soil colours, all of which can be derived from aerial photographs. This derived model was later applied to other catchments and validated in the field.

1. Introduction

Land degradation, including soil erosion and soil mining are serious problems in the Ethiopian Highlands. To reverse these trends, many soil conservation programs have started in these regions. Adequate knowledge about the distribution and properties of soils is a key issue to support sustainable land management, which, among others, includes erosion control, fertility management, crop choice, risk of mass movements and possibilities for irrigation. However, existing knowledge of the soils in Ethiopia's northernmost Tigray region is limited to either maps with a small scale (Virgo and Munro, 1978; Nedeco, 1997; BoANR-LUPDR, 2000) or with a small scope (Assefa, 2005; Nyssen et al., 2008).

Because intensive soil-surveys are very expensive, one smaller catchment, the May-Leiba catchment (1800 ha) was chosen as a reference for the surrounding basalt-dominated uplands of the Geba catchment.

The goal of this study is to establish a model and a soil map that explains the spatial soil variability found in the May-Leiba catchment, and to open the scope for extrapolating this information to the surrounding basalt-dominated uplands.

To create the soil map, different approaches are possible: the pedologic approach and the physiographic or geomorphologic approach (Wielemaker et al., 2001). The first method tries to create maps with taxonomic pure soil data or soil associations. The geomorphologic approach uses soils as part of the landscape. We have chosen for this geomorphologic approach because extrapolating the results of the soil map needs this geomorphologic information, and we believe that for most uses of the soil map will be combined with this geomorphologic information. Within this geomorphologic approach, digital soil mapping methods are used increasingly (e.g. Moore et al., 1993). For this study however, we have chosen the more classic approach by using aerial photographs, due to the high

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doi:10.1016/j.catena.2008.04.006

Please cite this article as: Van de Wauw, J. et al., Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia, Catena (2008), doi:10.1016/j.catena.2008.04.006

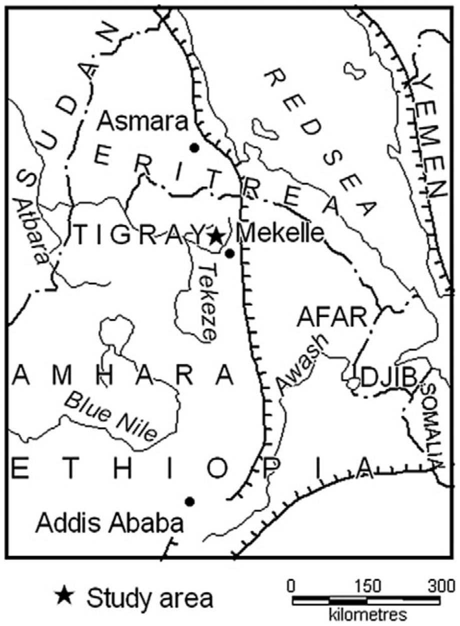

Fig. 1. Location of the study area in the Northern Highlands of Ethiopia.

complexity of the landscape and the lack of detailed georeferenced information at the mapping scale.

2. The study area: May-Leiba catchment

2.1. Location

The May-Leiba catchment (13°41'N 41′N–39°15′E, Fig. 1) is located at 45 km west of Mekelle, along the road from Mekelle to Abi-Adi, about 10 km east of Hagere Selam. It is part of the woreda (or district) of Dogua Tembien. The lower edge of the study area is the May-Leiba dam at 2290 m a.s.l. The study area is approximately 18 km^2.

This catchment was chosen as a reference for the surrounding basalt-dominated stepped uplands due to its diverse geology and the fact that other research is carried out in the catchment (De Wit, 2003).

2.2. Geology

The May-Leiba catchment is a part of the Mekelle outlier which consists of sub horizontal alternating series of cliff-forming and non cliff-forming Antalo limestone of Jurassic age, overlain by Agula Shale (Jurassic age) in the SE corner of the study area (Fig. 2). The top of the table mountains consists mainly of Amba Aradam sandstone of Cretaceous age and by two series of Tertiary basalt flows (Nyssen et al., 2003). In between these basalt layers silicified lacustrine deposits (Garland, 1980) can be locally found. The Mesozoic succession of the Mekelle outlier is described by Bosellini et al. (1997).

The formation of the rift valley tectonic uplifts of about 2500 m and differential erosion resulted in stepped sub horizontal landforms (Nyssen et al., 2003). The highest point of the catchment is located on a basalt ridge at 2835 m a.s.l. At the south-east of the study area a dolerite sill outcrops, inducing an extra uplift in the higher lying sandstone and basalt.

2.3. Geomorphology

Important in this area are different landslides. They occur within the limestone area, but can also cause basaltic material to be deposited on downslope located limestone areas, which makes them very important for soil distribution. Research on these landslides has been done in nearby areas, including the southern fringe of the catchment (Nyssen et al., 2003).

Regarding soil development, two important types of mass movements can be distinguished (Moeyersons et al., 2008-this issue): (a) large scale landslides which move basaltic parent material downslope; and (b) flows of vertic clays, deposited at the foot of the

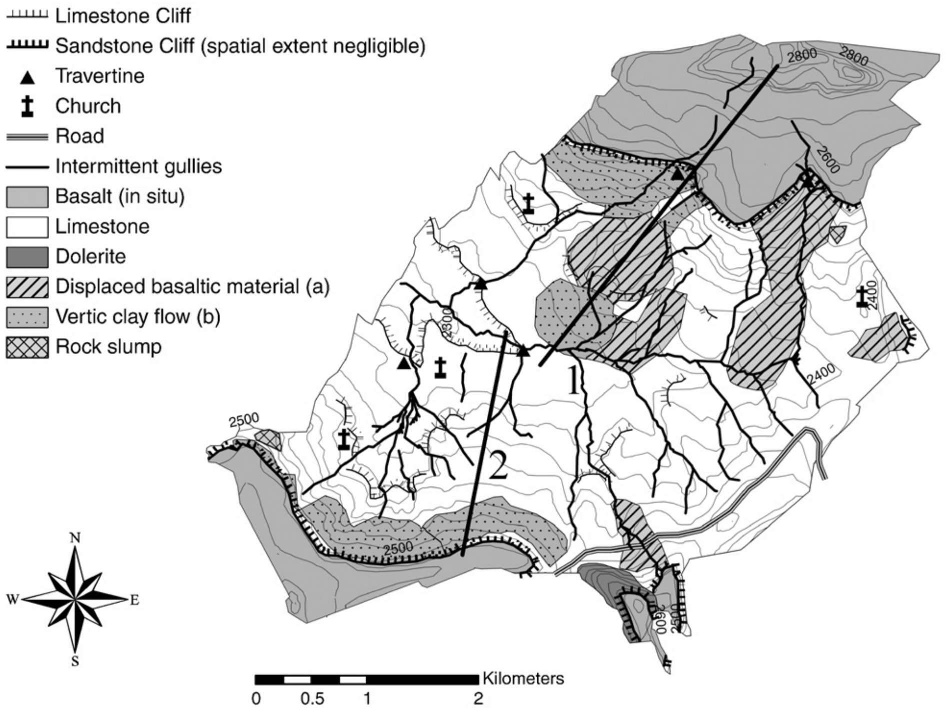

Fig. 2. Geologic and Geomorphologic map of the May-Leiba catchment.

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sandstone cliff, or similar secondary flows at the foot of large scale landslides (Fig. 3).

2.4. Hydrology

The Amba Aradam sandstone functions as an aquiclude or aquitard in the area (Tesfaye and Gebretsadik, 1982). At different locations on the sandstone cliff, Quaternary freshwater tufa deposits and ancient landslides are proof of ancient water tables, thicker and more extensive than today. Few active springs were found on top of the Amba Aradam sandstone at the time of mapping. Also within the limestone exist layers and layer combinations, functioning as aquitards. One hard layer, sealed at its base by thin shale deposits, can easily be traced back throughout the catchment, and even outside the catchment at May Ba'ati (about 5 km SW of May-Leiba) where it is a very prominent part of the landscape. In line with the geomorphologic map of Moeyersons et al. (2006) this layer combination is called “May Ba'ati aquitard”. Also on this layer remnants of tufa deposits can be found. Some springs still exist near this layer. A second massive limestone, probably also sealed at its base by shales, is referred to as “Adiwerat”-layer in the rest of this study. According to mapping by Bosellini et al. (1997), this aquitard belongs to the base of the Agula shales. Also here some low-discharge springs were found. The Quaternary tufa deposits found near the Amba Aradam sandstone and the May Ba'ati aquitard are no longer active. Similar tufa deposits in the same area were studied by Moeyersons et al. (2006). The authors relate the disappearance of the tufa rather to deforestation and human impact than to climatic changes.

2.5. Climate

The climate is characterised by an ustic moisture regime with a distinct rainy season in July and August. The average yearly rainfall for Hagere Selam (at 15 km of the catchment) is 716 mm. Rainfall patterns in Ethiopia are very variable even at catchment scale. The rainfall patterns of the region have been studied in detail by Nyssen et al. (2005).

The average monthly temperature in Hagere Selam varies between 12 and 19 °C.

2.6. Land use

The dominant land use in the May-Leiba catchment is cropland (about 50%). The remainder is used for grazing (30%), housing (15%) and a small part (5%) is closed for grazing and cropping. The major crops grown in the study area are barley (*Hordeum vulgare*), wheat (*Triticum* sp.), teff (*Eragrostis tef*) and grass pea (*Lathyrus sativus*). Soil erosion rates are high in the catchment. Soil loss is estimated to be on average around 9.9 t ha^{-1} y^{-1} for cropland and 13.5 t ha^{-1} y^{-1} for rangeland (De Wit, 2003). On some places soil erosion is so severe that agricultural land is abandoned.

3. Methodology

3.1. Fieldwork

After a reconnaissance study, ten representative profile pits were described using the FAO guidelines for soil profile description (1990). They approximately form a North–South transect through the May-Leiba catchment (Fig. 2), and together they describe two catenas (Fig. 4). The profiles were classified according to the World Reference Base for soil resources (WRB) (IUSS Working Group WRB, 2006). Using aerial photographs on a scale 1/50 000 from 1994 and the geological map of the area (Ethiopian Institute of Geological Surveys, 1978) a base map was created. After aerial photo interpretation, augering was carried out along downslope oriented transects. The distance between traverses was approximately 400 m, and within the traverses one observation was made approximately every 200 m (depending on the landscape variability). A total number of 236 augerings was done and described. A large part of catchment is terraced by means of stone bunds. When this was the case, care was taken to auger in the middle between these stone bunds, where the least erosion or deposition is expected. Profile and topography descriptions were made for every augering. Often it was not possible to auger 1 m deep, either soil depth was limited by very stony layers (in this case augering was tried 3 times and the deepest profile was described) or dry vertic horizons were encountered. The results from augering were converted to a field-mapping code (Table 1) which includes the parent material, texture, coarse fraction, drainage and profile development. No samples were taken while augering.

3.2. Chemical analysis

All samples from the profile pits were dried, crushed, ground and sieved through a 2 mm sieve. The chemical analysis has been done on the fine-earth (<2 mm) fraction.

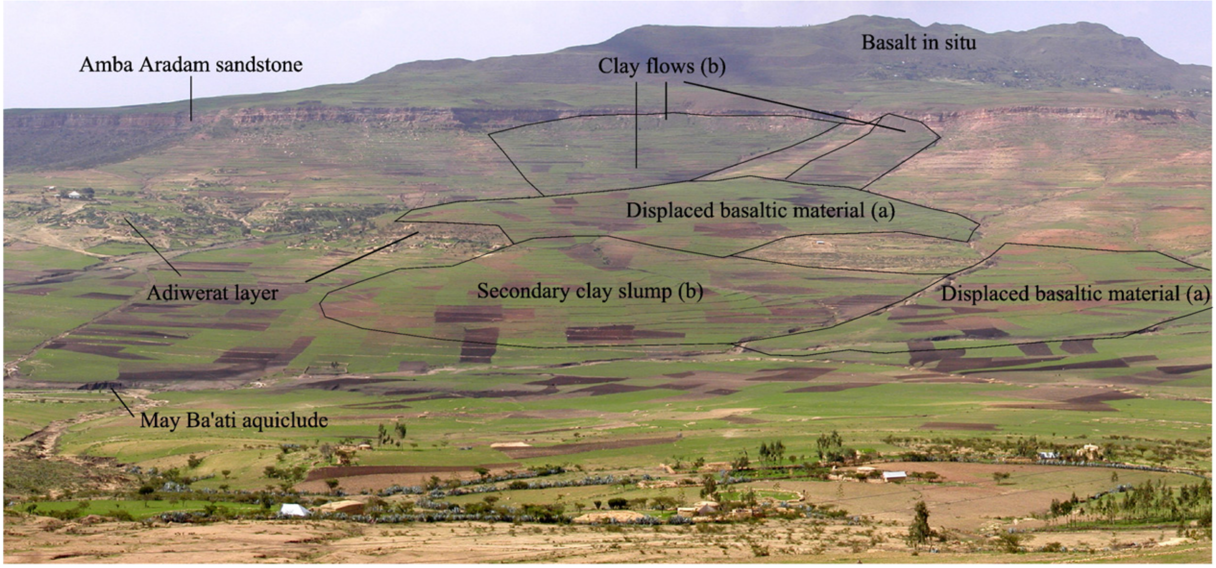

Fig. 3. Overview photo of the northern side of the May-Leiba catchment. Different kinds of mass movements are depicted: (a) large scale landslides which move basaltic parent material downslope; and (b) flows of vertic clays, deposited at the foot of the sandstone cliff, or similar secondary flows at the foot of large scale landslides.

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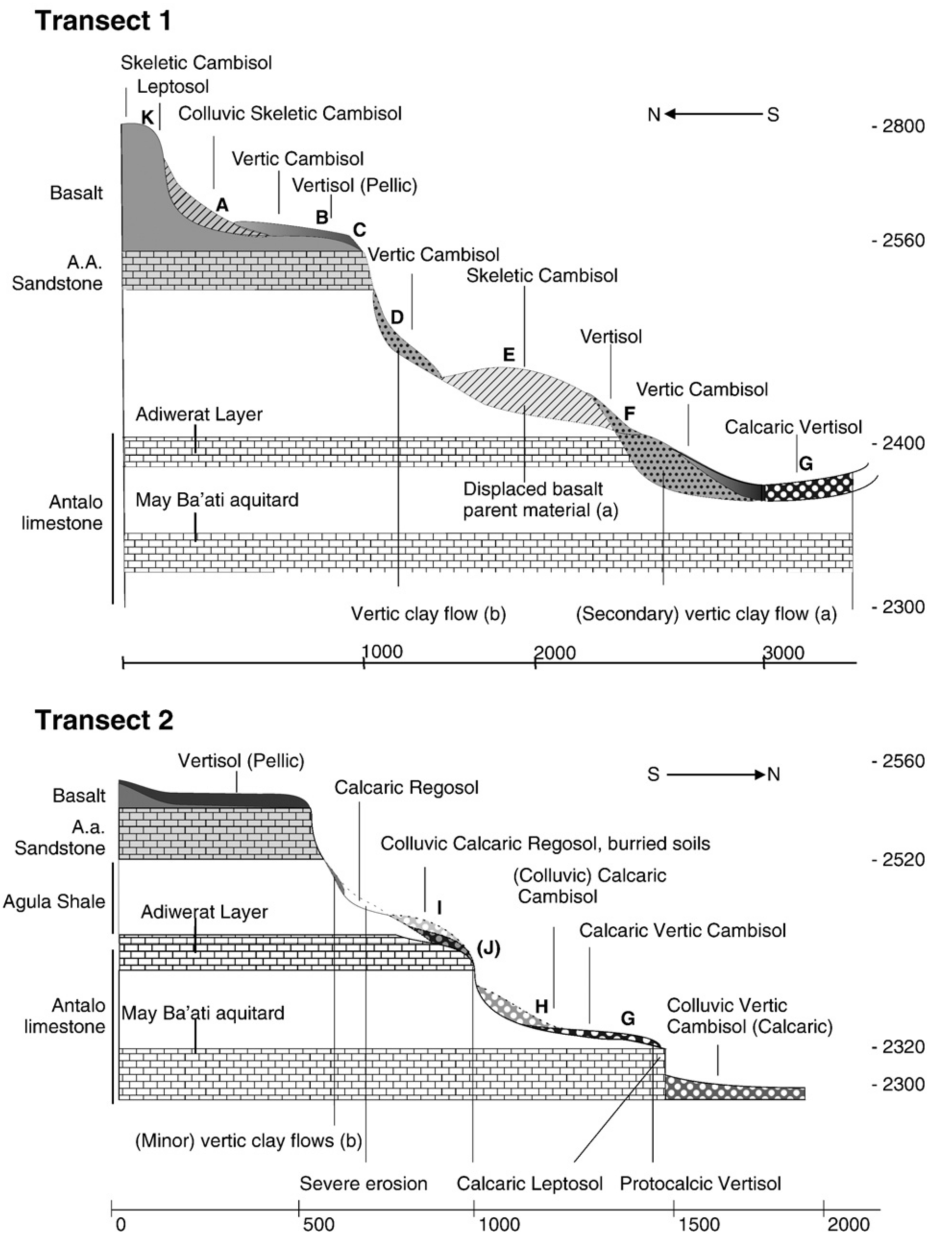

Fig. 4. Catenas on basalt and basaltic mass movement deposits (transect 1) and on limestone (transect 2). The letters show the (typical) location of the profile pits described in Tables 3 and 4. Hatched greys show displaced basaltic parent material. Dark grey denotes vertic clays, white dots calcaric properties.

Based on standard soil analysis techniques (Van Reeuwijk, 2002) texture (pipette and sieve), pH-H_2O, pH-KCl, electrical conductivity, $CaCO_3$-equivalent, total carbon and nitrogen (Dumas combustion method) and available P (ammonium lactate extraction and spectrophotometry) were determined. CEC (at soil pH) and exchangeable cations (Ca, Mg, K, Na) were determined using the thio-urea method. Organic carbon was derived as (total carbon — $CaCO_3$ equivalent).

3.3. Upscaling the augering data

The boundaries that were originally derived during the base-map creation were used as the basis for the mapping units. These units were delineated based on aerial photography interpretation and represent units with a similar parent material (based on geology and geomorphology), landscape position and colour on the aerial photograph. During and after the fieldwork some boundaries were added, but only based on visible boundaries in the aerial photograph. No boundaries were added that could only be derived locally, because this would not fit the mapping scale, and would not be useful for the further development of a soil–landscape model based on aerial photograph interpretation. Given the scale of the aerial photographs (1:50 000), these units correspond best to “landform elements” (Wielemaker et al., 2001).

To give a soil code to the soils that are present in landform element, a weighted per-class user-accuracy (Rossiter, 2004) was calculated for all the factors in the mapping code in every landscape element that was mapped. This weighted user-accuracy method is based on a confusion matrix representing the predicted and actually observed properties, in this case within each landscape element. This weighted user-accuracy for every property is derived by multiplying the vector of proportions with the weights matrix.

$$\mathrm{wua}_{ix} = \sum_{j=1}^{r} W_{ij} p_{jx} \qquad (1)\ \text{(Rossiter, 2004)}$$

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Table 1
Field-mapping codes used for mapping in May-Leiba

Parent material	B	Basalt/dolerite
	K	Limestone
	M	Mixed: limestone + basalt
Texture (field estimation)	l	Loam, clay loam
	a	Silty clay loam
	e	Clay, silty clay
	u	Heavy clay (>70%)
	p	Sandy clay, sandy clay loam, sandy loam
Coarse fraction	1	0–15%
	2	15–40%
	3	>40%
Calcareous	*	Calcareous soil material (reacts with 1 M HCl)
Drainage	W	Well drained
	E	Excessive drainage
	P	(slightly) poor internal drainage
Profile development	x	AR (A horizon on hardrock)
	p	AC (A horizon on unaltered soft parent material)
	b	ABw: A horizon on a cambic horizon
	v	Vertic horizon
	f	Alluvial layering
	c	Colluvial material

wua_{ix}	weighted user-accuracy for class i in landform element x
W_{ij}	weights matrix
p_{ix}	proportion of mapped class i within landform element x
r	number of classes for the property.

This method gives weights to various mapping errors, because not all errors have the same implications. When heavy clay (u) is predicted and clay (e) is found, the error is obviously less than when heavy clay is predicted and silt (a) is found. For known applications, these weights might be changed according to the utility function (Næsset, 1996). In this case however, no direct application was available and the weights were assigned by expert judgement and are given in Table 2. The choice of the off-diagonal weights is very important: if the weights are chosen too low, the user-accuracy will be underestimated, especially when classes are similar. On the other hand, using too high weights will favour average properties when mapping, ultimately leading to map units with the same average property everywhere, and little informative content. In each landscape element, the class with the highest weighted user-accuracy for every property was used in the soil–landscape model as the mapping code. This means that the user-accuracies for model building should not be considered as an independent validation, but rather as (non-independent) map purity: the values give an impression of the explained soil variability within the landscape elements.

In the final soil map of May-Leiba (Van de Wauw, 2005; Fig. 5), a few polygons were updated after the creation of the soil–landscape model: these polygons were located on the same landform element, with the same landscape position and colours on the aerial photograph, but some of their soil properties were different.

3.4. Validating the soil–landscape model

For validation, a method based on the same weighted user-accuracy was used. Based on the developed model and aerial photographs, soil expectation maps were made for two unvisited areas and their weighted user-accuracy was determined. This time however, this accuracy is an independent validation of the developed soil–landscape model.

An unvisited area, around the village of Melfa (13°38′N–39°02′E, 2360–2760 m a.s.l.) located at approximately 15 km of the studied May-Leiba catchment was chosen and a soil expectation map was created based on aerial photograph interpretation.

A second validation was conducted by creating a soil expectation map (also using aerial photographs) for parts of the May-Zeg-Zeg catchment (13°40′N–39°10′E, 2240–2400 m a.s.l.) at 10 km of the May-Leiba catchment. This area was subject to a soil survey (De Geyndt, 2001; Nyssen et al., 2008) and the augering data of that survey was used for validation.

In Melfa this soil expectation map was validated by 18 augerings along different transects along the slope, all located on basalt parent material. In May-Zeg-Zeg validation was done by using 36 observations, all located on limestone, but partly covered with different kinds of basaltic mass movements. Like in the May-Leiba catchment, a massive cliff-forming limestone layer sealed of by shales and marls is present in this catchment: the Tinsehe-Hetchi aquiclude (Moeyersons et al., 2006).

Finally, a comparison was made for every predicted property using the full soil–landscape model and two more simple models, to check how much information the full model really adds. The first "one soil" model just predicts one soil type for the whole study area. The second "geologic" model makes a distinction between soils in the basalt domain (the area above the sandstone cliff) and soils in the limestone domain, without taking the basaltic mass movements into account, comparable to using only the geologic map for prediction.

4. Results and discussion

4.1. Soils found in the May-Leiba catchment.

Table 3 gives an overview of the physical characteristics of the major soil types that were found in the May-Leiba catchment. Table 4 gives an overview of the chemical characteristics of the same soils. Two major types of profile development are found: the development of vertic horizons and the development of mollic horizons. Vertic horizons or vertic properties occur on places where water accumulates either due to the low slope or due to impermeable geological layers close to the surface. In the rest of the landscape, one would rather expect the formation of a mollic horizon. However, most described profiles are not completely developed and show only a cambic horizon or are buried by colluvial material. The typical location of the discussed soils is shown on the catenas in Fig. 2.

The WRB-qualifier "Eutric" is valid for all soils in the studied catchment and is therefore not included in the rest of this article.

4.1.1. Soils developed on basalt

4.1.1.1. Profile A: Colluvic Skeletic Cambisol. This profile is situated at the footslope of a basalt ridge. It has a high stone content varying with depth, clearly related to different sedimentation events. This also explains the relatively high organic carbon content of this soil. Even though some cracks were present in this soil, they were not expressed well enough to qualify for Vertic properties.

Table 2
Weights used in the derivation and extrapolation of the soil properties, using the codes of Table 1

	Predicted													
	Parent material					Drainage					Coarse fraction			
Observed		B	M	K			E	W	P			1	2	3
	B	1	0.5	0		E	1	0.2	0		1	1	0.2	0
	M	0.5	1	0.5		W	0.2	1	0.2		2	0.2	1	0.2
	K	0	0.5	1		P	0	0.2	1		3	0	0.2	1
	Texture							Profile development						
		l	a	e	u	p			b	c	p	v	x	
	l	1	0.5	0.5	0	0.5		b	1	0	0.5	0.5	0	
	a	0.5	1	0.3	0	0.3		c	0	1	0	0	0	
	e	0.5	0.3	1	0.5	0.3		p	0	0	1	0	0.5	
	u	0	0	0.5	1	0		v	0.5	0	0	1	0	
	p	0.5	0.3	0.3	0	1		x	0	0	0.5	0	1	

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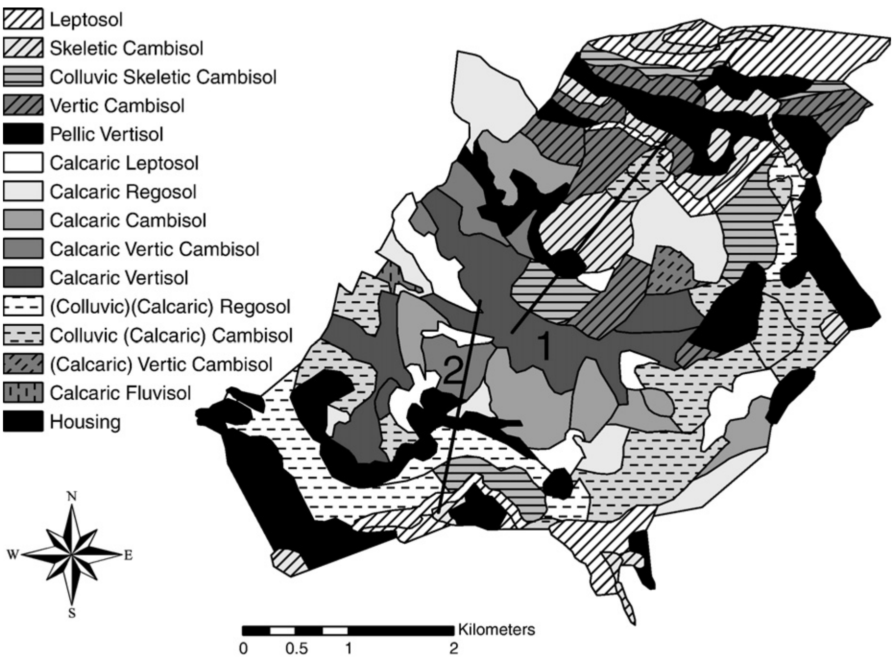

Fig. 5. Soil map of the May-Leiba catchment. Full lines indicate basalt parent material. Dashed lines indicate a complex of limestone and basalt parent material. The grey-value determines the degree of profile development. The horizontal pattern indicates colluvial deposits.

4.1.1.2. Profile B: Pellic Vertisol. This profile is situated on a slightly concave flat area in basalt. It shows a clear Vertic horizon, with both slickensides and wedge-shaped structure elements.

4.1.1.3. Profile K: Skeletic Cambisol. This profile is located on a convex area on basalt. It is shallow and very stony, only little developed, but redder hues (especially when dry) and a blocky structure can be observed.

4.1.1.4. Profile C: Skeletic Cambisol. This profile is also on a young soil, located on a shoulder in basalt. It has a very high stone content, and a blocky structure. In contrast to profile K, no red hues are present here.

4.1.1.5. Profile D: Vertic Cambisol. This is a soil profile located below the sandstone cliff. It has formed on black clays that originate from the basalt on top of the sandstone cliff. Even though the slope is steep (20%), it has deep cracks. However, no slickensides or wedge-shaped structures are found.

4.1.1.6. Profile E: Skeletic Cambisol. This soil has developed on a mass movement of basalt parent material. Apparently this didn't happen as a single occurrence as a buried profile is found. The stoniness is still very high and not much soil development is observed.

4.1.1.7. Profile F: Haplic Vertisol. This soil has developed on the edge of the same mass movement as Profile E. However it is located in a concave slight slope. The soil has developed to a typical Vertisol. It is located just on the edge of the Adiwerat aquitard, which is probably the reason why a vertic soil could develop here.

4.1.2. Soils developed on limestone

4.1.2.1. Profile G: Calcaric Vertisol. This soil has developed on the valley bottom of the limestone area. At the time of the study, the profile was too wet to determine structure and the presence of slickensides. However, the high content of very sticky clays and the fact that the soil gets deep cracks during the dry season (according to local farmers) made the surveyors conclude to classify it as a Vertisol.

4.1.2.2. Profile H: Colluvic Calcaric Regosol. This soil is developed on the footslope of a step in the limestone area developed on stone-rich colluvic material. The lower part of the profile is a buried soil.

4.1.2.3. Profile I: Colluvic Calcaric Regosol (Thapto-Vertisol). This soil is developed on a limestone step (Adiwerat layer) close to the sandstone cliff. The upper part of the profile shows nearly no profile development and consists of limestone colluvium. In the lower part however a buried A horizon is found, also developed on limestone colluvium. The lowest part of this profile consists of a buried Vertisol that was developed on a mixture of limestone parent material and basalt clays, as appears clearly from the magnesium content and the pH.

4.1.2.4. Profile J: Calcaric Regosol. This soil is found on the shoulder of a limestone step (Adiwerat layer). It shows continuous hard rock at a depth of 68 cm, and the upper part consists almost purely of only slightly weathered soft limestone.

4.2. Soil–landscape relationships

4.2.1. Catena on basalt

The typical catena found on basalt (Fig. 2, transect 1) is usually called a “red-black” soil catena (Kantor and Schwertmann, 1974; Driessen et al., 2001), with “red soils” (profiles K, E) on the higher positions of the landscape, and black Vertisols (profile B) in the lower positions.

The “red soils” that were found in the May-Leiba catchment are young shallow stony soils, like profiles K and E that show only a slight red hue and a high CEC_{clay}, and contain some free carbonates, without an argic horizon. These “red soils” occur even when only very small convex areas are found, and not only on high ridges. It is not unlikely that previously more developed layers have eroded in the past from these soils, as a Chromic Cambisol, transitional to Chromic Luvisol was found in the same region on similar parent material (dolerite) by Virgo and Munro (1978).

On the flat steps of the landscape, with impeded drainage due to the impervious geological layer (Amba Aradam Sandstone), Vertisols, like profile B, develop. In between the red soils and Vertisols, stoniness

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Table 3
Summarized profile description of 11 soil profiles in May-Leiba catchment

Horizon	Depth	Diagnostic properties/materials/horizons	Munsell colour		Texture	Structure	Stone content	Reaction with HCl
			Dry	Moist				
Profile K: Convex area on basalt; 2% slope; grazing land; Skeletic Cambisol								
Ap	0–15		7.5YR 5/4	2.5YR 3.5/2	C	wk fn sb	40%	0
Bw	15–68	Cambic horizon	7.5YR 5/4	2.5 YR 3.5/2	C	wk fn ab	60%	0
R	68+	Continuous hard rock						
Profile A: Basalt footslope; 4% slope; 40% surface stoniness; grazing land; Colluvic Skeletic Cambisol								
A	0–25		10YR 6/3	10YR 3/2	C	md fn cb	70%	0
Bw1	25–60	Cambic horizon	10YR 4/3	5YR 2.5/1	C	md fn gr-sb	30%	0
Bw2	60–100	Cambic horizon		5YR 2.5/1	C	md fn gr-sb	60%	0
C	100–170			5YR 2.5/1	C	md fn gr-sb	30%	0
Profile B: Concave plateau on basalt; 2% slope; 10% surface stoniness; cropland; Pellic Vertisol								
Ap	0–20	Vertic properties	10YR 5/2	10YR 3/1	C	st fn cb-sb	5%	0
Bss1	20–100	Vertic horizon	10YR 4.5/2	10YR 2/1	C	st co ab	5%	0
B1	100–140	Vertic properties		10YR 2/1	C	st co ab	5%	0
Profile C: Convex shoulder of basalt; 4% slope; 15% surface stoniness; grazing land; Skeletic Cambisol								
A	0–15		10YR 5/4	7.5YR 3/2	C	mo fn gr-bl	40%	0
Bw	15–80	Cambic horizon	10YR 4/3	7.5YR 2.5/1	C	mo md b	70%	0
CR	80–140	Weathering basalt						
Profile D: Black clays just underneath the sandstone cliff; 20% slope (terraced); cropland; Vertic Cambisol								
A	0–20		7.5YR 5/3	7.5 YR 3/2	CL	wk fn cb	30%	0
Bw	20–180	Vertic properties	10YR 5/3	5YR 2.5/1	C	st md ab	5%	0
Profile E: Convex part near the top of a large basalt movement; 2% slope; cropland; Skeletic Cambisol								
Ap	0–15		10YR 5/3	10YR 3/4	C	mo fn cr-sb	15%	0
Bw	15–80	Cambic horizon	10YR 6/4	10YR 3/3.5	C	mo fn sb	80%	0
C	80–115		10YR 6/4	10YR 4/4	C	no structure	95%	0
2AB	115–125			10YR 3/4	C	st fn ab	20%	0
2C	125–200			10YR 3/3	C	st mo ab	90%	0
Profile F: Concave slope on a basalt movement; 5% slope; cropland; Haplic Vertisol								
Ap	0–20	Vertic properties	10YR 5/3	10YR 3/3	C	mo md cr-sb	5%	0
Bss	20–90	Vertic horizon	10YR 6/4	10YR 2/1	C	st co ab	5%	0
Profile G: Valley bottom in the limestone area; 2% slope; cropland; Calcaric Vertisol								
Ap	0–20	Vertic horizon	2.5Y 6/2	10YR 3/2	C	mo md ab	none	++
B	20–80	Vertic horizon	2.5Y 6/3	10YR 3/1	C	(too wet to determine)	5%	++
Profile H: Footslope of a limestone step; 4% slope; cropland; Colluvic Calcaric Regosol								
Ap	0–20		2.5Y 7/3	10YR 3/3	C	wk fn cb	20%	++
C1	20–80		10YR 5/2	10YR 3/2	C	wk fn sb	30%	++
C2	80–115		10YR 5/2	10YR 2/2	C	wk md ab	5%	++
2C	115–140			10YR 2/1	C	mo md ab	15%	++
R	140–200	Weathering limestone						
Profile I: Limestone step close to the sandstone cliff; 5% slope; grazing land; Colluvic Calcaric Regosol Thapto-Vertisol								
A	0–25		10YR 7/3	7.5YR 4/3	C	wk fn wb	40%	++
2A	25–40	Buried A horizon	10YR 5/2	7.5YR 3/1	C	wk md cl	10%	++
2Bc	40–85		2.5Y 7/3	10YR 6/2	C	wk md cl	40%	++
3Bss	85–180	Buried vertic horizon	10YR 5/2	2.5Y 2.5/1	C	st vco cl	5%	+
Profile J: Limestone step on cliff-forming layer (Adiwerat layer); 32% slope; grazing land; Calcaric Regosol								
A	0–10		2.5Y 7/2	2.5 5/3	CL	wk fn sb	10%	++
C1	10–30		5Y 8/3	2.5 4/3	C	wk fn sb	20%	++
C2	30–60		7.5Y 8/3	2.5Y 6/4	C	wk vfn sb	5%	++
R	60+	Continuous hard rock	Weathering limestone(hard rock)					

All abbreviations according to FAO (1990).
Texture: C: clay; CL: clay loam.
Structure:

wk: weak; mo: moderate; st: strong.
vfn: very fine; fn: fine; md: medium; co: coarse; vco: very coarse.
ab: angular blocky; sb: subangular blocky; cl: columnar.

decreases and clay content increases gradually, leading to Vertic Cambisols.

The soils on the shoulders are very stony and show only little development. This is related to soil erosion and mass-wasting from this position. The lack of red hues compared to the red soils (profiles K, E) is attributed to the poorer drainage in these positions (the same impervious layers are also present here).

On steep slopes (>30%), almost all soil has been eroded (free grazing), which results in very undeep (<15 cm) soils. On the footslope of these steep slopes, colluvial material accumulates. The soils found

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Table 4
Chemical properties of the analyzed horizons

Profile	Horizon	Depth	pH-H_2O	pH-KCl	$CaCO_3$	P_{av}	Clay	Silt	Sand	C_{org}	N_{tot}	Ca	Mg	K	Na	CEC
		cm			g/100 g	mg/100 g	g/100 g			g/100 g		cmol(+)/kg soil				
A	1	0–25	7.6	6.3	2.2	55.8	45	27	29	2.1	0.19	32.5	14.1	1.2	0.9	39.0
A	2	25–60	7.6	6.4	2.5	76.1	36	30	34	1.7	0.14	36.1	15.1	0.8	0.7	37.3
B	1	0–20	7.2	5.4	2.6	8.5	62	27	11	1.1	0.09	40.1	17.0	1.4	1.4	50.0
B	2	20–100	7.7	5.8	2.2	7.4	57	34	9	1.1	0.07	43.6	13.8	1.2	1.6	55.7
C	1	0–15	7.0	5.6	1.7	9.4	61	32	7	1.4	0.10	40.8	18.6	1.5	1.2	57.9
C	2	15–80	7.1	5.6	1.4	23.8	44	49	8	1.5	0.11	34.7	15.9	0.8	0.9	47.0
D	1	0–20	7.4	6.0	1.4	20.6	34	29	37	1.5	0.12	26.9	8.3	0.3	0.4	30.2
D	2	20–100	7.5	5.9	1.1	19.3	54	29	18	1.6	0.09	43.1	12.2	2.8	1.1	53.9
E	1	0–15	7.7	6.1	1.6	7.2	48	26	26	1.1	0.11	39.9	10.7	0.8	0.6	44.0
E	2	15–80	7.9	6.4	2.0	4.9	57	26	18	0.6	0.07	48.0	11.6	0.7	0.9	
E	3	80–100	7.9	6.4	1.8	17.4	65	23	12	0.4	tr	46.6	13.5	1.2	1.0	54.9
F	1	0–20	7.3	5.9	1.7	14.0	60	27	14	1.1	0.09	35.7	16.3	1.4	0.8	45.1
F	2	20–90	7.8	6.2	2.0	3.6	47	44	9	1.2	0.09	34.6	23.1	0.9	1.5	
G	1	0–20	8.2	7.1	9.6	11.1	43	38	18	1.6	0.16	91.0	4.2	1.6	0.2	39.1
G	2	20–80	8.3	7.2	32.2	6.5	53	34	13	1.0	0.10	92.5	3.0	1.0	0.5	
H	1	0–20	8.3	7.3	32.1	12.3	78	19	2	1.0	0.14	120.3	3.2	2.0	0.8	38.9
H	2	20–80	8.3	6.9	7.9	9.2			14	1.7	0.13	83.5	3.6	1.3	0.8	29.3
H	3	80–100	8.1	7.1	22.8	22.2	47	42	10	1.9	0.16	112.3	3.6	1.2	0.9	46.5
I	1	0–25	8.1	7.2	31.2	11.7	71	18	11	1.2	0.15	114.2	3.5	1.2	0.7	
I	2	25–40	8.2	7.2	29.7	6.2	75	19	6	1.6	0.20	129.3	3.5	1.5	1.0	36.5
I	3	40–85	8.3	7.4	36.9	7.1	75	19	7	1.2	0.10	95.8	3.1	1.4	0.7	
I	4	85–100	8.0	7.1	7.9	63.8	67	26	7	2.2	0.13	95.9	8.1	1.3	1.5	
J	1	0–10	8.3	7.4	44.7	43.0	39	31	31	2.0	0.28	37.3	2.3	1.9	0.5	
J	2	10–30	8.3	7.4		19.0	53	34	13		0.17	26.4	1.4	0.7	0.3	22.2
J	3	30–60	8.6	7.4	59.2	7.4	85	13	2	tr	tr	49.4	1.8	1.2	0.4	17.3
K	1	0–20	7.4	5.8	1.4	12.0	45	36	19	1.7	0.15	32.4	14.3	0.3	0.8	39.6
K	2	20–68	7.3	5.7	1.5	10.4	50	35	14	1.5	0.18	27.3	12.2	1.0	1.1	37.4

CEC: Cation Exchange Capacity, C_{org}: organic carbon, N_{tot}: total nitrogen, P_{av}: available phosphorus. Analytical methods are explained in Section 3.2; analyses were done on the fine-earth fraction (<2 mm).

here are (profile A) usually richer in organic matter. Even though they are usually very stony, they are often used for cultivation. Usually all soils derived from basalt are used for cropland, unless the slope is very steep (>30%).

4.2.2. Catena on limestone

When completely developed, the typical soil types that are expected on limestone in this region are Phaeozems (Descheemaeker et al., 2006) with a mollic horizon. However, due to the high soil erosion and deposition rates and the intensive land use, the typical soils that were found are Calcaric Leptosols and Calcaric Regosols (Profile J) on slopes and Colluvic Calcaric Cambisols in flatter areas (Fig. 2, transect 2).

At footslopes Colluvicalcaric Regosols/Cambisols (profiles I, H) are found, which are soils built up by colluvium, and which often have buried horizons. These soils are often found as a complex due to local stepped topography, and even on a field scale due to tillage erosion and deposition behind stone bunds (Nyssen et al., 2000; Vancampenhout et al., 2006).

On the flattest parts in the limestone area, Calcaric Vertic Cambisols and Calcaric Vertisols (profile F) are present. Similar to the catena on basalt, these Vertisols are associated with hard, impermeable geological layers with an impeded drainage. Close to the places where these impermeable geological layers outcrop, some secondary carbonates are formed and Calcic horizons start to develop. The places where secondary carbonates are formed are the same places where ancient tufa is exposed in gullies.

Most of the Calcaric Vertic soils that are found within the May-Leiba catchment have no clear slickensides or wedge-shaped structures near the surface. These are however very clear and prominent when buried soils and/or deeper layers are considered. The upper horizons also frequently have a coarser texture than the lower ones. This is probably due to environmental changes induced by deforestation and increased human activity (Nyssen et al., 2004a). The current ustic moisture regime is still suitable for the formation of Vertisols. But due to the removal of vegetation and gully incision, surface drainage increases and less weathering occurs. Increased runoff deposits coarser material on top of the Vertic soils. And last but not least, the Vertic soils themselves are also subject to sheet, gully and pipe-erosion.

The flatter parts of the limestone area, with Cambisols (Vertic and Colluvic) and Vertisols are used for cropland, the steeper areas (>10%), which represent the major part, are dominantly used for grazing.

4.2.3. Soils developed on Amba Aradam Sandstone

No soils were found that developed on this cliff-forming layer. The soils found here were always derived from covering basaltic deposits or bare rock was outcropping. Fragments of this sandstone are found in soils at the bottom of the cliff, where they increase the (coarse) sand content (e.g. Profile D).

4.2.4. Soils developed on basaltic mass movement bodies

As noted in the description of the study area, in places, various forms of basaltic mass movements have covered the limestone parent material (Figs. 3 and 4 transect 1). Depending on the type of mass movement, different types of soils can occur: (a) large scale landslides which move basalt parent material downslope and (b) creep-like displacements of the black clays deposited at the foot of the sandstone cliff.

Large scale mass movements (tens to hundreds of meters wide and hundreds to thousands of meters long) moved a lot of basaltic parent material downslope. Their origin and history is not yet well understood and is subject of ongoing research. Compared to the previous work the region (Nyssen et al., 2003) the scale of these landsides is much larger. The soils that are found on these large scale landslides form exactly the same catena as found on in situ basalt: Skeletic Cambisols on the higher positions (profile E) and Vertisols on the lower end, or where a temporary water table occurs due to the

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underlying geology (profile F). Because fully developed Vertisols are found on these mass movement deposits, it is assumed that these large mass movements are ancient.

Close to the foot of the sandstone cliff, black swelling clays, coming from creep-like deposits of Vertic soil material on top of the cliff form Vertic Skeletic Cambisols (profile D). Although these soils are located on rather steep slopes, they still have typical characteristics of Vertic soils. Below the area that is covered by these black swelling clays, a very complex zone is usually found, where small landslides of basalt parent material, limestone material and vertic black clays can occur at a close distance and even on top of each other.

Very often, buried Vertic soils are found (e.g. profile I). From the analytical data, it is clear that the parent material for the lower part (horizon I-4: in Table 4) of this soil is at least partly derived from basalt, whereas the higher part consists only of limestone-derived material. This shows that the environment in which the soils have formed has changed. Probably, this is due to increased land degradation and soil erosion. It is unclear when exactly this process started. Nyssen et al. (2004) have shown that major man-induced erosion has started after 3000 BP, which has also lead to increased deposition; hence the only slight pedogenesis in limestone material on the steps in the landscape, which were originally covered by black clays originating from basaltic material.

The influence of these different types of basalt depositions on soil fertility cannot be underestimated. When looking at the aerial photos of May-Leiba, there is almost no cultivation in the areas on in situ limestone (especially on slopes). Almost all cultivation in the limestone domain takes place close to the areas with basalt or dolerite. This is probably related to better chemical properties: soils derived from limestone often lack some micro-nutrients, particularly iron and zinc (Sanchez et al., 2003). There are also imbalances between Ca and other bases (Mg and K). Basalt on the other hand has a more balanced content of these bases. But probably more important are the physical properties of the soil: sloping areas on limestone are often too dry for cropping, because the high carbonate content reduces their ability to store moisture (FAO, 1973).

4.3. Derivation of the soil–landscape model and the soil map of May-Leiba

Table 5 shows the different terrain elements that could be derived on the aerial photographs. For every terrain element, the best fitting mapping code was derived, and this was converted to a WRB classification. The map purities, derived by Eq. (1) are given for the chosen mapping code.

The first step of the model is to determine the parent material. It is obvious that above the sandstone cliffs only basalt is present. However, under this cliff, it must be checked if limestone is really the parent material. Up to 100 m away from the sandstone cliff often only basalt and sandstone material is found, and the mass movement can even extend to several kilometres. The areas covered by basalt are darker on the aerial photographs, even if the slope is steep. A comparison should be made with areas on limestone with a similar slope and landscape position. Land use is also an important factor: areas with a rather steep slope (>10%) are almost seldom used for cropping when only limestone is found. However fields can be found on basalt even on slopes with a gradient >30%. A second possibility is the usage of Landsat ETM colour imagery. Basalt-derived soils appear clearly different on these images, especially in near-infrared bands.

In some areas under the sandstone cliff, but even at some distance from the cliff, limestone and basalt appear too mixed to make a distinction. In that case the last entry of Table 5 should be used, but it is clear that local variability will remain high, given the low mapping purity unit. In this area, the soil mapping units for May-Leiba (Fig. 4) were updated because distinct differences occurred between different locations (the ratio between basalt-derived colluvium and eroding marls), even though the soil–landscape model was not able to distinguish between these units.

4.3.1. Soils on basalt

On basalt, almost no differences in land use or grey tone can be distinguished on the aerial photograph. This means that the model for soils on basalt depends almost only on their topographic position, and can only be derived using a stereoscope or a detailed digital elevation model. The differences between the groups can also occur due to

Table 5

Expected major soil type and its purity (Eq. (1)) based on the derivation by the soil–landscape model (based on 236 auger-observations); pm: parent material; txt: texture; cf: coarse fraction; *: $CaCO_3$ presence; dr: drainage; Pd: profile development; mapping code according to Table 1

				Map purity (%)						Major soil type	
Model	Parent material	Topography	Grey tone and determination on aerial photograph	pm	txt	cf	*	dr	pd	Mapping code	World Reference Base
Full model	Basalt or large mass movements of basaltic parent material	Steep slopes (>30%)	Light	100	62	62	100	75	55	Bl3Wx	Leptosol
		Summit, locally higher points in flat areas	Dark, no distinction based on grey tone	100	64	50	100	89	82	Ba2Wb	Skeletic Cambisol
		Footslope		100	62	67	100	91	64	Be2Wc	Colluvic Skeletic Cambisol
		Gentle slope (<15%)		100	61	64	100	67	70	Be2Pv	Vertic Cambisol
		Flat areas		100	79	84	100	76	88	Bu1Pv	Pellic Vertisol
	Limestone	Shoulders and steep slopes	Very light	100	58	76	100	68	60	Kl3*Ex	Calcaric Leptosol
		Slight slopes	Light	100	71	60	89	91	56	Kl2*Wp	Calcaric Skeletic Regosol
		Footslope	Medium	73	68	76	100	84	84	Kl2*Wc	Calcaric Colluvic Skeletic Cambisol
		Flat areas	Dark	76	74	65	89	65	57	K11*Wb	Calcaric Cambisol
		Flat area; close to water restricting layers	Dark; dark in infra-red band	75	73	81	95	79	88	Ku1*Pv	Calcaric Vertisol, Calcaric Vertic Cambisol
	Limestone (partly) covered by basaltic material (small mass movements, clay flows)	Steep slopes, located just under water restricting layers with basalt-derived vertic material on top: vertic clay flows	Very dark, much darker than limestone on similar slope	100	50	50	100	100	75	Be2Wc	Colluvic Skeletic Cambisol
		Slopes under sandstone cliff	Patchy light gray	70	56	50	69	76	44	Ml1(*) Wc	(Colluvic) (Calcaric) Regosol
	Overall accuracy			92	67	65	84	78	57		
"One soil" model				57	49	50	55	70	42	M1lWv	Cambisol
"Geologic" Model	Basalt domain			100	43	54	100	62	60	Bu1Wv	Vertic Cambisol
	Limestone domain			58	52	50	57	66	37	Ml1*Wv	Cambisol

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Table 6
Results of the validation of the complete soil–landscape model (Table 5)

Site	Predicted soil type	User-accuracy						
		n	Parent material	Texture	Coarse fraction	$CaCO_3$ presence	Drainage	Profile development
Melfa + MZZ	Be2Wc	8	56%	61%	55%	22%	70%	63%
Melfa + MZZ	Be2Wv	9	100%	49%	40%	100%	89%	89%
Melfa	Bl3Wx	5	100%	70%	88%	80%	100%	100%
Melfa	Bu1Pv	10	90%	90%	74%	90%	70%	80%
MZZ	Ku1*Pv	7	60%	100%	100%	43%	64%	100%
MZZ	Kl2*Ex	2	100%	30%	40%	100%	36%	0%
MZZ	Kl2*Wc	10	75%	51%	52%	80%	84%	50%
MZZ	Ml1(*)Wc	4	100%	33%	100%	100%	100%	75%
Complete model		55	82%	65%	67%	74%	79%	75%
“one soil” model		55	57%	49%	66%	55%	61%	40%
Geologic model								
Limestone domain		36	60%	37%	82%	77%	76%	26%
Basalt domain		18	100%	75%	26%	100%	25%	75%
Complete geologic model		55	72%	48%	66%	84%	61%	40%
Increase in user-accuracy								
(Geologic) — (one soil model)			12%	11%	0%	10%	0%	0%
(Full model) — (Geologic model)			10%	17%	1%	−7%	28%	35%

MZZ is the May-Zeg-Zeg catchment.

micro-relief (scale of 20 m), which is the major reason why texture and profile development errors are made.

4.3.2. Soils on limestone

All sloping areas on limestone that are used for grazing have the same properties: high stoniness and almost no profile development. It indicates that land use is an important feature when mapping. Also the colour on the aerial photograph changes a lot depending on the topsoil development from a Calcaric Regosol to a much darker Calcaric Vertisol. Thus a stereoscope is not strictly needed for interpreting the aerial photographs for the limestone area: by using only colour and land use, soil expectation maps can be made. The borders between the slight slopes (10–25%), footslope and flat areas can occur at scales below mapping scale, which causes some map impurity. Even though limestone or marls are the major parent material, on part of the profiles also basalt can be present.

4.3.3. Simple soil–landscape models

Two simple soil–landscape models were derived. Their results are also included in Table 5. For the first “one soil” model, the predicted soil type would be Ml1Wv. For the second model based on the lithological domain, the prediction would be Bu1Wv or a Vertic Cambisol for the basalt domain, and Ml1*Wv for the limestone domain. It is clear that the user-accuracies for these models are lower than for the full model

4.4. Validation of the soil–landscape model

The results of the validation can be found in Table 6. Since the soil expectation maps did not contain flat areas (5–10%) on limestone the predictions for these terrain elements could not be validated.

By examining the results of the validation, some trends are distinguished easily: parent material, presence of $CaCO_3$ and drainage are predicted quite well in general. Profile development is predicted well in most cases, and the prediction for coarse fraction and texture is the worst. Apart from misclassification due to the model the errors in course fraction and texture might also partly be attributed to the fact that a different survey team conducted the soil survey in May-Zeg-Zeg.

When looking to the accuracy, it is also clear that well defined soil types like Vertisol and Leptosol are predicted much better than the Regosol–Cambisol–Colluvic Skeletic Cambisol intergrades. This is not very surprising since the map purity for these units was also lower in May-Leiba.

Like mentioned in the methodology apart from checking which user-accuracies are high, it is also important to check how much better (or worse) the model predicts than simpler models.

The user-accuracies for these simple models are also given in Table 6.

If we compare the “one-soil” model with the “geologic” model, we see that parent material and the prediction of presence of $CaCO_3$ prediction increases. The prediction accuracy of texture, coarse fraction, drainage and profile development doesn't change significantly. If we add the information of the complete model, the prediction accuracy for parent material increases further due to the delineation of basaltic mass movements. The prediction accuracy of $CaCO_3$-presence however decreases. This is due to the fact that some predicted basaltic clay flows did not consist purely of basalt-derived material as predicted and some mixing with limestone occurred. Finally the predictions for texture, drainage and profile development improved considerably, mostly due to the fact that the topography was included in the model. The prediction for coarse fraction did not improve by applying the model. From this validation data it seems choosing the same value for every soil unit performs equally well as using the different values based on the soil–landscape model that was developed in May-Leiba.

5. Conclusions

The soil distribution found in the basalt-dominated highlands in Tigray is very complex when first observed. To understand the diversity and the distribution of the soils, the most important parameter is to identify the parent material, indicating the importance to delineate mass movement bodies.

The determination of the parent material is also the first and most important step to derive the soil chemical properties and soil fertility. Soils derived from basalt are almost all cultivated, whereas soils derived from limestone are often only grazed. This means that whenever mass movements of allochthonous material are present, correctly identifying them is a key for further soil–landscape relation development: in May-Leiba about 50% of all augering descriptions reveal at least some basaltic parent material, and in 35% basalt was the only parent material. For the validation area in May-Zeg-Zeg this was around 40%.

Apart from the mass movements of basaltic material, there is a second important factor: the occurrence of cliff-forming layers, sealed off at their base by shales. These lead to steps in the landscape, an

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impeded drainage (which results in a higher availability of water) and the development of Vertic soils. Moreover, on the fringe of these steps Calcic horizons can develop.

The third important factor is human influence, which is especially important in the limestone area: areas that are under grazing are usually severely eroded, while neighbouring flatter areas are covered by recent colluvium. The fact that more than 25% of the soils of May-Leiba catchment have dominantly colluvial parent material shows the importance of the new "Colluvic" qualifier in WRB (IUSS Working Group WRB, 2006) for description of soils in this region.

These three factors and the general topography can be delineated using aerial photographs and/or satellite imagery, which opens the scope for extrapolating the soil–landscape model. Even though local variability is high, applying the soil–landscape model will improve the user-accuracy of most important soil properties over simpler models: parent material (+14% to 82%), texture (+35% to 65%), drainage (+30% to 79%) and profile development (+35% to 75%). The predictions for coarse fraction (66%) and presence of $CaCO_3$ (77%) however are not better than the simpler models.

Acknowledgements

This study was conducted within the framework of the Institutional University Cooperation programme between Mekelle University (Ethiopia) and the Flemish Universities, funded by the VLIR (Flemish Interuniversity Council — Belgium). Much thanks goes to the farmers of the May-Leiba catchment for their hospitality and cooperation.

This paper benefited much from the constructive comments of two anonymous reviewers.

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Please cite this article as: Van de Wauw, J. et al., Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia, Catena (2008), doi:10.1016/j.catena.2008.04.006