Catena 131 (2015) 84–91

Contents lists available at ScienceDirect

Catena

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

Soil, land use and landform relationship in the Precambrian lowlands of northern Ethiopia

Kassa Teka [a,*], Jan Nyssen [b], Nurhusen Teha [a], Mitiku Haile [a], Jozef Deckers [c]

[a] Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia
[b] Department of Geography, University of Gent, Belgium
[c] Department of Earth and Environmental Sciences, KU Leuven, Belgium

ARTICLE INFO

Article history:
Received 27 March 2014
Received in revised form 12 March 2015
Accepted 14 March 2015
Available online 1 April 2015

Keywords:
DMSV
Landform
Lithology
Precambrian
Tigray

ABSTRACT

Soil, landscape and vegetation pattern at a detailed scale (1: 20,000) is non-existent in the Precambrian dominated lowlands (500–1500 m above sea level) of northern Ethiopia. Current studies at a detailed scale in the region have focused on the basalt and Mesozoic rock (limestone and sandstone)-dominated highland (>2300 m above sea level) areas. The aim of this research was, therefore, to explain the soil distribution as a function of lithology, land use and landform, and to develop a methodology for up-scaling to similar environments. This study was conducted at Aqushala Watershed in the Precambrian rock dominated Avergelle Lowlands. The research was done based on a discrete model of spatial variation (DMSV). Soil units identified: (1) in the metamorphosed black limestone formation are Vertic, Endoleptic Calcisol (Humic) at the upper slope (plateau); both Vertic, Endoleptic Cambisol (Calcaric, Humic) and Vertic Leptosol (Calcaric, Humic) at the middle slope (hill); Hypercalcic Calcisol at the foot slope and Grumic Vertisol (Calcaric, Humic) at the lower slope (valley bottom). Majority of the soil units were under cultivation; (2) in the schist and slate formations are Leptosol (Calcaric, Humic) both at the upper slope and at the foot slope positions; Regosol (Calcaric) over Hypercalcic Calcisol at the mid slope position and Fluvisol (Calcaric, Humic) at the valley bottom; and (3) in the green-reddish-gray metamorphosed banded marl formation are Leptic Calcisol at the upper slope, Haplic Calcisol at the foot slope, and Fluvisol (Calcaric, Humic) at the valley bottom. The model was tested in the Taget (control) Watershed and was 73% successful. So, if this model is used, it can help a lot in every aspect of agricultural or natural resource management and planning processes.

1. Introduction

Soil is a dominant factor of the land mainly through its effect on biomass production (Gessler et al., 1995; Brunner, 2012). It covers land as a continuum having properties that vary enormously and continuously with depth and with horizontal distances (Gessler et al., 1995). But this variation is not random i.e. at any given location on the landscape; there is a particular soil with a unique set of properties (Iqbal et al., 2005). For the most part, soils are the same wherever all elements of the five factors (climate, time, vegetation, topography and parent material) are the same (Jenny, 1941; Dokuchaev, 1883; McKenzie and Ryan, 1999; Chaplot et al., 2001; Phillips, 2010). This regularity permits prediction of the locations of many different kinds of soils.

When soils are studied in small areas, the effects of topography and parent material on soil becomes apparent (Fikru, 1995; Finzi et al., 1998; Van Breemen and Finzi, 1998; Delin et al., 2000; Bohlen et al., 2001; Fitzpatrick et al., 2003; Venterea et al., 2003). The soil varies along the landscape, even within limited areas, giving rise to a succession of soil types, known as a catena (Milne, 1935; Aweto and Enaruvbe, 2010). Studies (e.g. Nizeyimana and Bichi, 1992; Eash and Sandor, 1995; Dahlgren et al., 1997) showed that soil properties and landscape position are significantly related, mainly where the movement of soil and water is considered. Landscape topography affects soil physical and chemical properties by erosion and deposition processes, which greatly influence the characteristics and distribution of the soils (Onstad et al., 1985; Nizeyimana and Bichi, 1992; Delin et al., 2000; Bohlen et al., 2001; Venterea et al., 2003; Dotterweich, 2008; Houben, 2008; Aweto and Enaruvbe, 2010; Augustsson et al., 2013; Świtoniak, 2014) in addition to its effect on water table depth which can again impact soil genesis significantly. Many studies have shown that organic matter and soil nutrient levels are higher in the lower slope segment of the topography (Abrams et al., 1997; Kravchenko and Bullock, 2000). This can be due to soils in lower slope receive substantial amount of sediments transported from upslope which helps improve their nutrient status (Aweto and Enaruvbe, 2010). Moreover, soils in lower topographic location hold greater quantity of water than higher slope soils and are saturated with moisture for a much longer period than upper slope soils (Lopez et al., 2003; Aweto and Enaruvbe, 2010). Studies in dry areas of Australia (Fitzpatrick et al., 2003), for example, have shown

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* Corresponding author.
E-mail address: kassateka@yahoo.com (K. Teka).

http://dx.doi.org/10.1016/j.catena.2015.03.010

that shallow loam soils are on the crest, interspersed with shale and siltstone outcrops (i.e., 5–50% surface cover) and clay soils on steep upper slopes. Surface soil horizons loss occurs on convex parts of slopes and colluvial material deposition takes place on concave areas (Dotterweich, 2008; Świtoniak, 2014).

With the notable exception of the constructing patterns of vegetation in transition zones, local differences in vegetation are also closely associated with differences in relief and parent material (Fikru, 1995). In some cases, soil properties also affect the vegetation types (Finzi et al., 1998; Van Breemen and Finzi, 1998) and vice versa (Dotterweich, 2008). Studies (e.g. Finzi et al., 1998; Van Breemen and Finzi, 1998; Dotterweich, 2008) revealed that under natural conditions, vegetation cover and soil development largely mitigate geomorphic processes, resulting in a stable equilibrium. The natural water and matter fluxes change with deforestation and soil erosion. Furthermore, Dotterweich and Dreibrodt (2011) reported that reducing forest cover and/or increasing frequency of flood events render the fluvial system rich in sediment. The material is washed down slope and gullies have incised, leading to the deposition of sediments at the slopes and floodplains (Dotterweich, 2008; Hoffmann et al., 2011). These erosional landforms and depositional structures are the results of past land use, human impact and climate change at broad temporal and spatial scales. According to Dotterweich and Dreibrodt (2011), sediment fluxes in small catchments are highly sensitive to changes in local land use. Studies (e.g. Papendick and Miller, 1977; De Alba et al., 2004) showed that land use conversion modified soil morphological properties along the slope due to soil material redistribution.

Nevertheless, the distribution and quality of soil data are not homogeneous across the world (Dobos et al., 2000). Lacks of financial resources as well as the use of different survey methodologies, soil taxonomies, and mapping scales are the main obstacles towards creating globally valid soil data (Brunner, 2012). Furthermore, the soil, landscape and vegetation pattern at a detail scale (1: 20,000) is non-existent in the Precambrian dominated lowlands (500–1500 m above sea level) of northern Ethiopia. The age of the Precambrian rock extended from the origin of the earth (believed to have been about 4600 million years ago) to about 570 million years ago, representing nearly ninety percent of geological time (www.oxforddictionaries.com/definition/english/Precambrian).

In the case of Ethiopia, the existing maps, i.e. paper and digital maps at the national level, have their origin in the 1980s, when the Food and Agricultural Organization (FAO) created a set of maps on geomorphology and soils at a scale of 1:1 million to assist land use planning (FAO, 1983). Current studies at detail scale in northern Ethiopia have focused on the basalt (Van de Wauw et al., 2008), and limestone and sandstone 'Mesozoic rocks' (Rabia et al., 2013) which is dominated within the highland (>2300 m above sea level) areas. These studies did not look at land use.

Hence, this type of soil, landscape and vegetation pattern is likely to be useful predictions of where these soil issues are likely to occur in the landscape, land use and lithology. If so, the ability to predict these patterns will be important in managing these areas more effectively. The objectives of the research were: i) to investigate soil distribution as a function of lithology, land use and landscape position; ii) to produce a map of these soils and model the soil landscape relationship, and iii) to test the model if it can be used as a tool for similar environments.

2. Materials and methods

2.1. The study area

The Aqushala small scale dam (outlet) (Fig. 1) is located at 481,605 m East and 1,479,939 m North Universal Trans Mercator Global Positioning System (UTM GPS) coordinates and at an altitude of 1300 m above sea level. The watershed area is approximately 9.73 km^2. This is a dry, lowland (locally called *kolla*) agro-ecological zone. Data taken from Tekeze hydro-electric dam station, about 10 km south west of the Aqushala small scale dam, shows that the average annual rainfall of the area is 330 mm with an average annual minimum and maximum temperature of 20 °C and 28 °C, respectively. The terrain is undulating, hills alternating with plains and valleys. Vegetation cover is made up of scattered acacia trees, riverine forests and bush scrub (Draft Middle Tekeze Livelihood Zone, 2006).

The production system is mixed farming on low lying plains, valleys and foothills. The main crops grown are *Sorghum bicolor* (Sorghum), *Zea mays* (Maize), *Eragrostis tef* (teff), *Sesamum indicum* (sesame) and *Linum usitatissimum* (flax). The major limitations for agricultural production are low moisture availability and poor soil fertility (Draft Middle Tekeze Livelihood Zone, 2006). The bed rock is characterized by its dip direction (to the East) and having different lithologies. The dominant rock in this catchment is metamorphosed black limestone. Soils in the area are locally classified as *Walka* (black soil), *Baekel* (light colored soil) and *Afukala* (a mixture of soil properties from both *Walka* and *Baekel*).

2.2. Methodology

2.2.1. Pre-field work

The only available document was a small scale (1:250,000) topographic map. Considering the limited surface (973 ha) of the study area, not enough details were available on the topographical map to accurately delineate the different landforms. Hence, a base map was developed from Shuttle Radar Topographic Mission (SRTM_90) imagery. Land uses were delineated through aerial photo interpretation (API) using Integrated Land and Water Information Systems (ILWIS) 3.3 and mapped in ArcView GIS 3.2 software.

2.2.2. Field work

Prior to the systematic soil survey, a preliminary soil reconnaissance of the Aqushala Watershed was conducted. Transect walks were made through the watershed to become familiarized with the landscape, landform, land use, etc., as proposed by the World Bank (2005) and to do preliminary establishment of a representative catenae (FAO, 2006). Transect placement and sampling intervals along transects were determined subjectively to capture the full range of soil variability within landforms as described by Young et al. (1992). Characterizing both individual pedon properties and the soil relationships both above and below on the landscape is important (Soil Survey Staff, 2009). Thus, the methods used to collect data included both surface and subsurface methods of land investigation. The surface method of land investigation was based on visual observation to identify nature and extent of soil properties, rock outcrops and transported materials. The sub-surface investigations were carried out using profile pits.

The conceptual model used in this study was a discrete model of spatial variation (DMSV) (Bregt, 1992). The model assumes that the landscape can be divided into discrete polygons of 'natural' soil bodies. Hence, the entire area of the catchment was divided into twelve major mapping units based on surface (soil color, vegetation type and density, land use, slope steepness, erosion, stoniness and rock outcrops) and subsurface landscape parameters (such as $CaCO_3$ content, soil depth, horizon development and profile stoniness). A mapping unit is represented by a set of pixels characterized by the same value for the diagnostic attributes (Van Orshoven et al., 2011). The identification of major mapping (land) units helped to determine the number of pits excavated.

In each land mapping unit, a soil profile pit (at least 1.5 m × 1.5 m and to the depth of the underlying rock) was dug. These soil profile pits were used to demonstrate lateral and vertical changes in the soil and are important for the full description of the soils and for taking soil samples for chemical and physical laboratory analysis (FAO, 2006). The internal properties of the soil (depth of profile and horizon