1 INTRODUCTION

1.1 Problem statement

Soil resources are vital assets needed by small-scale farmers in developing countries to produce sufficient crops in order to achieve food security and income (Vlek, 1993). However, in many sub-Saharan African regions, such as in East Africa, rapid population growth and an unfavorable economy have exerted great pressures on soil resources. Thus, farmers in East Africa, who cultivate fragile environments such as steep hillslopes with high levels of rainfall, have experienced tremendous soil degradation and severe crop yield decline on their lands (Stoorvogel and Smaling 1990).

In Uganda, which about forty years ago was evaluated as one of the regions with the most 'fertile' land in sub-Saharan Africa (Chenery, 1960), soil degradation in the intervening years has by now drastically changed soil fertility. The once favorable natural resource conditions have generally declined in their agricultural potential (NEMA, 1998). As a consequence, Uganda's crop productivity, which forms the economic backbone of the nation, is now ranked among the lowest in the world (Walaga, et al. 2000).

Contrary to this general view, spatially explicit soil degradation studies at different scales suggest that the impact may be more heterogeneously distributed in Uganda. On the national scale, Stoorvogel and Smaling (1990) estimated that soil nutrient losses in Uganda were one of the highest among African countries in the early 1980s. Regionally, Wortmann and Kaizzi (1998) reported large negative nutrient balances for cropping systems in central and eastern Uganda. Gold et al. (1999) found that parts of the Lake Victoria Crescent became marginal even for the production of the once abundant banana due to several degradation factors. Across a hillslope, Brunner et al. (2003) identified high erosive soil losses within the Lake Victoria Basin.

Halting and reversing this severe soil degradation at the different spatial scales has been one of the greatest challenges for scientists and farmers as well as for policy makers, regional planners and extension services in Uganda (Sserunkuuma et al., 2001; Kaizzi, 2002). Success in this endeavor is increasingly important for Uganda's rapidly increasing population, which has an annual growth rate of ca. 2.5% and of which more than 90% live in rural areas (MPFED, 1999; Government of the Republic of Uganda, 2000). Achieving food security for this population by sufficient crop production is hampered by the lack of available land, which sharply decreased from 5.2 ha per capita in 1931, to 1.9 in 1969 and 0.8 in 2000, thereby increasing pressure on the available soil resources (National Environment Management Authority, 2001).

In order to prevent further soil degradation, agronomic researchers have promoted a range of different soil and water conservation techniques in the past few decades. These techniques include crop rotations, improved fallows and use of inputs to maintain and improve soil productivity (Ssali, 2000 and 2001). Unfortunately, very few farmers in Uganda have adopted these practices (Woelcke et al., 2002). This might be due to the fact that small-scale farmers, who cultivate fragmented fields in ecologically diverse environments, often lack the knowledge to assess and spatially demarcate the specific soil degradation problems within their land. For example, a farmer may achieve poor crop yields from some fields because they are in locations with high erosive soil loss, while other fields may experience strong nutrient mining or high acidity.

Many farmers in Uganda lack the means and the information to assess the management technologies, which are most appropriate to counter specific soil degradation problems on their land (Kaizzi, 2002), e.g. specific soil and water conservation measures for erosion sites and the right organic or inorganic fertilizer combination for fields with specific nutrient limitations. Instead, the majority of farmers have continued to employ low-tech practices often without taking into account the spatial heterogeneity of their soil problems and the site-specific solutions needed to overcome them, thus leading to further soil degradation.

With increasingly depleted soil nutrient resources and scarcer agricultural land, agricultural researchers in Uganda recently started to study methods of arresting soil degradation and increasing agricultural productivity by using locally available nutrient resources more efficiently. These integrated nutrient management (INM) methods seek to optimize land management by combined usage of organic and inorganic plant nutrients with soil conservation measures to attain higher crop productivity and prevent soil degradation (Wortmann and Kaizzi, 1998; De Jager et al., 1999).

Depending on the size of the area on which INM strategies are targeted, the spatial variability of soil resources and the factors that determine them might vary considerable (Kam and Oberthuer, 1996; Bourgeron et al., 2001). For INM recommendations on the national scale, the spatial distribution and the quality of soil resources might be determined by highly diverse natural resources and socio-economic conditions. Natural resources such as climate, terrain and vegetation may influence the agricultural potential of soil resources through the interaction of different hydrologic and pedological processes. Socio-economic conditions, such as the distribution of markets, may be important for farmers to acquire inputs such as fertilizers for improving soil resources. The density of the population may influence soil quality through the intensity of cultivation within a region. For example in areas with high population density, farmers may have little or no land leftover for shifting cultivation and are instead forced to practice continuous cultivation. If no nutrient replenishment is practiced in these areas, the nutrient status of these soils is expected to decline. Thus, the spatial distribution of both natural resources and socio-economic factors and their potentially complex interactions in determining soil variability need to be considered to arrive at appropriate INM strategies for larger regions (Carter, 1997; Wood et al., 1998).

All presently available information on the spatial variability of soils on national-scale in Uganda is mainly based on the reconnaissance soil surveys dating from the late 1950s (Chenery, 1960). These maps were digitized, aggregated and entered into the digital soil and terrain database of East Africa (FAO, 1997). Other, more recent natural resource studies on the national scale, such as the identification of the major land resource areas (Yost and Eswaran, 1990) and the agro-ecological zones (Wortmann and Eledu, 1999) of Uganda, rely on the same reconnaissance data.

However, about 50 years have past, since the measurement of this soil information until the demand to provide precise and up-to-date soil information today. Considering Uganda's recent history with continuous population increase and evolution of farming systems, it becomes clear that the soil determining natural resource and socio-economic factors, and with these factors in turn the soils themselves might have dramatically changed in this country in the meantime (NEMA, 2000; Ssali, 2000; Bashaasha, 2001). When using soil data from the 1950s for solving present-day challenges to improve land management, some of the information may be outdated, e.g. soil nutrients may now be depleted in some areas and erosion processes might have changed soil textures. Furthermore, the aggregated information by soil types does not directly show soil resource managers which nutrients may be limited for a specific crop production. The spatial patterns and detailed information on soil parameters that are crucial for policy makers and regional planners to evaluate soil quality are not directly linked in geographical information systems, as the old paper-map information is separate from the pedological information in books (Chenery, 1960). The spatial relationship of soil data with environmental processes and patterns is missing. In order to better prioritize investments and to recommend land management strategies for targeted regions, policy makers and regional planners in Uganda urgently need this precise and up-to-date spatial soil information on a regional and national scale (Vlek, 1990; Kaizzi, 2002).

On the scale of a hillslope, where small-scale farmers cultivate many fields, the farmer communities and the agricultural extension services lack information on soil spatial variability. Furthermore, information on the factors that influence soil changes and the major degradation processes is often not available. However, for successful INM on the hillslope-scale, such information may help them to target improved soil and water conservation as well as nutrient replenishment strategies to specific nutrient depletion and erosion hotspot positions within the landscape.

Soil erosion was investigated in Uganda for certain land uses on a field scale by run-off plots (Nakileza, 1992; Osinde, 1994; Tenywa and Majaliwa, 1998, Magunda et al., 1999). This measuring technique will not capture the soil redistribution processes by erosion, which may occur over the many fields within the complex terrain of landscape systems. It can thus not be used to demarcate the spatial soil redistribution patterns of both erosion and sedimentation over the landscape making soil and water conservation targeting in the landscape impossible.

One potential method for estimating the spatial soil redistribution rates in a landscape is the Caesium-137 (^{137}Cs) modeling approach (Collins et al., 2001; Zapata, 2003). This approach has successfully been used in studies within temperate regions. However, to date it has not yet been applied in the humid tropics of Africa (Ritchie, and McHenry, 1990; Walling, 1998). This might be because the collection of input parameters for this model was found to be difficult. Yet, if this model could be successfully applied in this region, it may facilitate the estimation of landscape-based soil redistribution rates and the design of site-specific soil and water conservation strategies.

1.2 Research objectives

This study aims to help design improved land management strategies for targeted soil resource locations in Uganda in order to promote more effective and sustainable agricultural development in this country. The research objectives are to investigate the spatial variability of soils on national and hillslope scale and to assess the soil redistribution rates and processes on hillslopes in Uganda.

The specific objectives are:

1) to stratify the spatially complex natural and socio-economic conditions that determine the quality of soil resources in the whole area of Uganda;
2) to characterize the spatial distribution of individual soil properties on both national and hillslope scales;
3) to identify the factors and processes that are dominant in explaining the spatial variability of soil properties on national and hillslope scale;
4) to estimate the rates, spatial patterns and determining processes of soil redistribution on hillslopes by the ^{137}Cs modeling approach.

1.3 Thesis outline

This thesis is structured into seven chapters that are summarized in the following.

Chapter 1 introduces the problem of soil degradation in Uganda and describes the necessity of research on spatial variability of soils on national and hillslope scale.

Chapter 2 gives a theoretical framework on soil variability on different spatial scales.

Chapter 3 presents the stratification of the complex natural and socio-economic resources of Uganda into spatial domains as a pre-stratification for the national-scale soil variability study. Parts of this chapter were published in Ruecker et al. (2003a).

Chapter 4 describes the national-scale soil variability assessment. This includes the selection procedure for the 107 research communities, the field data collection and processing. In three sub-chapters the spatial variability, the spatial structure, the interpolation of soil and the causes of soil variability on a national-scale are presented.