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Spatial variability of soils on national and hillslope scale in Uganda

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ABSTRACT

Halting and reversing the severe soil degradation in Uganda has been one of the greatest challenges for policy makers, regional planners, extension services and farmers in this country. This challenge is particular difficult because soil resources vary considerably on a national- and local-scale in Uganda. The research objectives of this study were 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 aim of this research was to help in the design of improved land management strategies to targeted soil-resource locations in Uganda for more effective and sustainable agricultural development.

A national- and a landscape-scale survey were undertaken in Uganda during which ca. 2,000 topsoil samples were extracted from 107 communities. These soil samples were analyzed for key soil-quality parameters including pH, soil organic matter (SOM), available phosphorus (P), exchangeable potassium (K), exchangeable calcium (Ca), sand, clay and silt. Environmental data on geology, geomorphology, climate, terrain, land use, land management, population density and market access were collected and integrated with the soil data in a Geographic Information System (GIS) in order to perform statistical, spatial and terrain analyses. On the hillslope scale, erosion and sedimentation patterns were investigated by Caesium-137 (^{137}Cs) modeling, an approach that had not yet been used in the humid tropics of Africa.

Population density, market access, agricultural potential and elevation were used as factors in a GIS-based stratification to separate the spatial domains of agricultural development that may influence soil variability in Uganda. This stratification resulted in 18 spatial development domains covering more than two-third of Uganda. The analysis of the variance characteristics of these factors showed that the stratification was suitable for separating the diverse natural resource and socio-economic factors into largely homogeneous spatial domains. All soil parameters exhibited a wide range, e.g. pH (4-7), SOM (1-24%), P (1-800 mg/kg), K (1-500 mg/kg), Ca (1-700 mg/kg). The average soil texture in Uganda was sandy clay loam. The spatially explicit analysis of soil samples revealed that local terrain may strongly influence the spatial distribution of pH, SOM, and clay, but not of P, K, Ca, sand and silt, which may be governed by land use and land management. Most soil parameters had a weak to moderate spatial dependency. The parameters pH, SOM, clay, P, and K had higher scattered semivariance than sand, silt and Ca. The spatial interpolation GIS-maps that were based on averaged community soil data revealed Uganda´s regional soil disparities with larger and rather homogeneous patterns for SOM, P, K, and Ca. The maps of pH and soil texture had spatial patterns changing within shorter distances. Sharply contrasting soil parameter patterns were identified between the lowland areas in central Uganda on the one side and the western region, the eastern as well as the south-western highlands on the other side. Moderately to strongly acid soil pH areas (pH 5.2 - 4.3) that limit crop growth were found in larger regions in the central area, the area bordering Lake Victoria and the south-western highlands. Favorable pH patterns (pH 5.4 - 6.2) were mainly existent in the west-south-west and the north-east. The spatial patterns of SOM in most areas of the study region reached levels that were sufficient for crop cultivation (> 4%), but SOM levels were nearly deficient in smaller areas within the central region (ca. 3%). Higher SOM levels (9-11%) were found in the eastern and

south-western highlands. The spatial patterns of the plant nutrients P, K and Ca were similar to those of SOM with values that were favorable for crop cultivation throughout the study region. The relatively lowest levels of K (15.8 - 25.2mg/kg), P (4.67 - 29.1mg/kg), Ca (57.4 - 65.5mg/kg) were still above the critical values and were mainly found within central Uganda. The highest levels of K (90.7 – 100mg/kg), P (200 – 225mg/kg) and Ca (122 – 130mg/kg) occurred in smaller areas within the highlands. The lowest sand content (26.8 - 33.3%) was in the highlands, whereas the highest sand content (77.9 – 84.2%) occured in the east and north-east. The areas with lower clay content (5.92 - 17.4%) were located in the central region and in the west, whereas the highest clay (52.0 - 57.7%) and the highest silt content (31.2 - 34.3%) was found in the highlands. Geology/Geomorphology had the strongest power to explain the national-scale spatial variability for all soil parameters, except P, which was mainly determined by Land use/Land management. Combining all predictors, the explanatory powers were for pH 22%, SOM 54%, K 33%, Ca 23%, sand 52%, clay 43%, silt 58% and for P 37%.

On a hillslope scale two study sites were selected, one in the highland, Kongta, and the other one in the lowland area, Magada, respectively. The average soil texture in Kongta was clay, whereas Magada’s dominant soil texture was sandy clay loam, in which laterites may develop to hardpans. All soil values in Kongta were far above critical soil fertility levels and in Magada the average SOM and P content were just at or clearly below those. In Kongta the soil parameters P, K, Ca, sand, clay and A-horizon thickness showed more scattered semivariance than pH and SOM. In Magada, pH, clay, P, SOM and K showed higher scattered semivariance than the more stable parameters Ca and sand. The zonation algorithm of the two hillslopes into landscape elements of homogeneous terrain characteristics was successful in characterizing the spatial distribution of soils. The spatial patterns of most soil quality parameters were largely arranged as contour bands along the elevation gradients. This overriding influence of terrain on spatial variability of most soil parameters was related to slope gradient, upslope contributing area and geometric shapes of landscape elements that in turn influence pedohydrological processes. The explanation of the soils′ spatial variability in Kongta and Magada, respectively, including the best combination of environmental predictors were for pH (37%, 41%), SOM (41%, 42%), P (24%, 9%), K (27%, 27%), Ca (42%, 41%), sand (16%, 43%), clay (36%, 50%) and A-horizon thickness (8%, 31%). In places where stonelines and vegetation structures were missing, SOM together with fine earth material was most likely eroded.

The ^{137}Cs modeling was found to be a suitable technique to estimate the soil erosion and sedimentation rates of soil on hillslopes in the humid tropics of Africa such as in Uganda. The average ^{137}Cs reference inventories were 392 and 439 Bq/m^2, for Kongta and Magada, respectively. The spatial pattern of ^{137}Cs inventories at both sites occurred in broad zones generally following the elevation contours. The modeled soil redistribution rates were for Kongta -21 t/ha/yr and for Magada -4.5 t/ha/yr. The overall soil erosion and sedimentation patterns followed mainly the sequence of landscape units with higher and lower slope gradients, whereas on a smaller scale the pattern follows the sequence of landscape elements, which changed by profile and plan curvature. The sedimentation pattern in Kongta seemed to be a result of the impact of stonelines, whereas the sedimentation pattern in Magada seemed to be related to the spatial distribution of vegetation structures. The strength of the ^{137}Cs approach is that only one field survey is necessary for sample collection compared to long-term observations of traditional erosion assessments.

This study showed the dominant influence of geomorphology on the national-scale and of terrain and land management on the hillslope-scale in determining the spatial variability of soils in Uganda. Policy makers in Uganda can use the national-scale soil quality GIS-information for targeting investment programs on soil improvement to specific regions. This new spatial soil quality information can be directly integrated with other GIS-information and should provide a sound basis for the formulation of national policies for soil improvement and land conservation and use in Uganda. For the land users themselves, the demarcation of the hillslopes into landscape elements is relatively straightforward. It can be done by farmers and/or agricultural extension services directly in the field as tested in one village. This technique is reliable as was proven with the ^{137}Cs modeling technique. These hillslope delineation tools can help farmers in tailoring land use systems that are targeted to different units within the landscape.

Räumliche Variabilität von Böden im nationalen Maßstab und in Hangeinzugsgebieten in Uganda

KURZFASSUNG

Für Politiker, Regionalplaner, landwirtschaftliche Beratungsdienste und Bauern in Uganda ist es eine der größten Herausforderungen die starke Bodendegradierung in ihrem Land aufzuhalten und umzukehren. Diese Herausforderung ist besonders groß, da die Bodenressourcen in Uganda eine sehr hohe Variabilität im nationalen und lokalen Maßstab aufweisen. Diese Studie soll die räumliche Variabilität von Bodenparametern im nationalen Maßstab und in Hangeinzugsgebieten untersuchen, sowie die Bodenerosions- und Sedimentationsraten und deren Prozesse in Hangeinzugsgebieten in Uganda feststellen. Der Zweck dieser Forschung war es, Hilfestellung in der Entwicklung von verbesserten und an die spezifischen Bodenressourcen in Uganda angepassten Landmanagementstrategien zu geben, um eine wirkungsvollere und nachhaltige landwirtschaftliche Entwicklung zu erreichen.

Auf nationaler und Landschaftsebene wurden Untersuchungen durchgeführt, um in 107 Dörfern ca. 2,000 Oberbodenproben zu entnehmen. Diese Bodenproben wurden auf die Hauptbodenqualitätsparameter pH-Wert, organische Substanz des Bodens (SOM), verfügbarer Phosphor (P), austauschbares Kalium (K), austauschbares Calcium (Ca), Sand, Ton und Schluff analysiert. Umweltdaten zu Geologie, Geomorphologie, Klima, Topographie, Flächennutzung, Landmanagement, Bevölkerungsdichte und Marktzugang wurden gesammelt und mit den Bodendaten in einem geographischen Informationssystem (GIS) integriert, um statistische, räumliche und Geländeanalysen durchzuführen. In zwei Hangeinzugsgebieten wurden Erosions- und Sedimentationsmuster mittels Caesium-137 (^{137}Cs) Modellierung untersucht, eine Methode, die bisher noch nicht in den humiden Tropen Afrikas angewendet wurde.

Um Regionen unterschiedlicher landwirtschaftlicher Entwicklung zu klassifizieren, welche die Bodenvariabilität beeinflussen können, wurden Bevölkerungsdichte, Marktzugang, landwirtschaftliches Potential und Geländehöhe als Eingangsparameter für eine GIS-basierte Stratifizierung von Uganda gewählt. Diese Stratifizierung ergab 18 Entwicklungsregionen, die mehr als zwei Drittel von Uganda bedecken. Die Analyse der Varianzeigenschaften dieser Faktoren zeigte, daß die Stratifizierung zur Klassifizierung der räumlich unterschiedlichen Naturressourcen und der sozio-ökonomischen Faktoren in nahezu homogene Entwicklungsregionen geeignet war. Alle analysierten Bodenparameter wiesen über das gesamte Untersuchungsgebiet eine hohe Streuung auf, z.B. pH-Wert (4-7), SOM (1-24%), P (1-800 mg/kg), K (1-500 mg/kg), Ca (1-700 mg/kg). Die durchschnittliche Bodenart in Uganda war sandig-toniger Lehm. Die detaillierte räumliche Analyse der Bodenproben ergab, daß die lokale Topographie die räumliche Verteilung von pH-Wert, SOM und Ton, aber nicht von P, K, Ca, Sand und Schluff stark beeinflussen kann, die eher durch die spezifische Landnutzung und das Landmanagement bestimmt werden. Die meisten Bodenparameter zeigten eine geringe bis mittlere räumliche Abhängigkeit. Die Parameter pH-Wert, SOM, Ton, P und K streuten stärker in der Semivarianz als Sand, Schluff und Ca. Die räumlich interpolierten GIS-Karten, die auf durchschnittslichen Bodendaten pro Dorf basierten, zeigten Uganda´s regionale Bodendisparitäten mit größeren und relativ

homogenen räumlichen Mustern für SOM, P und K. Die Karten des pH-Wertes und der Bodenart hatten feinere räumliche Muster, die sich innerhalb kürzerer Entfernung veränderten. Extrem konträre Bodenparametermuster wurden zwischen den Tieflandbereichen in Zentral-Uganda und der westlichen Region ermittelt, sowie dem östlichen und dem südwestlichen Hochland. Regionen mit mittleren bis stark sauren pH-Werten (pH 5.2 - 4.3), die das Pflanzenwachstum einschränken, wurden in größeren Einheiten im Zentrum von Uganda, in Gebieten, die an den Viktoriasee angrenzen und im südwestlichen Hochland festgestellt. Räumliche Muster mit günstigen pH-Werten (pH 5.4 - 6.2) existierten hauptsächlich im West-Süd-Westen und im Nordosten. Die räumliche Verbreitung von SOM erreichte in den meisten Gebieten der Forschungsregion ein Niveau, das für den Pflanzenbau ausreichend war (> 4%). Kleinere Gebiete innerhalb der zentralen Region hatten aber SOM-Werte, die nahe am Grenzwert lagen um limitierend zu sein (ca. 3%). Höhere SOM-Werte (9-11%) wurden im östlichen und südwestlichen Hochland gefunden. Die räumlichen Verbreitungsmuster der Pflanzennährstoffe P, K und Ca waren den SOM Mustern ähnlich und hatten Werte, die über die gesamte Untersuchungsregion günstig für den Pflanzenanbau waren. Die niedrigsten Werte von K (15.8 - 25.2 mg/kg), P (4.67 -29.1 mg/kg), Ca (57.4 - 65.5 mg/kg), relativ zu den Grenzwerten, befanden sich hauptsächlich in Zentral-Uganda. Die höchsten Werte von K (90.7 – 100 mg/kg), P (200 - 225 mg/kg) und Ca (122 – 130 mg/kg) über den Grenzwerten, traten in kleineren Gebieten innerhalb der Hochländer auf. Der niedrigste Sandgehalt (26.8 - 33.3%) war in den Hochländern, während der höchste Sandgehalt (77.9 - 84.2%) im Osten und im Nordosten zu finden war. Die Gebiete mit niedrigerem Tongehalt (5.92 - 17.4%) lagen in der Zentralregion und im Westen, während der höchste Ton- (52.0 - 57.7%) und der höchste Schluffgehalt (31.2 - 34.3%) in den Hochländern gefunden wurde. Im nationalen Maßstab wiesen die Faktoren Geologie und Geomorphologie das höchste Erklärungspotential für die räumliche Variabilität der meisten Bodenparameter auf mit der Ausnahme von Phosphor, der hauptsächlich durch die Landnutzung und das Landmanagement bestimmt war. Insgesamt ergaben sich für die Bodenparameter folgende Erklärungsgewichte: pH 22%, SOM 54%, K 33%, Ca 23%, Sand 52%, Ton 43%, Schluff 58% und P 37%.

Im Maßstab von Hangeinzugsgebieten wurden zwei Standorte ausgewählt: Kongta im Hochland, und Magada im Tiefland. Die durchschnittliche Bodenart in Kongta war Ton, während Magada sandig-toniger Lehm als dominierende Bodenart aufwies, in der sich Laterite zu harten Krusten entwickeln können. Alle Bodenwerte in Kongta waren weit über den kritischen Bodenqualiätswerten und in Magada war der durchschnittliche SOM- und P-Gehalt genau an oder deutlich unter diesen Werten. In Kongta zeigten die Bodenparameter P, K, Ca, Sand, Ton und A-Horizont-Mächtigkeit eine stärkere Streuung in der Semivarianz als der pH-Wert und SOM. In Magada zeigten pH-Wert, Ton, P, SOM und K eine stärke Streuung in der Semivarianz als die eher stabileren Parameter Ca und Sand. Der Zonierungsalgorithmus, der in den zwei Hangeinzugsgebieten Landschaftselemente mit homogenen Geländeparametern erzeugte, konnte erfolgreich genutzt werden, um die räumliche Verteilung des Bodens zu erfassen. Die räumlichen Muster der meisten Bodenqualitätsparameter waren größtenteils wie Bänder entlang der Höhengradienten angeordnet. Dieser vorrangige Einfluß der Geländetopographie auf die räumliche Variabiliät der Bodenparameter hing mit der Hangneigung, dem spezifischen Hangeinzugsbereich, und den geometrischen Formen der Landschaftselemente zusammen, die wiederum pedo-hydrologische

Prozesse beeinflussen. Die Erklärung der Bodenvariabilität unter Verwendung der besten Faktorkombinationen, waren jeweils in Kongta und Magada für pH-Wert (37%, 41%), SOM (41%, 42%), P (24%, 9%), K (27%, 27%), Ca (42%, 41%), Sand (16%, 43%), Ton (36%, 50%) und A-Horizont-Mächtigkeit (8%, 31%). In Hangbereichen, in denen Steinlinien und Vegetationstrukturen fehlten, wurde SOM zusammen mit Feinmaterial höchstwahrscheinlich erodiert.

Die Modellierung von ^{137}Cs hat sich als eine geeignete Technik erwiesen, um die Bodenerosions- und Sedimentrate in Hangeinzugsbereichen in den humiden Tropen von Afrika, wie z.B. in Uganda, zu berechnen. Die durchschnittlichen ^{137}Cs Referenzinventurwerte waren für Kongta 392 Bq/m^2 und für Magada 439 Bq/m^2. Die räumlichen Muster der ^{137}Cs Referenzinventurwerte bildeten in beiden Standorten breite Zonen, die überwiegend entlang der Höhenkonturen verliefen. Die modellierten Bodenumverteilungsraten betrugen für Kongta -21 t/ha/yr und für Magada -4.5 t/ha/yr. Die gesamten Bodenerosions- und Sedimentmuster folgten hauptsächlich der Abfolge der Landschaftseinheiten, die vor allem durch höhere und niedrigere Hangneigungen charakterisiert waren. Auf kleinerem Raum folgte dagegen das Bodenerosions- und Sedimentationsmuster der Anordnung von Landschaftselementen, die sich mit der horizontalen und vertikalen Krümmung der Hangeinzugsgebiete änderten. Das Sedimentationsmuster in Kongta schien sich auf Grund der Steinlinien entwickelt zu haben, während das Sedimentationsmuster in Magada mit der räumlichen Verteilung der Vegetationstrukturen zusammenzuhängen schien. Die Stärke der ^{137}Cs-Modellierungsmethode besteht darin, daß nur eine Probenentnahme im Feld für die Abschätzung der Erosionsrate notwendig ist, verglichen mit dem langwierigen Monitoring traditioneller Methoden.

Diese Studie zeigte den dominierenden Einfluß der Geomorphologie im nationalen Maßstab sowie der Topographie und des Landmanagements im Maßstab von Hangeinzugsgebieten auf die räumliche Variabilität von Böden in Uganda. Politiker in Uganda können die nationalen GIS-Informationen über die Bodenqualität für gezielte Investitionsprogramme zur Bodenverbesserung in spezifischen Regionen verwenden. Diese neuen räumlichen Bodenqualitätsinformationen können direkt mit anderen GIS-Informationen integriert werden und sollten eine solide Grundlage für die Formulierung der nationalen Politik zur Bodenverbesserung, -Konservierung und -Nutzung in Uganda sein. Für die Landnutzer ist die Abgrenzung der Hangeinzugsbereiche in Landschaftselemente verhältnismäßig unkompliziert. Sie kann durch Landwirte und/oder landwirtschaftliche Beratungsdienste direkt durchgeführt werden, wie in einem Dorf gezeigt wurde. Die Technik ist zuverlässig, wie mit der ^{137}Cs Modellierungsmethode nachgewiesen wurde. Diese Methode zur räumlichen Differenzierung von Hangeinzugsbereichen kann Landwirten helfen, ihre Flächennutzungsysteme gezielt auf die unterschiedlichen Raumeinheiten innerhalb der Landschaft abzustimmen.

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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.

Chapter 5 contains the discussion on the hillslope-scale soil variability. The selected hillslopes are described and the procedures for the soil, terrain, land use and land management surveys are documented. Based on terrain analysis, the hillslope delineation procedure is presented. The spatial variability, spatial structure, interpolation and the causes of soils´ spatial variability on hillslope-scale are described.

Chapter 6 includes the research on hillslope-scale soil redistribution by the ^{137}Cs modeling approach. The modeling approach and the selected models are reviewed. The sampling of ^{137}Cs on the hillslopes and the laboratory measurement of this radionuclide are described. The potential to use this technique for spatial soil redistribution estimations in the humid tropics of Africa is discussed. The spatial soil redistribution rates, patterns and determining processes are investigated.

Chapter 7 summarizes the major findings of this thesis, draws conclusions and gives recommendations.

2 THEORY OF SPATIAL SOIL VARIABILITY

2.1 Variability components

Spatial variability consists of two main variance components: deterministic and stochastic (Burrough, 1993; Wilding, 1994; McBratney et al, 2000). In the case of soil spatial distribution, the deterministic component is traditionally represented by the five soil forming factors: parent material, vegetation, topography, climate, and time (Jenny, 1941). The stochastic components are defined as random functions, studied through data sampling. The investigation of these variance components is directly related to the question as to where the spatial system boundary should be set. Figure 2.1 visualizes the variability of soil attributes on different spatial systems comprising of a hillslope, field and nation.

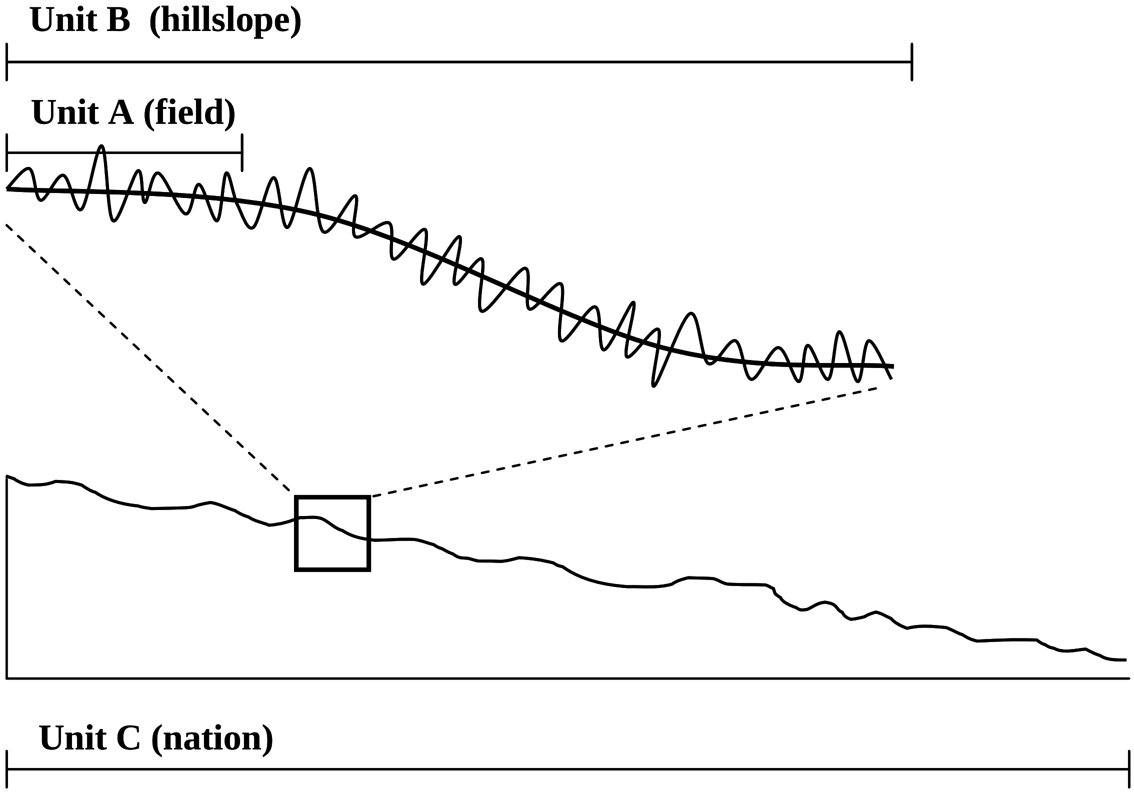

Figure 2.1: Schemata of spatial variability of soil on different scales (after Park, 2002)

Soil properties on a hillslope often vary in response to the way water and soil materials are transported through and over the terrain. Many studies have proven the existence of such spatial variation, defined as catena (Conacher and Dalrymple, 1977; Moore et al., 1993; Park and Burt, 1999). When the variation of soil properties is investigated along a hillslope transect, one may consider two different sampling units:

A, equivalent to field, and B, equivalent to hillslope. Intensive sampling within the unit A will reveal enormous variation of soil properties in this unit (Beckett and Webster, 1971). If the observation unit is changed to B, then a spatial pattern can be easily discerned by means of either intensive or scarcer sampling. Similar spatial behavior occurs at higher order spatial systems, e.g. on the national-scale the hillslope becomes Unit A and the national boundary becomes unit B with the respective soil variability.

2.2 Scale dependency

It can be anticipated that the change of system boundary is closely linked with the changes of the dominant system components and their interaction (Kirky et al., 1996). This very often results in a change of the dominant processes explaining the spatial variance within that spatial boundary. Much previous pedological research confirms that topography is the dominant variance generator for the spatial variance observed on a hillslope. However on the national scale, other environmental factors, such as geomorphology, parent material and climatic factors, may have a stronger influence on soil spatial variability than topography. Similarly, family structure and division of labor may be the most important socio-economic factors for resource management on the farm level, but infrastructure, commodity prices and commercialization may become more important on the regional scale (Dumanski and Craswell, 1996).

Such scale dependency of biophysical and socio-economic processes imposes various constraints on soil management. Individual system components and interaction show a wide range of variance characteristics. In their detailed analyses on the spatial distribution of 32 soil properties, Park and Vlek (2002) showed that individual soil attributes respond differently to geomorphologic and pedological processes, which resulted in very different spatial distribution patterns of each soil attribute. This diversity of process-response relationships among different system elements requires the isolation of the most significant elements that explain both the signal and the variance in the response (Becker and Braun, 1999; Park and Vlek, 2002). It is frequently recognized that one process may dominate in eliciting the response. As an example, rainfall distribution may strongly govern specific land use patterns in a semiarid region. The density of the road network may be the key influence of farmers on the selection of specific cash crop production, even with unfavorable climatic and soil condition.

2.3 Modeling spatial variability

The variance characteristics of certain system element and processes can be divided as deterministic ($m(x)$) and stochastic ($\varepsilon(x)$) components (Burrough, 1993). The stochastic component can be further divided into spatially dependent ($\varepsilon'(x)$), and spatially independent random variations ($\varepsilon''(x)$) including errors associated with measurement or observation, which might be presented as:

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon''(x)$$

where x is a location on the surface.

In current literature, there are three distinct approaches to capture such variance components: 1) deterministic approaches, 2) stochastic approaches, 3) stratification approaches.

2.3.1 Deterministic approaches

The deterministic approaches implicitly assume that the spatial variability of individual natural and anthropogenic variables is a function of certain dependent variables and error ($Z(x) = m(x) + \varepsilon''(x)$). This is most often done by traditional Euclidean distance based statistics, such as regression analyses. Under this framework, the deterministic approach to include soil characteristics into model structure only focuses on the spatial association of individual soil attributes with various environmental factors ignoring the stochastic component.

2.3.2 Stochastic approaches

The statistical method, which is called geostatistics, focuses on the stochastic components of spatial variability ($Z(x) = \varepsilon'(x) + \varepsilon''(x)$). A variogram describes the variance of the stochastic component of spatial variability of a property as a function of the distance between sample points. This theory assumes that places that are near to each other are more alike than those that are further away. If the mean and variance of a property do not exhibit systematic spatial trends (second-order stationary), the variogram will reach a maximum (the sill) at a certain lag (range). This stationarity assumption is clearly unrealistic in field survey, ignoring the deterministic variance components known as “drift”. The main limitation is that accurate interpretations of the stochastic components of model input parameters over the space require a large number of samples to identify the spatial dependency (Burrough, 1993; McBratney et al., 2000).

2.3.3 Stratification approaches

One possible alternative is to ensure the representativeness of collected soil information based on a stratification of the landscape according to *a priori* criteria and to specify the magnitude of the variability at each domain. In this approach, the spatial variability of certain variables may be considered as the realization of spatial dependent random variability embedded into the deterministic component of soil variability. The spatial determistic components may be considered as spatial hierarchical, which can be defined as follows (Park and Vlek, 2002):

$$Z(x) = m_i(\varepsilon_i'(x) + \varepsilon_i''(x)) + \varepsilon''(x)$$

where i is defined as the spatial observation unit, which takes the scale-dependency of variance components into account.

The justifications for this argument are 1) there are distinct spatial domains over the landscape where similar processes occur; 2) spatial processes and resultant variability of soils are apparently continuous, but with differing intensities and magnitudes across the boundary of spatial domains due to the variability in prevailing earth surface processes. When the spatial domains are successfully delineated, then the variation within the domains is the product of the linear function of environmental variables (Puvaneswaran and Conacher, 1983; Becker and Braun, 1999). The validity of this assumption mainly depends on the range of spatial dependence of the particular variable related to the size of spatial domains. Above all, the criteria and thresholds used to stratify spatial domains are of paramount importance.

3 SPATIAL STRATIFICATION OF UGANDA

3.1 Introduction

It is widely accepted that blanket soil management strategies on a national-scale may not necessarily be suitable on lower administrative levels (Pender, 1999). However, the tailoring of soil management strategies to a specific scale is often exacerbated by the huge spatial complexity of biophysical and socio-economic conditions that may occur in a target region. In Uganda, natural resources such as geology, topography and climate, are highly diverse. Similar complexity occurs for socio-economic factors, e.g. population density and market access. Figure 3.1 shows Uganda's geographic location.

Figure 3.1: Geographic location of Uganda

As Figure 3.1 shows, Uganda is located astride the equator in East Africa stretching from 4° 12′ north to 1° 29′ south and from 29°34′ west to 35° 0′ east. The total area of the country is ca. 230,000 km^2. The land surface covers 179,400 km^2, while open water such as that of Lake Victoria takes about 18% of Uganda's surface area (Harrop, 1970).

The present plateau position of Uganda lies between the Western and the Eastern African Rift Valleys and was caused by geological uplift of the pre-Cambrian age. Since then weathering and erosion processes have dissected the old peneplain and created four main surfaces (Harrop, 1970). The younger and less represented geological resources comprise alluvial, colluvial and volcanic material. Recent erosion processes produced the present spatial distribution of land surfaces including flat-topped, gently rolling ridges that are separated by wide valleys in the centre, rolling and undulating plains in the north and landscapes with steep slopes and deep valleys in the eastern and western highlands (Wortmann and Eledu, 1999).

The average annual rainfall declines from 2160 mm in the south (Lake Victoria) to 510 mm in the northeast (area bordering Sudan). Very steep rainfall gradients exist in short transition zones from lowland to highland areas. Two distinct rainy seasons occur in the southern and central part of Uganda, whereas uni-modal rainfall distribution prevails in the northern and southwestern dry areas as well as in the highlands. Annual average temperature shows little spatial variation in the lowland. It ranges from 30 to 32 °C in the north and from 30 to 25 °C in central Uganda. The annual average temperature decreases markedly in the highlands, and ranges from 25 to 4 °C (Jameson and McCallum, 1970).

More than 90% of Uganda's population inhabit rural areas. The population decreases generally along a south-north gradient, from ca. 150 persons per km^2 around Kampala in the south to less than 40 persons per km^2 in the north. The population decreases further from the highlands to the rural lowlands, from over 300 persons per km^2 in the eastern and south-western highlands to less than 15 persons per km^2 in the north-eastern lowlands (MPFED, 1999).

The annual cultivation area in Uganda covers about 8.4 million ha. Most of this area is under small-scale farming with an average farm size of 2.5 ha (MPFED, 1999). The agricultural markets to purchase inputs such as improved seeds, pesticides and fertilizers are weakly developed in Uganda. Mineral fertilizers are mainly applied to cash-crops such as maize, tobacco, coffee and tea, but only in small quantities. The capital Kampala is the dominant output market, whereas the markets at district capitals have a relatively insignificant output share (FAO, 1999).

The approach of this study is to stratify the whole territory of Uganda into spatial domains that are homogeneous in terms of chief natural resource and socio-economic factors influencing soil variability by applying a GIS-based stratification model. Since the natural and socio-economic conditions that may influence soil resources on the national-scale in Uganda may have very complex interactions, and due to the difficulty of collecting very detailed soil sample information for the whole country, this stratification serves as a pre-classification on which more detailed soil variability studies can be built.

3.2 Material and methods

3.2.1 Conceptual framework

The identification of the dominant factors that determine the variance of an agro-ecosystem can help to reduce spatial variability. This strategy has been used in many conceptual approaches on the national and the continental scale. On these scales, the diverse natural resource and socio-economic conditions can be classified into homogeneous spatial domains, although internal variability may still be large within each domain. Different spatial stratification approaches have been reported to assist agricultural policy formulation aiming at soil improvement (Ruecker et al., 2001). Wood and Pardey (1998) grouped these approaches into three categories: 1) generic stratification, 2) clustering approach, and 3) model-based stratification.

A *Generic stratification* uses a generally and broadly defined set of ecological and socio-economic variables to demarcate homogeneous domains in terms of major production systems and natural-resource degradation hazards. One example for the application of the generic stratification on a global scale is the agro-ecological zones (AEZ) project (FAO, 1996). The TAC/CGIAR further generalized FAO´s AEZ on the continental scale and used two derived climatic variables, one based on temperature and another one on moisture availability to delineate homogeneous eco-regions (Gryseels et al., 1992). Generic stratification was mainly applied for coarse stratifications to suit a large range of potential research questions at broad scale. However, applications of this concept on this scale are rare. Specific research questions are commonly addressed on a more detailed scale such as on the national level, and spatial variations need to be investigated on a commensurate scale.

In the *clustering approach*, natural and socio-economic variables are statistically grouped to reduce the variability of the considered agro-ecosystem. There are many different clustering methods (Gauch, 1980; Estivill-Castro, 2002). All of these methods are applied with the common objective of classifying a sample of entities into a smaller number of exclusive groups or clusters based on the multivariate similarities among the entities. Since the choice of the similarity criteria is subjective, it is generally recommended to replicate the analysis under varying conditions (Everitt, 1977).

Multivariate cluster analysis was for example applied by Batjes (2002). He included the variables soil unit, topsoil texture class, and topsoil depth to cluster the horizon data of over 9600 soil profiles held in the World Inventory of Soil Emission Potential (WISE) database. The generated spatial clusters and derived soil attributes are appropriate for regional- to global-scale soil resource studies. Cluster analysis was also employed by Kelly et al. (1997) to demarcate agricultural sub-divisions for the whole territory of India. They integrated various data on crop production and socio-economic factors, e.g. gross value of production of 15 major crop activities and gross value of production of two major livestock activities. Cluster approaches have mainly been used in large-scale studies, where the objective is to delineate zones that are suitable for a wide range of potential research questions. If more precise and more specific scientific information is required, a different stratification approach needs to be chosen, which is more accurately designed for the spatial variability of resource conditions of the target areas and more tightly coupled to the specific research agenda (Batjes, 2002).

The *model-based stratification* is an approach in which carefully selected natural resource and socio-economic variables that characterize the specific agro-ecosystem processes of interest within a study region are systematically combined to demarcate spatial domains. The selection and combination of variables require comprehensive ex-ante assessment of the processes in the target region and is often based on a conceptual model. In an IFPRI study in Burkina Faso, Wood et al. (1999) demarcated different domains of agricultural potential by model-based stratification using multi-temporal satellite data from NOAA´s Advanced Very High Resolution Radiometer (AVHRR). They combined average normalized difference vegetation index (NDVI) and its inter-annual variability using GIS-based intersections. The NDVI-based agricultural potential was chosen since it represents the integrated effects of climate and soil processes on agricultural potential. This model-based stratification is very flexible because criteria and boundary conditions of the stratification domains are developed only for a specific target-area based on ex-ante assessments (Pardey and Wood, 1994). Although the model-based stratification has been applied mainly on national-level studies, it is also suited to agricultural resource stratification on a more detailed scale, where specific agro-ecosystem processes are studied. However, this specific model-based procedure does not allow direct comparisons of stratification results from several regions with contrasting processes because of the different conceptual models applied.

Based on methodological reviews on existing national-scale spatial stratification concepts, the model-based stratification approach was chosen in this study to reduce the variability of natural and socio-economic factors related to soil conditions over Uganda[1]. The complexity of the different agricultural processes on the national scale and the currently available small scale national-level GIS data may easily result in conceptual and generalization errors. However, the purpose of this study is a pre-classification of the whole territory of Uganda into homogeneous spatial domains. Since the spatial distribution of major natural and socio-economic factors that influence soil resources is relatively similar within each domain, the available GIS data are suitable at this spatial scale.

3.2.2 Development pathway model

Natural resource and socio-economic factors that determine soil conditions in a region can be spatially integrated by using a conceptual model. The model chosen for the proposed stratification is that of ”development pathways” (Pender et al., 1999). A “development pathway” is defined as a common pattern of change in farmers´ livelihood strategies, associated with its causal and conditioning factors (Ibid.). If, for example, factors such as high population density, high agricultural potential and low

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[1] The detailed theoretical discussion on how to capture spatial variability on national scale and a comparison of different spatial stratification strategies is presented at Ruecker et al. (2003a).

market access are gaining dominance in an agricultural region, farmers might intensify cash crop production as their pathway of development (Pender et al., 1999; Pender, 1999). This intensification might, in turn, change soil resources by soil nutrient depletion if the nutrient losses are not replenished. In contrast, if factors such as low population density, low agricultural potential and low market access dominate, farmers might adopt development strategies to decrease crop cultivation and to increase livestock production. These strategies might again improve soil nutrient resources in the region due to nutrient inputs from livestock and extensive systems including fallowing. Since the pathway of development model integrates the complex interactions of natural resource and socio-economic factors that may largely determine soil conditions within regions, this model may be appropriate as a pre-classification tool to capture the spatial variability of soil resources on a national scale of Uganda.

3.2.3 Stratification factors and data

Pender et al. (1998) suggested four main factors that are particularly important in development pathways in sub-Saharan Africa. These factors include population density, market access, agricultural potential and elevation (cited in Wood and Pardey, 1998).

1) Population density may influence the intensity of labor in agricultural production by affecting the land/labor ratio. Higher population density within a region may affect the natural resources by increased cultivation and soil nutrient depletion.

2) Access to markets is critical to determining the comparative advantage of a site given its production potential for agricultural products. For example, there is little or no comparative advantage in perishable crop production if the production site is located far from urban markets. Access to inputs will similarly be affected by market proximity.

3) Agricultural potential is an abstraction of many factors such as rainfall amount and its temporal distribution, soil type and depth, presence of pests and diseases. These factors influence the absolute advantage of a particular site to generate agricultural products, and may in turn determine soil conditions.

4) Elevation of land has a major influence on agro-climate, soil, and crop management in mountainous regions. Elevation affects rainfall distribution, soil erosion processes and growing cycles of crops, which in turn influence the soil resources by the combined interactions of hydrological, pedological and agronomic processes.

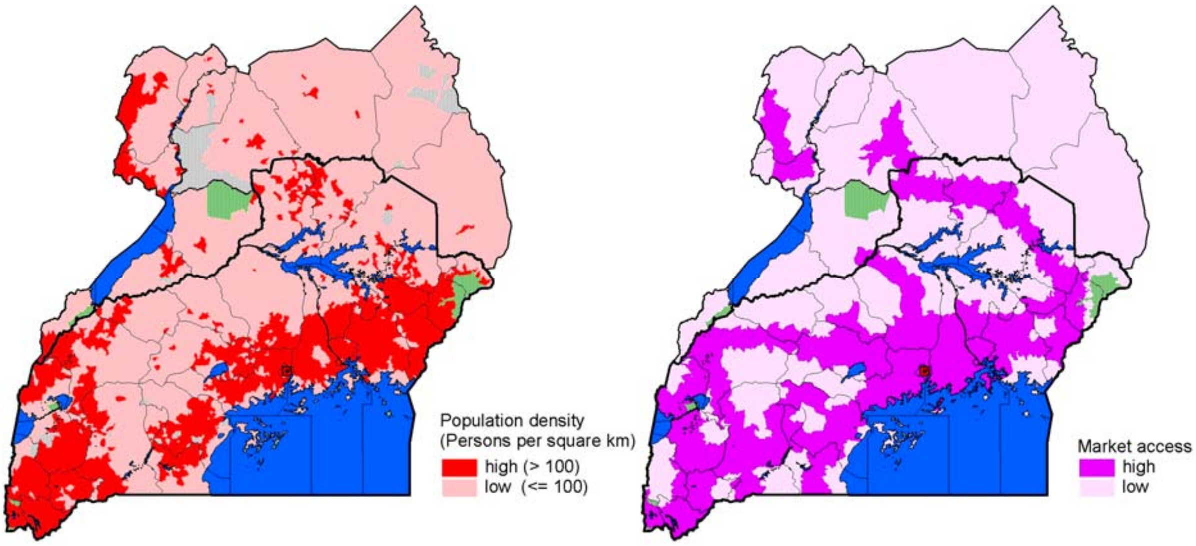
These four factors were combined in a GIS-based stratification to spatially demarcate “development domains” for the territory of Uganda. The description of the raw data, spatial scales and sources to generate these factors is listed in Table 3.1.

Table 3.1: Data description and sources used in the stratification

Stratification factor	Scale	Source	Remarks
Population density	“Parish” (corresponding to one local administrative unit above community level)	GIS-parish boundaries: Ministry of Natural Resources, Department of Forestry, Uganda, (1999); Population data: Ministry of Finance and Economic Planning - Statistics Department-Cartography Unit (1997)	Population data from the latest available national census (1991)
Market access	5 x 5 km raster	World Resource Institute (WRI) (1999)	Algorithm after Deichmann (1997)
Agricultural potential	5 x 5 km raster	Corbett and O´ Brien (1997) Corbett and Kruska (1994)	Average data from long-term monthly mean climatic records
Elevation	1 x 1 km raster	Hutchinson et al. (1995)	Digitized data from air navigation charts and maps at more detailed scales; ANUDEM algorithm to construct DEM (Hutchinson 1989)

The detailed algorithms needed to generate the spatial distribution of the factors are reported in Ruecker et al. (2003a) and the maps are shown in Figure 3.2.

Population density **Market access**



Elevation **Agricultural potential**

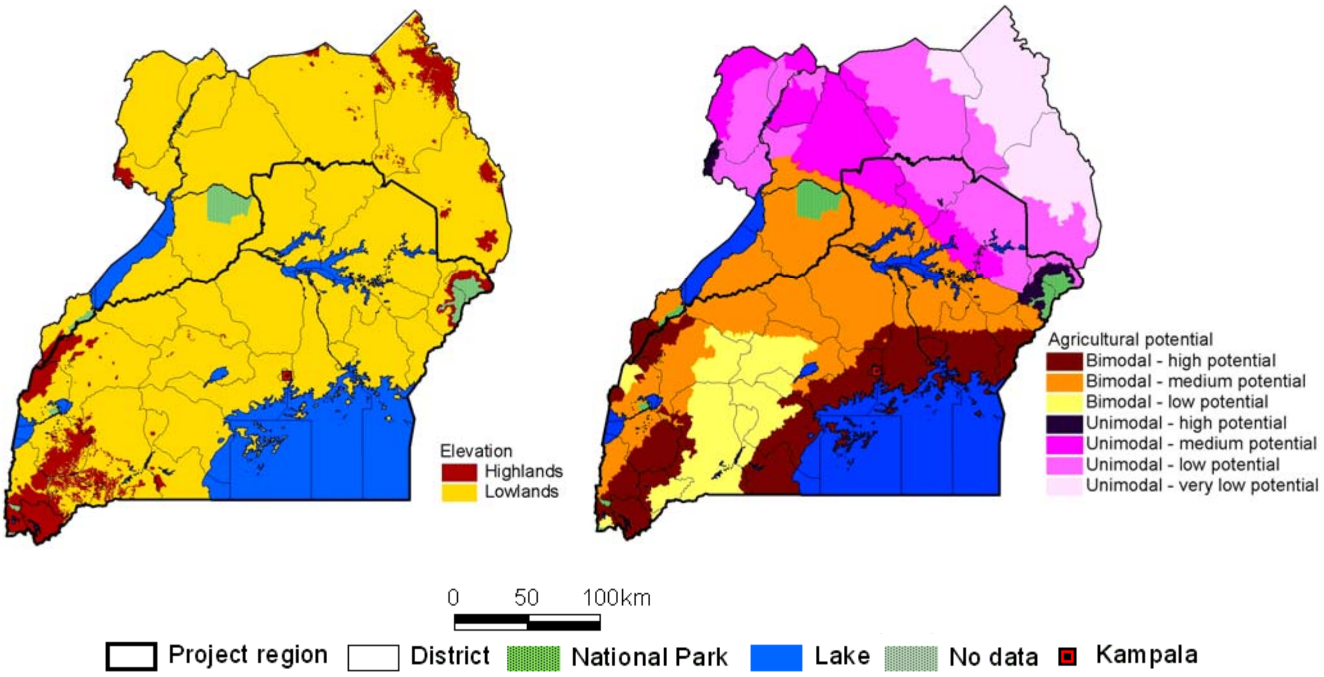


Figure 3.2: Input factor level distribution for the spatial stratification of Uganda

Due to the fact that the factor agricultural potential was generated by integrating several spatial domains, including seasonality, length of growing period, annual precipitation potential and temperature potential, the spatial representation of these individual domains is shown in Figure 3.3.

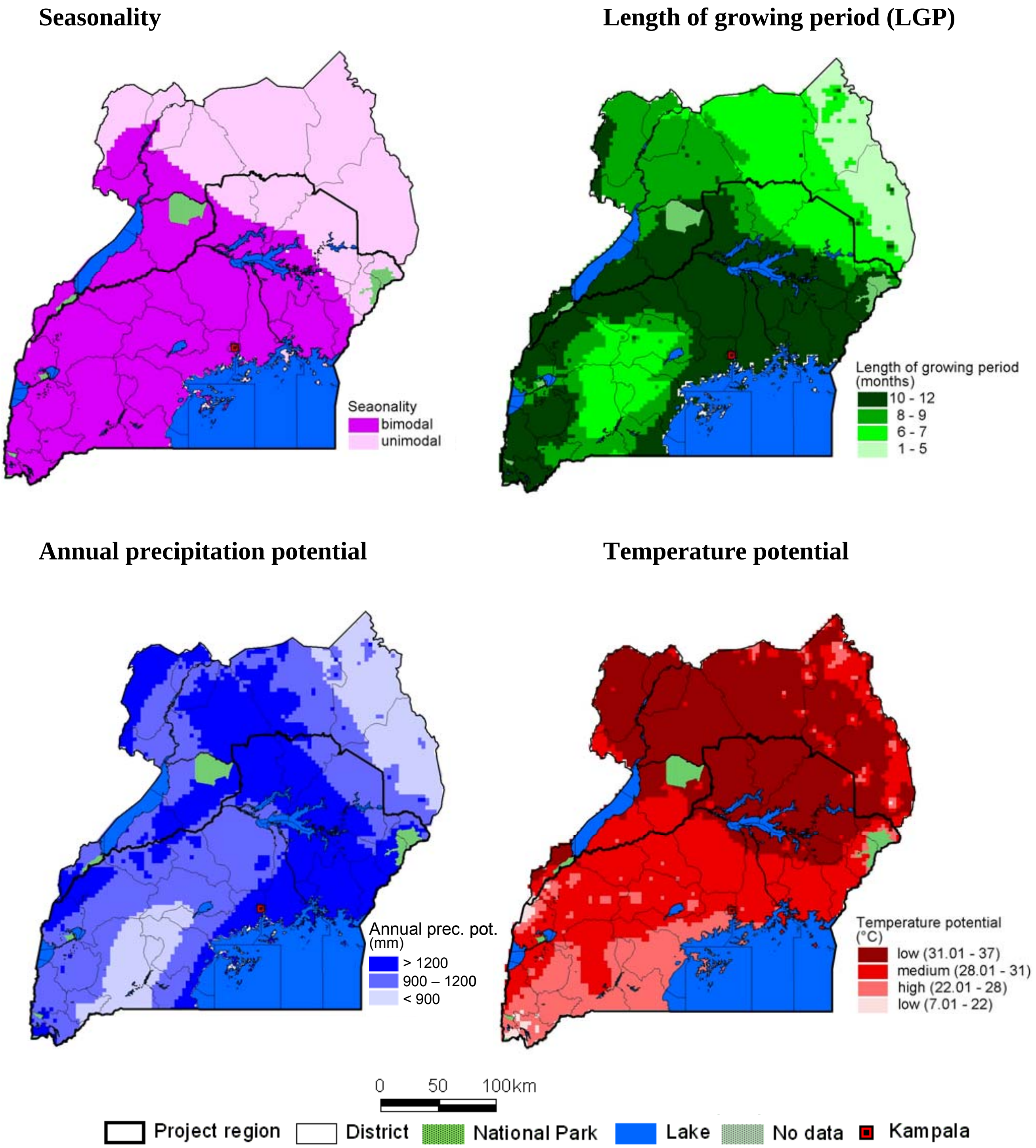


Figure 3.3: Spatial domains used to map agricultural potential in Uganda

3.3 Results and discussion

3.3.1 Stratification of Uganda into development domains

The factors population density, market access, agricultural potential and elevation were stratified by a spatial overlay in a Geographic Information System. In this overlay each factor was treated with equal weight to classify Uganda into development domains. Considering seven agricultural potential domains (including the eastern and western highlands as separate domains and combining unimodal low and medium potential domains), and two domains each for population density and market access, twenty-eight domains were theoretically possible. Some combinations of domains were non-existent or unimportant in Uganda and were eliminated or combined. The final stratification represents eighteen domains (Figure 3.4, Table 3.2).

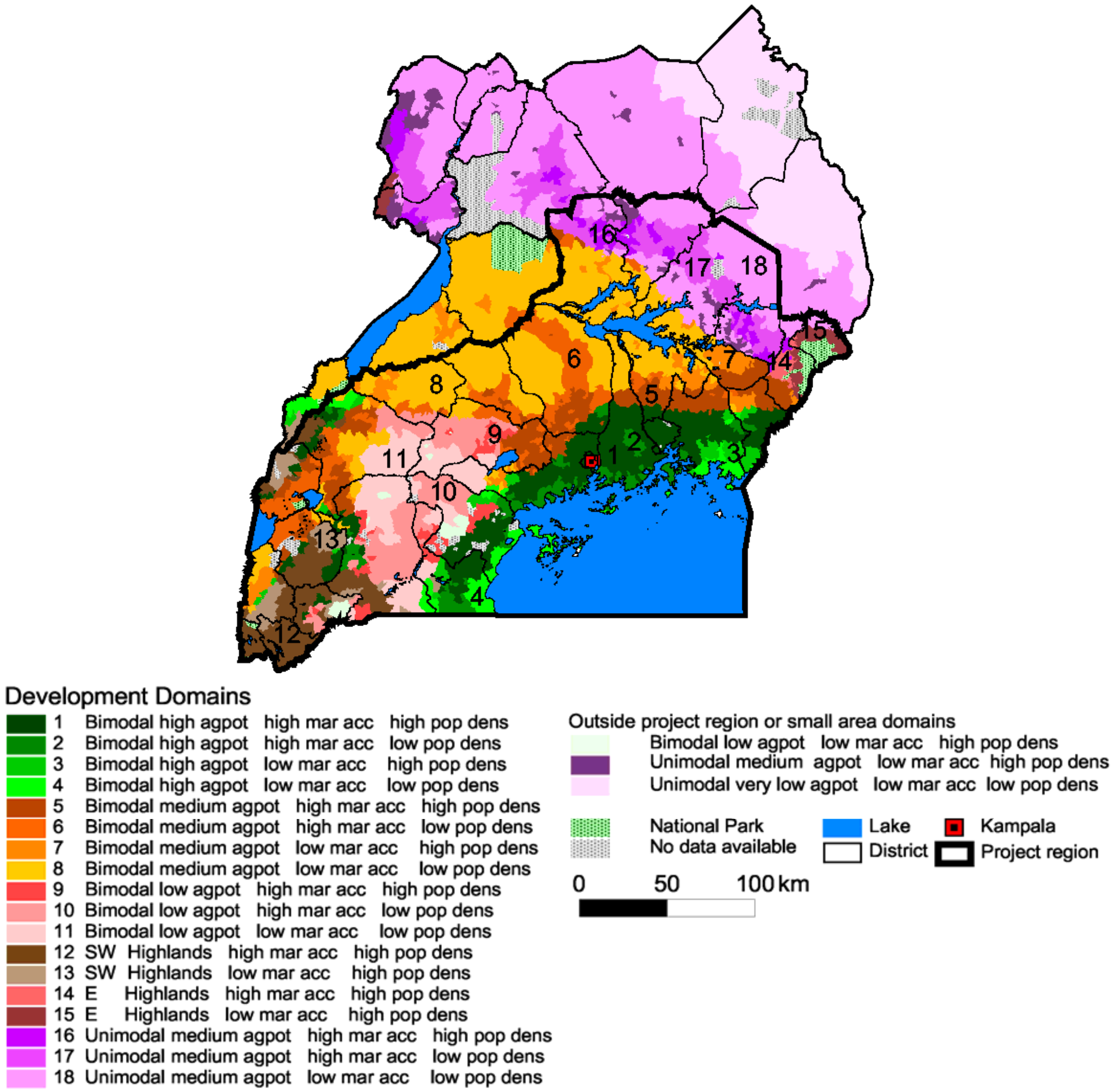


Figure 3.4: Spatial stratification of Uganda into development domains

Note: agpot = agricultural potential, pop dens = population density, mar acc = market access.

3.3.2 Spatial variation of indicators characterizing development domains

The development domains that are demarcated in Figure 3.4 are characterized by specific values of population density, market access, agricultural potential and elevation. Furthermore, the domains vary in terms of area extent and districts covered by specific domains. These indicators that may influence the spatial variability of soil conditions according to the pathway of development theory are indicated in Table 3.2.

Table 3.2: Factor combinations, area and covered districts of development domains[2]

#	Agricultural potential	Market access	Population density	Area [km^2] total	Area % survey region	Districts having more than 10% of their area covered by a specific development domain
1	Bimodal high	high	high	**14292**	9.4	IGANGA, MASAKA, MPIGI, MUKONO, RAKAI
2	Bimodal high	high	low	6756	4.4	MPIGI, MUKONO, RAKAI
3	Bimodal high	low	high	2201	1.4	BUGIRI, BUSIA, IGANGA, MASAKA, RAKAI
4	Bimodal high	low	low	**13167**	8.6	KALANGALA, MASAKA, MUKONO, RAKAI
5	Bimodal medium	high	high	9723	6.4	IGANGA, KABAROLE, LUWEERO
6	Bimodal medium	high	low	8682	5.7	KABAROLE, KASESE, KIBOGA, LUWEERO, NAKASONGOLA
7	Bimodal medium	low	high	4264	2.8	KAMULI, KIBAALE, PALLISA, RUKUNGIRI
8	Bimodal medium	low	low	**24678**	16.2	APAC, KIBOGA, LUWEERO
9	Bimodal low	high	high	2199	1.4	MASAKA, MBARARA, MUBENDE, RAKAI
10	Bimodal low	high	low	7842	5.1	KABAROLE, MASAKA, MBARARA, MUBENDE
11	Bimodal low	low	low	8185	5.4	KABAROLE, MBARARA, MPIGI, MUBENDE
12	SW Highlands	high	high	7183	4.7	BUSHENYI, KABALE, MBARARA, NTUNGAMO
13	SW Highlands	low	high	2582	1.7	BUSHENYI, KASESE, NTUNGAMO, RUKUNGIRI
14	E Highlands	high	high	<u>523</u>	0.3	KAPCHORWA, MBALE
15	E Highlands	low	high	<u>1094</u>	0.7	KAPCHORWA, MBALE
16	Unimodal medium	high	high	2019	1.3	APAC, KUMI, LIRA
17	Unimodal medium	high	low	5418	3.6	APAC, KATAKWI, KUMI, LIRA, SOROTI
18	Unimodal medium	low	low	**10308**	6.8	KATAKWI, LIRA

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[2] The development domains are listed by their number (#). Domains with a relatively large spatial extent are displayed in bold, while relatively small domains are underlined.

As Table 3.2 shows, the factors and area sizes of the development domains vary considerably across Uganda[3]. These domains are a pre-stratification. The smallest development domains were classified by the area size comprising less than 2% of the project region. This class included the domains # 3, 9, 13, 14, 15 and 16. Domain # 3 is located along Lake Victoria fringe adjacent to the Kenya border. Market access is poor in this niche position. Domain # 9 lies in the West/SW of Uganda at the rim of the drier areas, which is known as the "cattle corridor" (Figure 3.5). This area is mainly characterized by grassland, bushland or woodland (NEMA, 1998).

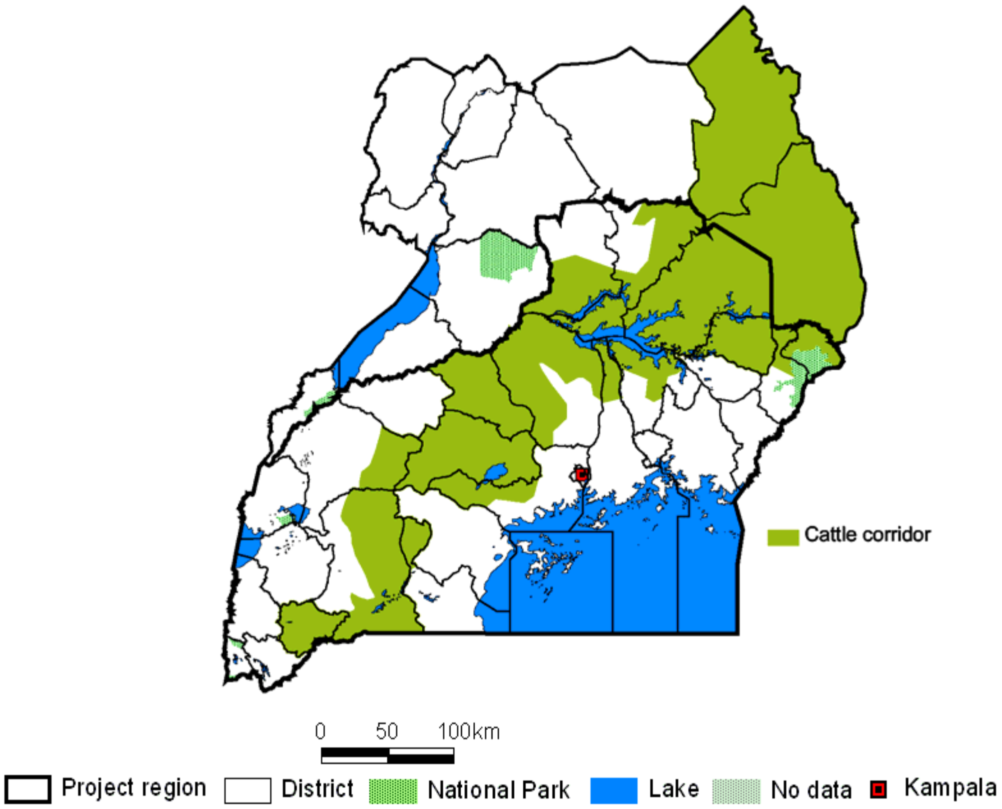

Figure 3.5: Cattle corridor of Uganda (modified after NEMA, 1998)

Agricultural potential is low within the area of this cattle corridor. The small area domain # 13 is located within the southwestern highlands where market access is lacking. Similar marginal agricultural production and market access conditions, which may again influence soil conditions, occur for domains # 14, 15, and 16.

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[3] The small areas that were excluded earlier comprise 1.3% of the study region.

The largest development domains cover each more than 8% of the project region. These areas comprise the domains # 1, 4 and 8. They are distributed as belts surrounding Lake Victoria. Domain # 1 is located within the central part of the Lake Victoria Crescent where agricultural production conditions are favorable and Kampala as well as other big cities provide good market access leading to high population density. Southward of domain # 1 is the location of domain # 4 bordering Lake Victoria, whereas domain # 8 is located northward, surrounding Lake Kyoga. Although the domains # 4 and 8 are just a few kilometers apart from domain # 1, good market access is already lacking, because no major roads and cities exist in these areas. The remaining development domains fall in between these larger and smaller domains and represent mixed factor combinations of agricultural potential, population density and market access. Further indicators that characterize the development domains are the stratification factors *population density, elevation and* the agricultural potential input factors *July rainfall, annual rainfall potential, length of growing period and temperature potential.* The variance statistics of these indicators are shown in Table 3.3.

Table 3.3: Variation of specific indicator values within development domains (#)

#	**July rainfall**			**Ann. rainfall pot.**			**Growth period**			**Temp. pot.**			**Population density**			**Elevation**		
	[mm]			[mm]			[months]			[°C]			[persons / km^2]			[m]		
	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
1	58	14	124	1198	837	1464	9.7	7	12	28.6	23.4	30.8	1223	101	26577	1224	1028	2496
2	49	13	83	1240	787	1463	9.9	7	12	28.0	24.3	30.8	99	3	3507	1234	800	2169
3	56	12	92	1157	882	1347	9.1	7	11	28.8	25.9	30.8	187	103	419	1211	915	1933
4	47	6	84	1321	833	1624	10.0	7	12	27.5	26.0	31.4	33	1	99	1219	727	1556
5	72	30	157	1178	916	1575	9.5	7	11	29.6	26.3	32.6	242	101	10877	1176	864	2115
6	60	27	119	1132	916	1370	9.2	7	11	29.7	26.9	32.3	63	6	100	1119	739	1795
7	79	29	145	1175	874	1586	9.1	7	10	30.4	25.5	32.8	195	101	2463	1134	755	1810
8	79	28	117	1169	858	1353	9.1	7	11	30.7	23.2	32.8	49	1	99	1097	610	2169
9	26	5	60	904	754	1100	8.0	6	9	27.7	25.8	28.9	229	101	1612	1335	1151	1859
10	30	7	61	898	701	1239	8.2	6	10	28.3	24.8	29.9	49	7	99	1300	1086	1781
11	28	4	48	882	706	1129	7.4	6	8	28.2	26.1	29.5	45	14	98	1285	947	1749
12	28	4	105	1099	755	1815	9.9	7	12	25.2	16.0	30.8	338	0	5741	1694	1070	3944
13	36	5	127	1118	718	2083	9.5	7	12	24.7	7.1	29.2	198	27	1947	1873	1059	4563
14	133	108	163	1312	1132	1575	9.0	9	9	29.2	23.6	30.6	949	42	7451	1383	1108	1992
15	148	120	164	1278	966	1586	7.7	7	9	27.8	23.8	31.3	423	6	1906	1713	1169	2595
16	124	110	146	1256	1093	1416	8.1	7	9	31.8	28.6	32.8	535	102	5899	1103	1002	1741
17	124	111	143	1232	1063	1408	8.1	7	9	32.3	30.8	33.2	66	4	122	1080	998	1229
18	124	104	155	1165	886	1373	7.5	6	9	32.4	27.0	34.2	51	3	100	1072	971	1768

Table 3.3 shows that most of the indicator values differ widely across and to a smaller extent within domains. Mean July rainfall in Uganda is particular high in the domains # 14 – 18 (ca. 124 - 148 mm) and is low in the domains # 9 – 13 (ca. 26 - 36 mm). While the first domains are located in the North-East of Uganda relatively distant from the Equator with mainly uni-modal rainfall distribution, the latter ones are in the South-Western part of the country near or intersected by the Equator, where bi-modal seasonality is prevalent. Relatively moderate July rainfall amount occurs in the center of Uganda including domains # 1 – 8 (ca. 50 – 80 mm) (Figure 3.3). These findings on seasonality closely match the results of Wortmann and Eledu (1999), who classified agro-ecological zones of Uganda.

The highest annual rainfall occurs in the eastern highlands (domains # 14, 15) due to local orography (ca. 1280 – 1310 mm). High annual rainfall (ca. 1320 mm) is furthermore found in domain # 4, which comprises a small lowland area in the South-West. This rainfall amount is caused by the adjacent location of this domain to the water body of Lake Victoria, where most rainfall water is generated. The areas with the lowest annual rainfall are the domains # 9, 10 and 11, where the cattle-corridor with less rainfall is located (Figure 3.5).

The areas with the longest growing period (9.7 and 10.0 months) are located in the central region adjacent to Lake Victoria with domains # 1, 2 and 4. This is mainly due to the favorable rainfall condition and the moderate evapotranspiration in these areas. In contrast, domains # 11, 15, 18 have the shortest growing period in Uganda (ca. 7.4 – 7.7 months per year on average). In domains # 11 and 18, the short growing period is mainly caused by the relatively high evapotranspiration rates combined with low rainfall as in the south-western and north-eastern part of the cattle corridor (Figure 3.3 and 3.5). The shorter growing period in domain # 15 is due to the low temperatures on Mount Elgon (Figure 3.3), which restrict plant growth. These seasonal patterns match well with the corresponding patterns identified by Foster (1970).

The highest average potential with respect to temperature is found in the North of Uganda comprising domains # 16 – 18, with high annual temperatures of 31.8 – 32.3 °C due to proximity to the tropic of cancer. The lowest temperature potential is in the south-western highlands (domains # 12, 13), where higher elevation causes lower temperatures throughout the year (24.7 – 25.2 °C) (Figure 3.3).

The highest population density values occur within the central part of the Lake Victoria Crescent (domain # 1) and in the eastern highlands (domain # 14), with 949 and 1223 persons/km^2, respectively. In contrast, the areas with the lowest population density are the western part of the Lake Victoria Crescent (domain # 4), the central area around Lake Kyoga (domain # 8) and parts of the cattle corridor in the South-West (domain # 11) (33, 49, 45 persons/km^2). These high population density areas coincide generally with areas that have good road infrastructure, market access and agricultural potential, whereas the low population density areas are poorly connected to markets and have marginal agricultural potential. These distribution patterns correspond well with the compilations of Rwabwoogo (1998) on the population density and infrastructure of Uganda from the MFEP-Statistics Department (1992).

The elevation in Uganda varies considerably with highest values (1694 – 1873 masl) in the south-western and eastern highlands (domains # 12 – 15). These areas, which have also mainly steeper slopes and higher rainfall, are expected to be more susceptible to erosion, which may influence local soil conditions. The areas with the lowest elevation (1072 - 1103masl) are located in the center of Uganda (domains # 8, 16, 17, 18), where sedimentation may be a dominant process.

Overall, many of these factor combinations will affect the spatial variability of soil resources differentially and may lead to marked differences in soil productivity between the respective development domains. To serve the purpose of helping to develop policies for soil conservation and use, subsequent soil variability studies will be needed to confirm this hypothesis and identify possible options for policy makers. To serve the farmers within the domains, further differentiation of land suitability and land use options will be needed.

3.4 Summary and conclusions

In accordance with the pathways of development theory, population density, market access, agricultural potential and elevation were used in a GIS-based stratification to separate the spatial domains of agricultural development factors that may influence soil variability in Uganda. This stratification resulted in 18 spatial development domains covering more than two-thirds of Uganda.

The spatial variation of the chief natural and socio-economic factors characterizing the domains was mapped over the whole spatial extent of Uganda. These factors included July rainfall, annual rainfall potential, length of growing period and temperature potential that represented agricultural potential. The analysis of the variance characteristics of these indicators showed that the stratification was suitable for separating the spatially diverse natural resource and socio-economic factors into largely homogeneous spatial domains. Since these domains represent combinations of factors that may impact soil variability in Uganda, this spatial stratification may be used as a pre-classification of Uganda’s land suitability. Detailed soil variability studies need to be conducted to assess the usefulness of this pre-classification.

With this pre-classification the amount of soil samples that is necessary for a national-scale soil variability assessment may be drastically reduced. The information on the spatial distribution of stratification factors, their causes and their potential influence on spatial soil variability may be supportive for explaining variance patterns of soil parameters. These should provide a sound basis for the formulation of national policies for soil conservation and land use.

4 NATIONAL-SCALE SPATIAL VARIABILITY OF SOILS

4.1 Introduction

Policy makers and regional development planners in Uganda increasingly request site-specific and up-to-date soil information to better advise farmers on appropriate strategies for arresting soil degradation and developing sustainable land management (NEMA, 2001; Pender et al., 1999, 2001; APSEC, 2000). However, there is no appropriate information available on how the different soil resources are spatially distributed in Uganda and if certain spatial patterns of these soil resources currently exist within the country. Furthermore, there is a lack of knowledge on which of the many natural resource and socio-economic factors are the most important in determining this spatial distribution of soils in Uganda.

This information gap may be overcome by a new national-scale soil survey that provides the data to assess the spatial variability of soil. However, such a survey usually requires a large number of soil samples to be collected from locations that are distributed all over the country to adequately capture the inherent soil variability and the underlying soil-determining factors. In this study, representative soil-sampling sites were selected from the agricultural land of rural communities based on the pre-classification of Uganda into development domains (chapter 3). Altogether, 107 communities were selected covering Central, East and West Uganda. Intensive natural resource mapping and socio-economic surveys were carried out in these communities from July until September 2000 to assess the spatial variability of soils in Uganda.

The objectives of this national-scale study are 1) to investigate how the most important soil parameters that determine soil conditions in Uganda are spatially distributed, 2) to examine the spatial structure and patterns of these soil parameters, and 3) to explain the causes of spatial soil variability based on the identification of the prime determining factors.

4.2 Material and methods

4.2.1 Community selection

In order to investigate national-scale spatial soil variability in Uganda, soil samples were collected from the land of representative rural communities. The chosen land area aimed to capture the impacts of agricultural and natural processes, e.g. crop cultivation and erosion, respectively. Thus, the soil samples reflected the status of soil resource conditions on agricultural land in these communities. The spatial sampling framework to select the communities was based on the development domains covering Central, East and West Uganda and excluded insecure regions in northern Uganda (Figure 3.4).

The smallest administrative units in Uganda for which digital geographic information was available were *parishes*. The administrative level *Local Council 1 (LC1)*, which is one level below parish, corresponds to the *community*. The primary sampling unit was the *enumeration area (EA)*, a population census unit. The EA can be smaller than LC1, but in some areas it could be on a higher administrative level (Guillaume and Lambotte, 1998). If the EA was smaller than LC1 and entirely within one LC1, the LC1 was selected. If the EA included more than one LC1, one of them was chosen. The number of EAs within development domains was based upon the total population of each domain, but a minimum of 4 samples was used for each domain. The resulting number of communities studied within the domains is shown in Table 4.1.

Table 4.1: Number of study communities in domains with stratification characteristics

Study Communities	Domain #	Lowland / Highland	Population Density	Market Access	Agricultural Potential
4	18	Lowland	Low	Low	Unimodal
4	11	Lowland	Low	Low	Bimodal low
7	8	Lowland	Low	Low	Bimodal medium
4	4	Lowland	Low	Low	Bimodal high
4	17	Lowland	Low	High	Unimodal
4	10	Lowland	Low	High	Bimodal low
4	6	Lowland	Low	High	Bimodal medium
4	2	Lowland	Low	High	Bimodal high
6	7	Lowland	High	Low	Bimodal medium
4	3	Lowland	High	Low	Bimodal high
6	16	Lowland	High	High	Unimodal
4	9	Lowland	High	High	Bimodal low
11	5	Lowland	High	High	Bimodal medium
18	1	Lowland	High	High	Bimodal high
4	13	SW highlands	High	Low	-
12	12	SW highlands	High	High	-
4	15	E highlands	High	Low	-
4	14	E highlands	High	High	-

From the selected parishes, one EA was randomly selected. If a selected LC1 belonged to an urban municipality or was located on an island, it was dropped and a replacement was drawn. Research communities of collaborating institutions were added to include natural resources and soil management conditions of communities where agricultural research and extension has been active for many years. These additional communities comprise 1) three communities in Iganga District from the International Center for Tropical Agriculture (CIAT), 2) two communities in Kabale District from the African Highlands Initiative (AHI) and 3) two communities in Mbale District and one community in Pallisa district from the National Agricultural Research Organization. The final national-scale sample population amounted to 107 communities. The location of these communities is presented in Figure 4.1.

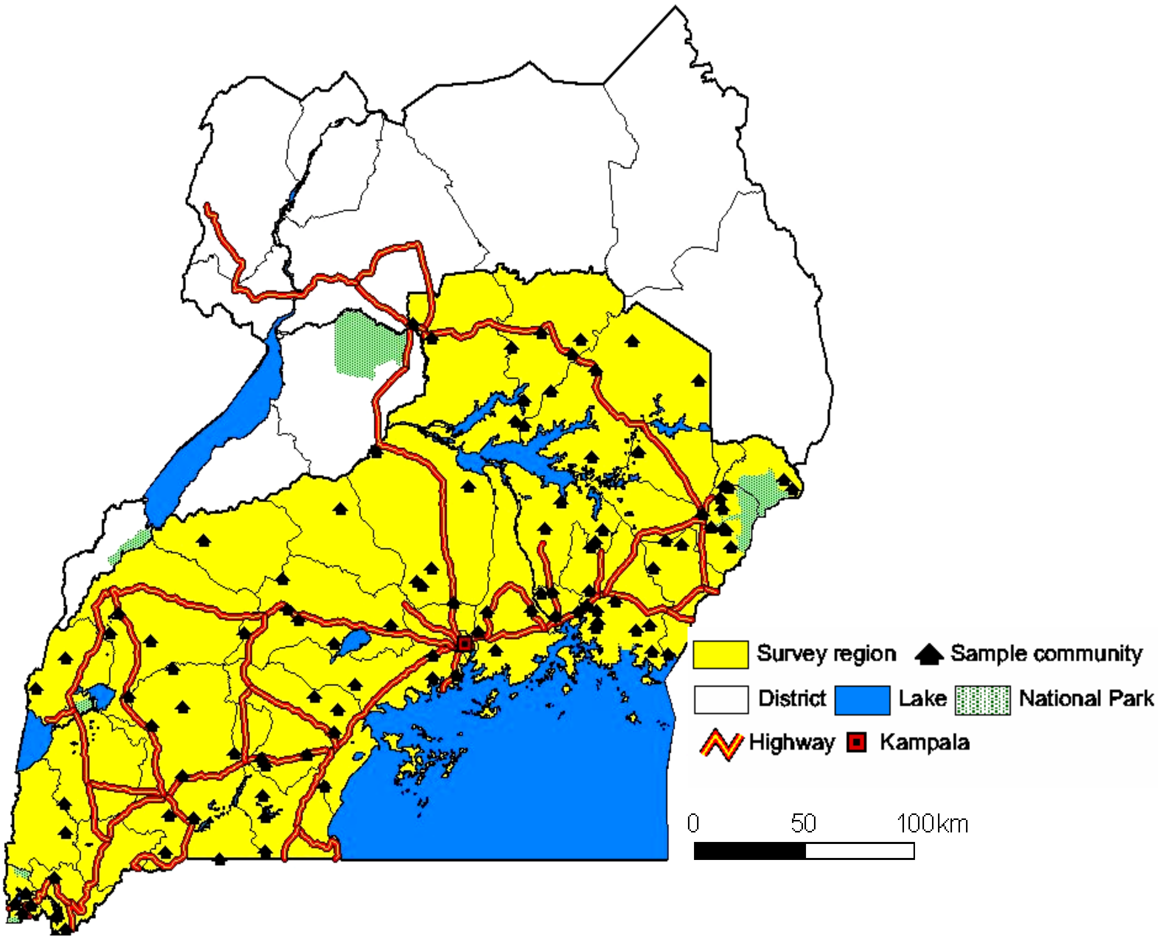

Figure 4.1: Location of study communities within the survey region of Uganda

4.2.2 Data collection

Community terrain delineation and soil survey

The detailed identification of soil resources was based on the delineation of each community's land into major spatial terrain units that were visually identified as upper, middle and lower slopes as well as flat areas. This delineation is based on the idea that soil variation within community land can be best captured along a representative toposequence traversing the major terrain units of each community (Hall and Olson, 1991). The selection of these four terrain units allowed quick and reproducible identification of representative units characterizing the toposequences of the 107 study communities (Ruecker and Lufafa, 2000).

Approximately ten composite topsoil samples at 0-20 cm depth, which has the greatest relevance to crop cultivation, were extracted by hand-hoe at an equal surface distance along a representative community toposequence. The geographic position of each sample location was recorded by handheld GPS. The collected soil samples were slightly disaggregated, air-dried and analyzed in the laboratory of the Kawanda Agricultural Research Institute, Kampala, Uganda.

Choice and collection of environmental correlation data

Possible factors that may determine the spatial distribution of soils over Uganda were studied by review of local literature including Davies (1952), Harrop (1970), Foster (1976), Yost and Eswaran (1990), Wortmann and Eledu, (1999), Ssali (2000), Ssali (2001) and Bashaasha (2001). Based on this review, the major environmental factor categories determining national-scale spatial soil variability in Uganda were identified and respective environmental variables were selected for environmental correlation with soils data. These environmental factor categories and variables are listed together with descriptive information in Table 4.2.

Table 4.2: Selected environmental categories and variables with characteristics determining spatial soil variability on national-scale in Uganda.

Environmental category	Environmental variable	Spatial scale	Type	Definition, units of measurement	Influence on soil variability	Source
Geology / Geomorphology	Geological age	National scale	Nominal	Geological era: Precambrian, Tertiary, Quartary [0,1]	Parent material weathering	Geological department of Uganda (1962): Geology of Uganda, simplified by Harrop (1970)
	Geotectonic land surface type		Nominal	Erosion surfaces: Buganda, Tanganyka, Ankole, Volcanics [0,1]	Soil erosion	Geological department of Uganda (1962): Geomorphology of Uganda
	Parent material		Nominal	Parent rock types: [0,1]	Soil nutrients and texture composition	Chenery (1960): Soil map of Uganda
	Elevation	1 x 1 km raster	Interval	Elevation above sea level [m]	Parent material weathering	Hutchinson et al. (1995)
Climate / Drought proneness	Annual precipitation	5 x 5 km raster	Interval	Precipitation amount [mm/year]	Soil weathering and acidity	Corbett and O´ Brien (1997), Corbett and Kruska (1994): Average data from long term monthly mean climatic records; algorithms for variables as cited in Ruecker et al. (2003a)
	Length of growing period		Interval	Period with mean monthly rainfall exceeding half mean potential ET [month]	Soil weathering, acidity, nutrient cycling	
	Rainfall seasonality		Interval	Proportion of mean July rainfall to mean annual rainfall [uni/bimodal]	Soil weathering and acidity	
	Maximum temperature during hottest month		Interval	Mean maximum temperature in February [°C]	Soil organic matter dynamics	
	Drought proneness	1 : 50.000	Nominal	Farmers estimation of drought occurence [0,1]	Soil organic matter dynamics	Ruecker et al. (2003b): Farmers´ assessment on drought proneness
Land use / Land Management	Farming system	National scale	Nominal	Major farming system	Soil organic matter and nutrient dynamics	National Environmental Management Authority (1998): Stratification of Uganda into nine farming systems

The selected environmental factor categories included Geology/Geomorphology, Climate/Drought vulnerability and Land use/Land management. To each of these categories specific environmental variables were assigned for use in environmental correlation. The choice of these variables was based on environmental reasoning of processes causing spatial variability patterns in soils of Uganda that are discussed in the following.

Since the geology of Uganda can be clearly stratified by rocks that originated mainly during the pre-Cambrian and those that developed during the Tertiary, the corresponding soils experienced different time periods of weathering (Harrop, 1970). The *geological age* was therefore selected as a factor to determine national-scale soil variability. The geomorphologic land surface types include the *Buganda, Tanganyika, Ankole and Kooki, and Volcanics surfaces*. These surfaces evolved from tectonic uplift or warping processes during the Tertiary and were subjected to further weathering and in addition degraded by erosion processes (Davies, 1952; Harrop, 1970). As these processes in turn influenced spatial variability of soil, these surfaces were included in the environmental correlation. After these geological and geotectonic surface activities, more recent alluvial and colluvial material movement followed and produced spatially different parent materials. From these parent materials soils with corresponding mineral composition developed, thus *parent material* was added as another important environmental variable (Ssali, 2000). Finally *elevation* was included as an environmental factor because the elevation of the sampling sites has an influence on the rate of weathering of parent material and the decomposition of organic matter, which in turn may determine the spatial variability of corresponding soil parameters (Wortmann and Eledu, 1999).

Precipitation influences many soil processes, such as weathering, leaching, erosion, and acidification (Foster, 1970; Jameson and McCallum, 1970; Ssali, 2000). *Annual precipitation* was selected as an integrated measure that captures precipitation over a year. *Rainfall seasonality* with unimodal versus bimodal rainfall distribution was chosen as a seasonal precipitation indicator (Wortmann and Eledu, 1999). *Length of growing period* was used as an environmental factor that reflects the seasonal intensity of precipitation (FAO, 1996). The level of the air and soil temperature influences the rate of organic matter decomposition and was taken into account by inclusion of the *maximum temperature during the hottest month of a year* (Ssali, 2001, Ruecker et al. 2003a). All these climatic factors were derived from averaged long-term climatic records covering the years from 1960 until 1990 (Hutchinson et al., 1995, Corbett and O'Brian, 1999, Corbett, 1995). The more recent impact of climatic factors on soil variability, specifically the impact of precipitation and temperature, was captured by the indicator *drought vulnerability*, which was assessed by farmers who were questioned during the soil survey in each community (Ruecker et al., 2003b). This indicator describes whether the community land has been exposed to a drought, as defined by "receiving at least once less than usual rainfall during a growing season within the period from 1990 until 1999, such that crops suffered severe water stress".

The combined impact of land use and land management on national-scale soil variability was represented by the factor *farming systems* (Sserunkuuma et al., 2001; Ruecker et al., 2003a). This factor integrates the information on the major cultivated crops with the general management information of the land and crops (Parsons, 1960; Bashaasha, 2001). There are eight farming systems within the study region, including the intensive banana coffee lake shore system, the western banana coffee cattle system, the banana millet cotton system, the pastoral and annual crops system, the medium altitude intensive banana coffee system, the annual cropping and cattle Teso system, the annual cropping and cattle Northern system, and the Montane systems (Pender et al., 2001). Since the soil samples from each community were combined to represent average values, more disaggregated land use and land management information was not further considered for this national-scale soil variability investigation.

The spatial distribution of the environmental variables *elevation, annual precipitation, length of growing period, rainfall seasonality* and *maximum temperature during the hottest month* was already displayed as maps within the study on the spatial stratification of Uganda into development domains (chapter 3.2.3). The maps of the remaining variables, including *geological age, geotectonic land surface, parent material, drought vulnerability* and *farming system* are shown in Appendix 1.

4.2.3 Sample and data processing

Soil sample analysis

Air-dried soil samples were gently ground to pass a 2mm sieve. Texture was analyzed by hydrometer method (Hartge and Horn, 1989). Soil organic matter content was measured by modified Walkley and Black method (Nelson and Sommers, 1975) and pH in 1:2.5 H_2O solution by pH meter (Dewis and Freitas, 1970). Concentrations of extractable bases K and Ca were measured in a single ammonium lactate/acetic acid extract buffered at pH 3.8 after Foster (1971) and Anderson and Ingram (1993). Available Phosphorus was determined calorimetrically by the molybdate blue method after bi-carbonate extraction (Olsen and Dean, 1965).

Environmental data integration

The environmental data from different sources were integrated together with the soil analysis information under the same GIS database to generate a complete and geographically referenced data set for the statistical and spatial analyses. Based on the location of soil samples in the GIS, the spatially corresponding information of the GIS environmental data sets was extracted and assigned to the soil-sample data set using publicly available ArcView GIS extension *GetGridValue (V2)* and GIS spatial join operations. The resulting GIS data tables were then exported to ASCII-data format and imported to SPSS format for statistical analyses and to S-PLUS for spatial analyses.

4.2.4 Statistical and spatial analyses

Several statistical and spatial analyses were complementarily performed to assess the different criteria that characterize the soils´ spatial variability on a national scale. The applied analyses included descriptive statistics, correlation analysis, analysis of variance, semivariance analysis, spatial interpolation, and hierarchical generalized linear modeling. The statistical analyses of data were performed in SPSS 11.0 (SPSS inc., 2003) and S-PLUS 6.0$^{®}$ Professional for Windows (Insightful Corp., 1989-2001). The spatial analysis was performed in S+Spatial Stats$^{®}$ 1.0 (Mathsoft 1998), ARC/VIEW Spatial analyst$^{®}$ 2.0 (Environmental Systems Research Institute, Inc., 1999a) and some FORTRAN programs. For visualization ARC/VIEW 3.2$^{®}$ (Environmental Systems Research Institute, Inc., 1999b) and Surfer 7.0$^{®}$ (Golden Software Inc., 1999) were used.

Variable transformation and descriptive statistics

The Lilliefors Test was used to test variables for normal distribution (Norusis and SPSS inc., 1993). If a variable did not show normal distribution, it was transformed to close to the normal distribution according to the *ladder of powers* (Table 4.3).

Table 4.3: Variable transformations (*ladder of powers*) after Hamilton (1990)

Power	Transformation	Name	Effects	Abbreviations	Inverse functions
3	X^3	Cube	Reduces extreme negative skewness	CU	$(X^*)^{1/3}$
2	X^2	Square	Reduces negative skewness	SQ	$(X^*)^{1/2}$
1	$X^1 = X$	Raw	No effect	-	-
-0.5	$X^{1/2}$	Square root	Reduces mild positive skewness	SQRT	$(X^*)^2$
-1	Log10(X)	Log	Reduces positive skewness	LOG	10^{X^*}
-1.5	-1/SQRT(X)	Negative reciprocal root	Reduces extreme positive skewness	NRR	$(-X^*)^{-2}$
-2	-(X-1)=-1/X	Negative reciprocal	Reduces even more extreme positive skewness	NR	$(-X^*)^{-1}$

Note: X*: transformed variable

Further variable transformation was avoided due to interpretation difficulties. When a variable failed this statistical test for normal distribution, the best function to reduce skewness was used, since data with approximate normal distribution are generally agreed to be sufficient for most statistical tests (Norusis and SPSS inc., 1993). In order to analyse the variations within the total sample population, the applied descriptive statistics included the calculation of mean, minimum, maximum, standard deviation and coefficient of variation. The coefficient of variation was calculated as standard deviation / mean * 100.

Correlation analysis

After transformation, each variable was converted into a Z-score, where the mean is 0 and the standard deviation is 1 to permit comparison of scores from different distributions (Sokal and Rohlf, 1995). The following Z-score function was used:

$$Z_i = (X_i - X) / S$$

where X_i is the sample, X is sample mean and S is standard deviation.

For the identification of the spatial correlation among soil samples, the Pearson's product moment correlation coefficient was used. The relative contribution of different environmental variables to soil variation was assessed by the coefficient of determination using a hierarchical generalized linear model. This model is described in detail below. The rules of thumb for interpreting the correlation coefficient and the coefficient of determination are displayed in Table 4.4.

Table 4.4: Rules of thumb for the interpretation of the coefficient of variation and the coefficient of determination (after Hamilton, 1990, Table 14.5)

Correlation coefficient (r)	Coefficient of determination (R^2)	Interpretation
1.00 (-1.00)	1.00	Perfect positive (negative) correlation
(-) 1.00 > r > (-) 0.8	$1.00 > R^2 > 0.64$	Strong positive (negative) correlation
(-) 0.8 > r > (-) 0.5	$0.64 > R^2 > 0.25$	Moderate postive (negative) correlation
(-) 0.5 > r (-) 0.2	$0.25 > R^2 > 0.04$	Weak positive (negative) correlation
(-) 0.2 > r > 0	$0.04 > R^2 > 0.00$	No correlation

Analysis of variance and boxplots

The significance of the national-scale hillslope delineation into zones of terrain units for explaining the variance of soil properties was determined by a one way analysis of variance (ANOVA). The F-ratio in the ANOVA was used to test the null hypothesis that the population means in these different hillslope zones are equal. The Bonferroni test and the Dunnet T3 test were applied to indicate which zones have significantly different means. The many available multiple comparison procedures differ mainly in how they adjust the observed significance level. The Bonferroni and Dunnet T3 test adjust the observed significance level on the basis of the number of comparisons. Because six comparisons are made, the observed significance level for the original comparison must be less than 0.05, or 0.01, for the difference to be significant at the 0.05 significance level (Norusis and SPSS Inc., 1994). In order to visualize the changes of different soil property means between hillslope zones, boxplots were employed.

Semivariance analysis

The spatial dependency of soil properties over the national-scale study sites was modeled by the geostatistical technique of semivariogram analysis. For direct comparison of semivariograms, soil variables with different measuring scales were transformed according to the following equation (Deutsch and Journel, 1992).

$$Z' = (Z - Z_{min}) / (Z_{max} - Z_{min})$$

where Z is the Z-transformed sample, Z_{max} is the maximum value and Z_{min} is the minimum value of all Z-transformed samples of a variable.

Zonal anisotropy was not identified on the national scale. There are many complex considerations to determine the settings of angle tolerance and lag tolerance and other semivariogram settings. Semivariogram analysis is used in this study mainly to compare the relative changes of spatial dependency among different soil parameters, instead of exact quantitative assessments of semivariograms for specific soil parameters. Therefore, general recommendations such as lag tolerance, greater than half of lag h and standard semivariogram parameters were applied. On the national scale, the maximum distance (lag) was set to 200 km and the individual lag was either 10 km or 1.25 km (Journal and Huijbregts, 1978). Initial analyses shows that directional anisotropy is not severe for most variables. Therefore, only one uni-directional variogram (0°) was constructed for most cases. Lag and angle tolerance was set half of the lag and 45° respectively.

The calculated semivariograms were fitted chosing from several different variogram funtions, such as exponential, gaussian, spherical, and linear, the one giving the best function that shows the lowest error to fit a curve for each variogram. Webster and Oliver (1990) recommend more than a hundred points for two-dimensional variability as given in a line transect, and a few hundred sampling points for three-dimensional spatial variability. The maximum of 107 sampling points might be considered as marginal; thus the use of spatial statistics are limited to assessing the relative importance of spatial distribution of measured variables and to comparing them spatially.

Spatial interpolation

After the semivariance analyses, soil parameters were interpolated over the whole national-scale sampling frame to visualize and to identify the spatial extent and the spatial patterns of the soil parameters. The fitted semivariogram model of each soil parameter was used for kriging interpolation. When a semivariogram showed only nugget variance, then Inverse Distance Weighting (IDW) algorithm was applied to interpolate the respective soil parameter. Since only 107 sample points from community hillslopes were used for national-scale interpolation, the interpolated soil maps may not necessarily represent natural soil conditions outside of these hillslopes, largely because these hillslopes may represent landscapes highly modified by agriculture.

Hierarchical generalized linear model

The correlation of soil parameters against environmental variables was performed by hierarchical generalized linear model (GLM) within SPSS (SPSS Inc. 2003). This GLM served two purposes: 1) to explain spatial variability of soil parameters, 2) to identify the most dominant factors that determine the spatial variability of soil parameters.

First, the spatial variability of soil parameters on the national-scale was attempted to be explained by environmental variables that are derived from geology/geomorphology, climate/drought vulnerability, land use, and land management categories. Since most of these environmental variables were generated from secondary data, they can be more easily obtained for the complete spatial extent of the national-scale than soil samples that need to be manually extracted from the same spatial extent and analyzed in a laboratory to determine the respective soil parameters. The selection of these variables relied on the assumptions that the most dominant variables that explain soil distribution were included in the environmental correlation and that all these variables are independent from each other (Table 4.2).

GLM was chosen as the environmental correlation technique for explaining spatial variability of soils. GLM has several advantages compared to the widely used multiple regressions (McCullagh and Nelder 1989): 1) Dependent and response variable do not have to be continuous, but can be of categorical or of nominal scale. This advantage is used in this study by integrating continuous scale soil variables and nominal scale geology variables in the regression model; 2) Linear combinations among dependent variables are allowed in the GLM. These combinations are helpful to model the interactions of independent variable categories, such as geology/geomorphology and land use/land management in terms of their relationship with the soil parameter predictors (Mathsoft, 1999).

The second purpose for using hierarchical GLM was to identify, which environmental variable category among the different environmental categories is more dominant in explaining soil spatial variability on a national scale. These variance characteristics were examined by hierarchical regression analysis (Schaap et al., 1998). The variables that were grouped into the categories geology/geomorphology, climate/drought vulnerability and land use/land management were sucessively entered into the GLM and regressed against soil parameters. Combining the three different environmental categories in the GLM, seven different combinations of regression analyses were performed for each of the eight soil parameters. The comparative assessment of changes in the coefficients of determination revealed the performance of each environmental category to explain spatial variability of soil parameters. This allowed identification of the most dominant single and combined predictor variables for estimation of spatial soil parameter variability.

4.3 Results and discussion

4.3.1 Spatial distribution of soils on national scale

The spatial distribution of soil parameters on the national-scale of Uganda was investigated by the assessment of the variability over the total sample population, the correlations among soil parameters and the spatial variability over the community hillslopes.

Total variability of soils

The total variability of topsoil samples on national-scale was analyzed by descriptive statistics. The results of this statistics were compared with the critical threshold values of Foster (1971) as shown in Table 4.5.

Table 4.5: Descriptive statistics and critical threshold values of topsoil samples on national-scale in Uganda

Soil parameter	Mean	Minimum	Maximum	Critical value[1]	STD	CV[2] (%)	CV[3] (%)
pH in water	5.34	3.90	7.20	5.20	0.60	11.2	11.2
SOM (%)	4.92	0.60	24.4	3.00	3.02	61.3	35.1
Avail. PO_4^{3-} (mg/kg)	49.5	0.24	825	5.00	105	212	55.9
Exch. K^+ (mg/kg)	30.8	0.89	497	0.40	32.9	107	27.7
Exch. Ca^{2+} (mg/kg)	86.1	1.26	739	0.90	66.7	77.5	22.2
Sand (%)	56.6	13.7	91.5	NA	15.8	27.9	27.9
Clay (%)	26.9	2.20	66.3	NA	11.9	44.3	44.3
Silt (%)	16.5	0.00	49.6	NA	8.56	52.0	52.0

N = 1050; STD = standard deviation; CV = coefficient of variation; NA = Not applicable

[1] Below this value, soil parameter level is deficient (Foster, 1971)

[2] = CV of soil parameter, [3] = CV of transformed soil parameter

Based on the national-scale soil-sample collection, the average soil texture in Uganda is sandy clay loam. This texture provides for both good water infiltration and water retention and is very suitable for the cultivation of many crops. The higher mean values of pH (5.34), soil organic matter (SOM) (ca. 5%) and of the plant nutrients phosphorus (ca. 50 mg/kg) and potassium (30 mg/kg) compared to the critical thresholds (Foster, 1971) indicate relatively favorable soil fertility conditions for plant growth. These findings are in congruence with the summarized evaluation of the 1960s nation-wide reconnaissance survey, in which Chenery (1960) argued that “compared to other places in the tropics the soils of Uganda are, on the whole, very fertile”. Thus, a generally homogeneous and favorable assessment appears to be holding for the national soil inventory in terms of soil fertility conditions in Uganda.

However, these general findings may mask degraded soil conditions in one area that may be masked on the national-level or compensated by higher soil values in another area. Minimum soil values in Table 4.5 are far lower than the corresponding critical levels, e.g. pH (ca. 4% compared to 5.2%), SOM (ca 1% compared to 3.0%) and P (0.24 mg/kg compared to 5.0 mg/kg), respectively, suggesting that some regions may be degraded already.

As shown in Table 4.5, all soil parameters have a wide range between minimum and maximum values, e.g. pH (ca. 4 - 7), SOM (ca. 1 - 24%). Moreover, the soil nutrients such as available P, exchangeable K, and exchangeable Ca exhibit extremely wide ranges from ca. 1 to 800 mg/kg, 500 mg/kg and 700 mg/kg, respectively. Kaizzi (2002) found similarly wide ranges of soil parameter values in a study covering several sites in eastern Uganda, e.g. the ranges within the soil samples from the site Kongta were: pH (4.7 - 5.9), SOM (4.2 – 7.1), P (4.5 – 58.9). These variance characteristics may give a first indication that the soil values are apparently more heterogeneously distributed over Uganda than the summary evaluation of Chenery (1960) and the mean statistics of this research presented.

In order to describe soil parameters by their total variability across Uganda, the standardized variability was compared using the variation coefficients of soil parameter values. The ranked variation of the transformed coefficients is shown in Table 4.6.

Table 4.6: Total variability ranking of national-scale transformed soil parameters

Total variability	Soil parameter	CV (%)	Transformation
Least (CV < 15%)	pH in water	11.2	-
Moderate (15% <= CV < 35%)	Exch. Ca^{2+} (mg/kg)	22.2	Logarithm
	Sand (%)	27.9	-
	Exch. K^+ (mg/kg)	27.7	Logarithm
	SOM (%)	35.1	Logarithm
High (CV >= 35%)	Clay (%)	44.3	-
	Silt (%)	52.0	-
	Avail. PO_4^{3-} (mg/kg)	55.9	Logarithm

The different ranks indicate that pH has the least variability and P, silt and clay have the highest variability, whereas Ca, Sand, K and SOM have a moderate variability across Uganda. These differences raise the question, why some soil parameters have similar, other soil parameters have higher and again others have lower variance. The heterogeneous distributions may be caused by heterogeneously distributed factors that determine soil development on the national scale. Since some soil parameters are known to have similar behavior, thus may respond similarly to their determining factors, correlations among soil parameters were investigated and the findings are presented in the next section.

Soil correlations

The relationships among the soil parameters of the total sample population were assessed by Pearson's product moment correlation coefficient to reveal possible similar dependency on soil forming factors and corresponding pedological processes. The correlation coefficients of the soil parameters are displayed in Table 4.7.

Table 4.7: Correlation matrix of soil parameters on the national-scale in Uganda

Soil parameter	pH in water	SOM (%)	Avail. PO_4^{3-} (mg/kg)	Exch. K^+ (mg/kg)	Exch. Ca^{2+} (mg/kg)	Sand (%)	Clay (%)	SILT (%)
pH in water	1.00							
SOM (%)	0.24**	1.00						
Avail. PO_4^{3-} (mg/kg)	0.41**	0.48**	1.00					
Exch. K^+ (mg/kg)	0.49**	0.41**	0.52**	1.00				
Exch. Ca^{2+} (mg/kg)	0.59**	0.56**	0.49**	0.52	1.00			
Sand (%)	0.03	-0.35**	-0.13**	-0.30**	-0.30**	1.00		
Clay (%)	-0.03	0.19**	-0.02	0.21**	0.16**	-0.85**	1.00	
SILT (%)	0.00	0.38**	0.27**	0.26**	0.33**	-0.67**	0.17**	1.00

N=1050; significance level: * less than 0.05; ** less than 0.01 (2-tailed).

This matrix indicates that most of the soil parameters are correlated among each other. pH has a relatively high positive correlation with the soil nutrients P, K, and Ca. Areas with higher acidity, often found on geologically old erosion surfaces of mainly granite rock type, have a lower content of these soil nutrients. This parent material is strongly weathered, thus few minerals are remaining and consequently pH is relatively low (Ssali, 2000). The intensive weathering of these surfaces over many millions of years provides sand as the major weathering product yielding the negative correlation between sand and these soil nutrients.

Another positive correlation can be seen between SOM and soil nutrients, clay and silt. Areas with low SOM may therefore show also moderately low content of soil nutrients, clay and silt. This relationship may be determined by general soil chemical processes as well as specific processes that have been occurring more recently: 1) Since SOM is negatively charged, it attracts the positively charged soil nutrients, such as K^+ and Ca^{2+}; 2) Due to erosion, fine earth material and SOM of the topsoil is lost from the intensively cultivated land that is often not covered by vegetation against the strong tropical rainfall. Such SOM and soil nutrient enriched soil material has been frequently observed to be eroded from agricultural land use systems into Lake Victoria (Tenywa and Majaliwa, 1998; Magunda et al., 1999).

Spatial variability of soils over hillslopes

On this scale, correlations among the samples of the total sample population cannot reveal the effect of soil processes causing soil variations on a smaller scale. The impact of these processes may be studied along hillslopes, as topography is generally known to be a major factor determining soil variability. The spatial variability of soil parameters was investigated within the study communities. The analysis of variance was applied on soil parameters that were differentiated in groups according to the terrain units of the community hillslopes and the results are shown in Table 4.8.

Table 4.8: Variance of soil parameters in terrain units (0, 1, 2)[a] of hillslopes in Uganda

Soil		Descriptive statistics				ANOVA	Tests[d]
parameter		(0)[a]	(1)[a]	(2)[a]	total		Bonferroni/Dunnett T3
pH in water	Mean	5.4	5.1	5.4	5.3	35.7[b]	0 ≠ 1;
	STD	0.6	0.5	0.5	0.6	0.00[c]	1 ≠ 0,2; 2 ≠ 1;
SOM (%)	Mean	5.3	4.8	3.2	4.9	28.0[b]	0 ≠ 2;
	STD	3.2	2.9	1.4	3.0	0.00[c]	1 ≠ 2; 2 ≠ 0,1;
Avail. PO_4^{3-} (mg/kg)	Mean	64.2	35.7	12.4	49.5	16.9[b]	0 ≠ 1,2;
	STD	126	68.5	16.0	105	0.00[c]	1 ≠ 0; 2 ≠ 0;
Exch. K^+ (mg/kg)	Mean	35.4	25.6	21.6	30.8	15.1[b]	0 ≠ 1,2;
	STD	37.4	27.5	11.5	32.9	0.00[c]	1 ≠ 0; 2 ≠ 0;
Exch. Ca^{2+} (mg/kg)	Mean	95.5	78.3	59.6	86.1	18.5[b]	0 ≠ 1,2;
	STD	72.1	61.7	34.7	66.7	0.00[c]	1 ≠ 0,2; 2 ≠ 0,1;
Sand (%)	Mean	54.5	57.3	65.6	56.6	26.7[b]	0 ≠ 1,2;
	STD	15.0	16.8	13.6	15.8	0.00[c]	1 ≠ 0,2; 2 ≠ 0,1;
Clay (%)	Mean	29.1	25.7	19.0	26.9	42.0[b]	0 ≠ 1,2;
	STD	11.9	11.9	7.8	11.9	0.00[c]	1 ≠ 0,2; 2 ≠ 0,1;
Silt (%)	Mean	16.4	17.0	15.4	16.5	1.63[b]	0 ≠ -;
	STD	7.93	9.30	9.49	8.56	0.20[c]	1 ≠ -; 2 ≠ -;

[a] Terrain units: (0) = upper and middle slope, (1) = lower slope, (2) = flat land.
[b] F-ratio in ANOVA; [c] Propability; [d] significantly different at $p < 0.05$ level.
N = 607, 320, 123 in (0), (1), (2) respectively.

As Table 4.8 shows, the stratification of soil parameters by hillslope terrain units exhibits high F-ratios for pH, SOM, sand and clay. Since a high F-ratio indicates that the variance of a parameter within units is smaller than the variance among units, these high values prove that this hillslope delineation into terrain units could satisfactorily partition the variation of these soil parameters over the hillslopes. The relatively lower F-ratio of the soil nutrients P, K, Ca and of silt suggests that other factors could be more dominant in influencing the spatial distribution of these soil parameters.

Complementary to the F-statistics, the Bonferroni and the Dunnet T3 tests were employed, showing the same results (Table 4.8). Box plots (Figure 4.2) reveal for which of the terrain units the means for a particular soil parameter are significantly different.

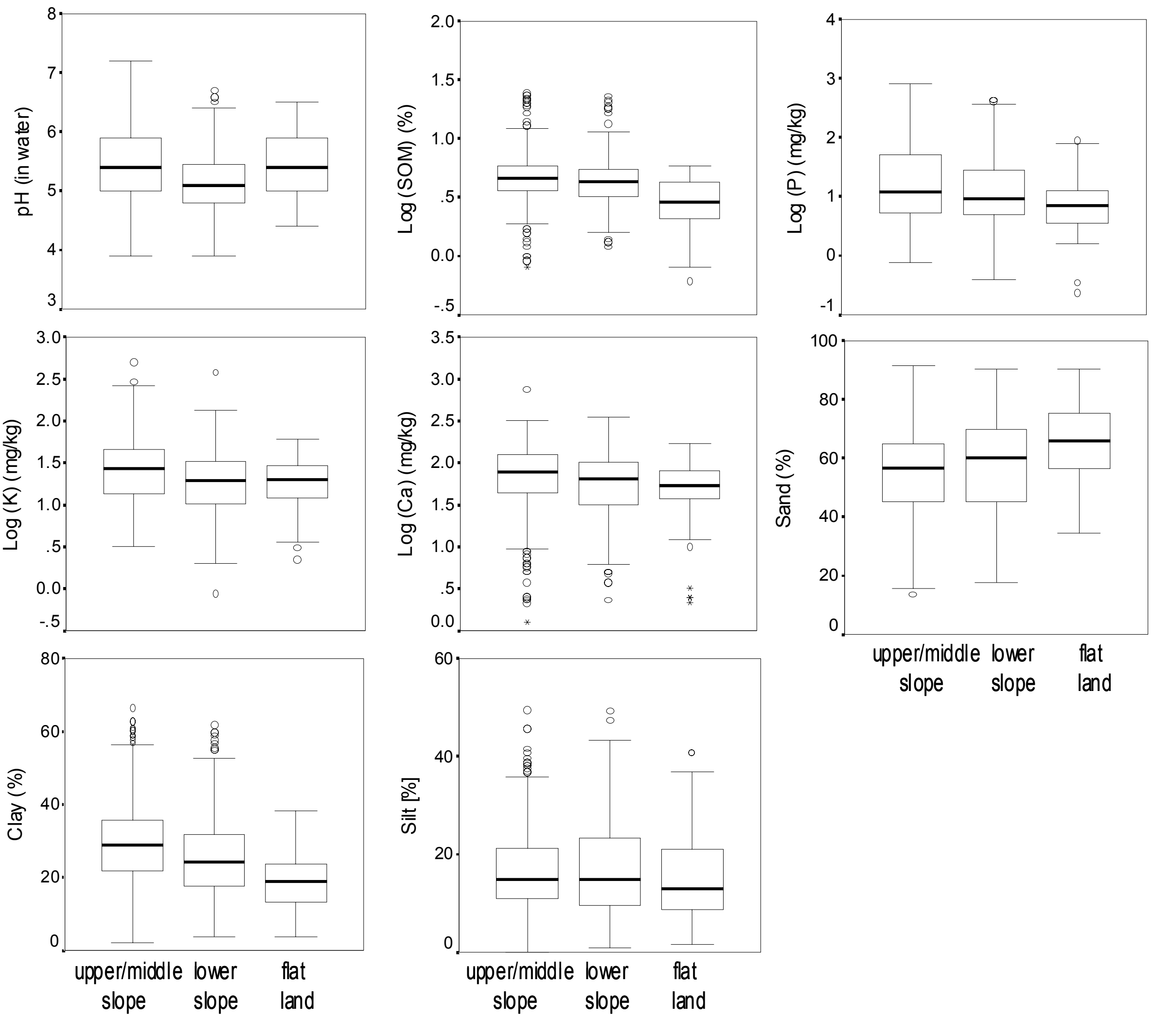

Figure 4.2: Box plots of transformed soil values for terrain units on hillslopes in Uganda

The results from these tests and the boxplots show that the spatial variation of sand, clay and Ca is different in all terrain units over the hillslopes. These findings are clearly visualized by the alternating position of the boxes, which represent the distribution of these soil values around the means (Figure 4.2). This may give indication that different hillslope processes, such as erosion and sedimentation have led to a significantly different redistribution of these soil parameters among the terrain units on the investigated hillslopes.

The spatial variation of pH and SOM is different in all terrain units except for the upper/middle slope and the flat land for pH and the upper/middle slope and the lower slope for SOM. The soil nutrients P and K have different spatial variation in all terrain units, but are each similarly distributed in the upper/middle slope and the flat land. Silt was in all terrain units similarly distributed. The spatial variation for pH, SOM, P, K and silt is similar in one or more terrain units. Processes, such as land-use-induced nutrient flows, may be more important for the spatial distribution of these parameters. These processes were not captured by this delineation of hillslopes into terrain units.

Based on these hillslope analyses it is concluded that the spatial variation of the soil parameters pH, SOM, sand and clay on the national-scale may be governed by terrain factors. However, the 107 investigated hillslopes were located in very different environments in which terrain factors might have different effects on soil-parameter distribution, thus causing a loss of information. Scale dependency and the structure of spatial patterns of the variability of soil parameters based on spatial interpolation are discussed in the next chapter.

4.3.2 Spatial structure and patterns of soils on national scale

Spatial structure of soils

The soils´ spatial dependency among soil parameters on the national-scale was analyzed using semivariogram analysis. Variogram models were fitted to the standardized soil parameter values and are shown in Figure 4.3. The corresponding parameters are listed in Table 4.9.

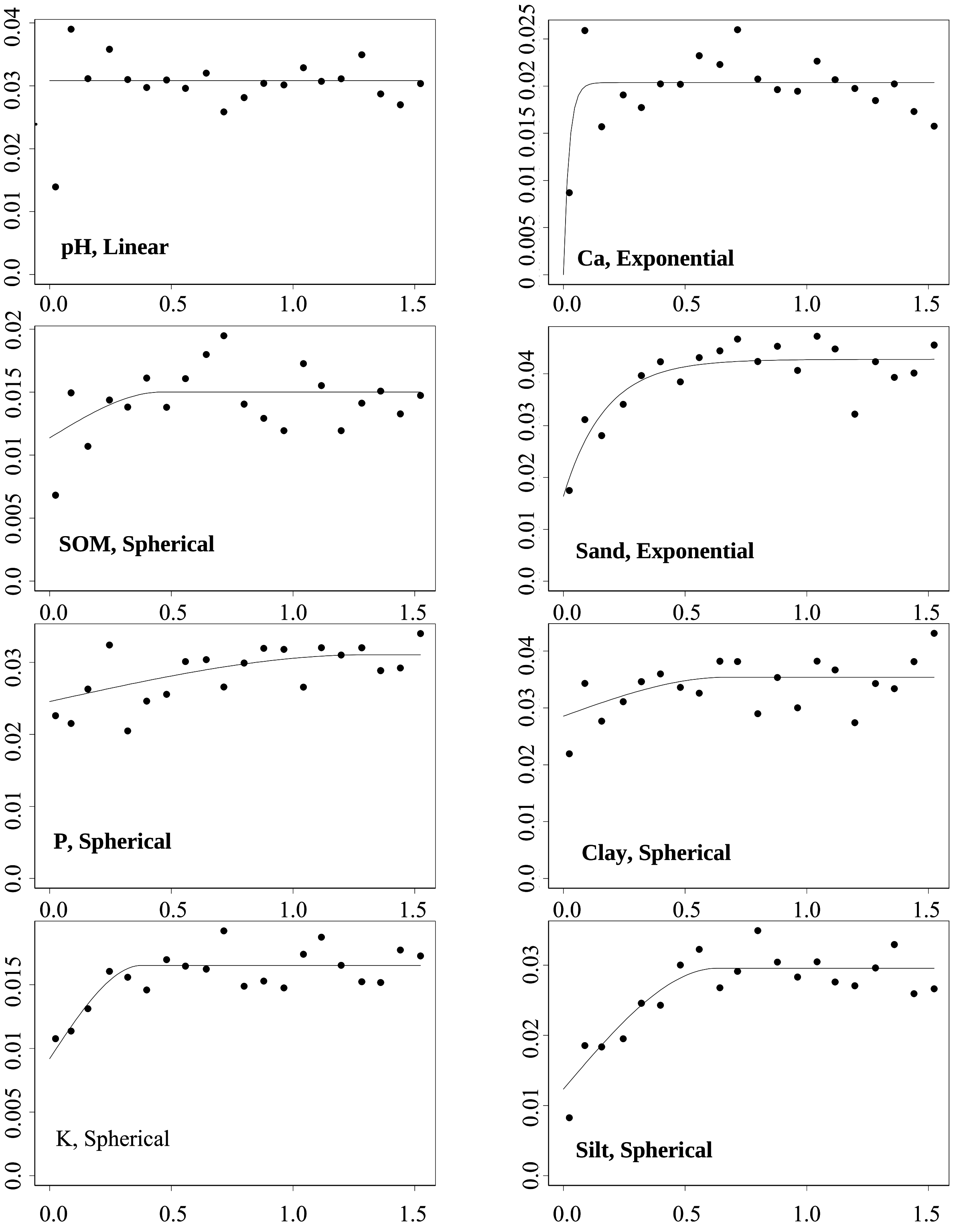

Figure 4.3: Variogram models of standardized soil parameters on national scale in Uganda

Table 4.9: Variogram model parameters of transformed soil parameters on national-scale in Uganda

Soil parameter	Model	Range	Sill	Nugget	Slope	Objective
pH in water	Linear	-	-	0.03	0.00	0.0248
SOM (%)	Spherical	0.46	0.00	0.01	-	0.0001
Avail. PO_4^{3-} (mg/kg)	Spherical	1.31	0.01	0.02	-	0.0002
Exch. K+ (mg/kg)	Spherical	0.38	0.01	0.01	-	0.0000
Exch. Ca^{2+} (mg/kg)	Exponential	0.02	0.02	0.00	-	0.0002
Sand (%)	Exponential	0.17	0.03	0.02	-	0.0003
Clay (%)	Spherical	0.67	0.01	0.03	-	0.0003
Silt (%)	Spherical	0.63	0.02	0.01	-	0.0001

The variogram models show for all soil parameters, except for pH, slightly to strongly curved graphs. These curved graphs follow a spherical or an exponential shape in the X-direction (Figure 4.3 and Table 4.9). This X-direction represents the standardized spatial distance of the semivariance on the national scale, suggesting the corresponding soil parameters have a certain spatial dependency.

SOM, P and clay exhibit a similar high semivariance, indicated by the *objective* value in Table 4.9, yet there is little spatial dependency recognizable with weakly curved spherical variogram graphs. Other soil attributes, such as K, Ca, sand and silt, show typical semivariogram characteristics by strongly curved spherical or exponential variogram models. The semivariance of these last soil parameters increases to a peak level until a certain distance and stabilizes thereafter.

In contrast, the variogram of pH follows a linear shape with distance, thus does not have a spatial dependency on a national scale. This is also indicated by the high nugget value of pH, which reflects that the micro-variability is so high that there is no clear spatial dependency among different sampling locations (Burrough, 1993). Considering the differences in micro-variability among all soil samples, the sequence from highest to lowest micro-variability is:

pH > clay > P > sand > silt > SOM > K > Ca

In general, it is likely that the more mobile soil parameters such as soil pH, clay, P, SOM, and K show much higher scattered semivariance than the more stable soil parameters, such as sand, silt and Ca (Figure 4.3). In soil spatial variability research, it is acknowledged that more mobile soil attributes, which change rapidly in both space and time, achieve equilibrium quickly (Park and Vlek, 2002).

The highly scattered semivariance for more mobile soil attributes suggest that local conditions, such as topography, land use and land management are more important to explain spatial variability of soils than conditions prevailing nation wide, such as geology and climate. These findings are thus consistent to those from the ANOVA analysis, where local factors such as topography were found to be the most influential for spatial variability of these soil parameters on the hillslope level. Due to the large sampling interval used in this national study, such local spatial dependency of these soil attributes may not be captured in the semivariogram. This may be the opposite for the more stable soil parameters sand, silt and Ca (Tables 4.8, 4.9 and Figure 4.3).

A better view of the spatial patterns of these soil parameters in Uganda was gained through the interpolation and visualization of soil sample values, presented in the next section.

Spatial patterns of soils

The soils data of 107 communities were averaged per site, then spatially interpolated and critical values for crop growth deducted to reveal the soil quality status (Figure 4.4).

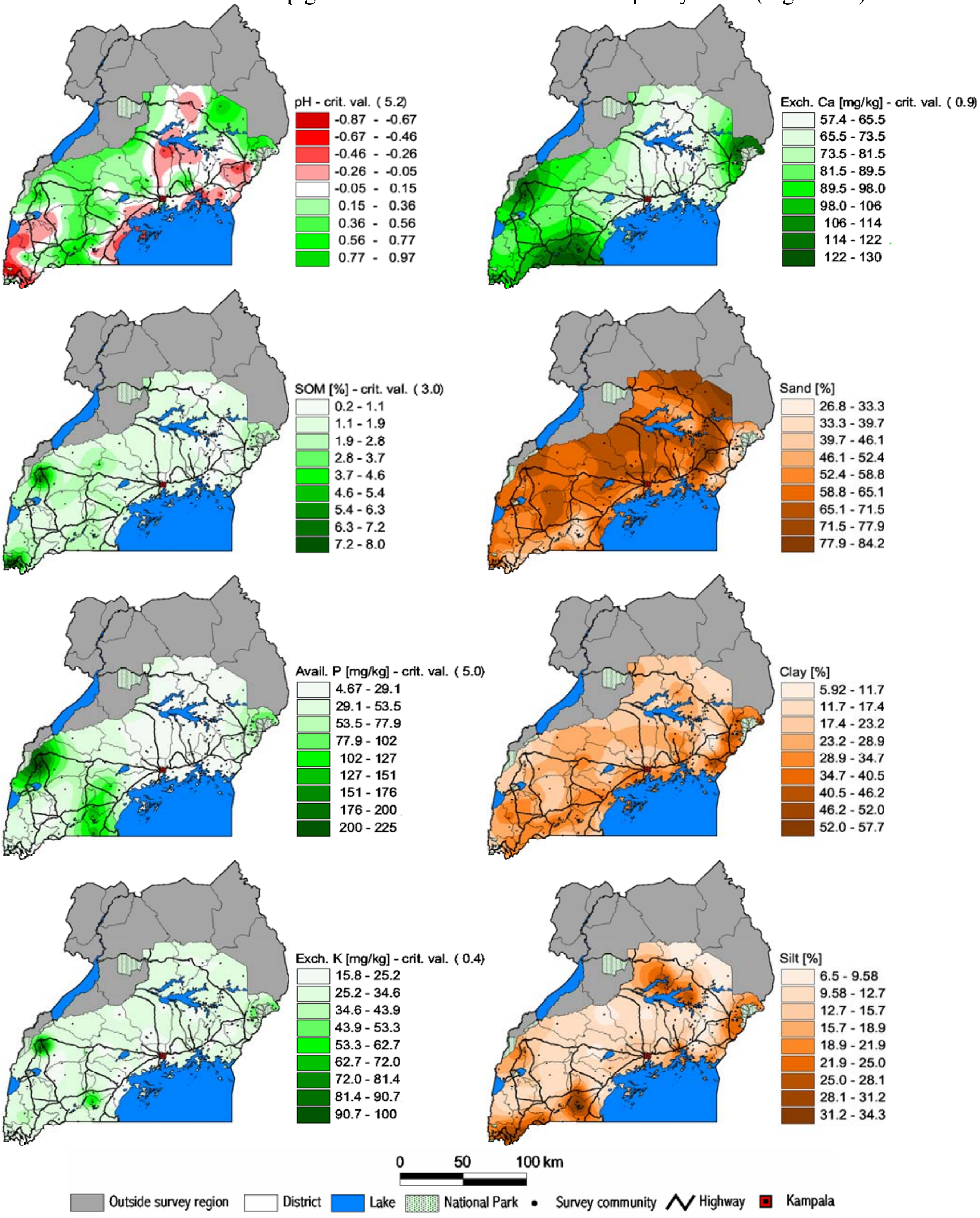

Figure 4.4: National scale spatial patterns of soil parameters deducted by their critical values

Figure 4.4 reveals clearly contrasting soil attribute patterns between the lowland areas in central Uganda on the one side and the western region, the eastern as well as the south-western highlands on the other side. The spatial distributions of SOM, P, K, and Ca have generally larger and relatively homogeneous patterns. For these soil parameters, spherical or exponential variogram models were identified in the previous semivariogram analysis. The spatial patterns of pH, sand, clay and silt have a finer resolution, with soil values changing within a shorter distance.

Soil pH is moderately to strongly acid (pH 5.2 - 4.3) in larger regions of Uganda as indicated by reddish spatial patterns. These deficient regions are markedly limiting for crop growth. They cover the central area around Lake Kyoga (eastern Luwero, northern Mukono, Kamuli and most of Lira district) and parts of south-eastern Uganda (Tororo, southern Iganga, Busia, south-western Mbale district (compare Figure 3.1 for location of districts in Uganda)). Further areas with pH deficiency stretch along the shores of Lake Victoria (southern Mpigi, south-eastern part of Mukono, the eastern parts of Masaka and Rakai district), the far west of Uganda (Rukungiri, Busheni and western parts of Mbarara district) and the south-western highlands (Kabale and Kisoro district). The soil pH is little above, just at, or little below the critical value of 5.2, shown in white color, in smaller belts surrounding the pH deficient areas (eastern Apac, outer areas of Lira, southern Kumi, central Pallisa and northern Iganga district). The soil pH values at or immediately around the critical value can also be found along the shores of Lake Victoria (southern Kamuli, south-western Mukono, eastern parts of Mpigi, Masaka and Rakai district). The highest pH levels of the study region range between pH 5.35 and 6.17 (indicated in greenish color). These pH levels, which are more favorable for crop cultivation, are mainly in the west-south-west (Kiboga, Kibaale, Kabarole, Mubende, Kasese, north-western Masaka, central and eastern Mbarara and eastern Ntungamo district) and the north-east (Soroti and Kapchorwa district).

Soil organic matter levels are nearly deficient for crop cultivation in smaller areas within the central region of Uganda (only 0.2 to 1.1% higher than the 3% critical value). These areas, indicated by white color, are located north and east of Lake Kyoga (central Lira, north-western Soroti, northern part of Iganga, Kamuli and western Pallisa district) and the Mpigi district area bordering Kampala to the north. However, the major area of the study region has SOM levels that are sufficient for crop cultivation. These values range from 1.1 to 1.9% above the critical level and cover larger areas in west and central Uganda as reflected by the very light green spatial patterns. Favorable SOM levels, which exceed the critical value by more than 1.9 to 2.8%, occur in smaller areas within the eastern and south-western highlands (indicated by dark green color). These areas cover the districts Kapchorwa, northern Mbale, western Mubende, Rakai, Masaka and southern Mbarara. The highest SOM levels of the study region reach 9 to 11% and occur in the western montane farming systems (western Kabarole, Kisoro and Kabale district).

Potassium ranges in the study region between 15.8 and 100 mg/kg, phosphorus between 4.67 and 225 mg/kg and calcium between 57.4 and 130 mg/kg above their critical levels at 0.4, 5.0 and 0.9 mg/kg, respectively. The values of these plant nutrients are far above their critical values, thus relect favorable to very favorable conditions for crop cultivation throughout the study region. The spatial distributions of K, P and Ca show similar patterns as SOM. The relatively lowest K, P, Ca levels are displayed in white color and are mainly located within central Uganda. The respective K levels range between 15.8 and 25.2 mg/kg above the critical value and are distributed as fragmented patches. The biggest patches are around Kampala (southern Luwero, eastern Mpigi, south-western Mukono district), south of Lake Kyoga (northern Kamuli district), towards east Uganda (western Tororo district) and along the west shore of Lake Victoria (eastern Masaka district). The lowest Ca values are between 57.4 and 65.5 mg/kg above the critical value and occur in central Uganda within a radius of ca 80 km surrounding the Lake Kyoga (southern Apach, most of Lira, western Soroti, most of Kamuli, northern Mukono, eastern Luwero district). The lowest P values are between 4.67 and 29.1 mg/kg above the critical value and stretch in one extensive region from the Lake Victoria to the area north of the Lake Kyoga (the whole of Apach, Lira and Soroti, western Pallisa, the whole of Iganga, Kamuli, Jinja, Mukono, Kampala and Luwero, as well as eastern Mpigi, Mubende and Kiboga district). A smaller pattern with the lowest P values is located in the south-western highlands (southern Bushenyi, northern Ntungamo, south-western Mbarara district).

Relatively slightly higher K values range between 25.2 and 34.6 mg/kg above the critical value and dominate most of the study region. Relatively slightly higher P and Ca values (29.1 to 53.5 mg/kg and 65.5 to 89.5 mg/kg above their critical values, respectively) occur in smaller areas towards west and east Uganda (Kibaale, Kiboga, western Mubende, Tororo, eastern Pallisa and Kumi district). These soil values are indicated by very light green spatial patterns. The highest levels of K (90.7 – 100 mg/kg), P (200 – 225 mg/kg) and Ca (122 – 130 mg/kg) above the critical values are shown in dark green color. They occur in smaller areas within the south-western highlands (Masaka and Kabarole district) and the eastern highlands (Kapchorwa and Mbale district).

Soil texture is distributed in a wide range in Uganda. The sand content ranges between 26.8 and 84.2%, clay between 5.92 and 57.7% and silt between 6.5 and 34.3%. The lowest sand content (26.8 - 33.3%) covers the eastern and western highlands (Mbale, Kapchorwa, Rakai and Kabale district). Relatively medium sand content (46.1-65.1%) is mainly along the shores of the Lake Victoria (southern area of Iganga, Jinja, Mukono, Kampala, Mpigi and eastern Masaka district) and in the western region (Kibaale, Kabarole, Kasese, west Mubende, western Mpigi and Masaka district). These medium sand levels occur also north of Lake Kyoga (Apac, southern Lira and western Soroti district). The highest sand content (77.9 – 84.2%) is in the east and north-east (Pallisa, north-east Soroti district). The areas with lower clay content (5.92 - 17.4%) are located in the central region around Lake Kyoga (the whole of Apac, Lira, Soroti, Kumi, Pallisa, the northern area of Kamuli, Mukono and Luwero district) and the northern, north-western and north-eastern area of Kampala (Kampala, western Mubende, eastern Kiboga, southern Luwero and parts of central Mukono district). Further areas with low clay content are in the west (Mbarara, Kasese and western Kabarole district). The areas with the highest clay (52.0 - 57.7%) and the highest silt content (31.2 - 34.3%) are in the eastern and western highlands (Mbale, Kapchorwa, Rakai and Kabale district).

4.3.3 Causes of spatial soil variability on national scale

Dominant environmental factors to explain spatial soil variability

The dominant environmental factors that may explain national-scale soil variability were identified among Geology/Geomorphology, Climate/Drought vulnerability and Land use/-management by hierarchical linear regression. Each factor was first entered alone and then as combinations of two or three and the result is shown in Table 4.10.

Table 4.10: Hierarchical generalized linear model of environmental factors that explain spatial variability of soil parameters on national-scale in Uganda

Soil parameter	Environmental factors	R^2	R^2 adjusted	Residual standard deviation	Durbin-Watson Test	Standard error of the estimate
pH in water	GEGE, CLDR, LULM	0.40	0.22	0.76	2.37	0.87
	CLDR, LULM	0.18	0.07	0.91	2.36	0.96
	GEGE, LULM	0.32	0.18	0.83	2.44	0.91
	GEGE, CLDR	0.30	0.17	0.84	2.34	0.91
	LULM	0.13	0.07	0.93	2.25	0.96
	CLDR	0.11	0.08	0.94	2.22	0.96
	GEGE	0.19	0.09	0.90	2.22	0.95
SOM (%)	GEGE, CLDR, LULM	0.65	0.54	0.60	2.53	0.68
	CLDR, LULM	0.52	0.46	0.69	2.27	0.74
	GEGE, LULM	0.57	0.48	0.66	2.68	0.72
	GEGE, CLDR	0.57	0.50	0.63	2.53	0.71
	LULM	0.40	0.36	0.78	2.27	0.80
	CLDR	0.34	0.31	0.81	2.17	0.83
	GEGE	0.49	0.43	0.71	2.42	0.75
Avail. PO_4^{3-} (mg/kg)	GEGE, CLDR, LULM	0.52	0.37	0.70	2.31	0.79
	CLDR, LULM	0.37	0.28	0.80	2.03	0.85
	GEGE, LULM	0.47	0.36	0.73	2.48	0.80
	GEGE, CLDR	0.39	0.28	0.78	2.16	0.85
	LULM	0.32	0.27	0.82	2.13	0.85
	CLDR	0.14	0.10	0.93	2.07	0.95
	GEGE	0.30	0.21	0.84	2.21	0.89
Exch. K^+ (mg/kg)	GEGE, CLDR, LULM	0.48	0.33	0.72	2.32	0.82
	CLDR, LULM	0.31	0.22	0.83	1.88	0.88
	GEGE, LULM	0.42	0.30	0.76	2.12	0.83
	GEGE, CLDR	0.31	0.19	0.83	1.84	0.90
	LULM	0.21	0.15	0.89	1.60	0.92
	CLDR	0.10	0.06	0.95	1.96	0.97
	GEGE	0.28	0.19	0.85	1.98	0.90

Soil parameter	Environmental factors	R^2	R^2 adjusted	Residual standard deviation	Durbin-Watson Test	Standard error of the estimate
Exch. Ca^{2+} (mg/kg)	GEGE, CLDR, LULM	0.40	0.23	0.77	2.41	0.88
	CLDR, LULM	0.23	0.14	0.88	2.30	0.93
	GEGE, LULM	0.36	0.23	0.80	2.51	0.88
	GEGE, CLDR	0.34	0.23	0.81	2.38	0.88
	LULM	0.19	0.13	0.90	2.34	0.93
	CLDR	0.14	0.10	0.93	2.26	0.95
	GEGE	0.30	0.21	0.84	2.28	0.89
Sand (%)	GEGE, CLDR, LULM	0.63	0.52	0.61	2.01	0.70
	CLDR, LULM	0.39	0.31	0.78	1.81	0.83
	GEGE, LULM	0.58	0.49	0.65	1.90	0.72
	GEGE, CLDR	0.59	0.52	0.64	1.89	0.69
	LULM	0.35	0.30	0.81	1.81	0.84
	CLDR	0.18	0.14	0.91	2.03	0.93
	GEGE	0.57	0.52	0.66	2.24	0.69
Clay [%]	GEGE, CLDR, LULM	0.56	0.43	0.67	2.45	0.76
	CLDR, LULM	0.34	0.26	0.81	2.16	0.86
	GEGE, LULM	0.53	0.43	0.69	2.31	0.76
	GEGE, CLDR	0.52	0.43	0.69	2.30	0.75
	LULM	0.26	0.21	0.86	1.97	0.89
	CLDR	0.15	0.10	0.92	2.01	0.95
	GEGE	0.50	0.45	0.70	0.24	0.74
Silt (%)	GEGE, CLDR, LULM	0.68	0.58	0.57	2.00	0.65
	CLDR, LULM	0.53	0.47	0.68	1.71	0.73
	GEGE, LULM	0.51	0.42	0.70	1.86	0.76
	GEGE, CLDR	0.52	0.43	0.69	1.62	0.75
	LULM	0.39	0.35	0.78	1.74	0.81
	CLDR	0.17	0.13	0.91	1.82	0.93
	GEGE	0.45	0.38	0.74	1.80	0.79

Abbreviations: GEGE = Geology/Geomorphology, CLDR = Climate/Drought proneness, LULM = Land use/-management

Table 4.10 continued

The adjusted R^2 values in Table 4.10 indicate that altogether fifty-six environmental factor combinations for the eight soil parameters have a wide range of explanatory power, e.g. Land use/Land management explained 10% of spatial variability of clay, whereas Geology/Geomorphology explained 45% of the same parameter. In order to identify the dominant predictor categories influencing the spatial variability, the respective adjusted coefficients of determination were ranked by highest, moderate and least dominant explanatory power (using the rules shown in Table 4.4) and displayed in Table 4.11.

Table 4.11: Ranking of predictor factors by their power for explaining the spatial variability of soil parameters in Uganda

Soil parameter	Environmental factors					
	GEGE	CLDR	LULM	GEGE, CLDR	GEGE, LULM	CLDR, LULM
pH in water	***	**	*	**	***	*
SOM (%)	***	*	**	***	**	*
Avail. PO_4^{3-} (mg/kg)	**	*	***	*	***	**
Exch. K^+ (mg/kg)	***	*	**	*	***	**
Exch. Ca^{2+} (mg/kg)	***	*	**	**	***	*
Sand (%)	***	*	**	***	**	*
Clay (%)	***	*	**	***	**	*
Silt (%)	***	*	**	**	*	***

*** = highest, ** = moderate, * = least explanatory rank of a predictor factor based on adjusted R^2.

Framed explanatory ranks emphasize the highest explanatory ranks for a soil parameter.

Abbreviations: GEGE = Geology/Geomorphology, CLDR = Climate/Drought proneness, LULM = Land use/-management

Table 4.11 clearly shows that Geology/Geomorphology alone has the strongest power for explaining the national-scale spatial variability of all soil parameters, except for phosphorus. The explanatory powers were 9% for pH, SOM 43%, K 19%, Ca 21%, sand 51%, clay 45% and silt 38%. For phosphorus, the dominant single environmental factor was Land use/Land management, explaining 21% of the spatial distribution of P.

The combination of Geology/Geomorphology and Land use/Land management had the strongest power to explain the spatial variability of most of the soil parameters. The explanation of pH, P, K and Ca were 18%, 36%, 30% and 23%, respectively. The combination of Geology/Geomorphology and Climate/Drought vulnerability had the strongest power to explain the spatial variability of SOM, sand and clay, with 50%, 52% and 43%, respectively. Climate/Drought vulnerability combined with Land use/Land management was best to explain the distribution of silt with 47% explained variation. These rankings point out that Geology/Geomorphology is the most dominant environmental factor and together with Land use/Land management is the most dominant two-factor combination for explaining the spatial variability of most soil parameters in Uganda.

In order to identify which soil parameters are better and which are worse predicted, environmental categories were ranked by their adjusted coefficient of determination (Table 4.12).

Table 4.12: Ranking of soil parameters by strength of environmental explanatory power in Uganda

Strength of environmental correlation	Soil parameter	Environmental factors	R^2 adjusted
Moderate (0.64 > adj. R^2 >= 0.25)	Silt (%)	GEGE, CLDR, LULM	0.58
	SOM (%)	GEGE, CLDR, LULM	0.54
	Sand (%)	GEGE, CLDR	0.52
	Sand (%)	GEGE	0.52
	Sand (%)	GEGE, CLDR, LULM	0.52
	SOM (%)	GEGE, CLDR	0.50
	Sand (%)	GEGE, LULM	0.49
	SOM (%)	GEGE, LULM	0.48
	Silt (%)	CLDR, LULM	0.47
	SOM (%)	CLDR, LULM	0.46
	Clay (%)	GEGE	0.45
	SOM (%)	GEGE	0.43
	Clay (%)	GEGE, CLDR	0.43
	Silt (%)	GEGE, CLDR	0.43
	Clay (%)	GEGE, LULM	0.43
	Clay (%)	GEGE, CLDR, LULM	0.43
	Silt (%)	GEGE, LULM	0.42
	Silt (%)	GEGE	0.38
	Avail. PO_4^{3-} (mg/kg)	GEGE, CLDR, LULM	0.37
	Avail. PO_4^{3-} (mg/kg)	GEGE, LULM	0.36
	SOM (%)	LULM	0.36
	Silt (%)	LULM	0.35
	Exch. K^+ (mg/kg)	GEGE, CLDR, LULM	0.33
	Sand (%)	CLDR, LULM	0.31
	SOM (%)	CLDR	0.31
	Exch. K^+ (mg/kg)	GEGE, LULM	0.30

Strength of environmental correlation	Soil parameter	Environmental predictor factors	R^2 adjusted
Moderate (0.64 > adj. R^2 >= 0.25)	Sand (%)	LULM	0.30
	Avail. PO_4^{3-} (mg/kg)	CLDR, LULM	0.28
	Avail. PO_4^{3-} (mg/kg)	GEGE, CLDR	0.28
	Avail. PO_4^{3-} (mg/kg)	LULM	0.27
	Clay (%)	CLDR, LULM	0.26
	Exch. Ca^{2+} (mg/kg)	GEGE, LULM	0.23
	Exch. Ca^{2+} (mg/kg)	GEGE, CLDR, LULM	0.23
	Exch. Ca^{2+} (mg/kg)	GEGE, CLDR	0.23
Weak (0.25 > adj. R^2 >= 0.04)	pH in water	GEGE, CLDR, LULM	0.22
	Exch. K^+ (mg/kg)	CLDR, LULM	0.22
	Exch. Ca^{2+} (mg/kg)	GEGE	0.21
	Avail. PO_4^{3-} (mg/kg)	GEGE	0.21
	Clay (%)	LULM	0.21
	Exch. K^+ (mg/kg)	GEGE	0.19
	Exch. K^+ (mg/kg)	GEGE, CLDR	0.19
	pH in water	GEGE, LULM	0.18
	pH in water	GEGE, CLDR	0.17
	Exch. K^+ (mg/kg)	LULM	0.15
	Exch. Ca^{2+} (mg/kg)	CLDR, LULM	0.14
	Sand (%)	CLDR	0.14
	Exch. Ca^{2+} (mg/kg)	LULM	0.13
	Silt (%)	CLDR	0.13
	pH in water	GEGE	0.12
	Clay (%)	CLDR	0.10
	Avail. PO_4^{3-} (mg/kg)	CLDR	0.10
	Exch. Ca^{2+} (mg/kg)	CLDR	0.10
	pH in water	CLDR	0.08
	pH in water	LULM	0.07
	pH in water	CLDR, LULM	0.07
	Exch. K^+ (mg/kg)	CLDR	0.06

Ranking is based on adjusted R^2 in the order from highest to lowest value.

Abbreviations: GEGE = Geology/Geomorphology, CLDR = Climate/Drought proneness, LULM = Land use/-management

Table 4.12 continued

As shown in Table 4.12, the highest correlation for the spatial variability of silt (more than 50%) is obtained by the combined factors Geology/Geomorphology, Climate/Drought vulnerability and Land use/Land management. The lowest prediction was 6% in the case of the spatial variation of K, when explained by Climate/Drought vulnerability alone. The prediction of the best single, pair and three combinations of factors for explaining the spatial variability of soil parameters in Uganda is displayed in Figure 4.5.

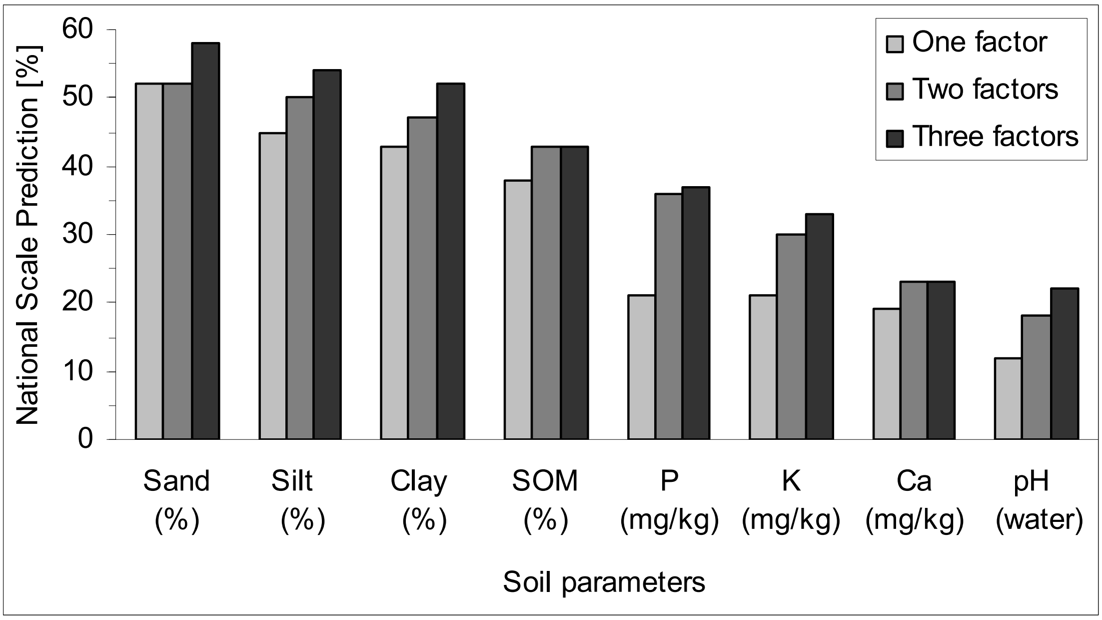

Figure 4.5: Prediction of spatial variability of soil parameters in Uganda by number of environmental predictor factors

The different bar lengths in Figure 4.5 illustrate the strength of the best single, pair and three environmental factor combinations in explaining the variability of soil parameters. The highest predictions are for the spatial variability of sand, silt, clay and SOM. Moderate to low predictions were possible for P, K, Ca and pH.

4.4 Summary and conclusions

This study assessed the spatial variability of soils on a national-scale in Uganda. The assessment relied on an extensive survey in the year 2000 when 1050 topsoil samples were collected along transects of 107 rural community hillslopes in Central, East and South Uganda. The community selection was based on a pre-classification of Uganda into spatial development domains. The soil samples from these communities were analyzed for pH, SOM, available phosphorus, exchangeable potassium, exchangeable

calcium, sand, clay and silt. Environmental data were collected at the geographic location of these soil samples for identifying the most important factors determining spatial variability by hierarchical generalized linear regression model (GLM). The environmental variables were grouped into three major factors:
1) geology/geomorphology capturing the variables geological age, geotectonic land surface type, parent material, elevation, 2) climate/drought vulnerability including the variables annual precipitation, length of growing period, rainfall seasonality, maximum temperature during hottest month, drought vulnerability and 3) land use/land management with the variable farming system.

The average soil texture is sandy clay loam. Higher average values than the critical soil fertility threshold values (Foster, 1971) were identified for pH (5.34), SOM (5%), P (50 mg/kg) and K (31 mg/kg). These represent favorable agricultural conditions. However, all soil parameters exhibit a wide range, thus higher values may mask lower values in this analysis, e.g. pH (4-7), SOM (1-24%), P (1-800 mg/kg), K (1-500 mg/kg), Ca (1-700 mg/kg).

The spatially explicit analysis of each soil sample in relation to its position on the hillslope revealed that local terrain may strongly influence the spatial distribution of pH, SOM, and clay, but not of P, K, Ca, sand and silt. It was concluded that other factors, such as land use and land management may be more important for these latter soil parameters. The geostatistical analysis showed that most soil parameters have a weak to moderate spatial dependency as indicated by spherical and exponential variogram models. The parameters soil pH, SOM, clay, P, and K had higher scattered semivariance than sand, silt and Ca. This behavior is generally observed for more mobile soil parameters, such as the ones from the first group, which may change quickly in both space and time with local pedogenetic, land use and land management processes occurring on hillslopes (Park and Vlek, 2002).

Further spatial analysis revealed the specific soil parameter patterns across Uganda. Overall, the central area and the buffer area around the Lake Victoria had soil parameter levels that were markedly limiting for crop growth (e.g. for pH) or at a lower level that was close to limit crop growth (e.g. for SOM). Furthermore, these areas had mainly higher sand and lower clay content. In contrast, the western region and the highlands had generally higher soil quality, indicated for example by higher pH, SOM, clay and lower sand levels. Considering the plant nutrients soil P, K and Ca, much higher levels than crictical values were found throughout the study region.

Among the environmental predictors, Geology/Geomorphology had the strongest power to explain the national-scale spatial variability for all soil parameters, except phosphorus, which was mainly determined by Land use/Land management. The explanatory powers were 9% for pH, SOM 43%, K 19%, Ca 21%, sand 51%, clay 45%, silt 38% and for P 21%. If all three factors were combined the prediction of soil parameters was for pH 22%, SOM 54%, K 33%, Ca 23%, sand 52%, clay 43%, silt 58% and for P 37%. SOM was well explained after the silt + clay content was added as a predictor (59%). Thus, Geology/Geomorphology related processes may mainly determine the national-scale spatial variability of soils in Uganda. The Land use/Land management and Climate/Drought vulnerability related processes contributed partly to the soil’s spatial variability and are expected to have a perhaps stronger influence on the hillslope scale.

The established soil database and the captured knowledge on soils´ spatial variability may help policy makers and regional development planners to better target development strategies to the prevailing soil conditions, especially taking soil organic matter distribution into account.

5 HILLSLOPE-SCALE SPATIAL VARIABILITY OF SOILS

5.1 Introduction

Agricultural extension services in Uganda generally work at the landscape level for direct implementation of improved soil management strategies. Landscapes integrate hydrological processes as well as a farming community within one spatial system (Thomas, 1997). Within this system, natural and human factors that determine spatial variability of soils and soil nutrients may be captured and appropriate INM strategies may be targeted to precise locations (Vlek et al., 1997).

However, Uganda's landscapes are usually complex hillslopes with smallholder farms comprising a large number of land uses on small plots in different slope positions. Many farmers on these hillslopes increasingly struggle with deteriorating soil quality and are forced to grow low-nutrient tolerant crops or to abandon degraded fields. However, other farmers on the same hillslopes report favorable crop production (Ruecker and Brunner, 2001; Woelcke, 2002). Quantifying and demarcating soil variability over a hillslope is important in order to design INM strategies that fit all farmers on a hillslope and can improve soil conditions for sustainable production (Swallow et al., 2001).

A successful INM strategy requires an accurate inventory of the spatial variability of the natural resources, land use and land management variability on hillslopes. However, since detailed soil surveys are rare in Uganda, the spatial distribution of the crucial soil parameters that may determine soil quality on hillslopes is usually not available. Furthermore, agricultural extension services usually lack the knowledge on the different terrain conditions, land use distribution and land management practices and their likely impact on soil conditions on hillslopes (Cleaver and Schreiber, 1992).

The objectives of this hillslope-scale study are 1) to investigate how the most important soil-quality parameters that determine soil conditions on hillslopes in Uganda are spatially distributed, 2) to delineate hillslopes into terrain units that may capture variability of soils, 3) to examine the structure of the patterns of these soil parameters, and 4) to explain the causes of soil variability over hillslopes.

5.2 Material and methods

5.2.1 Selection and description of hillslopes

For intensive soil variability studies on a landscape scale, two community sites were selected based on the 107 community survey samples of the national-scale study (chapter 4.2.1). The general selection criteria were that these communities represent contrasting natural resource and socio-economic characteristics in terms of elevation (highland versus lowland), agricultural potential (bimodal high versus unimodal high potential), and market access (high versus low access). The Kongta and Magada communities met these criteria and represent the corresponding development domains #15 and #1, respectively (chapter 3.3.1). Within each of these communities one hillslope was identified. The location and view on the hillslopes is shown in Figure 5.1.

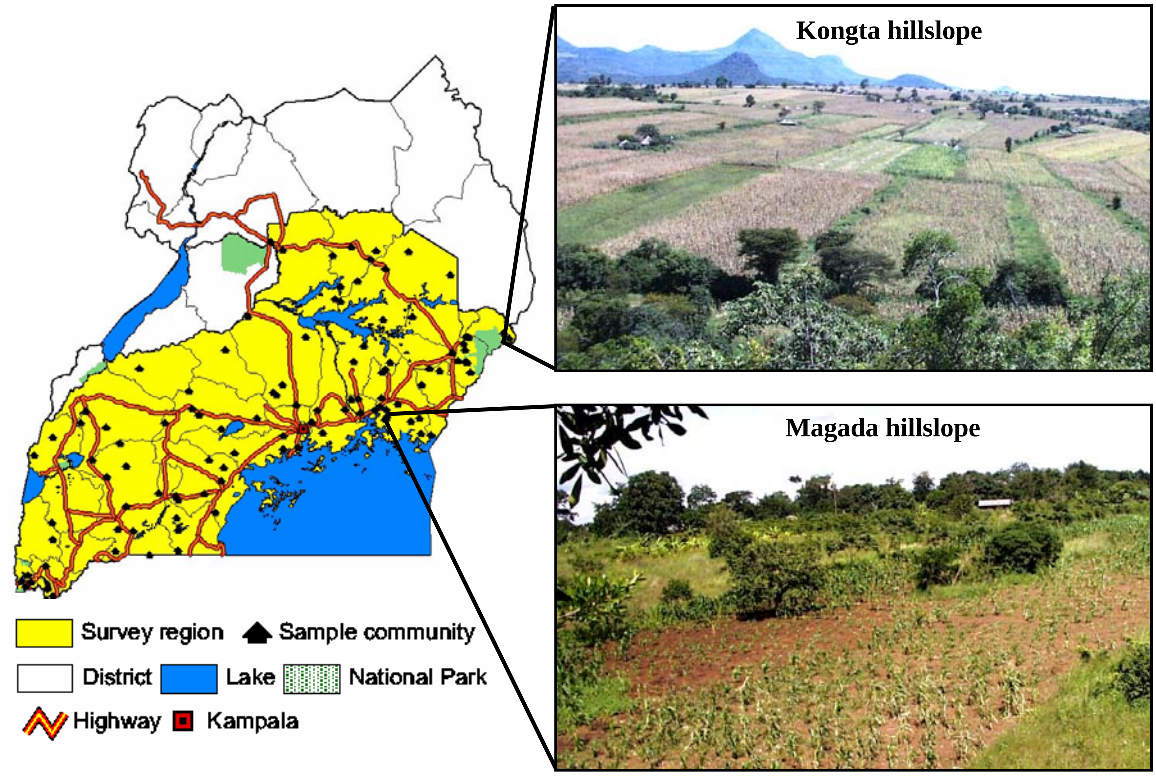

Figure 5.1: Location and view on the Kongta and Magada hillslopes in Uganda

The Kongta hillslope is located at the latitude of 34°45´E and the longitude of 1°16´N, while the Magada hillslope is situated at the latitude of 33°28`E and the longitude of 0°32`N. The characteristics of each site are shown in Table 5.1.

Table 5.1: Characteristics of Kongta and Magada hillslopes

Major characteristic	Specific characteristic	Kongta	Magada
Geographical orientation / Extent	Administration	Kapchorwa District, Kongasis County, Bukwa Sub-County, Muimet Parish, Kongta LC1, Kongta Community	Iganga District, Bunya County, Imanyiro Sub-county, Magada Parish, Magada LC1, Magada Community
	River catchment	Armanang catchment	Walungogo catchment
	Hillslope	Length 300m, width 200m, size 6 ha	Length 480m, width 300m, size 14.4 ha
Geology / Geomorph-ology	Geology	Tertiary extrusiv and intrusiv	pre-Cambrian
	Parent material	Mount Elgon volcanics	Basement complex gneisses and amphibolites
	Geomorphological unit	Volcanic mountains and hills	Buganda surface
	Average Elevation [m]	1819	1146
	Maximum slope gradient [°]	18	8
Climate	Annual rainfall [mm]	1259	1319
	Length of growing period [months]	8	10
	Growing seasons	1	2
	Max. Temperature in Feb. [°C]	27.6	29.7
Soil	Soil type (FAO / Uganda classification system)	Mollic Andosols / Dark brown clays, clay loams	Plinthic Ferralsols / Deep red clay loam over laterite
	Soil quality for crop cultivation (farmers´ assessment)	Favorable	Favorable to marginal
	Soil erosion problem (farmers´ assessment)	High erosion	Moderate erosion
	Soil fertility problem (farmers´ assessment)	Soil fertility is still good	Soil fertility is generally low
Land use / Land management	Farming system	Montane farming system	Intensive banana coffee lake shore system
	Major crops	Maize	Banana, coffee, maize, cassava, sweet potato, beans
	Tillage implement	Ox-plough	Hand hoe
	Major soil fertility management technology	Inorganic and organic fertilizers, agro-chemicals	Crop rotation, intercropping
	Major soil and water conservation technology	Stonelines	Cover crops, trees, bushes
Socio-economics	Population density	High	High
	Market access	Low	High

The majority of farmers at these sites have settled on the summits of the hillslopes close to feeder roads. Average household size is ca. 6 people and agriculture is the main source of income. Due to continuing high population pressure in these areas (ca. 120 and 270 persons per km^2 in Kongta and Magada, respectively), most of the available land is used (Wortmann et al., 1998; Wortmann and Kaizzi, 1998; Esilaba et al. 2002). Although the Kongta farmers consider their soil quality good for crop cultivation, maturation of maize, which is the dominant crop, takes more than six months due to the colder temperatures at the higher elevation on the mountain. In order to achieve the maximum yield from the one possible harvest, farmers in Kongta apply inorganic fertilizers, cow dung and agro-chemicals (Kaizzi, 2002).

5.2.2 Data collection

Combined soil and terrain survey as well as participatory hillslope mapping procedures were carried out on the hillslopes from November 2000 until April 2001 to collect data on the spatial variability of soils, terrain, land use and land management.

Soil survey

Composite topsoil samples were collected from the corner points of a regular 20 x 20 m^2 grid that covered the cultivated, fallow and natural vegetation areas of each hillslope. A-horizon depth was measured by soil auger at the corner points of a regular 40 x 40 m^2 that covered the same hillslope areas as for the soil sampling. Since Kongta was approximately half as large as Magada (Table 5.1), the number of samples for the majority of the soil parameters was 154 and 285, respectively, while A-horizon depth was measured at 48 and 83 locations, respectively. The soil-sampling layout of the two hillslopes is shown in Figure 5.2.

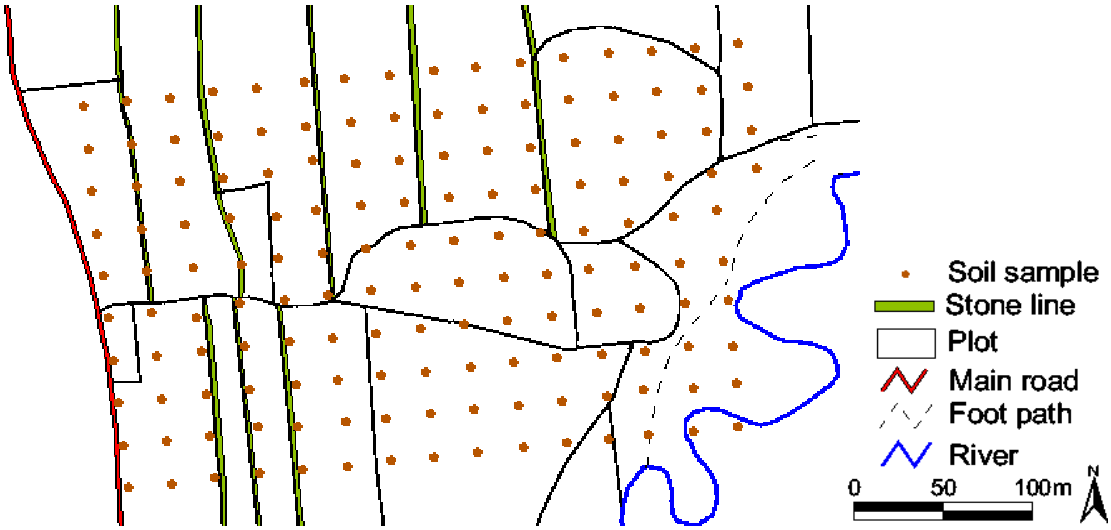

Figure 5.2 a): Soil sampling layout on Kongta hillslope.

Figure 5.2 b): Soil sampling layout on Magada hillslope

As Figure 5.2 a) shows, soil samples in Kongta were collected on a regular grid basis roughly between the main road and the river. This sample layout was independent of the layout of the stone lines that partly coincided with plot boundaries, which were arranged in a North/South direction. In Figure 5.2 b) the regular soil sample layout stretches from the cultivation plots close to the main road down to the valley, including soil samples from areas within natural bush vegetation and under trees.

Terrain survey

Terrain was measured by recording latitude, longitude and elevation coordinates of locations across the hillslopes using a Trimble surveyor differential global positioning system (DGPS) (Trimble, 2002). The DGPS was applied to achieve the high measurement accuracy that is necessary for detailed terrain analyses. Due to the remote location of Kongta, no WGS-84 reference point was yet available within 200 km for setting up the base station to a known coordinate. Therefore, a base station coordinate was generated by fast static DGPS measurements on an elevated location near Kongta. The recording time was set to one hour, the maximum possible recording time interval of this DGPS. The average of five measurements was calculated to determine the Kongta base station coordinate. For measurements in Magada the base station was positioned on the nearest available WGS-84 reference point with known coordinates, which was located at a distance of ca. 7 km in Iganga town. The TSC1 Rover-DGPS equipment was set to point measurements and post-processed kinematic survey mode (Trimble, 2002). DGPS measurements were carried out on the Kongta and Magada hillslopes at the 20 m x 20 m soil sample grid locations. Additional measurements were taken on the grid center positions and on steep slopes where terrain changed considerably within this grid. This survey was extended ca. 200 m in each direction beyond each soil sample grid to avoid boundary effects during DEM construction.

Land use and land management survey

The DGPS was used to record the geographic location of plot boundaries that were demarcated on the hillslopes. The plot boundaries are shown in Figure 5.2. Farmers who cultivate these plots were asked during transect walks traversing the plots about their specific land use, land management and socio-economic conditions and the responses were coded in a questionnaire.

5.2.3 Data processing

Soil sample analysis

Air-dried soil samples were prepared and analyzed as described in chapter 4.2.3. Based on these analyses, the soil parameters pH, soil organic matter content, extractable bases K and Ca, available P and texture were selected for spatial variability analysis.

Terrain analysis

DGPS baseline processing and DEM construction

The DGPS baselines that were recorded between the base station and the rover were post-processed using Trimble Geomatics software (Trimble, 2003) to achieve accurate coordinates. In total, 340 DGPS points were collected on the Kongta and more than 1000 points on the Magada hillslope. A one-meter-elevation DEM was generated for each site using universal kriging with linear drift and a search radius of 147.882 in Surfer software (Golden Software Inc., 1999). Visual comparison of the contour maps and the DEM with some rapidly changing points on the hillslopes was satisfactory.

Terrain parameters calculation

Six primary topographical parameters (elevation, slope gradient, aspect, plan curvature, profile curvature and upslope area) were calculated using a FORTRAN programme provided by Zevenbergen and Thorne (1987). These were among the most frequently used terrain parameters in soil-terrain correlation analysis (Dikau, 1989; Quinn et al., 1994; Moore et al., 1993, Park et al., 2001). The multi-flow algorithm was used to calculate the upslope area to better represent the divergent properties of the convex hillslope topography compared to the available single flow algorithm, which mainly considers the linear flow direction (Quinn et al. 1994). The two secondary terrain parameters, wetness index and stream power index, were calculated from these primary parameters using the following functions.

Wetness index (w) = $\ln (A_s / \tan \beta)$ (Moore et al. 1993)
Stream power index (Ω) = A_s, $A_s \tan \tan \beta$ (Moore et al. 1993)
Terrain Characterization Index (TCI) = $Cs * \log10 (As)$ (Park et al. (2001)
where A_s is the upslope area, and β is the slope gradient.

Hillslope zonation

Conceptual framework

A delineation of the hillslopes into zones was performed to test whether broader terrain zones may be useful as a first step to explain the spatial variability of soils over these two sites. The theoretical framework for delineating hillslopes into zones was based on Ruhe´s widely used hillslope classification concept (1960). In this approach pedogeomorphological processes were identified that characterize geometrically shaped hillslopes, which cause similar spatial soil variability. This concept has been widely used in many soil-landscape analyses to determine the major spatial variability of soil parameters on hillslopes (Conacher and Dalrymple, 1977, Pennock, 1987, Dikau, 1989, Schoeneberger et al., 1998, Park et al., 2001). The basic geometric forms of these hillslopes are shown as block diagrams in Figure 5.3.

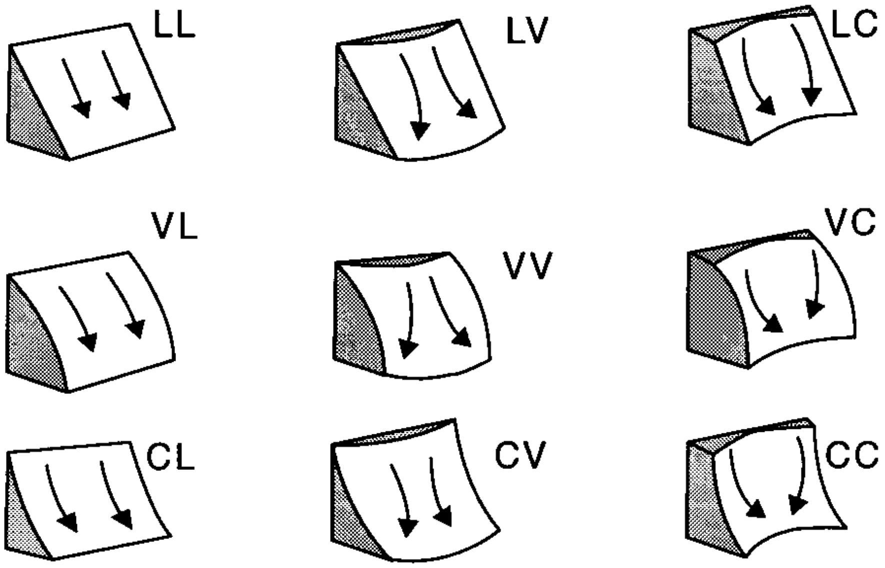

Figure 5.3: Basic geometric hillslope forms after Ruhe (1960) from Wysocki et al. (2000)

Note: The first letter of the abbreviation represents the hillslope shape in downslope orientation, while the second letter indicates the shape across the slope, with L = linear, V = convex and C = concave: LL=collinear, VL=convex-linear, CL=concave-linear, LV=linear convex, VV=convex-convex, CV=concave-convex, LC=linear-concave, VC=convex-concave, CC=concave-concave.

These nine basic hillslope forms vary in terms of complexity from the most simple form, which is straight both downslope and across slope (LL) to the most complex forms that are in both directions concave, convex or a combination of both. Based on the geometric form of a hillslope, certain hydrological processes are expected to be dominant, which in turn influence soil redistribution. Thus, on linearly-shaped hillslopes (LL) runoff should mainly move as sheet flow and soil materials should be homogeneously distributed over the hillslope. On a convex linear shaped (VL) hillslope, sheet flow dominates over the hillslope. However, sheet flow is smaller in the upper section, possibly causing some soil erosion and therefore soil redistribution. Sheet flow increases with stronger velocity on the steeper slope gradients, resulting in greater erosion and soil redistribution. In contrast, smoother hillslope sections as in the lower part of the CL geometry shape have lower velocity, and thus usually promote soil sedimentation. Across-slope curvature, such as in the linear-convex hillslope type leads to diverging runoff flow, whereas linear-concave hillslope types tend to converging runoff flow that may form drainage lines. Diverging runoff flows may cause soil parameter divergence, converging runoff flows may generally lead to more homogeneous soil parameters. The combination of convex and concave slope shapes leads to very complex runoff and velocity systems (Ruhe, 1960).

Based on Ruhe´s fundamental concept on the geometric hillslope forms and the resulting spatial soil redistribution patterns, the occurrence of these geometric forms was investigated on the two hillslopes. First observations in the field and of the DEMs revealed that the two hillslopes appeared to be more complex than Ruhe´s generalized hillslopes. Therefore, a combination of different geometric forms on one hillslope was assumed to represent the overall geometric form composition of each of the more complex hillslopes in Uganda more realistically. This approach to consider the geomorphologic elements of complex hillslopes as a combination of different terrain units was used in other studies before, such as by Pennock (1987) and Park et al. (2001). The next section describes how the two Uganda hillslopes were composited from larger hillslope forms or landscape unit to smaller landscape elements.

Delineation of landscape elements

The procedure for delineating landscape elements from the hillslopes was carried out in two steps using terrain parameters that were calculated from the corresponding digital elevation models. At first, geometric hillslope forms or landscape units were derived based on GIS stratification of slope gradient and upslope contributing area. In a second step, more detailed landscape elements were delineated within these landscape units by distinguishing patterns of convex and concave plan and profile curvature. The theoretical justification for using slope gradient is that this terrain parameter represents the major rate of change of water and soil processes downslope (Dikau, 1989; Hammer et al., 1995; Barringer and Lilburne, 1997; Young and Hammer, 2000; Stefano et al., 2000). The upslope contributing area characterizes the catchment area above a sampling point. This was used to characterize landscape elements by different levels of water and soil accumulation and distribution (Moore et al., 1993, Quinn et al, 1994; Tarboton, 1997; Park, et al., 2001). Plan and profile curvature were applied in several soil-landscape studies for the characterization of convergent and divergent landscape elements on hillslopes (Pennock, 1987, Zevenbergen and Thorne, 1987; Stefano et al., 2000). The threshold values for slope gradient were set to 0° - 1° (flat, absent to weak downslope processes), 1° - 3° (gently sloping, moderate downslope processes) and > 3° (steep, strong downslope processes) (Pennock et al., 1987, Park et al., 2001). Govers (1985) concluded that water velocity on slopes below 3° was not enough to generate rills, but may lead to deposition of soil (Moss and Walker, 1978) and vertical infiltration (Conacher and Dalrymple, 1977). Threshold values for upslope contributing area were adjusted after Park et al. (2001) and were set to –3.0 to +1.0 and –0.5 and +0.5 of the standard deviation for upslope contributing areas in Kongta and Magada, respectively. This differentiates areas with minor from areas with major upslope area. The landscape unit delineation procedure is shown in Figure 5.4.

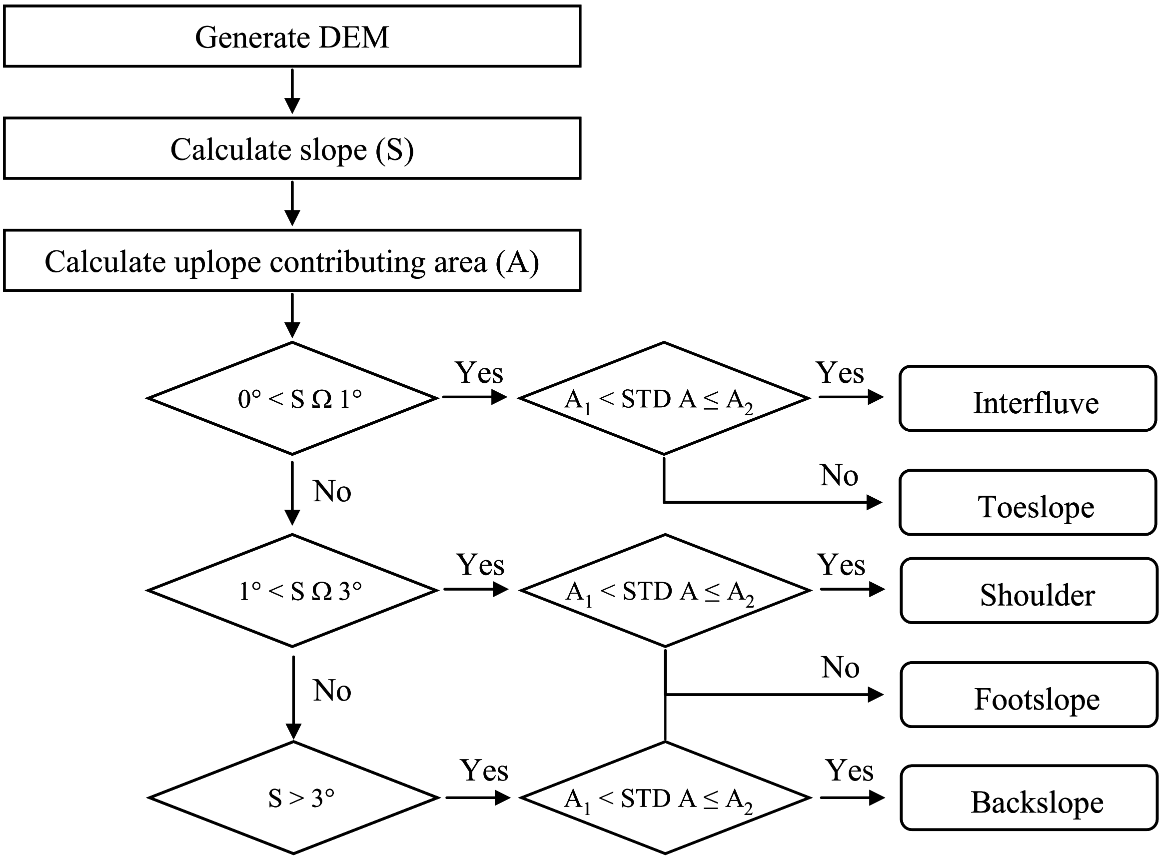

Figure 5.4: Procedure to delineate landscape units on hillslopes by terrain analysis
Note: In Kongta A_1 = -3.0, A_2 = +1.0; in Magada A_1 = -0.5, A_2 = +0.5.

Based on this delineation procedure the landscape units interfluve, shoulder, backslope, footslope and toeslope were delineated from the Kongta and Magada hillslopes, if they were existent on these hillslopes. After this coarse demarcation of the hillslopes, each landscape unit was then further subdivided into landscape elements taking the dominant plan and profile curvature patterns into account. The threshold values for dominant profile curvature patterns were set after Young (1972) and Stefano et al. (2000): concave (< -0.10 °/m), linear (> -0.10 and < 0.10 °/m) and convex (> 0.10 °/m). Major plan curvature patterns were distinguished into concave (< 0.0 °/m) and convex (> 0.0 °/m) (Pennock, 1987). If the dominant profile and plan curvature were both concave (convex), the overall pattern of the landscape element was determined to be convergent (divergent). If profile and plan curvature had different curvature form, the most dominant curvature form (either convergent or divergent) was determined to characterize the respective landscape element. The suitability of this procedure to delineate landscape elements for reducing the spatial variability of soil samples was tested by statistical analysis as described in section 5.3.1.

Land use and land management data integration

Using the DGPS information of the plot boundaries, digital GIS-maps of the plots on the hillslopes were constructed in ArcView GIS. The characteristics of the land use and land management that has been recorded in a questionnaire was entered into a Microsoft Access database. The GIS-maps comprising the boundary information of farmers´ plots were then joined with the georeferenced information in the questionnaire. Using spatial overlay GIS operation, the respective land use and land management information that spatially coincided with the respective soil sample location was read out from the GIS maps and assigned to the soil attribute table. The resulting GIS data table was then exported to ASCII-data format and imported to SPSS format for statistical analysis and to S-PLUS for spatial analysis.

5.2.4 Statistical and spatial analyses

Various statistical and spatial analyses were performed in a complementary matter to assess the range of criteria that characterize soils´ spatial variability on the hillslope. The applied analyses included descriptive statistics, correlation analyses, analyses of variance, semivariance analysis, spatial interpolation, and hierarchical generalized linear modeling. These analysis techniques were on the whole identical to the national-scale soil spatial variability analyses, where they are described in detail (chapter 4.2.4).

Therefore, only additional or different information from these analyses will be presented in the following.

The significance of the hillslope separation into landscape units and landscape elements on soil properties was determined by a one way *Analysis of Variance* (ANOVA). The Bonferroni test and the Dunnet T3 test were applied to indicate which of these hillslope zones have significantly different means.

The spatial dependency of soil properties over each hillslope was modeled by the geostatistical semivariogram analysis. Zonal anisotrophy was observed in 90° direction along the hillslope and accounted for together with a ratio of 1.5 in the calculation of the semivariance. On the hillslopes the number of lags was set to 20, lag tolerance was 5 and maximum distance was 200 (Journal and Huijbregts, 1978). Initial analyses showed that directional anisotropy is not severe for most of variables analyzed. Therefore only one uni-directional variograms (0°) was constructed in most cases. Lag and angle tolerance was set half of the lag and 45°, respectively. Webster and Oliver (1990) recommend more than a hundred points for two-dimensional variability (line transect), and a few hundred sampling points for three-dimensional spatial variability. The maximum of 115 and 285 points from the hillslopes might thus be considered marginal. Therefore, the use of spatial statistics is limited to assessing the relative importance of the spatial distribution of measured variables.

5.3 Results and discussion

5.3.1 Spatial distribution of soils on hillslope scale

Total variability of soils

The total variability characteristics of topsoil samples on the two hillslopes were analyzed by descriptive statistics and the results were compared with critical threshold values as shown in Table 5.2.

Table 5.2: Descriptive statistics and critical values of soil topsoil samples on a hillslope-scale in Uganda

Soil parameter	Site	N	Mean	Minimum	Maximum	Critical value[1]	STD	CV[2] (%)	CV[3] (%)
pH in water	Kongta	154	5.74	5.00	7.00	5.20	0.40	6.90	3.89
	Magada	285	5.41	4.00	6.30		0.45	8.28	5.21
SOM (%)	Kongta	154	5.12	2.90	9.70	3.00	1.16	22.7	13.8
	Magada	285	2.99	1.90	5.30		0.70	23.4	20.7
Avail. PO_4^{3-} (mg/kg)	Kongta	154	41.4	3.00	539	5.00	79.2	191	35.9
	Magada	285	3.22	0.40	9.40		1.79	55.5	66.5
Exch. K^+ (mg/kg)	Kongta	154	73.1	23.0	124	0.40	17.9	24.4	24.4
	Magada	285	18.5	1.80	40.5		8.97	48.4	48.4
Exch. Ca^{2+} (mg/kg)	Kongta	154	113	22.6	222	0.90	33.6	29.7	29.7
	Magada	285	44.8	0.20	95.4		21.0	47.0	47.0
Sand %	Kongta	154	27.2	15.8	43.2	NA	4.95	18.2	9.71
	Magada	285	69.1	55.8	89.1		5.93	8.58	2.07
Clay (%)	Kongta	154	50.9	38.0	64.3	NA	5.45	10.7	5.39
	Magada	285	20.6	4.00	31.2		5.61	27.2	15.4
Silt (%)	Kongta	154	21.8	8.60	37.6	NA	4.20	19.2	19.2
	Magada	285	10.3	1.30	28.9		3.29	31.9	47.4
A-Horizon depth (cm)	Kongta	48	23.3	17.0	30.5	NA	3.87	16.6	6.45
	Magada	83	21.3	5.00	31.0		5.83	27.3	46.5

Abbreviations: STD = standard deviation; CV = coefficient of variation; NA = Not applicable

[1] Below this value, soil parameter level is deficient (Foster, 1971)

[2] = CV of soil parameter, [3] = CV of transformed soil parameter

Based on the soil sample collection and soil analyses, the average soil texture in Kongta is clay and in Magada sandy clay loam. The clay soil texture of Kongta provides generally better water holding capacity than the more sandy clay loam soils such as in Magada (Doorenbos and Kassam, 1979). However, clay soil may allow less infiltration, causing loss of runoff water on the steeper hillslopes (Doorenbos and Pruitt, 1977), and requiring thorough tillage. But after the dry season on the Mount Elgon this clay hardens, thus is usually extremely difficult to till, and it becomes very sticky when moist during the rainy season. Farmers in Kongta therefore use strong tillage power by oxen to perform this heavy soil ploughing (Kaizzi et al., 2003).

In contrast, the sandy clay loam texture in Magada provides usually for both good water infiltration and fairly good water storage and is easy for the cultivation of many crops (Sys et al., 1993; FAO, 1996). But with erosive removal of topsoil plinthites that were often formed in sub-soils may be exposed and form hard laterites (Alexander, 1962, Harrop, 1970) that pose enormous problems for crop cultivation to the Magada farmers. Considering that the small-scale farmers in Magada are generally capital-poor, the majority of them must rely on the handhoe to perform soil tillage (Woelcke et al., 2002), which on the hard pans becomes virtually impossible.

The average soil pH in Kongta is a little higher (ca. 5.7) than in Magada (ca. 5.4), but both sites are still above the critical limits that were established by Foster (1971). The average SOM content in Kongta (ca. 5%) is almost double that in Magada (ca. 3%). Moreover, P, K and Ca have more than ten, four and three times higher average levels in Kongta (ca. 41 mg/kg, 73 and 113 mg/kg, respectively) than in Magada (3, 19 and 45 mg/kg, respectively). In Magada, the average content of SOM is therefore just marginal and the corresponding value of P is already below the critical soil fertility levels of Foster (1971). In contrast, all of these soil parameters in Kongta are far above the critical levels and show a far greater range of values (Table 5.2). The average A-horizon depth is in Kongta also relatively higher (ca. 23 cm) than in Magada (ca. 21 cm).

In order to differentiate the soil parameters by their magnitude of total variability over the hillslopes, the standardized variability was compared using the variation coefficients of soil parameter values. The variation coefficients are ranked in Table 5.3.

Table 5.3: Ranking of total variability of transformed soil parameters on a hillslope-scale in Uganda

Variability	Soil parameter	Site	CV (%)	Transformation
Least (CV < 15%)	Sand (%)	Magada	2.07	LOG
	pH in water	Kongta	3.89	LOG
	pH in water	Magada	5.21	LOG
	Clay (%)	Kongta	5.39	SQRT
	A-Horizon depth (cm)	Kongta	6.45	LOG
	Sand (%)	Kongta	9.71	SQRT
	SOM (%)	Kongta	13.8	LOG
	Clay (%)	Magada	15.4	SQ
Moderate (15% <= CV < 35%)	Silt	Kongta	19.2	-
	SOM (%)	Magada	20.7	LOG
	Exch. K^+ (mg/kg)	Kongta	24.4	-
	Exch. Ca^{2+} (mg/kg)	Kongta	29.7	-
High (CV >= 35%)	Avail. PO_4^{3-} (mg/kg)	Kongta	35.9	LOG
	A-Horizon depth (cm)	Magada	46.5	SQ
	Exch. Ca^{2+} (mg/kg)	Magada	47.0	-
	Silt	Magada	47.4	LOG
	Exch. K^+ (mg/kg)	Magada	48.4	-
	Avail. PO_4^{3-} (mg/kg)	Magada	66.5	LOG

Abbreviations: CV = coefficient of variation of transformed soil parameters;
LOG = Logarithm; SQRT = Square Root; SQ = Square.

The ranking of soil variation coefficients from the two sites indicates that different soil parameters have different variability within each hillslope and between hillslopes. As shown in Table 5.3, sand, pH and clay have the least total variability, whereas P, Ca, K, silt have moderate to high, SOM has low (in Kongta) to moderate (in Magada) and A-horizon thickness has low (in Kongta) to high (in Magada). Since some soil parameters are known to have similar variance behavior, and thus may respond similarly to their determining factors, correlations among soil parameters and between soil parameters and terrain factors were investigated. The findings of these investigations are presented in the next section.

Soil correlations

The relationships among the soil parameters of each hillslope were assessed by Pearson's product moment correlation coefficient to reveal possible similar dependency on soil forming factors and corresponding pedological processes. The correlations among soil parameters are displayed in Table 5.4 a) and Table 5.4 b) for Kongta and Magada, respectively.

Table 5.4 a): Correlation matrix of z-transformed soil parameters in Kongta

Soil parameter	pH in water	SOM (%)	Avail. PO_4^{3-} (mg/kg)	Exch. K^+ (mg/kg)	Exch. Ca^{2+} (mg/kg)	Sand (%)	Clay (%)	Silt (%)	A-Horizon depth (cm)
pH in water	1.00								
SOM (%)	0.34**	1.00							
Avail. PO_4^{3-} (mg/kg)	0.59**	0.35**	1.00						
Exch. K^+ (mg/kg)	0.48**	0.32**	0.47**	1.00					
Exch. Ca^{2+} (mg/kg)	0.61**	0.37**	0.35**	0.27**	1.00				
Sand (%)	0.16	0.31**	0.26	0.22*	0.19*	1.00			
Clay (%)	-0.35**	-0.56**	-0.46**	-0.36**	-0.37**	-0.68**	1.00		
Silt (%)	0.26**	0.35**	0.29**	0.21**	0.25**	-0.29**	-0.50**	1.00	
A-Horizon depth (cm)	-0.05	-0.09	-0.06	0.13	-0.12	-0.12	0.04	0.08	1.00

N=154 for all soil parameters except for AHOR where N=48.

Table 5.4 b): Correlation matrix of z-transformed soil parameters in Magada.

Soil parameter	pH in water	SOM (%)	Avail. PO_4^{3-} (mg/kg)	Exch. K^+ (mg/kg)	Exch. Ca^{2+} (mg/kg)	Sand (%)	Clay (%)	Silt (%)	A-Horizon depth (cm)
pH in water	1.00								
SOM (%)	-0.13*	1.00							
Avail. PO_4^{3-} (mg/kg)	-0.11	0.31**	1.00						
Exch. K^+ (mg/kg)	0.54**	0.28**	0.16**	1.00					
Exch. Ca^{2+} (mg/kg)	0.60**	0.09	-0.02	0.52**	1.00				
Sand (%)	-0.21**	-0.14*	0.12*	-0.29**	-0.33**	1.00			
Clay (%)	0.25**	-0.03	-0.16**	0.27**	0.35**	-0.84**	1.00		
Silt (%)	-0.03	0.21**	0.04	0.00	-0.04	-0.35**	-0.16**	1.00	
A-Horizon depth (cm)	0.26*	-0.34**	-0.30**	0.14	0.29**	-0.14	-0.02	0.17	1.00

N=285 for all soil parameters except for AHOR where N=83.
Significance level: * less than 0.05; ** less than 0.01 (2-tailed).

The correlation matrices in the Tables 5.4 a) and b) indicate that nearly all soil parameter values of Kongta and many parameters of Magada are mostly weakly related among each other (Table 4.4 for interpretation of the coefficient of variation). A few soil parameter combinations such as pH-Ca and sand-clay show moderate correlation in both Kongta and Magada. These correlated soil parameters are likely to be determined by similar environmental processes.

However, the comparison of further correlations across the two sites reveals that some soil parameters that are related in one site do not necessarily have the same relationships at the other site. For example pH is moderately correlated with P in Kongta, but for the same pair no relationship was found in Magada. The same applies for SOM and clay at these sites. Such a discrepancy of the soil correlation patterns between different hillslopes may be caused by different environmental factors or human influences that determine the spatial distribution of these soil parameters.

A strong correlation exists in Kongta between SOM and soil nutrients, clay and silt. In Magada, these relationships were less marked or did not exist at all, indicating that these sites must have some different environmental and human influence factor combinations that determine the spatial distribution of SOM.

Soil – terrain correlations

One way to further investigate the impact of possible processes on soil spatial variability is to identify how terrain parameters that are expected to be characteristic for each hillslope, are related with the soil parameters. Table 5.5 shows the results of the correlation analysis between soil parameters and terrain factors on the hillslopes.

Table 5.5 a): Correlation matrix of soil parameters and terrain factors in Kongta

Terrain factors	Soil parameters							
	pH in water	SOM (%)	Avail. PO_4^{3-} (mg/kg)	Exch. K^+ (mg/kg)	Exch. Ca^{2+} (mg/kg)	Sand (%)	Clay (%)	A-Horizon depth (cm)
ELEV	-0.06	-0.51**	0.04	0.23**	-0.32**	-0.04	0.12	0.00
SLOP	0.36**	0.53**	0.17*	-0.08	0.50**	0.12	-0.34**	-0.08
UPSA	-0.38**	0.15	-0.30**	-0.34**	-0.15	-0.16	0.19*	0.06
PROF	-0.17*	-0.34**	-0.19*	-0.21**	-0.10	0.00	0.22**	-0.11
PLAN	0.26**	0.15	0.20*	0.21*	0.26**	0.10	-0.11	0.13
CURV3	0.26**	0.28**	0.21**	0.20*	0.22**	0.10	-0.19*	0.10
CURV5	0.28**	0.31**	0.21**	0.18*	0.21**	0.17*	-0.23**	0.03
WETI	-0.51**	-0.13	-0.36**	-0.31**	-0.36**	-0.22**	0.33**	0.08
TECI3	0.24**	0.27**	0.20*	0.19*	0.19*	0.11	-0.18*	0.09
TECI5	0.26**	0.29**	0.20*	0.18*	0.17*	0.18*	-0.22**	0.02
STRI	-0.21**	0.31**	-0.21**	-0.32**	0.04	-0.12	0.07	0.02

N=154 for all soil parameters except for AHOR where N=48.

Table 5.5 b): Correlation matrix of soil parameters and terrain factors in Magada

Terrain factors	Soil parameters							
	pH in water	SOM (%)	Avail. PO_4^{3-} (mg/kg)	Exch. K^+ (mg/kg)	Exch. Ca^{2+} (mg/kg)	Sand (%)	Clay (%)	A-Horizon depth (cm)
SLOP	-0.15*	0.17**	0.24**	-0.17**	-0.37**	0.24**	-0.35**	-0.48**
UPSA	-0.55**	0.23**	0.22**	-0.27**	-0.44**	0.10	-0.21**	-0.36**
PROF	-0.25**	0.03	0.07	-0.05	-0.20**	0.21**	-0.22**	-0.06
PLAN	0.29**	-0.08	-0.10	0.06	0.24**	0.03	0.05	0.03
WETI	-0.48**	0.11	0.09	-0.16**	-0.27**	0.01	-0.05	0.00
CURV3	0.33**	-0.07	-0.10	0.08	0.27**	-0.13*	0.17**	0.05
CURV5	0.36**	-0.09	-0.10	0.09	0.26**	-0.14*	0.20**	0.05
TECI3	0.35**	-0.08	-0.11	0.08	0.27**	-0.13*	0.18**	0.05
TECI5	0.40**	-0.11	-0.13*	0.12*	0.30**	-0.18**	0.24**	0.06
STRI	-0.40**	0.25**	0.27**	-0.25**	-0.49**	0.20**	-0.33**	-0.50**

N=285 for all soil parameters except for AHOR where N=83.

Significance level: * less than 0.05; ** less than 0.01 (2-tailed).

Abbreviations: Slop = slope, UPSA = upslope contributing area, PROF = profile curvature, PLAN = plan curvature, WETI = wetness index, CURV3 = surface curvature [3 cells average], CURV5 = surface curvature [5 cells average], TECI3 = terrain charact. index [3 cells average], TECI5 = terrain characterization index [5 cells average], STRI = stream power index.

The soil-terrain correlation matrices in Tables 5.5 a) and b) reveal for the spatial distribution of soil parameters in Kongta that several moderate correlations exist between pH and wetness index ($r = -0.51$), SOM and slope (0.53), SOM and elevation ($r = 0.51$) and Ca and slope ($r = 0.5$). There are weak relationships between P, K, sand, clay and specific combinations of wetness index, slope, upslope contributing area, elevation, profile curvature, and surface curvature ($0.2 < r < 0.38$). The relationships between Magada soil and terrain factors show moderate correlations between pH and upslope contributing area ($r = 0.55$) and between A-horizon depth and stream power index ($r = -0.50$). The weak correlations are between different soil parameters and upslope contributing area, wetness index, profile curvature, stream power index and plan curvature ($0.21 < r < 0.48$).

These soil-terrain relationships may indicate that the spatial distribution of pH on both sites, SOM and Ca in Kongta and A-horizon depth in Magada are largely determined by terrain. The weak relationships of other soil-terrain combinations show that other factors may have a more dominant influence.

As a next step to investigate the influence of terrain on soils spatial variability, specific terrain factors that were correlated with soil samples were used to delineate the hillslopes by landscape units. On the basis of these landscape units, the variability of soil parameters within and between these units was studied.

Spatial delineation of hillslopes into landscape units

The hillslopes were delineated into landscape units to identify possible relationships of soil parameters with terrain. The corresponding terrain factors that were selected for the hillslope delineation to explain spatial variability of soils were slope gradient and upslope contributing area. The terrain factor maps used to delineate the hillslope and the resulting landscape units are shown in Figure 5.5.

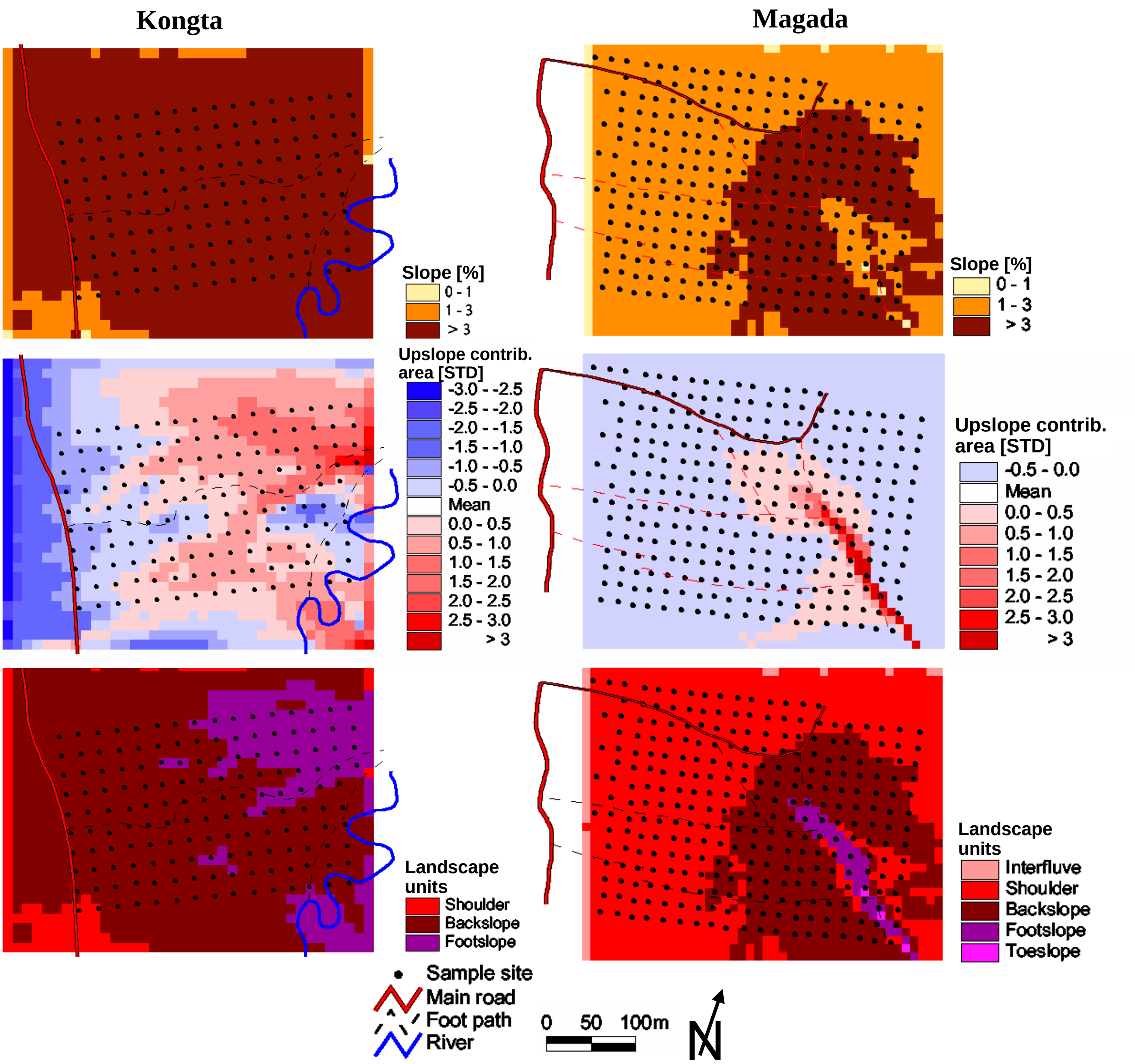

Figure 5.5: Hillslope zonation parameters and landscape units

Note: The limited number of cells at the edge of the digital elevation models and in areas that were outside of the soil sample grid caused erroneous pixels in the establishment of the slope gradient and upslope contributing area maps. This may have led to possibly misclassified landscape unit pixels at these locations. Thus, the assignment of pixels to landscape units at the edge of the DEM and at areas outside the soil grid should be interpreted with great care.

This hillslope zonation shows that Kongta´s agricultural land is mainly on the backslope, in some areas down to the footslope. It includes a small shoulder position as well. In contrast, Magada’s agriculture is mainly on shoulder, backslope and a small footslope landscape unit. Since the Kongta site is located on the slopes of the Mount Elgon volcano, the farmers of this community demarcated their land by a road, which they cut into the backslope of this larger hillslope system during the last century. This relatively young and still developing hillslope stretches from the road down to the river

Armananagh. Due to the relatively small road and young age of the Kongta hillslope, an interfluve has not yet developed, but a shoulder is gradually forming.

The Magada hillslope belongs to the Buganda surface, which is representative of a large share of the lowland areas in central Uganda. On this old surface the Buyaga catena has emerged since the Precambrian, with ridges, gently rolling slopes and wide valleys (Harrop, 1970). The gently rolling slope is in Magada clearly marked by the dominant shoulder with little slope gradient connecting to the backslope with moderate slope gradient. The shoulder landscape unit represents the majority of the land that is used for crop cultivation in Magada, while the steeper backslope is partly shared between crop cultivation, grazing, natural bush and shrub vegetation (Figures 5.2, 5.5). The interfluve in Magada in Figure 5.5 was only represented as a small line at the edge of the digital elevation model. This under representation of upslope landscape units is caused by the coverage of the DEM, which focused on the agricultural land of the hillslope from where the soil samples were collected. The flat interfluves in Uganda are traditionally used as the area on which the main roads are constructed, which connect the communities and cities among each other (Dunbar and Stephens, 1970). Next to the main road farmers usually construct settlements for shortest market access and to live safe from river flooding (Aggrey, 2002). The location of the settlements may therefore coincide with the relatively flat interfluve and with the upper part of the shoulder.

In Kongta and Magada, the footslopes connect with the backslopes and can be found at the bottom of the hillslopes. These footslopes are characterized by the greatest upslope contributing area. Since Kongta is part of the larger Mount Elgon hillslope area, the corresponding upslope contributing area stretches over a wider area than the relatively small and more linear footslope of Magada, which delineates a smaller catchment. Some cells within the footslope in Magada were designated as toeslope. This indicates that the actual toeslope could be expected outside the investigated site, close to the Walungogo River, where slope gradient is level and upslope-contributing area is maximum. Similarly, the toeslope in Kongta may be expected at the bottom of the Mount Elgon volcano where this major hillslope system connects to the lowland system.

Catenary soil variation of hillslopes in landscape units

The variation of soil parameters within and between landscape units delineating the hillslopes is presented in the boxplots as shown in Figure 5.6.

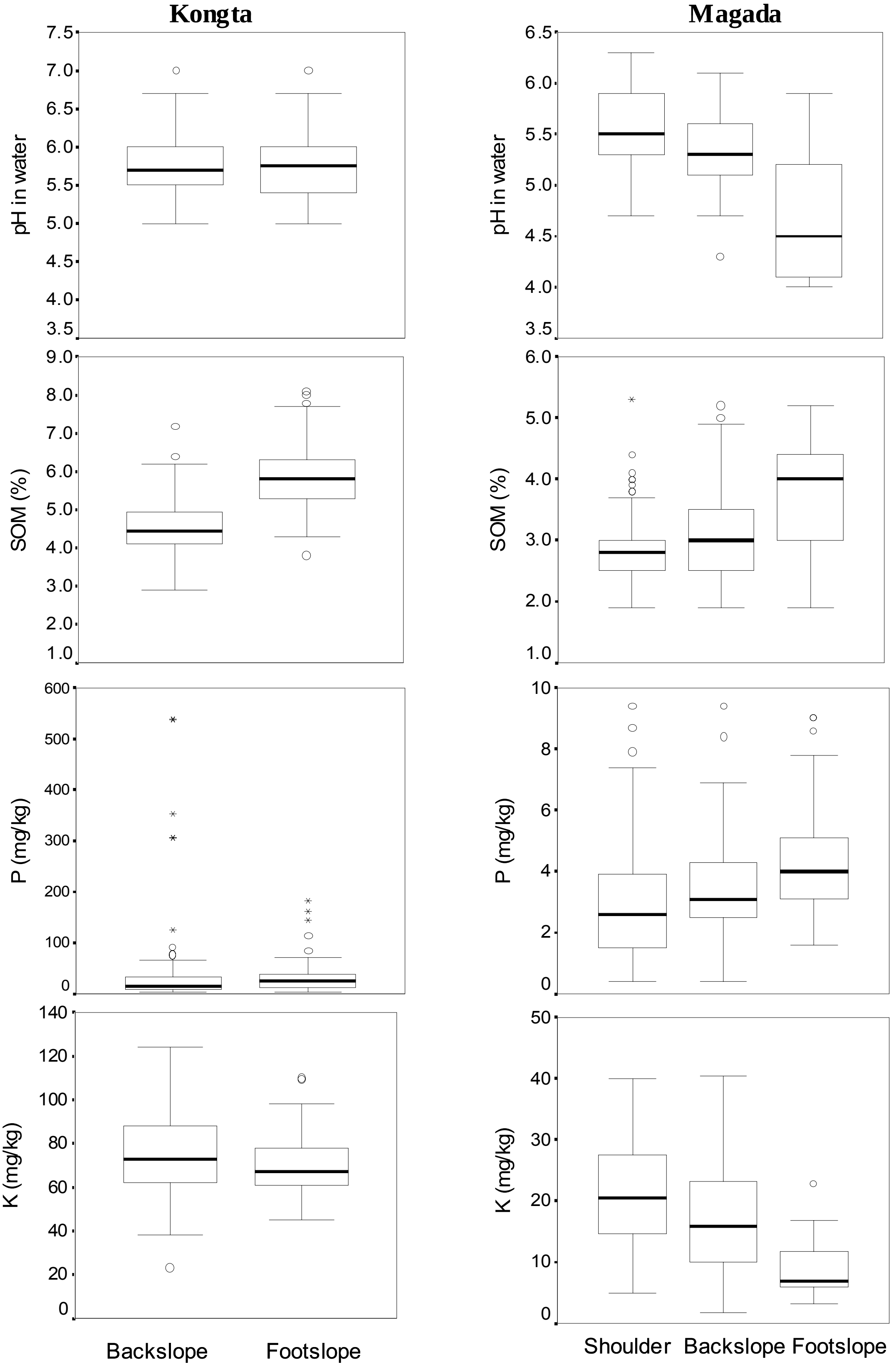

Figure 5.6: Box plots of soil attributes within landscape units at hillslope scale

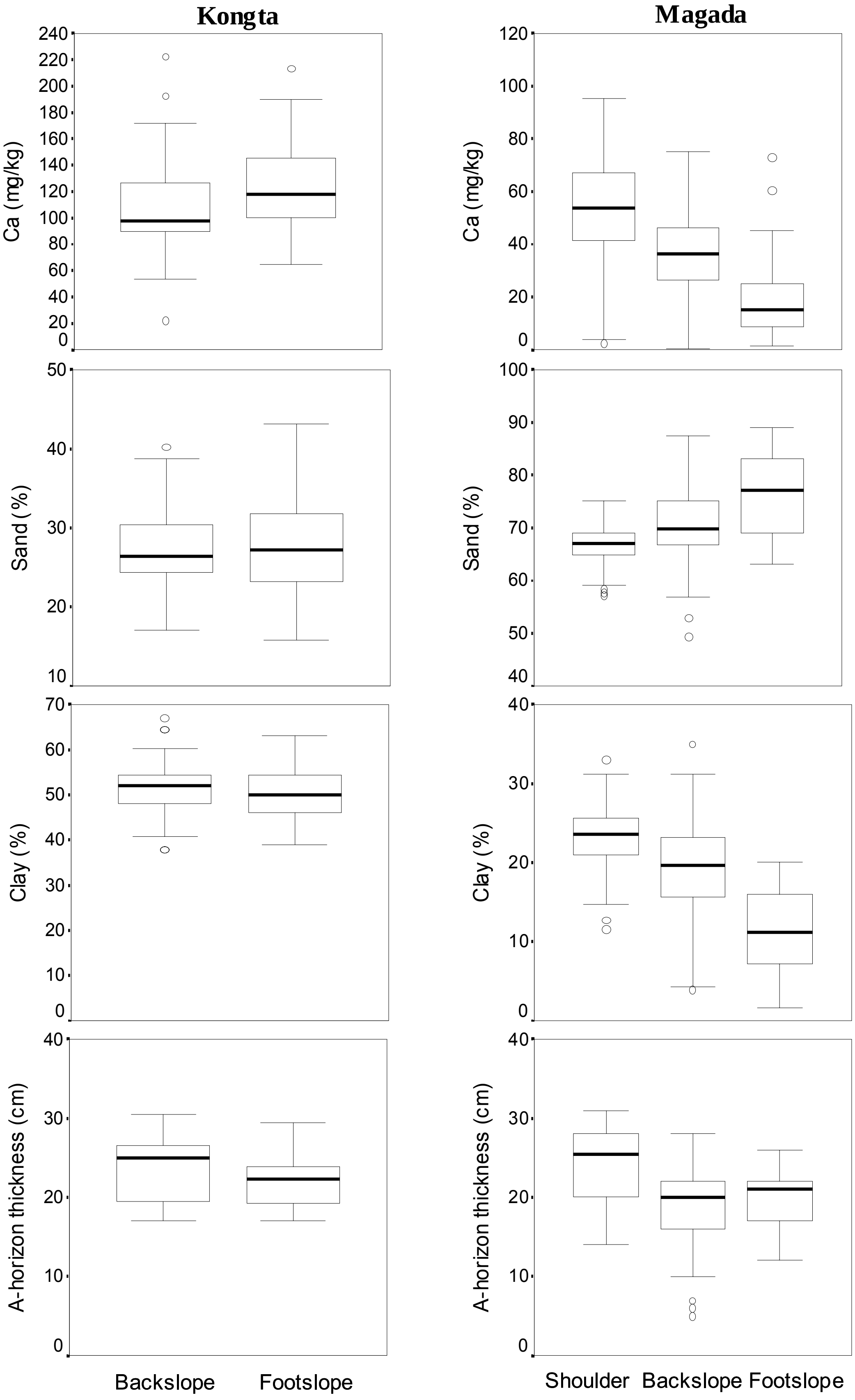

Figure 5.6 continued

The spatial variation of SOM and Ca in Kongta shows a catenary soil distribution over this hillslope, with increasing values from backslope to footslope. The remaining soil parameters are similarly distributed between these landscape units. All soil parameters in Magada follow a catenary sequence. The pH, K, Ca, clay and A-horizon thickness decrease, while SOM, P and sand increase from shoulder to footslope. The suitability of this hillslope delineation for capturing the spatial variation of soil parameters was tested by ANOVA (Table 5.6).

Table 5.6: ANOVA of soil parameters in landscape units on hillslope scale

Soil parameter	Site	Stats	Landscape units[a]				ANOVA	Tests[d]
			(2)	(3)	(4)	total		Bonferroni/Dunnett T3
pH in water	Kongta	Mean	-	5.71	5.80	5.74	1.89[b]	-[e]
		STD	-	0.35	0.46	0.40	0.17[c]	-[e]
	Magada	Mean	5.58	5.34	4.68	5.41	66.58[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	0.35	0.33	0.59	0.45	0.00[c]	4 ≠ 2,3;
SOM (%)	Kongta	Mean	-	4.64	5.91	5.12	59.7[b]	-[e]
		STD	-	1.01	0.95	1.16	0.00[c]	-[e]
	Magada	Mean	2.80	3.09	3.66	2.99	20.9[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	0.49	0.76	0.97	0.70	0.00[c]	4 ≠ 2,3;
Avail. PO_4^{3-} (mg/kg)	Kongta	Mean	-	46.0	33.9	41.4	0.84[b]	-[e]
		STD	-	96.0	37.4	79.2	0.36[c]	-[e]
	Magada	Mean	2.88	3.41	4.54	3.23	10.9[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	1.74	1.61	2.08	1.78	0.00[c]	4 ≠ 2,3;
Exch. K^+ (mg/kg)	Kongta	Mean	-	75.2	69.9	73.2	3.27[b]	-[e]
		STD	-	19.4	14.4	17.8	0.07c	-[e]
	Magada	Mean	21.3	16.9	9.37	18.5	25.96[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	8.18	9.0	4.98	8.97	0.00[c]	4 ≠ 2,3;
Exch. Ca^{2+} (mg/kg)	Kongta	Mean	-	106	125	113	14.08[b]	-[e]
		STD	-	30.2	34.8	33.4	0.00[c]	-[e]
	Magada	Mean	54.5	36.9	20.3	44.8	56.6[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	18.4	17.1	17.6	21.0	0.00[c]	4 ≠ 2,3;
Sand (%)	Kongta	Mean	-	27.0	27.6	27.2	0.42[b]	-[e]
		STD	-	4.69	5.39	4.95	0.52[c]	-[e]
	Magada	Mean	66.9	70.4	75.7	69.0	33.47[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	3.83	6.68	7.66	6.06	0.00[c]	4 ≠ 2,3;
Clay (%)	Kongta	Mean	-	51.6	49.9	50.9	3.26[b]	-[e]
		STD	-	5.37	5.52	5.47	0.07[c]	-[e]
	Magada	Mean	23.2	19.3	11.7	20.7	68.4[b]	2 ≠ 3,4; 3 ≠ 2,4;
		STD	3.51	6.03	5.45	5.83	0.00[c]	4 ≠ 2,3;
A-Hor. thickness (cm)	Kongta	Mean	-	23.6	21.9	23.0	2.26[b]	-[e]
		STD	-	3.97	3.55	3.87	0.14[c]	-[e]
	Magada	Mean	23.8	18.6	19.6	21.5	9.16[b]	2 ≠ 3; 3 ≠ 2;
		STD	4.86	6.09	4.88	5.84	0.00[c]	4 ≠ -;

[a] Landscape units: (2) = shoulder, (3) = backslope, (4) = footslope.

[b] F-ratio in ANOVA; [c] Propability; [d] significantly different at $p < 0.05$ level.

[e] Tests were not performed for Kongta soil parameters because there were fewer than three LSU.

Table 5.6 Notes continued

N = 96, 58 in (3), (4) respectively for pH, SOM, P, K, Ca, Sand, Clay in Kongta.
N = 30, 18 in (3), (4), respectively for A-horizon thickness in Konga.
N = 151, 109, 25 in (2), (3), (4) respectively for pH, SOM, P, K, Ca, Sand, Clay in Magada.
N = 44, 30, 9 in (2), (3), (4), respectively for A-horizon thickness in Magada.
In Kongta the two soil samples on the shoulder were attributed to the backslope.

High F-statistics were observed for the variation of SOM and Ca in Kongta and for pH, SOM, K, Ca, sand, clay in Magada. A high F-ratio indicates that the variance of a variable within units is smaller than the variance among units, suggesting successful partitioning. Apparently, terrain, represented by landscape units, influences the spatial distribution of these soil parameters over the hillslopes. The relatively lower F-ratio of P and of silt may show that other factors have a more dominant influence.

In addition to the ANOVA F-statistics, the Bonferroni and the Dunnet T3 tests were employed. These tests were used to reveal, which of the terrain units have significantly different means of a soil parameter among the landscape units. The Bonferroni and Dunnet T3 tests in Magada confirm that all neighboring landscape units were different from each other (Table 5.6).

Spatial delineation of hillslopes into landscape elements

The delineation of the Kongta and Magada hillslopes into more detailed landscape elements within landscape units was performed to refine the spatial variability of soil parameters into smaller units. The terrain factor maps that were used as inputs to delineate the hillslopes and the more detailed resulting landscape elements are shown in Figure 5.7.

Compared to the previous hillslope dissection into two and three coarser landscape units, this more detailed delineation produced four and five landscape elements for Kongta and Magada respectively, based on the major plan and profile curvature patterns in these sites. The detailed hillslope zonation led to the following landscape elements (Figure 5.7). The southern part of Kongta was classified into a divergent shoulder, followed by a convergent backslope that connected further downslope to a divergent backslope. The northern hillslope part of Kongta was demarcated by a divergent backslope followed by a convergent footslope.

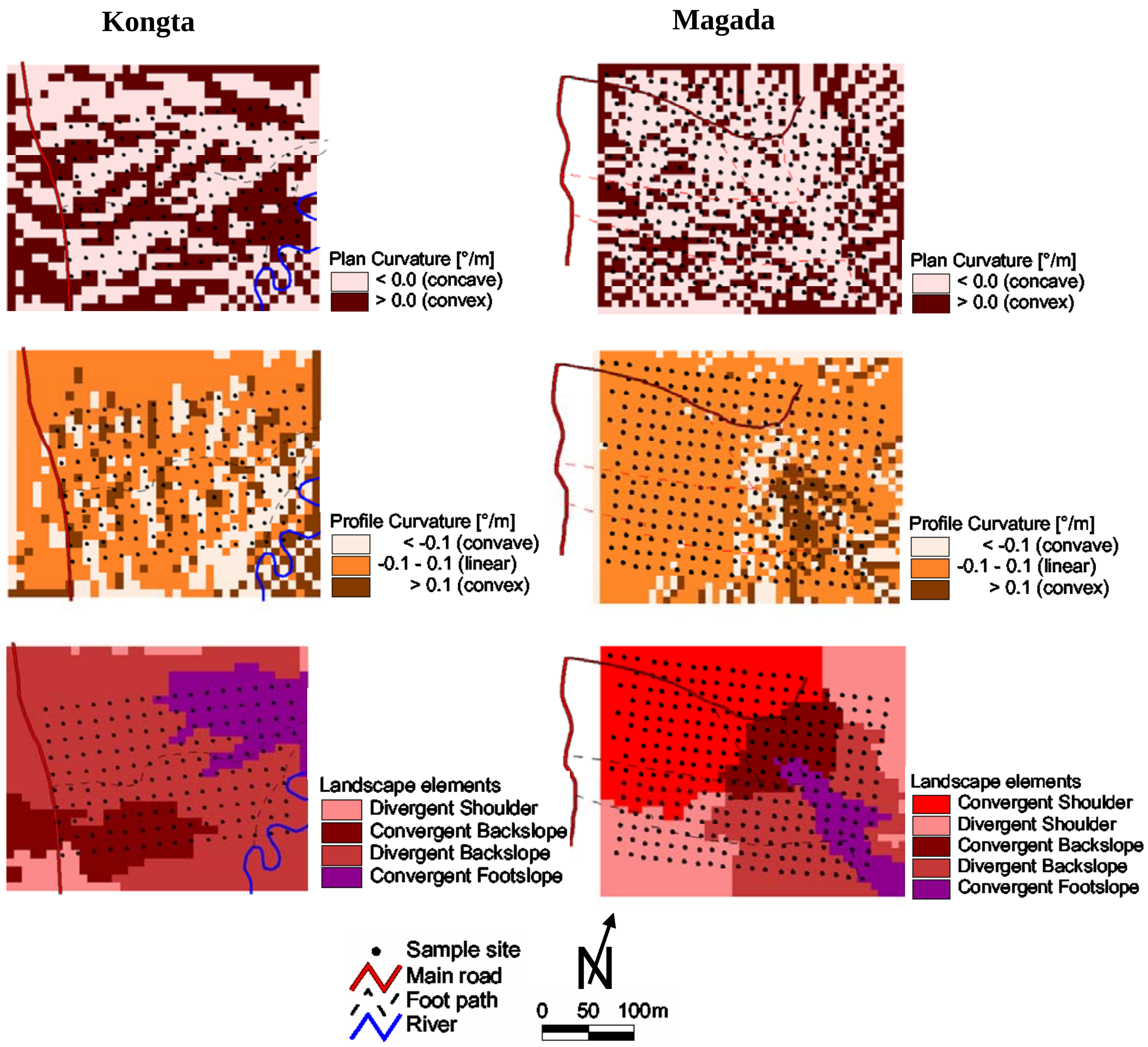

Figure 5.7: Hillslope zonation parameters and landscape elements at hillslope scale

The landscape elements in the southern and north-eastern part of Magada included a divergent shoulder that was linked with a divergent backslope, which led to a convergent footslope. In north-west to south-east direction of the Magada hillslope, the delineated landscape elements comprised a convergent shoulder, followed by a convergent backslope connecting to the central convergent footslope (Figure 5.7).

Catenary soil variation of hillslopes in landscape elements

The variation of soil parameters within and between landscape elements delineating the hillslopes is visualized by the boxplots as shown in Figure 5.8.

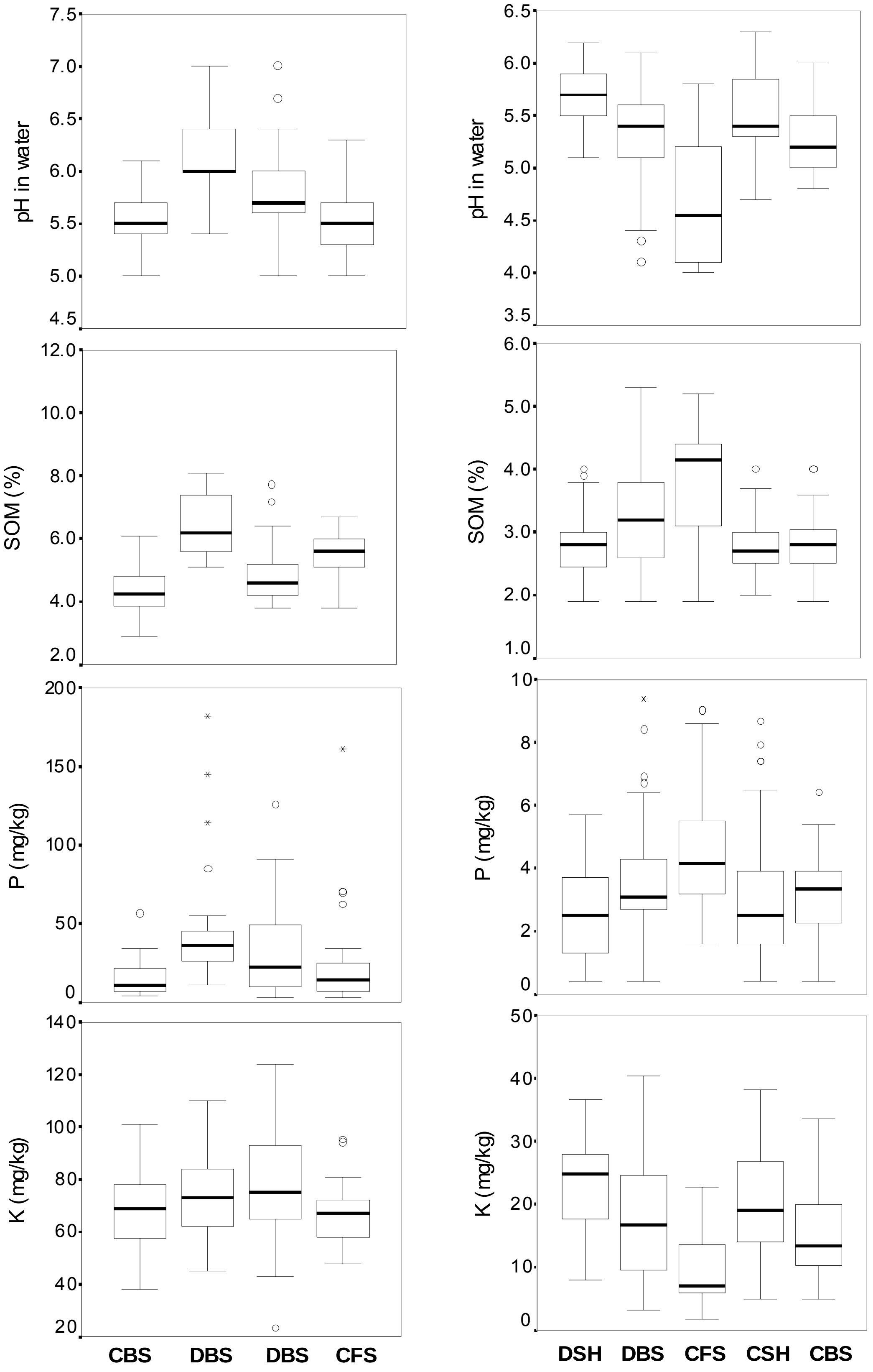

Figure 5.8: Box plots of soil attributes within landscape elements at hillslope scale
DSH/CSH = divergent/convergent shoulder, DBS/CBS = divergent/ convergent backslope,
CFS = convergent footslope.

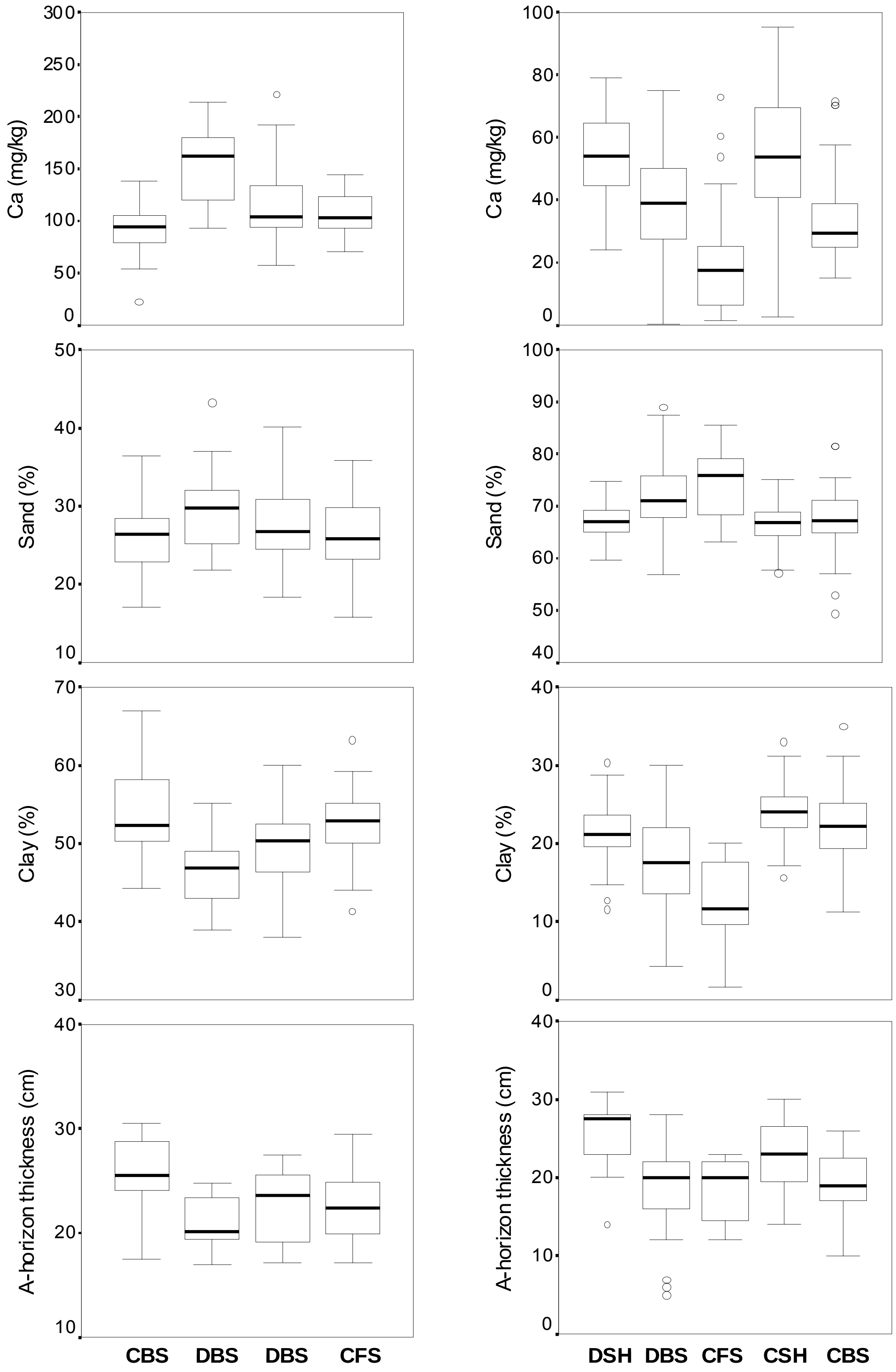

Figure 5.8 continued

At both sites, a catenary sequence of soil parameter variation can clearly be recognized for the spatial distribution of pH, SOM, P, K and clay. The pH and K mainly decrease and SOM increases from divergent backslope positions to convergent footslope positions. P decreases in Kongta but increases in Magada and clay increases in Kongta but decreases in Magada from the divergent backslopes to the convergent footslopes. The relationships between other soil parameters, such as K, Ca and the landscape elements were less pronounced. In order to statistically test the separation procedure, ANOVA of soil parameters variation in landscape elements was conducted for the two sites (Table 5.7).

Table 5.7 a): Analysis of variance of soil parameters in landscape elements in Kongta

Soil parameter	Stats	Landscape elements[a]					ANOVA	Tests[d]	
		(1)	(2)	(3)	(4)	total		Bonferroni	Dunnett T3
pH in water	Mean	5.58	6.16	5.80	5.52	5.74	22.1[b]	1 ≠ 2,3; 2 ≠ 1,3,4;	1 ≠ 2,3; 2 ≠ 1,3,4;
	STD	0.22	0.36	0.40	0.31	0.40	0.00[c]	3 ≠ 1,2,4; 4 ≠ 2,3;	3 ≠ 1,2,4; 4 ≠ 2,3;
SOM (%)	Mean	4.32	6.45	4.87	5.50	5.12	30.2[b]	1 ≠ 2,3,4; 2 ≠ 1,3,4;	1 ≠ 2,3,4; 2 ≠ 1,3,4;
	STD	0.70	0.96	1.14	0.72	1.16	0.00[c]	3 ≠ 1,2,4; 4 ≠ 1,2,3;	3 ≠ 1,2,4; 4 ≠ 1,2,3;
Avail. PO_4^{3-} (mg/kg)	Mean	42.2	48.0	48.7	23.2	41.4	0.79[b]	1 ≠ -; 2 ≠ -;	1 ≠ -; 2 ≠ -;
	STD	103.00	41.5	91.2	30.4	79.2	0.50[c]	3 ≠ - ;4 ≠ -;	3 ≠ - ;4 ≠ -;
Exch. K^+ (mg/kg)	Mean	69.1	74.1	79.5	66.7	73.2	4.93[b]	1 ≠ 3; 2 ≠ -;	1 ≠ 3; 2 ≠ -;
	STD	14.9	16.8	21.1	11.5	17.8	0.01c	3 ≠ 1,4; 4 ≠ 3;	3 ≠ 1,4; 4 ≠ 3;
Exch. Ca^{2+} (mg/kg)	Mean	93.2	150	114	107	113	21.8[b]	1 ≠ 2,3; 2 ≠ 1,3,4;	1 ≠ 2,3,4; 2 ≠ 1,3,4;
	STD	22.4	35.4	32.1	19.4	33.4	0.00[c]	3 ≠ 1,2; 4 ≠ 2;	3 ≠ 1,2; 4 ≠ 1,2;
Sand (%)	Mean	25.8	29.6	27.9	26.1	27.2	4.23[b]	1 ≠ 2; 2 ≠ 1,4;	1 ≠ 2; 2 ≠ 1;
	STD	4.40	5.21	4.72	5.08	4.95	0.01[c]	3 ≠ -; 4 ≠ 2;	3 ≠ -; 4 ≠ -;
Clay (%)	Mean	53.8	46.4	50.0	52.6	50.9	13.5[b]	1 ≠ 2,3; 2 ≠ 1,3,4;	1 ≠ 2,3; 2 ≠ 1,3,4;
	STD	5.50	4.46	4.73	4.72	5.47	0.00[c]	3 ≠ 1,2; 4 ≠ 2;	3 ≠ 1,2; 4 ≠ 2;
A-Hor. thickness (cm)	Mean	25.7	21.0	22.4	22.5	23.0	2.98[b]	1 ≠ -; 2 ≠ -;	1 ≠ 2; 2 ≠ 1;
	STD	3.75	2.84	3.64	3.97	3.87	0.04[c]	3 ≠ - ;4 ≠ -;	3 ≠ - ;4 ≠ -;

[a] Landscape elements: (1) = convergent backslope (CBS), (2) = divergent backslope (DBS),
(3) = divergent backslope (DBS); (4) = convergent footslope (CFS).

[b] F-ratio in ANOVA; [c] Propability; [d] significantly different at $p < 0.05$ level.

N = 40, 25, 6, 33 in (1), (2), (3), (4) respectively for pH, SOM, P, K, Ca, sand, clay.

N = 11, 7, 19, 11 in (1), (2), (3), (4) respectively for A-horizon thickness.

Table 5.7 b): Analysis of variance of soil parameters in landscape elements in Magada

Soil parameter	Stats	Landscape elements^a						ANOVA	Tests^d	
		(1)	(2)	(3)	(4)	(5)	total		Bonferroni	Dunnett T3
pH in water	Mear	5.69	5.4	4.68	5.53	5.25	5.41	32.365^b	≠ 2,3,5; 2 ≠ 1,3,4; 3 ≠ 1,2,4,	≠ 2,3,5; 2 ≠ 1,3,4; 3 ≠ 1,2,4,5;
	STD	0.28	0.4	0.57	0.38	0.32	0.45	0.000^c	4 ≠ 2,3,5; 5 ≠ 1,3,4;	4 ≠ 2,3,5; 5 ≠ 1,3,4;
SOM (%)	Mear	2.77	3.3	3.85	2.75	2.8	2.99	20.436^b	≠ 2,3; 2 ≠ 1,3,4,5; 3 ≠ 1,2,4,	1 ≠ 2,3; 2 ≠ 1,4,5; 3 ≠ 1,4,5;
	STD	0.47	0.9	0.88	0.38	0.5	0.7	0.000^c	4 ≠ 2,3; 5 ≠ 2,3;	4 ≠ 2,3; 5 ≠ 2,3;
Avail. PO_4^{3-} (mg/kg)	Mear	2.6	3.6	4.64	2.91	3.26	3.23	6.992^b	1 ≠ 2,3; 2 ≠ 1; 3 ≠ 1,4,5;	2 ≠ 2,3; 2 ≠ 1; 3 ≠ 1,4,5;
	STD	1.59	1.8	2.23	1.68	1.4	1.78	0.000^c	4 ≠ 3; 5 ≠ 3;	4 ≠ 3; 5 ≠ 3;
Exch. K^+ (mg/kg)	Mear	22.7	18	9.38	20.3	15.2	18.5	12.073^b	1 ≠ 2,3,5; 2 ≠ 1,3; 3≠ 1,2,4;	1 ≠ 2,3,5; 2 ≠ 1,3; 3≠ 1,2,4,5;
	STD	7.81	9.9	5.52	8.15	6.83	8.97	0.000^c	4 ≠ 3,5; 5 ≠ 1,4;	4 ≠ 3,5; 5 ≠ 1,3,4;
Exch. Ca^{2+} (mg/kg)	Mear	53.9	38	21.7	54.9	33.7	44.8	25.423^b	1 ≠ 2,3,5; 2 ≠ 1,3,4; 3 ≠ 1,2,4	≠ 2,3,5; 2 ≠ 1,3,4; 3 ≠ 1,2,4;
	STD	13.7	18	19.6	20.5	15.3	21	0.000^c	4 ≠ 2,3,5; 5 ≠ 1,4;	4 ≠ 2,3,5; 5 ≠ 1,4;
Sand (%)	Mear	67.3	72	74.5	66.6	67.4	69	20.316^b	1 ≠ 2,3; 2 ≠ 1,4,5; 3 ≠ 1,4,5;	1 ≠ 2,3; 2 ≠ 1,4,5; 3 ≠ 1,4,5;
	STD	3.87	6.6	6.91	3.77	6.68	6.06	0.000^c	4 ≠ 2,3; 5 ≠ 2,3;	4 ≠ 2,3; 5 ≠ 2,3;
Clay (%)	Mear	21.2	18	12.3	24.1	22.4	20.7	40.266^b	2,3,4; 2 ≠ 1,3,4,5; 3 ≠ 1,2,4	≠ 2,3,4; 2 ≠ 1,3,4,5; 3≠1,2,4,5
	STD	3.68	6.2	5.29	3.11	4.94	5.83	0.000^c	4 ≠ 1,2,3; 5≠ 2,3;	4 ≠ 1,2,3; 5≠ 2,3;
A-Hor. thickness (cm)	Mear	25.6	19	18.5	23.1	19.4	21.5	5.734^b	1 ≠ 2,3,5; 2 ≠ 1,4; 3 ≠ 1;	1 ≠ 2,3,5; 2 ≠ 1; 3 ≠ 1;
	STD	4.31	6.7	4.44	4.85	4.93	5.84	0.000^c	4 ≠ 2; 5 ≠ 1;	4 ≠ -; 5 ≠ 1;

^{a} Landscape element: (1) = divergent shoulder, (2) = divergent backslope, (3) = convergent footslope,
(4) = convergent shoulder, (5) = convergent backslope.
^{b} F-ratio in ANOVA; ^{c} Propability; ^{d} significantly different at $p < 0.05$ level.
N = 40, 25, 6, 33 in (1), (2), (3), (4) respectively for pH, SOM, P, K, Ca, Sand, Clay.
N = 11, 7, 19, 11 in (1), (2), (3), (4) respectively for A-horizon thickness.

The separation of the hillslopes into landscape elements shows for both sites an improvement in F-statistics for pH, SOM, Ca, clay variation. This means that this landscape element delineation was more suitable and superior to the landscape unit delineation to capture the spatial variation of these soil parameters. The Bonferroni and Dunnet T3 tests statistically confirm the catenary soil – landscape element sequences as presented in the boxplots. For pH, SOM, Ca and clay, all neighboring landscape elements were different from each other. These landscape elements were also recognized in the field (Brunner et al., 2003).

5.3.2 Spatial structure and patterns of soils on hillslope scale

Spatial structure of soils

The spatial variability of soils was subsequently analyzed by semivariogram analysis and variogram models were fitted to standardized soil parameter values (shown in Figure 5.9) for spatial structure comparisons.

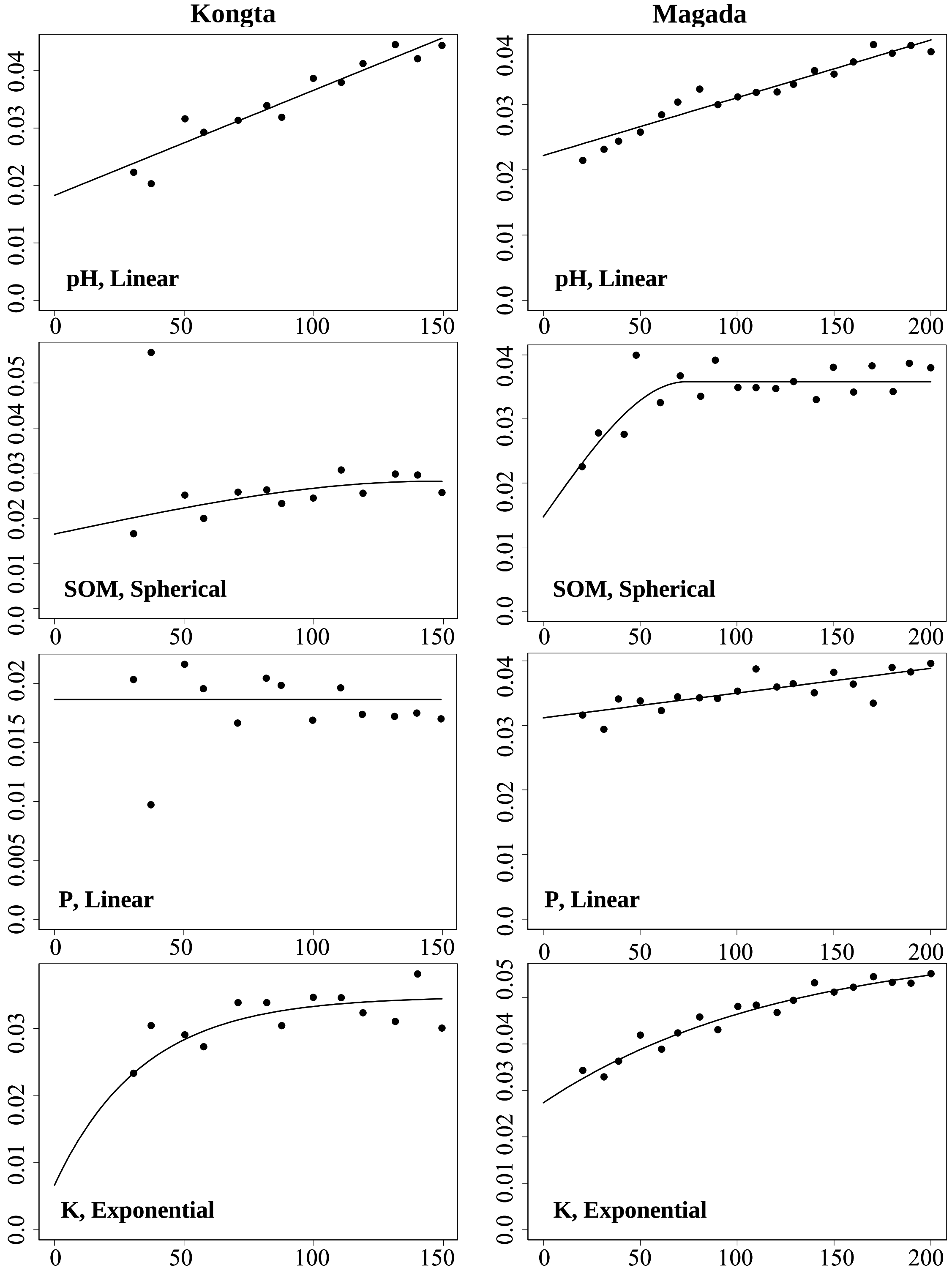

Figure 5.9: Variogram models of standardized soil parameters at local scale

Note: X-axis is lag (m), y-axis is semivarinace (y)

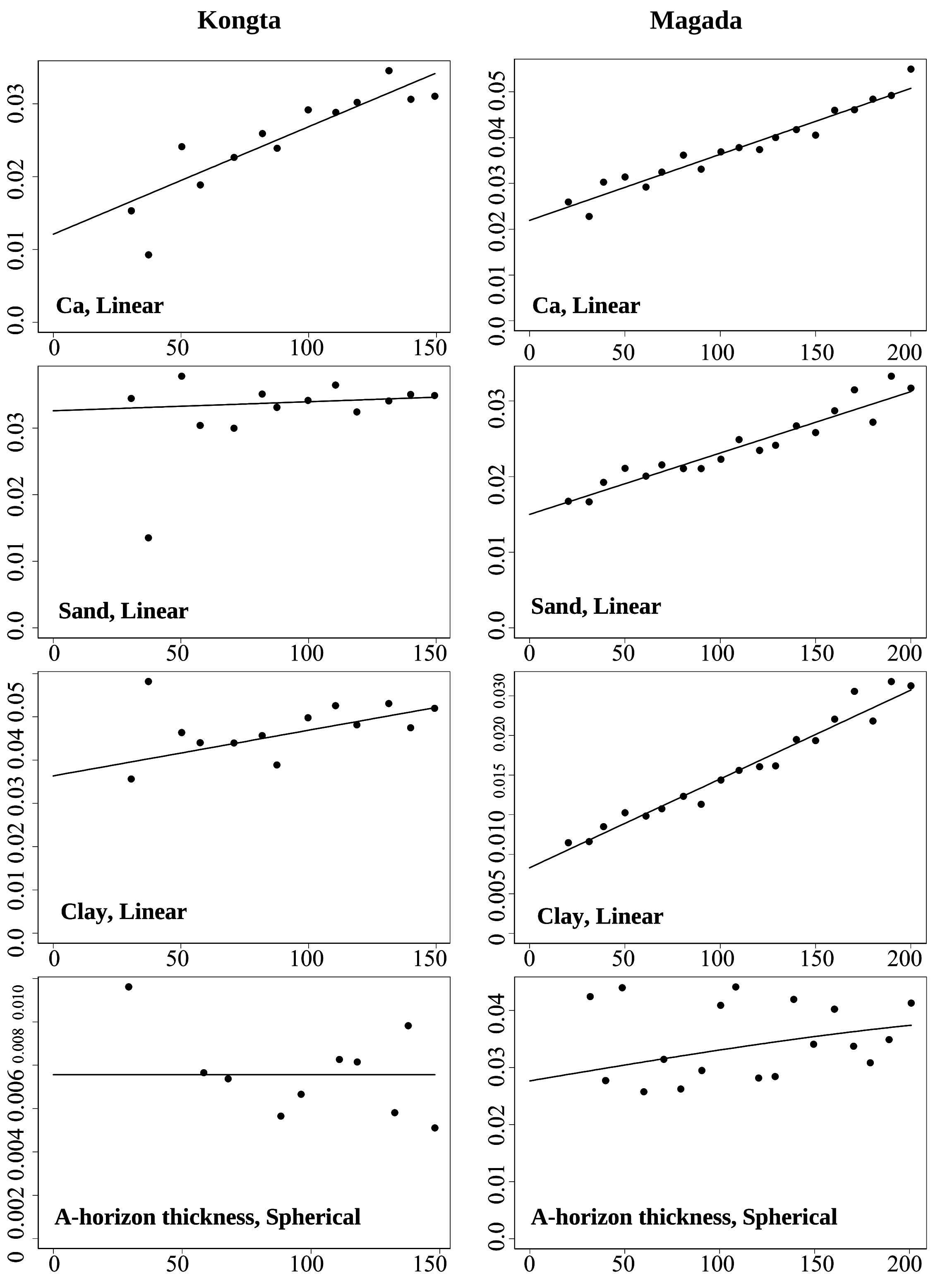

Figure 5.9 continued

Note: Note: X-axis is lag (m), y-axis is semivarinace (y)

Linear models could best fit the empirical variograms of most of the soil parameters including pH, P, Ca, sand, clay and A-horizon thickness on both hillslopes. This dominance of the linear model may indicate that the spatial trend over the sites was generated by topography. Most of these soil properties had, in addition, moderate correlations with terrain parameters (Table 5.5). For SOM and K, the variogram models showed weakly to strongly curved graphs fitting the spherical and the exponential model for SOM and K, respectively. Such models suggest that the corresponding soil parameters have a certain spatial dependency over the hillslopes. In order to further describe these spatial structures, the variance characteristics of the transformed soil parameters underlying the variogram models were quantified and listed in Table 5.8.

Table 5.8: Variance characteristics of fitted variogram models for transformed soil parameters on hillslope scale

Soil parameter	Site	Model	Range	Sill	Nugget	Slope	Objective
pH in water	Kongta	Linear	-	-	0.02	0.0002	0.0001
	Magada	Linear	-	-	0.02	0.0001	0.0000
SOM (%)	Kongta	Spherical	145	0.01	0.02	-	0.0014
	Magada	Spherical	73.8	0.02	0.01	-	0.0001
Avail. PO_4^{3-} (mg/kg)	Kongta	Linear	-	-	0.02	0.0313	0.0001
	Magada	Linear	-	-	0.03	0.0000	0.0000
Exch. K+ (mg/kg)	Kongta	Exponential	33.9	0.03	0.01	-	0.0001
	Magada	Exponential	123	0.03	0.03	-	0.0000
Exch. Ca^{2+} (mg/kg]	Kongta	Linear	-	-	0.01	0.0001	0.0001
	Magada	Linear	-	-	0.02	0.0001	0.0001
Sand (%)	Kongta	Linear	-	-	0.03	0.0000	0.0004
	Magada	Linear	-	-	0.02	0.0001	0.0000
Clay (%)	Kongta	Linear	-	-	0.04	0.0001	0.0005
	Magada	Linear	-	-	0.01	0.0001	0.0000
A-Horizon thickness (cm)	Kongta	Spherical	74.0	0.00	0.06	-	0.0022
	Magada	Spherical	321	0.01	0.03	-	0.0008

The variogram characteristics show that many soil parameters have different values for these indicators of spatial structure within each site and between sites. For example, the nugget indicator, which represents the micro-variability of soil parameters, takes generally very different values for the soil parameters. However, if the nugget values are arranged in a sequence from highest to lowest micro-variability, the soil parameters in the two sites show the following order:

A-Horizon thickness (K) > clay (K) > sand (K) > P (M) > A-Horizon thickness (M) > K (M) > pH / Ca (M) > P (K) > pH (K) > SOM (K) > SOM / sand (M) > Ca (K) > clay (M) > K (K), where (K) and (M) represent Kongta and Magada, respectively.

Thus, in Kongta, clay, sand and A-horizon thickness have relatively high micro-variability. However, the three soil parameters are ranked with a lower (for A-horizon thickness) and with the lowest micro-variability (for clay, sand) in Magada. Furthermore, K, Ca, SOM, pH, and P were among the soil parameters with low to moderate micro-variability in Kongta, but high to moderate micro-variability in Magada.

In a site-specific assessment of the micro-variability the following sequences of soil parameters were found and presented in order from highest to lowest micro-variability:

A-Horizon thickness > clay > sand > P > pH > SOM > Ca > K,
for Kongta and
P > A-Horizon thickness > K > pH / Ca > SOM / sand > clay,
for Magada.

These rankings show in the case of Kongta that the soil physical parameters A-horizon thickness, clay and sand have higher micro-variability, while the soil-nutrient related parameters P, pH, SOM, Ca and K have lower micro-variability. This soil micro-variability pattern is reversed for most soil parameters in Magada. The environmental and human influences that determine the micro-variability of these physical and nutrient related soil parameter groups must be very different between and within the two sites.

Furthermore, the range, a measure of the distance up to where soil parameters are spatially dependent, varies among the soil parameters and between the two sites. The sequence from the longest to the shortest spatial dependency is:

A-Horizon thickness (M) > SOM (K) > K (M) > A-Horizon thickness (K) >
>SOM (M) > K (K),
where (K) and (M) represent Kongta and Magada, respectively.

For these few soil parameters, the sequence shows that A-horizon thickness and K in Magada, and SOM in Kongta have higher spatial dependency than A-horizon thickness and K in Kongta and SOM in Magada. The site-specific sequences of spatial dependency for the different soil parameters are in the sequence from the longest to the shortest spatial dependency:

SOM > A-Horizon thickness > K, and
A-Horizon thickness > K > SOM
for Kongta and Magada, respectively.

Finally, the site-specific perspective revealed that in Magada, pH, clay, P, SOM, K and A-horizon thickness showed a more scattered semivariance than Ca, sand and clay. The same semivariance pattern as in Magada was previously found for soil parameters on the national-scale. This congruence may indicate that the spatial dependency of these soil parameters is not dependent on the spatial scale of investigation. These more mobile soil parameters with higher semivariance including pH, clay, P, SOM, K and A-horizon thickness, change rapidly in both space and time and achieve equilibrium quickly with local pedogenetic and human induced processes occurring on hillslopes under intensive land use and land management. This is not true for the more stable soil parameters Ca and sand (Park and Vlek, 2002).

Spatial patterns of soils

In order to identify the spatial distribution patterns of soil parameters on hillslope scale, the soils data were spatially interpolated to construct hillslope maps (Figure 5.10).

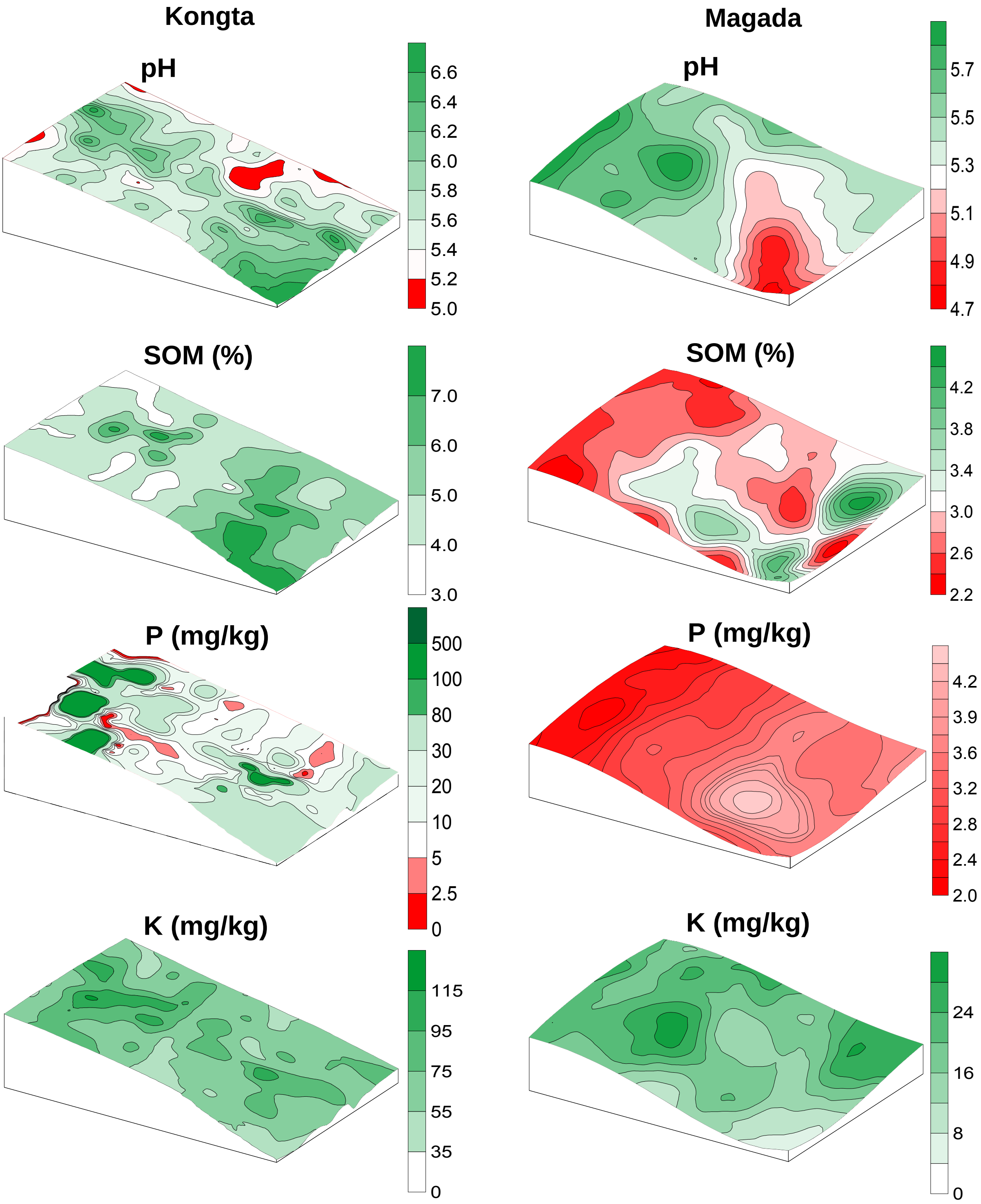

Figure 5.10: Interpolated maps of soil parameters in Kongta and Magada

Note: Green signatures represent areas with higher values than the critical value, white signatures are areas just at the critical value and red signatures are areas with values lower than the critical soil value. The critical values are: pH 5.2, 3.0% SOM, 5.0 mg/kg P, 0.4 mg/kg K, 0.9 mg/kg Ca (Forster, 1971).

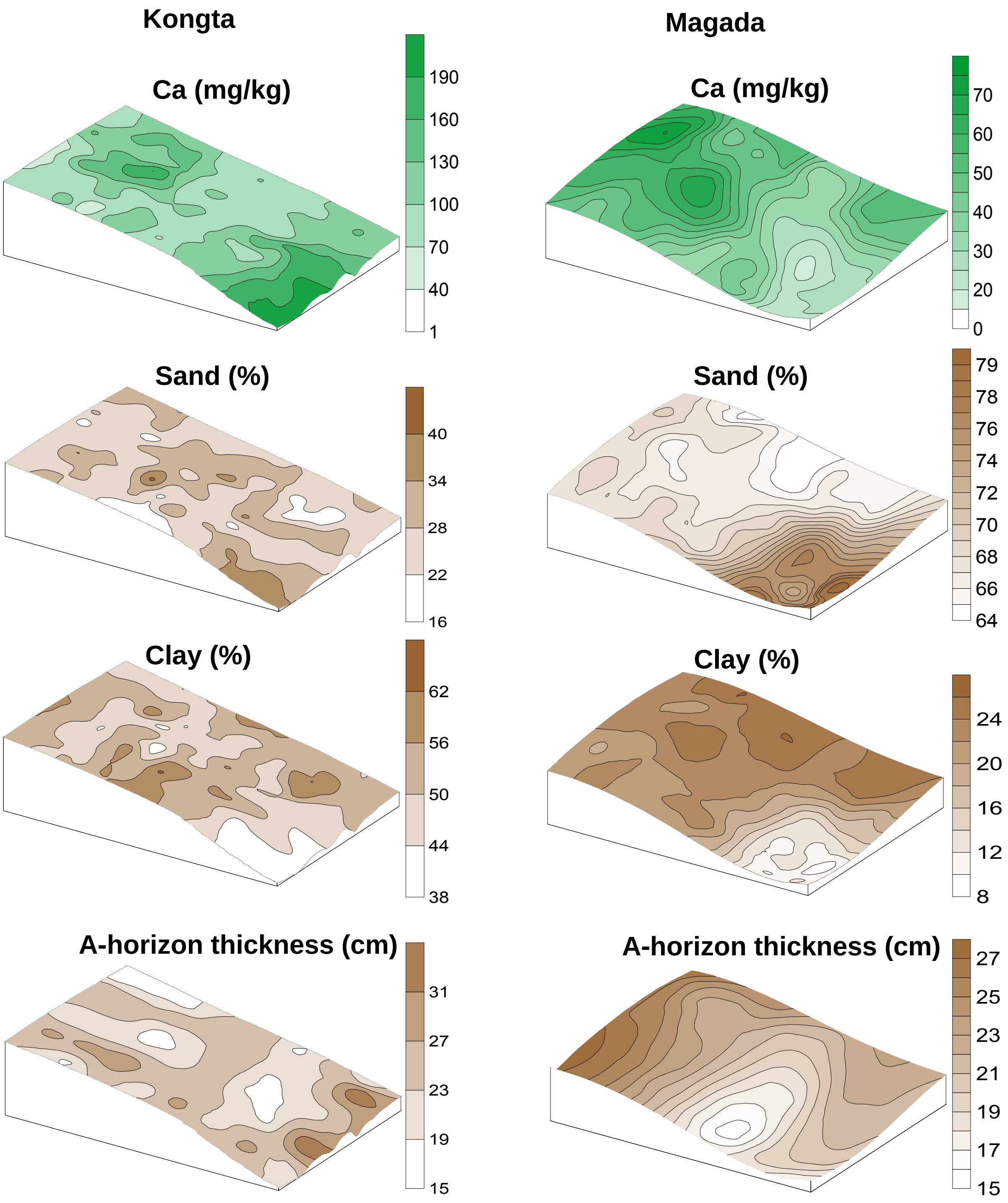

Figure 5.10 continued

The spatial interpolation produced patterns for most soil parameters in Kongta and Magada that are largely arranged as contour bands along the elevation gradients stretching from the upper slope to the footslope. This contour like pattern is more pronounced in Magada than in Kongta, where the pattern is generally noisier. The soil parameters pH, P, Ca, sand, clay and A-horizon thickness mainly follow this pattern. All these soil parameters were previously characterized by linear variogram models with highly scattered semivariance and the possibility of a strong influence of topography as the dominant factor determining spatial distribution was construed. The maps of the remaining soil parameters show more scattered spatial patterns. Several small island contours with either high or low soil parameter values are included within broader contour layers. This is especially recognizable for the spatial distribution of SOM and K. The variogram models which produced this pattern were exponential and spherical.

Magada is deficient in P, whereas upper and mid slope of this site is deficient in SOM and footslope position is deficient in pH. In Kongta pH and P deficiencies occur only in smaller areas in the midslope position. There are high P values striking as spots in the upslope area of Kongta. The upper slope position (upper parts of convergent and divergent backslope in Kongta and middle position of convergent shoulder, transition between divergent shoulder and divergent backslope in Magada) has higher values for pH, Ca, K and clay (green color), while it shows low values for sand (bright brown color). In the midslope position (upper part of the convergent footslope and the divergent backslope in Kongta and transition between divergent backslope and convergent footslope in Magada) larger island patterns can be recognized. These island patterns are for example visible in the P map where higher values (green color) and in the A-horizon thickness map where the lowest values (white color) are indicated at this location. This pattern can also be found in the maps of SOM, Ca, K (green color), and partly for clay (darker brown color) with moderate soil parameter values. The footslope position is characterized by relatively lower (bright green to red) or higher values (dark green) for almost all soil properties (e.g. low pH, Ca, K, clay and high sand and SOM values).

5.3.3 Causes of spatial soil variability on hillslope scale

Choice of environmental variables

The possible environmental factors determining spatial soil variability on the two hillslopes were identified by literature review (Jenny, 1941, Moore et. al, 1993) and observations and the respective environmental variables were selected (Table 5.9).

Table 5.9: Selected variables for hillslope-scale soil environmental correlation.

Factor category	Environmental variable	Type	Definition, units of measurement	Influence on soil variability	Site relevance
Terrain	Elevation	interval	meters above sea level [m]	micro-climate variability	Kongta Magada
	Slope (*b*)*	interval	slope angle [°]	water and soil redistribution	Kongta Magada
	Upslope area (*a*)*	interval	catchment area above sampling point [m^2]	water and soil redistribution	Kongta Magada
	Profile curvature*	interval	rate of change of slope [°/m]	water and soil redistribution	Kongta Magada
	Plan curvature*	interval	rate of change of aspect along a contour line [°/m]	water and soil redistribution	Kongta Magada
	Wetness index**	interval	ln (a/tan b)	water and soil redistribution	Kongta Magada
	Stream power index**	interval	atan *b*	erosive power of overland flow	Kongta Magada
Landuse	Maize	nominal	absence [0], presence [1]	soil nutrient dynamics and ground cover	Magada
	Sweet potato	nominal	absence [0], presence [1]	soil nutrient dynamics and ground cover	Magada
	Banana / Coffee	nominal	absence [0], presence [1]	soil nutrient dynamics and ground cover	Magada
	Grazing	nominal	absence [0], presence [1]	soil nutrient dynamics and ground cover	Magada
Land management	Shrub	nominal	absence [0], presence [1]	soil nutrient dynamics and ground cover	Magada
	Tree distance	interval	euclidian distance of sample point to tree trunk [m]	soil nutrient dynamics and ground cover	Magada
	Stoneline distance ratio	interval	euclidian distance of sample point to next upper stoneline in relation to upslope position [dimensionless]	water and soil redistribution	Kongta
	Organic fertilizer use	nominal	no org. fertilizer application [0], org. fertilizer application [1]	soil nutrient dynamics	Kongta
	Inorganic fertilizer use	nominal	no inorg. fertilizer application [0], inorg. fertilizer application [1]	soil nutrient dynamics	Kongta

* after Zevenbergen and Thorne (1987); ** after Moore et al. (1993)

The chosen variables were grouped to three environmental factors: Terrain, Land use and Land management. These represent the influence the environment has on the variability of soil parameters on the hillslopes in Uganda.

Climate was considered to be largely homogeneous over each hillslope, because of the small spatial extent of the sites that covered only a few hundred square meters. These homogeneous climatic conditions were confirmed by comparison of the variations of seasonal climatic data between meteorological stations at locations nearby Magada and Kongta. The respective stations nearby Magada were Ikulwe station (0° 27′N, 33° 29′ E, 1160masl) and Jinja station (0° 28′ N, 33° 11′ E, 1175masl). Kitale station (1° 02′ N, 35° 00′E, 1830masl) and Mbale station (1° 06′ N, 34° 11′ E, 1220 masl) were the closest stations to Kongta.

However, micro-climatic differences of temperature and humidity were observed during field investigations across each site. For example, the intensity of dew was markedly different between upslope and downslope locations due to micro-climatic influence from the wetland and the river in the valley on each site with Armanangh River in Magada and Walungogo River in Kongta. Farmers confirmed this observation, which was therefore accounted for in the correlation analysis by selecting elevation as the representative environmental variable.

Terrain factors slope gradient, upslope area and profile curvature were already employed in the delineation of the hillslope into landscape elements. Slope gradient influences speed of water and mass movement over the hillslope surfaces, thus contributing to different intensity of erosion and sedimentation processes. Profile curvature differentiates the spatial pattern of accelerated and retarded water and soil mass movement on the hillslopes and thus is expected to explain further soil variability pattern. Plan curvature was selected to account for the spatially variable impact of run-off water on soil variability in contour direction. Upslope area is an indicator of the surface water flow at a certain point on the hillslope, influenced by the catchment area above and the relative convergent or divergent location of that point. Therefore, upslope area is an integrative variable that reflects erosion and sedimentation as well as soil-water saturation processes (Moore et al., 1993). Finally, wetness index and stream power index were selected as terrain indicators that combine slope gradient and upslope area, to identify areas with different wetness level and erosive power of overland flow, respectively, which in turn influences soil variability. These selected variables are among the most used terrain parameters in similar geomorphologic and hydrologic studies for environmental correlation (Pennock et al., 1987; Jenson and Domingue, 1988; Dikau, 1989; Moore et al., 1993).

Land use is mainly in the form of crop cultivation and grazing in smaller areas. Farmers in Kongta grow mainly maize, whereas Magada farmers cultivate maize, sweet potato, banana and coffee as dominant crops. The latter two crops are usually grown together and thus were considered as one. The areas with closed grass vegetation, which are often fallow areas, are dedicated to grazing of cows and goats. The cropping and grazing areas were dummy-coded as present (1) or absent (0).

Natural vegetation refers in these sites mainly to shrubs and trees. The remaining shrubs and trees were considered land management. The dense canopy of these shrubs and trees (e.g. Mango trees) suppresses erosive rainfall splash, which in turn reduces soil erosion. Nutrients are recycled to the soil system through litter fall, thus replenishing soil organic matter and nutrients such as phosphorus and potassium in the soil. The dense plant litter and accompanying grass vegetation under shrubs and trees may help sedimentation of soil material. The natural shrub vegetation that was identified at the coordination of soil samples was dummy coded as present (1) or absent (0). The spatial indicator *Tree distance* was generated by GIS-analysis and used to specify from each point of the hillslope the Euclidian distance to the coordinates of the nearest tree trunk, in order to account for the spatially explicit influence of tree canopies on soil variability. The map of the tree distance in Magada is shown in Figure 5.11.

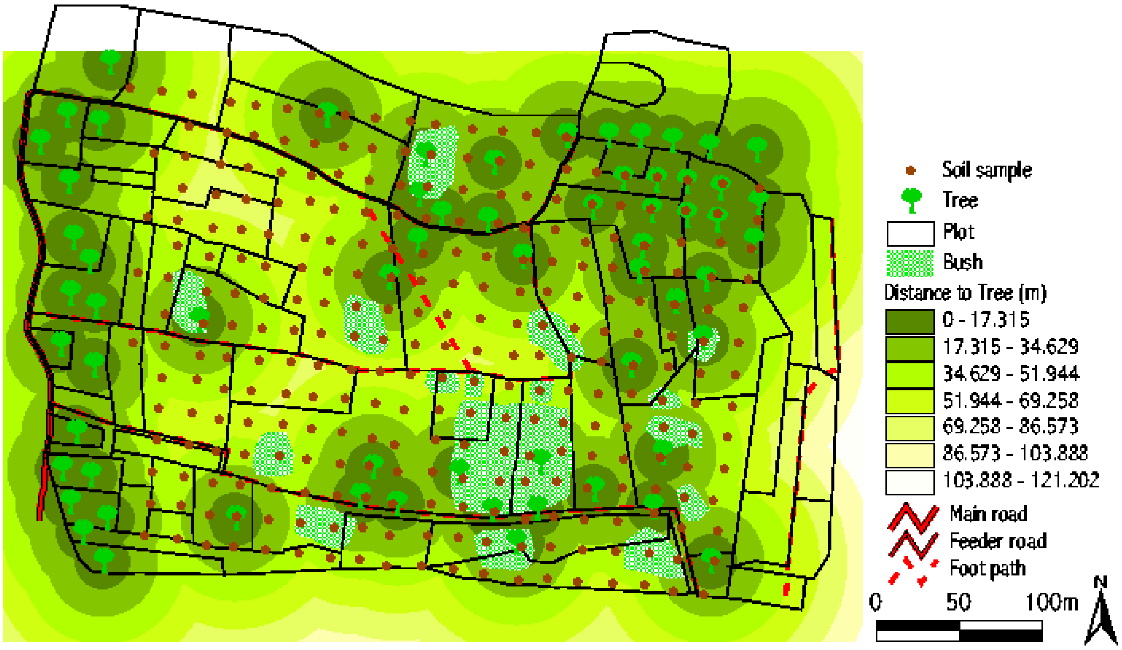

Figure 5.11: Tree distance in Magada

Additional land management factors with relevance only for further explaining the spatial variability of soils in Kongta were the use of stonelines, cow dung and different inorganic fertilizers. Farmers traditionally demarcate plot or field boundaries by placing a line of stones, on parts of which trees are planted. The map of the stoneline distance is shown in Figure 5.12.

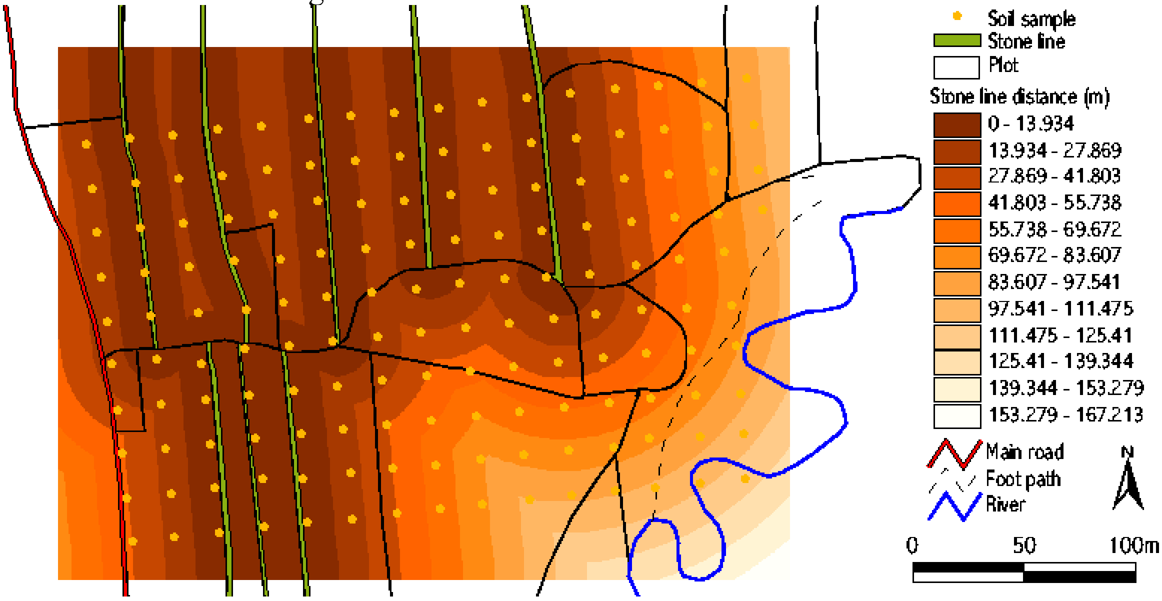

Figure 5.12: Euclidean distance to stone lines in Kongta

Note: This Figure gives the total view on the Euclidean distance of each point to all stonelines in Kongta. This explains for example the artifacts in the south-eastern part of the hillslope in this Figure. However, in the analysis the vertical distance of every point within the Kongta hillslope to the nearest stone line upslope was calculated separately from the other stonelines. These in total eight distance maps were not displayed due to the large number of stonelines and the corresponding maps.

After decades of agricultural use these stonelines have formed a structure of terraces on the formerly relatively straight hillslope. Each section between two stonelines in downslope orientation was therefore regarded as a hillslope system by itself with authentic pedo-geomorphological processes (Figure 5.2 a). The stoneline factor was parameterized by introduction of the indicator *Stoneline distance ratio*. This indicator was defined as the vertical distance of each soil sampling point to the next upper terrace divided by the length of the respective terrace. The indicator was logarithm transformed to reduce the measure scale. The minimum and maximum possible indicator values are 0 and 1 for the upper and lower stoneline position, respectively.

The possible soil forming factors geology and parent material were excluded in this analysis, because intensive soil profile surveys along transects that were traversing the hillslopes proved that these factors were homogeneously distributed within the relatively small extent of the hillslopes (Brunner et al., 2002).

This selection of variables was grouped into factors, of which the most dominant was determined. The results from the hierarchical regression of soil parameters with environmental variables that were grouped into terrain, land use and land management predictors (factors) are listed in Table 5.10.

Dominant environmental factors that explain spatial soil variability

In order to identify the dominant environmental factors that explain hillslope scale soil variability, Terrain, Land use and Land Management were correlated by hierarchical GLM. The modeling results are listed in Table 5.10.

Table 5.10: Hierarchical generalized linear model to explain spatial variability of soil parameters on the Kongta and Magada hillslopes

Soil parameter	Site	Environmental factors	R^2	R^2 adjusted	Residual standard deviation	Durbin-Watson Test	Standard error of the estimate
pH in water	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.43	0.37	0.76	1.82	0.79
		TE, LU	-	-	-	-	-
		LM	0.21	0.19	0.89	1.55	0.90
		LU	-	-	-	-	-
		TE	0.39	0.35	0.78	1.74	0.81
	Magada	TE, LU, LM	0.45	0.41	0.74	1.81	0.77
		LU, LM	0.17	0.15	0.91	1.72	0.92
		TE, LM	0.44	0.42	0.75	1.79	0.76
		TE, LU	0.44	0.42	0.75	1.72	0.76
		LM	0.04	0.03	0.98	1.59	0.99
		LU	0.16	0.15	0.92	1.43	0.92
		TE	0.43	0.41	0.76	1.73	0.29
SOM (%)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.46	0.41	0.73	1.93	0.77
		TE, LU	-	-	-	-	-
		LM	0.15	0.12	0.92	1.27	0.37
		LU	-	-	-	-	-
		TE	0.41	0.38	0.77	1.87	0.79
	Magada	TE, LU, LM	0.45	0.42	0.74	1.62	0.76
		LU, LM	0.35	0.33	0.81	1.56	0.82
		TE, LM	0.38	0.35	0.79	1.52	0.81
		TE, LU	0.33	0.29	0.82	1.44	0.84
		LM	0.32	0.31	0.83	1.54	0.83
		LU	0.19	0.18	0.90	1.25	0.91
		TE	0.11	0.08	0.94	1.28	0.96
Avail. PO_4^{3-} (mg/kg)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.30	0.24	0.84	2.14	0.87
		TE, LU	-	-	-	-	-
		LM	0.17	0.15	0.91	2.00	0.92
		LU	-	-	-	-	-
		TE	0.19	0.14	0.90	2.00	0.93
	Magada	TE, LU, LM	0.14	0.09	0.93	2.17	0.95
		LU, LM	0.11	0.09	0.94	2.08	0.95
		TE, LM	0.14	0.10	0.93	2.16	0.95
		TE, LU	0.13	0.09	0.93	2.07	0.96
		LM	0.09	0.08	0.95	2.08	0.96
		LU	0.09	0.08	0.95	2.02	0.96
		TE	0.10	0.07	0.95	1.99	0.96

Soil parameter	Site	Environmental factors	R^2	R^2 adjusted	Residual standard deviation	Durbin-Watson Test	Standard error of the estimate
Exch. K^+ (mg/kg)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.33	0.27	0.82	1.86	0.86
		TE, LU	-	-	-	-	-
		LM	0.26	0.24	0.86	1.79	0.87
		LU	-	-	-	-	-
		TE	0.21	0.16	0.89	1.74	0.92
	Magada	TE, LU, LM	0.31	0.27	0.83	1.72	0.85
		LU, LM	0.23	0.21	0.88	1.69	0.89
		TE, LM	0.24	0.21	0.87	1.58	0.89
		TE, LU	0.29	0.26	0.84	1.78	0.86
		LM	0.01	0.00	1.00	1.44	1.00
		LU	0.23	0.22	0.88	1.72	0.89
		TE	0.20	0.18	0.89	1.68	0.91
Exch. Ca^{2+} (mg/kg)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.47	0.42	0.73	1.78	0.76
		TE, LU	-	-	-	-	-
		LM	0.15	0.13	0.93	1.51	0.94
		LU	-	-	-	-	-
		TE	0.43	0.39	0.75	1.65	0.78
	Magada	TE, LU, LM	0.45	0.41	0.75	2.04	0.77
		LU, LM	0.34	0.32	0.82	2.06	0.83
		TE, LM	0.40	0.37	0.78	1.89	0.80
		TE, LU	0.41	0.39	0.77	1.76	0.78
		LM	0.09	0.08	0.96	1.66	0.96
		LU	0.31	0.30	0.84	1.68	0.84
		TE	0.37	0.35	0.80	1.67	0.81
Sand (%)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.23	0.16	0.88	2.10	0.92
		TE, LU	-	-	-	-	-
		LM	0.12	0.10	0.94	1.81	0.95
		LU	-	-	-	-	-
		TE	0.10	0.04	0.95	2.10	0.98
	Magada	TE, LU, LM	0.46	0.43	0.73	1.94	0.76
		LU, LM	0.14	0.12	0.93	1.55	0.94
		TE, LM	0.46	0.43	0.74	1.93	0.75
		TE, LU	0.42	0.40	0.76	1.78	0.78
		LM	0.01	0.00	1.00	1.37	1.00
		LU	0.13	0.12	0.93	1.49	0.94
		TE	0.41	0.39	0.77	1.73	0.87

Table 5.10 continued

Soil parameter	Site	Environmental factors	R^2	R^2 adjusted	Residual standard deviation	Durbin-Watson Test	Standard error of the estimate
Clay (%)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.41	0.36	0.77	2.02	0.80
		TE, LU	-	-	-	-	-
		LM	0.17	0.15	0.91	1.52	0.92
		LU	-	-	-	-	-
		TE	0.25	0.20	0.87	1.82	0.90
	Magada	TE, LU, LM	0.53	0.50	0.77	1.74	0.79
		LU, LM	0.21	0.19	0.99	1.30	1.01
		TE, LM	0.53	0.50	0.77	1.74	0.79
		TE, LU	0.51	0.49	0.79	1.63	0.80
		LM	0.04	0.03	1.10	1.09	1.10
		LU	0.20	0.19	1.00	1.33	1.01
		TE	0.50	0.48	0.79	1.59	0.81
A-horizon thickness (cm)	Kongta	TE, LU, LM	-	-	-	-	-
		LU, LM	-	-	-	-	-
		TE, LM	0.29	0.02	0.84	1.77	0.99
		TE, LU	-	-	-	-	-
		LM	0.16	0.08	0.92	1.90	0.96
		LU	-	-	-	-	-
		TE	0.14	0.06	0.93	1.72	1.03
	Magada	TE, LU, LM	0.44	0.31	0.75	2.13	0.83
		LU, LM	0.29	0.22	0.85	2.26	0.88
		TE, LM	0.43	0.33	0.76	2.13	0.82
		TE, LU	0.42	0.31	0.76	2.17	0.83
		LM	0.20	0.17	0.87	2.25	0.91
		LU	0.27	0.24	0.85	2.01	0.87
		TE	0.35	0.27	0.80	2.12	0.85

Abbreviations: TE=Terrain, LU=Land use, LM=Land management.
- = not applicable, since homogenous land use in Kongta was not used in regression.

Table 5.10 continued

The adjusted coefficients of determination in Table 5.10 reveal that the different environmental factors have different magnitudes of power to explain the spatial variability of various soil parameters on the hillslopes. The adjusted coefficients of determination of the predictors were ranked using the rules from Table 4.4. This ranking is displayed in Table 5.11.

Table 5.11: Ranking of environmental factors that explain the spatial variability of soil parameters on the Kongta and Magada hillslopes

Soil parameter	Site	Environmental factors					
		TE	LU	LM	TE,LU	TE,LM	LU,LM
pH in water	Kongta	**	-	*	-	-	-
	Magada	***	**	*	**	***	*
SOM (%)	Kongta	**	-	*	-	-	-
	Magada	*	**	***	*	***	**
Avail. PO_4^{3-} (mg/kg)	Kongta	*	-	**	-	-	-
	Magada	**	*	***	*	***	**
Exch. K+ (mg/kg)	Kongta	*	-	**	-	-	
	Magada	**	***	*	***	*	**
Exch. Ca^{2+} (mg/kg)	Kongta	**	-	*	-	-	-
	Magada	***	**	*	***	**	*
Sand (%)	Kongta	*	-	**	-	-	-
	Magada	***	**	*	**	***	*
Clay (%)	Kongta	**	-	*	-	-	-
	Magada	***	**	*	**	***	*
A-Horizon thickness (cm)	Kongta	**	-	*	-	-	-
	Magada	***	**	*	**	***	*

*** = highest, ** = moderate, * = least explanatory rank of a predictor factor based on adjusted R^2.
Framed explanatory ranks emphasize the highest explanatory ranks for a soil parameter.
- = not applicable, since homogenous land use in Kongta was not used in regression.
Abbreviations: TE=Terrain, LU=Land use, LM=Land management.

The hierarchical ranking shows that terrain has the strongest power to explain the spatial variability of most of the soil parameters on the hillslopes. They include pH in Kongta and Magada, SOM in Kongta and Magada, Ca in Kongta and Magada, sand in Magada, clay in Kongta and Magada and A-horizon thickness in Magada, with the adjusted R^2 ranging between 48 and 27%. Land management was the factor with the overriding explanatory power of the spatial variability for a smaller range of soil parameters comprising of SOM in Magada (ca. 31%), P in Kongta and Magada (ca. 15% and 8%, respectively), K in Kongta (24%), sand in Kongta (ca. 10%) and A-horizon thickness in Kongta (ca. 10%). Land use was able to explain the spatial variability of K in Magada (ca. 22%).

When two predictor factors were combined, terrain and land management had the strongest explanatory power for most of the soil parameters. The corresponding soil parameters with the respective adjusted R^2 include pH in Kongta and Magada (ca. 37% and 42%, respectively), SOM (ca. 41% and ca. 35%, respectively), P (ca. 24% and 10%, respectively), sand (ca. 16% and 43%, respectively), clay (ca. 36% and 50%, respectively) and A-horizon thickness in Magada (ca. 33%). Land use and land management as combined environmental factors were most dominant for explaining spatial variability of K in Magada (ca. 21%) and of Ca in Magada (ca. 32%).

The combination of all environmental factors further improved the strength to explain soils spatial variability in Kongta and Magada. Table 5.12 shows the ranking of soil parameters by the explanatory power of the different predictor factors.

Table 5.12: Ranking of soil parameters by prediction strength of environmental factors

Strength of relationship	Soil parameter	Site	Environmental factors	R^2	adjusted R^2
Moderate (0.64 > R^2 >= 0.25)	Clay	Magada	TE, LM	0.53	0.50
	Clay	Magada	TE, LU, LM	0.53	0.50
	Clay	Magada	TE, LU	0.51	0.49
	Clay	Magada	TE	0.50	0.48
	Sand	Magada	TE, LM	0.46	0.43
	Sand	Magada	TE, LU, LM	0.46	0.43
	Ca	Kongta	TE, LM	0.47	0.42
	pH	Magada	TE, LM	0.44	0.42
	SOM	Magada	TE, LU, LM	0.45	0.42
	pH	Magada	TE, LU	0.44	0.42
	pH	Magada	TE, LU, LM	0.45	0.41
	Ca	Magada	TE, LU, LM	0.45	0.41
	SOM	Kongta	TE, LM	0.46	0.41
	pH	Magada	TE	0.43	0.41
	Sand	Magada	TE, LU	0.42	0.40
	Ca	Kongta	TE	0.43	0.39
	Ca	Magada	TE, LU	0.41	0.39
	Sand	Magada	TE	0.41	0.39
	SOM	Kongta	TE	0.41	0.38
	pH	Kongta	TE, LM	0.43	0.37
	Ca	Magada	TE, LM	0.40	0.37
	Clay	Kongta	TE, LM	0.41	0.36
	SOM	Magada	TE, LM	0.38	0.35
	pH	Kongta	TE	0.39	0.35
	Ca	Magada	TE	0.37	0.35
	SOM	Magada	LU, LM	0.35	0.33
	A-horizon thickness	Magada	TE, LM	0.43	0.33
	Ca	Magada	LU, LM	0.34	0.32
	SOM	Magada	LM	0.32	0.31
	A-horizon thickness	Magada	TE, LU, LM	0.44	0.31
	A-horizon thickness	Magada	TE, LU	0.42	0.31
	Ca	Magada	LU	0.31	0.30
	SOM	Magada	TE, LU	0.33	0.29
	A-horizon thickness	Magada	TE	0.35	0.27
	K	Magada	TE, LU, LM	0.31	0.27
	K	Kongta	TE, LM	0.33	0.27
	K	Magada	TE, LU	0.29	0.26

Strength of relationship	Soil parameter	Site	Environmental factors	R^2	adjusted R^2
Weak (0.25 > R^2 >= 0.04)	K	Kongta	LM	0.26	0.24
	A-horizon thickness	Magada	LU	0.27	0.24
	P	Kongta	TE, LM	0.30	0.24
	A-horizon thickness	Magada	LU, LM	0.29	0.22
	K	Magada	LU	0.23	0.22
	K	Magada	LU, LM	0.23	0.21
	K	Magada	TE, LM	0.24	0.21
	Clay	Kongta	TE	0.25	0.20
	Clay	Magada	LU, LM	0.21	0.19
	Clay	Magada	LU	0.20	0.19
	pH	Kongta	LM	0.21	0.19
	K	Magada	TE	0.20	0.18
	SOM	Magada	LU	0.19	0.18
	A-horizon thickness	Magada	LM	0.20	0.17
	K	Kongta	TE	0.21	0.16
	Sand	Kongta	TE, LM	0.23	0.16
	P	Kongta	LM	0.17	0.15
	pH	Magada	LU, LM	0.17	0.15
	pH	Magada	LU	0.16	0.15
	Clay	Kongta	LM	0.17	0.15
	P	Kongta	TE	0.19	0.14
	Som	Kongta	LM	0.15	0.12
	Sand	Magada	LU, LM	0.14	0.12
	Sand	Magada	LU	0.13	0.12
	P	Magada	TE, LM	0.14	0.10
	Sand	Kongta	LM	0.12	0.10
	P	Magada	TE, LU, LM	0.14	0.09
	P	Magada	LU, LM	0.11	0.09
	P	Magada	TE, LU	0.13	0.09
	P	Magada	LM	0.09	0.08
	SOM	Magada	TE	0.11	0.08
	Ca	Magada	LM	0.09	0.08
	A-horizon thickness	Kongta	LM	0.16	0.08
	P	Magada	LU	0.09	0.08
	P	Magada	TE	0.10	0.07
No (0.04 > R^2 >= 0.00)	Sand	Kongta	TE	0.10	0.04
	Clay	Magada	LM	0.04	0.03
	pH	Magada	LM	0.04	0.03
	A-horizon thickness	Kongta	TE, LM	0.29	0.02
	K	Magada	LM	0.01	0.00
	Sand	Magada	LM	0.01	0.00
	A-horizon thickness	Kongta	TE	0.14	-0.06

Ranking is based on adjusted R^2 in the order from highest to lowest value.
Abbreviations: TE=Terrain, LU=Land use, LM=Land management.

Table 5.12 continued

The rankings in Table 5.12 show that environmental factors differ widely from highest predictive power of Terrain and Land management explaining ca. 50% of the spatial variation of clay in Magada to no predictive power of Land Management for explaining the spatial variation of sand in Magada. The more stable soil parameters such as Ca and sand were generally better explained by the environmental predictors than the more mobile soil parameters, such as A-horizon thickness, P, K and SOM.

5.4 Summary and conclusions

Kongta and Magada hillslopes, which are situated in the highlands and the lowlands of Uganda, respectively, were investigated in terms of spatial soil variability. The average soil texture in Kongta is clay, which needs significant power for tillage. Magada´s dominant soil texture is sandy clay loam, in which laterites may develop to hardpans. Since the farmers in Magada mainly use the handhoe for tillage, farmers typically abandon the land should hardpan development occur.

All average soil values in Kongta were distinctly above critical soil fertility levels and in Magada the average SOM and Phosphorus content were just at or clearly below those. Therefore, Kongta was regarded a favorable, while Magada was classified as a marginal hillslope for crop cultivation.

In Magada, the more mobile parameters pH, clay, P, SOM and K showed higher scattered semivariance than the more stable parameters Ca and sand similar to the national-scale survey. This may indicate that the spatial dependency of these soil parameters is not dependent on spatial scale. In Kongta this pattern was completely reversed with soil parameters P, K, Ca and sand, clay, A-horizon thickness showing more scattered semivariance than pH and SOM.

The zonation algorithm of the two hillslopes into landscape elements of homogeneous slope gradient, upslope contributing area, plan curvature and profile curvature, was successful in characterizing the spatial distribution of soils.

The patterns for pH, P, Ca, sand, clay and A-horizon thickness in Kongta and Magada were largely arranged as contour bands along the elevation gradients. The maps of SOM and K show more scattered spatial patterns. In the upper slope position higher values of pH, Ca, K and clay, while lower sand values occur. Large islands can be recognized in the midslope position, with highest P and lowest A-horizon thickness values. The footslope position has low values of pH, Ca, K and clay and high sand and SOM values.

Terrain had the strongest power to explain the spatial variability of pH, Ca, clay in Kongta and Magada, SOM, in Kongta, sand and A-horizon thickness in Magada. Land management mainly explained SOM in Magada, and P in Kongta and Magada, K, sand, A-horizon thickness in Kongta. Land use explained mainly K in Magada. The explanation of the soils´ spatial variability in Kongta and Magada by adjusted R^2 with the best combination of environmental predictors are for pH (37%, 41%), SOM (41%, 42%), P (24%, 9%), K (27%, 27%), Ca (42%, 41%), sand (16%, 43%), clay (36%, 50%), A-horizon thickness (8%, 31%).

This overriding impact of terrain is mainly caused by different slope gradient, upslope contributing area and geometric shapes of landscape elements that in turn influence pedohydrologic processes leading to corresponding spatially distributed soil. Since the lower hillslope sections have steeper slope sections, one would expect SOM losses due to erosion or decomposition. However, stonelines in Kongta and selectively maintained bushes and trees in Magada are assumed to both prevent erosion and provide input to the SOM pool at these locations. In places where stonelines and vegetation structures are missing, SOM together with fine earth material is most likely eroded.

Although these hillslopes have developed in contrasting agro-ecological environments in Uganda, the spatial variability of soils followed very similar catenary patterns. The knowledge on the developed hillslope delineation and the captured spatial variability of soil resources and their determining factors may help agricultural extension services to design appropriate INM technologies for targeted landscape elements in similar environments. Landscape-oriented INM may be a promising strategy for achieving sustainable cultivation for farmer communities in Uganda.

6 HILLSLOPE-SCALE SOIL REDISTRIBUTION PROCESSES AND RATES

6.1 Introduction

In Uganda, soil erosion is a widespread and serious problem that causes soil degradation (Magunda et al., 1999). The interaction of climate, soil type, relief, vegetation covers, intensive land use and lack of soil and water conservation strategies causes a medium to high potential for soil erosion in nearly all major farming systems (NEMA, 1998). Figure 6.1 shows the potential soil erosivity in Uganda.

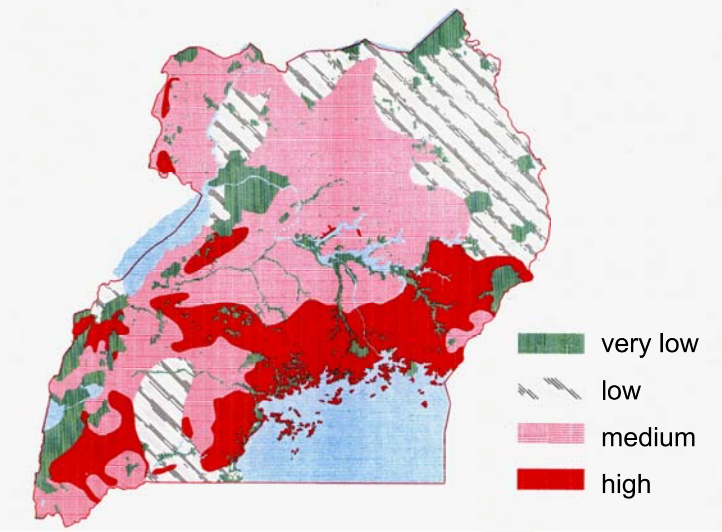

Figure 6.1: Potential soil erosivity in Uganda (after NEMA, 1998)

The major regions with high potential soil erosivity are located around the Lake Victoria and in the eastern highlands, the main areas with mainly the Banana-coffee and the Montane farming system. Soil erosion may also cause off-site problems by soil deposition into water bodies, such as the Lake Victoria leading to eutrophication and water pollution problems (Chabeda, 1983, NEMA, 1998).

In order to counteract these erosion problems it is necessary to identify the exact locations from where soil losses occur. Previous soil erosion studies in Uganda focused mainly on investigations of plots located within a landscape using run-off plots (Nakileza, 1992; Osinde, 1994; Tenywa and Majaliwa, 1998, Magunda et al., 1999). However, these plot studies did not consider the whole landscape system in which this plot is embedded. Over a hillslope, soil may be lost from some plots, while it may be accumulated in other plots, thus leading to the redistribution of sediment yield (Ritchie, 2000; Bacchi et al., 2003). Capturing these interactions of processes, soil erosion research has turned to process oriented models (Osinde, 1994; Biteete-Tukahirwa, 1995; Brunner et al., 2003). However, these models, which were developed in the USA, depend on an extensive list of input parameters, which are partly irrelevant to small-scale agriculture in developing countries (Flanagan and Nearing, 1995). Furthermore, long-term climatic records for reliable modeling are either not available or do not capture all necessary climatic data for modeling (Brunner et al., 2002).

One further method for estimating soil redistribution on erosion-prone hillslopes, such as those in Uganda might be tracing Caesium-137 (^{137}Cs). This approach relies on the assumption that the present redistribution of ^{137}Cs in the soil of agricultural hillslopes is a response of soil erosion, sedimentation and cultivation processes that occurred since the global ^{137}Cs fallouts in the 1960s (Walling, 1998). The approximate global deposition of ^{137}Cs is shown in Figure 6.2 and the distribution of sites where the ^{137}Cs approach was applied is displayed in Figure 6.3.

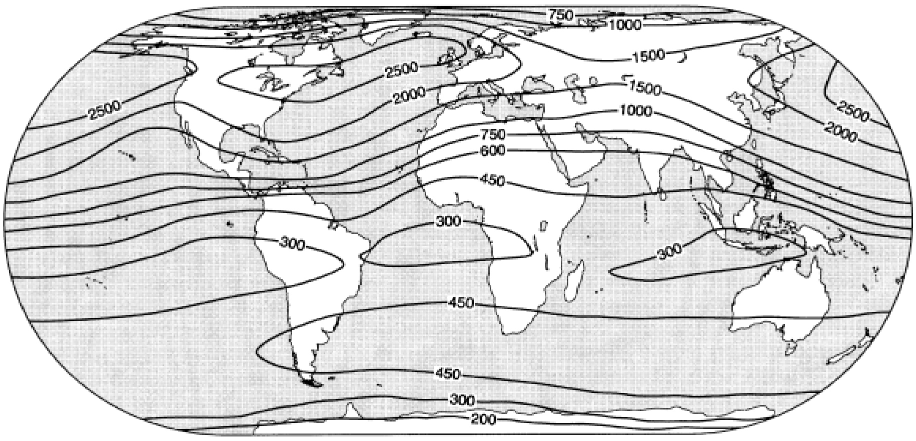

Figure 6.2: Approximate distribution of the global ^{137}Cs fallout inventories in 1998 (Walling (1998) based on Garcia Agudo (1998) and Larsen (1985))

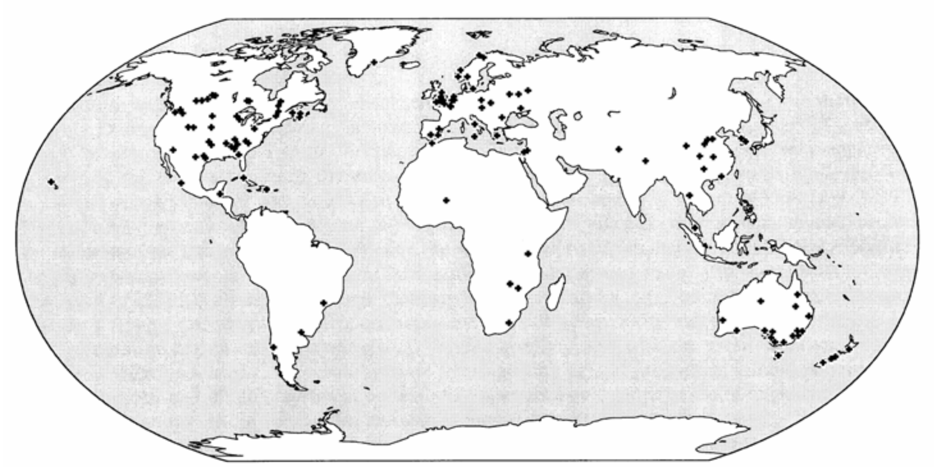

Figure 6.3: Distribution of sites where the ^{137}Cs approach was applied (Walling, 2001)

Figure 6.2 shows that the ^{137}Cs inventories decline from the mid-latitudes of the northern hemisphere, to almost an order of magnitude less over wide areas of the southern hemisphere. This may explain why most of the ^{137}Cs studies were carried out in Europe and North America where global ^{137}Cs fallout is relatively high (Figure 6.3).

This approach has only rarely been used in equatorial areas or in the Southern Hemisphere (Figure 6.3). To date, there has been no scientifically documented application of this method in the humid tropics of Africa.

During the last two decades, the efficiency and the value of the ^{137}Cs approach were increasingly recognized to estimate spatially distributed soil erosion and sedimentation rates in many places in the world (Ritchie, 1990; Walling, 1998; Collins et al., 2001; Zapata, 2003). The major advantages of ^{137}Cs approach are that it is possible to derive retrospective estimates of spatially distributed mid-term erosion and deposition rates, based on a single site visit for collecting samples. These estimates can be used to study spatial patterns of soil redistribution. Knowing the spatial location of these patterns may in turn help to target specific soil and water conservation measures for site-specific soil erosion control. Furthermore, due to its relatively small input data set for both three-dimensional as well as transect-based soil redistribution outputs, it might be superior to the intensively parameterized process models (Evans, 1995).

The research objectives for the ^{137}Cs studies on the hillsides of Uganda are, 1) to investigate the potential of applying the ^{137}Cs modeling approach for mid-term erosion and sedimentation assessments in the humid tropics of Africa; 2) to estimate the spatial distribution of mid-term erosion and sedimentation rates and corresponding patterns, and 3) to identify the main processes determining these soil erosion rates and patterns.

6.2 Material and methods

6.2.1 Caesium-137 soil redistribution

When ^{137}Cs deposited on the land surface, it was rapidly adsorbed into the fine soil fraction and became resistant to water detachment (Loughran et al., 1988). The loss or gain of ^{137}Cs inventory at a site relative to the ^{137}Cs reference inventory at an undisturbed site allows estimation of a maximum net rate of erosion and sedimentation since 1954 (Ritchie et al., 1974; Walling, 1998). Figure 6.4 displays the redistribution of ^{137}Cs in an agriculturally used hillslope with examples of ^{137}Cs inventories in reference and cultivated sites.

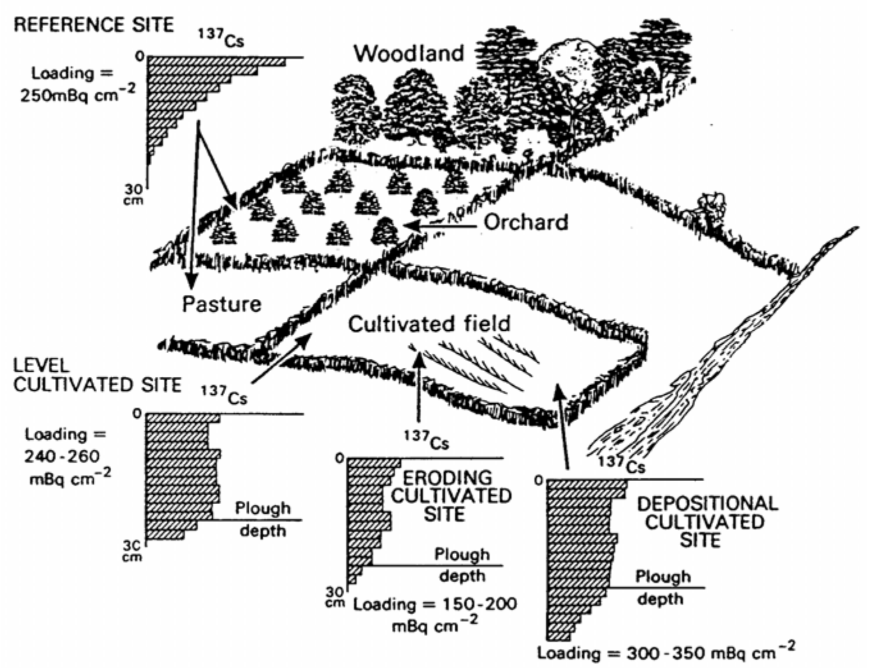

Figure 6.4: Redistribution of ^{137}Cs in a hillslope with typical ^{137}Cs inventory in profiles of reference and cultivated sites (Walling and Quine, 1993)

As Figure 6.4 shows, reference sites for ^{137}Cs studies are located on flat hillslope positions such as on the interfluve, where soil re-distribution by overland flow or splash erosion is largely excluded. The respective depth profile of the ^{137}Cs inventory of these reference sites exhibits a downward reduction of ^{137}Cs with soil depth. Cultivated sites usually experience a vertical redistribution of topsoil material by tillage, which leads to more homogeneously distributed ^{137}Cs inventory rates within the ^{137}Cs depth profiles. In leveled cultivated sites, the ^{137}Cs inventory has a relatively homogeneous vertical distribution in the depth profile. Cultivation sites with erosion, such as on steeper slope sections, have less ^{137}Cs in the upper profile layers due to erosive loss of ^{137}Cs enriched soil, but higher levels of ^{137}Cs inventories in lower profile layers, due to accumulation of ^{137}Cs by gradual vertical infiltration. Depositional sites, as for example in footslope positions, have accumulated ^{137}Cs-enriched soil from upslope and usually have higher ^{137}Cs inventories in the upper ^{137}Cs depth profile (Cawse and Horrill, 1986, Walling and Quine, 1993). The pedohydrologic and tillage processes determining soil redistribution can be simulated by models.

6.2.2 Soil redistribution estimation models

Walling and He (2001) developed several models to estimate spatial mid-term soil redistribution rates based on ^{137}Cs (Kachanoski and de Jong, 1984; Quine, 1989; Walling and Quine, 1990, 1993; He and Walling, 1997). These models vary in terms of the considered complexity of processes that determine the relationship between ^{137}Cs and soil redistribution. The simple model relates the amount of ^{137}Cs in the soil directly to the rate of soil redistribution. More complex models estimate the mass balance between the amount of ^{137}Cs at a sample point and the amount of ^{137}Cs at a reference point. These mass balance models were further improved to incorporate the impact of the dominant human-imposed processes on the re-distribution of ^{137}Cs in the soil profile, e.g. translocation of soil material by tillage operations (Walling and Quine, 1993, Govers et al., 1996).

The simple proportional model is based on the assumption that ^{137}Cs fallout inputs are completely mixed within the cultivation layer and that soil loss is proportional to the amount of ^{137}Cs removed from the soil profile since the ^{137}Cs fallout input that has occurred in 1963 exclusively (Kachanoski and de Jong, 1984; Frederick and Perrens, 1988). However, the assumptions of this model oversimplifies the reality in terms of ^{137}Cs deposition, because deposition took place over several years and some of the fallout input might have remained at the soil surface before it was ploughed into the soil. If ^{137}Cs on the soil surface is removed by erosion prior to incorporation into the profile, the modeled estimates of soil loss will yield an overestimation of soil loss. Likewise, since this model does not take into account the dilution of ^{137}Cs concentrations in the soil within the plough layer due to the incorporation of soil from below the original plough depth after surface lowering by erosion, the model results may underestimate soil loss (Walling and Quine, 1990; Walling and He, 2001)

Other mass balance models attempt to overcome some of the constraints of the simple proportional model. One of the more complex mass balance models, called *mass balance model 2*, considers the time-variant fallout ^{137}Cs input from the mid 1950s to the mid 1970s and the progressive reduction of ^{137}Cs within the plough layer due to ^{137}Cs dilution with soil from below the plough depth (Walling and Quine, 1993; He and Walling, 1997). This model assumes that a sampling point with a total ^{137}Cs inventory less than the local reference inventory represents an eroding site, while a point with a total ^{137}Cs inventory greater than the local reference inventory represents a depositional site. Besides the ^{137}Cs reference and the ^{137}Cs sample inventories, this model requires information on parameters such as plough depth, relaxation math depth, and proportional parameters (Walling and He, 2001).

The most complex mass balance model existing to date, called *mass balance model 3,* further improves previous mass balance models, because it recognizes that soil loss and gain is not simply proportional to loss and gain of ^{137}Cs as assumed in the mass balance model 2, but the response of ^{137}Cs in the soil is dependent on soil properties and the relevant process behavior (Walling and Quine, 1993; Walling and He, 2001). *Mass balance model 3* considers the effect of tillage-induced soil redistribution processes on cultivated land and is thus expected to estimate soil redistribution rates closer to reality. This model is only applicable to a linear transect parallel to the water flow direction.

In this study the latest available and most complex models were chosen to estimate soil redistribution rates. These models comprise firstly, the *mass balance model 2* to estimate the spatially distributed soil redistribution from random samples of a three-dimensional hillslope surface. Secondly, the *mass balance model 3* was chosen to estimate the impact of tillage and water induced processes on soil redistribution rates from sample points along representative slope transects traversing a hillslope. The specific descriptions, the input data and the equations for these models are documented in the Appendices 2-4. Both models are based on many research studies within the Coordinated Research Programme on Soil Erosion and Sedimentation of the International Atomic Energy Agency (Walling and He, 2001). The software of these models is available at http://iaea.org/programmes/nfa/d1/index.html.

6.2.3 Data collection

Hillslope selection

The selected soil redistribution models were applied on agriculturally used hillslopes in Uganda with contrasting agro-ecological conditions. These sites comprise the Kongta hillslope in the highlands and the Magada hillslope in the lowlands of Uganda. The detailed geographical location and the agro-ecological characteristics of these sites are presented in chapter 5.2.1.

^{137}Cs reference sample inventories

The most important input parameter into the ^{137}Cs models is the reference inventory. The reference inventory represents the amount of ^{137}Cs remaining in undisturbed soils. According to Walling and Quine (1993) the ideal reference site should fulfill the following criteria: 1) proximity to the study site, 2) no disturbance by tillage since 1953, 3) no soil erosion or sedimentation processes since 1953, 4) full vegetation cover throughout the year and during all years, and 5) coverage by grass or similar vegetation.

Sutherland and DeJong (1998) recommended a minimum of 12 sites to reduce possible large spatial variability of reference inventory values and to achieve statistical validity of reference inventory estimation. Unfortunately, such a large number of undisturbed sites could not be found within the agriculturally used sites. However, two possible suitable sites were identified in the vicinity of Magada in Mbale and Isikiro village. Near Kongta, an area within the village Chemuron was found to be a suitable reference site. The actual reference samples could be collected from schoolyards, which were in a leveled position and covered by pasparum grass throughout the year. On these sites no erosion, sedimentation, cultivation or other disturbance has been taking place after 1954 as several local citizens who have been living in these villages confirmed. In order to test that the requirements for reference sites are fulfilled for these sites, depth incremental profiles were collected and ^{137}Cs inventory distribution was measured in these profile. The depth profiles of ^{137}Cs inventories are shown in Figure 6.5.

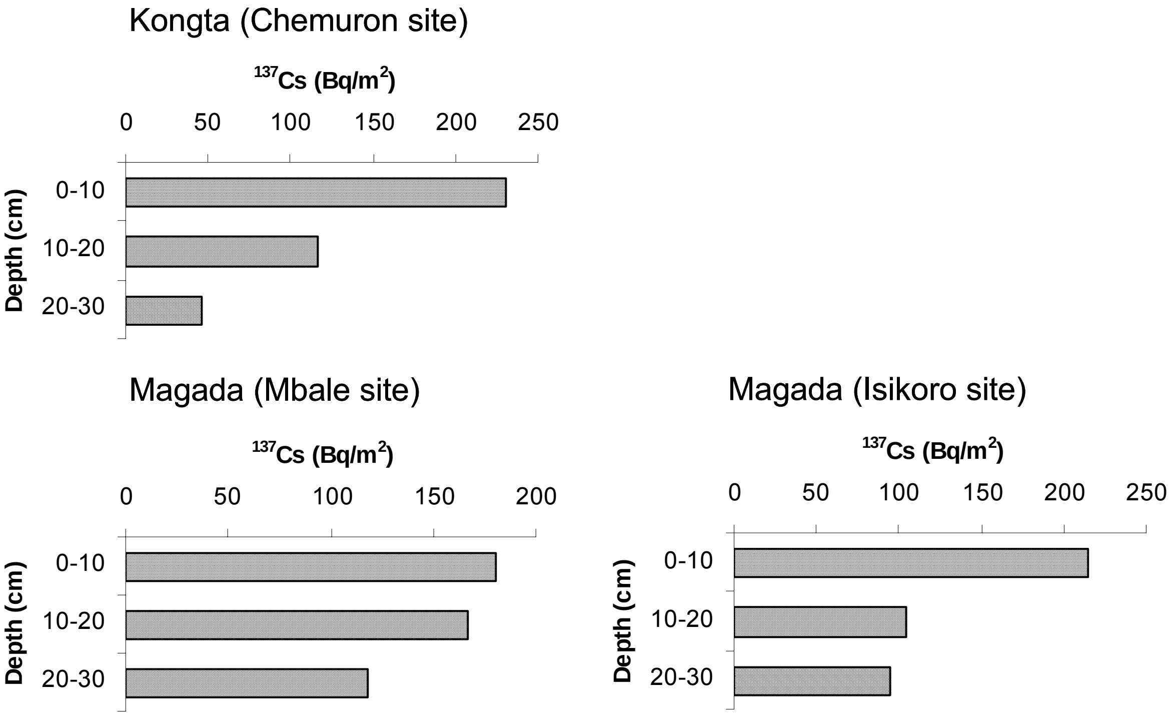

Figure 6.5: Depth incremental profiles of ^{137}Cs inventory in Kongta and Magada

These depth profile graphs show that ^{137}Cs inventories decrease gradually from surface near soil layers with profile depths, typical ^{137}Cs depth distribution patterns for undisturbed or reference sites, where ^{137}Cs that was deposited on the soil surface has been gradually infiltrating into the soil profile by natural mass translocation processes (Walling and Quine, 1993). Based on the indigenous site knowledge and ^{137}Cs profiles, these locations were considered suitable reference sites. The average ^{137}Cs reference inventory of four samples for Magada amounted to 439 Bq/m^2.

The one sample measurement that was available for determining the Kongta reference value yielded 392 Bq/m^2. This sample showed a similar ^{137}Cs profile as samples from the nearby Magada site (Figure 6.5). In order to further test the suitability of this one reference sample, the measured inventory value of this sample was compared with inventory estimates using a model from Sarmiento and Gwinn (1986). The chosen model considers the relationship between ^{90}Sr deposition and precipitation together with existing global-scale information on the distribution of bomb-derived ^{137}Cs inventories and the global precipitation pattern to determine estimates of bomb-derived ^{137}Cs inventories. The modeled reference value for Kongta was 485 Bq/m^2, a difference of 93 Bq/m^2 between measured and modeled value. The suitability of this model for the humid tropics study region was tested with the corresponding input data for Magada, which resulted to a value of 292 Bq/m^2, 147 Bq/m^2 less than the average value of several reference sites. Further sensitivity analysis was carried out by entering detailed site coordinates such as minutes or seconds into the model. These tests were set to identify whether the model is able to simulate different reference inventories within a smaller region. However, the simulation results revealed that the model was insensitive to detailed specification of geographic site coordinates.

Most of the previous ^{137}Cs measurements were carried out in mid-latitude regions of Europe and the USA (Walling and Quine, 1991; Garcia Agudo, 1998; Ritchie and Ritchie, 2001). It can be assumed that most inputs used in the model to calibrate and interpolate ^{137}Cs estimates to global-scale distributions came from these areas, whereas ground truth data from the humid tropics are lacking (Figure 6.2 and 6.3). Under these circumstances it was decided that the present model version might not yet be suitable for confidential predictions in the humid tropics. Thus, the measured ^{137}Cs inventory value was considered more suitable for Kongta than the modeled one.

^{137}Cs sample inventories

The ^{137}Cs sample inventories at the cultivated study sites were collected from spatially distributed locations of the hillslopes. The corresponding sampling frameworks are shown in Figure 6.6 a) and b).

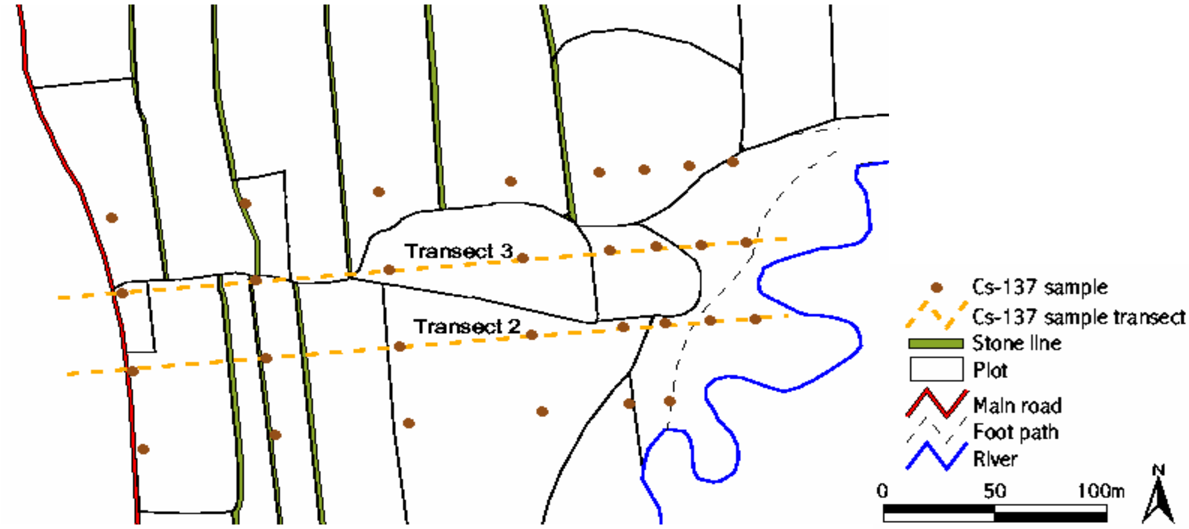

Figure 6.6 a): Sampling framework for collecting ^{137}Cs samples from Kongta

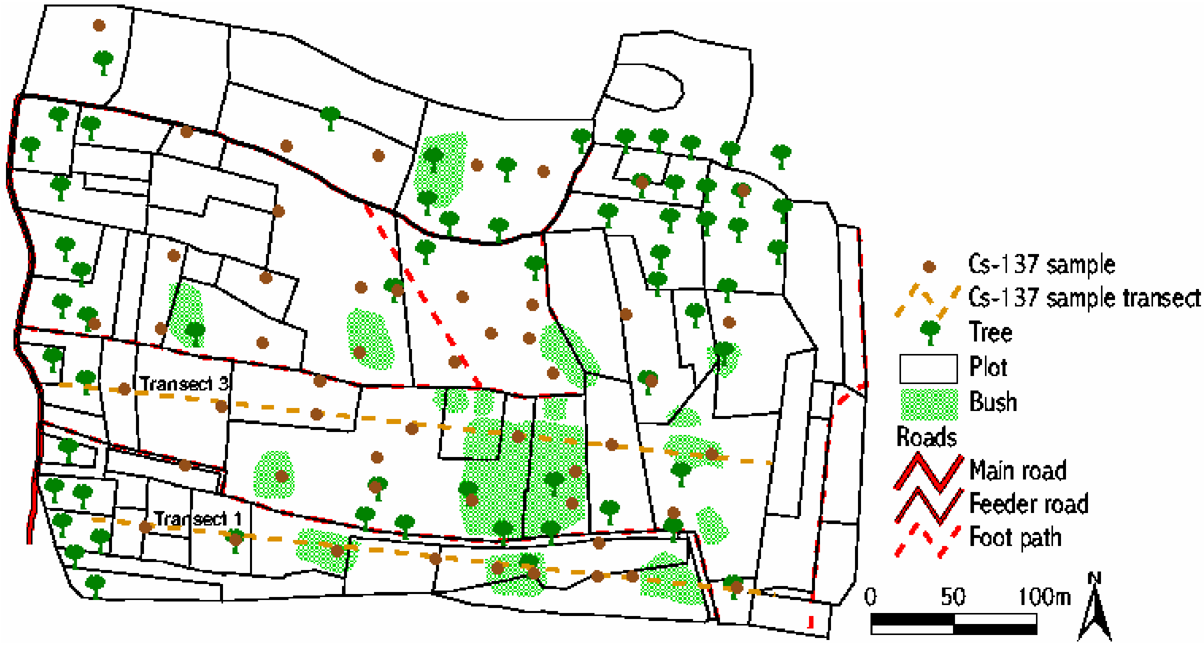

Figure 6.6 b): Sampling framework for collecting ^{137}Cs samples from Magada

Figures 6.6 a) and b) show that soil samples were collected from the intersections of a regular sampling grid that covered each site. Each grid element was 40 m in horizontal and 60 m in vertical dimension. The horizontal grid direction followed elevation contours, whereas the vertical grid direction was orientated straight downslope. In addition, samples were taken at locations in between that grid where erosion or sedimentation patterns were visually identified during field visits. These erosion patterns were for example located in erosion gullies, erosion rills and in patches with accumulated plinthite gravel. Sedimentation patterns were identified to be in locations where soil texture contained a high percentage of sand. The total sample population amounted in Kongta to 30 samples and in Magada to 52 soil samples. Split tube sampler equipment was used to collect these samples as well as the samples from the reference sites. The split tube sampler consisted of two steel tube halves with a length of 40 cm. This sampler was manually hammered into the soil to a depth of 0.3 m perpendicular to the ground surface. The sampler was then pulled out of the ground, the two halves opened and the samples were collected. All samples from the hillslope were used in the *mass balance model 2*. The inputs for *mass balance model 3* were collected from transect sample points at grid intersections that were oriented in straight downslope direction (Figures 6.6 a) and b)).

Ancillary model input parameters

There are several ancillary parameters that were necessary to run the ^{137}Cs models listed in Table 6.1 and described in detail in Appendix 2.

Table 6.1: Parameters used to model soil redistribution in Kongta and Magada

Model parameters	Kongta	Magada
^{137} Cs reference inventory (Bq/m^2)	392	439
Input year of sample collection	2001	2001
Input year t_0 of start of cultivation	1954	1954
Proportionality factor	0.7	0.7
Bulk density (kg/m^3)	855	982
Plough depth (m)	0.18	0.12
Particle size correction	1	1
Mass depth of the plough layer (kg/km^2)	154	118
Fraction of ^{137}Cs removed prior to tillage	0.5	0.5
Relaxation mass depth (kg/m^2)	3.8	3.8
Constant related to tillage practice (kg/m/year)	100	50

6.2.4 Data processing

^{137}Cs sample processing

Soil samples for ^{137}Cs measurement were slightly disaggregated, and then air-dried. The weight of the whole air-dried sample was recorded (TW). The fractions greater (CW) and less than 2 mm (FW) were separated and weighed. The corrected fine fraction weight (CFW) was then calculated by subtracting the coarse fraction weight from the total sample weight (TW-CW). A representative sub-sample of ca. 500 g of the fine fraction was submitted for ^{137}Cs measurement (Walling and Quine, 1993).

^{137}Cs measurement

^{137}Cs samples were measured by Mr. Josef Schikowski using a gamma spectrometer detector courtesy of the Isotope Laboratory, University of Göttingen, Germany. The core of the gamma spectrometer is a germanium crystal that is located between electrodes. The plot of counts against the gamma energy results in peaks, which indicate the occurrence of a radioactive isotope within a sample. The gamma energy of the ^{137}Cs decay is 662 keV. A count peak at this energy level indicates the presence of ^{137}Cs, while the number of counts indicates the ^{137}Cs concentration. The accuracy of measurement depends on the counting statistics, with the 1σ error in the number of counts defined as $\sqrt{n}$, where n is the number of counts (e.g. a count of 1,000 would correspond to an error of ± 31.62 or ca. ± 3%). For a small error, each sample was measured during a sufficient time period taking into consideration detector's efficiency, sample size and ^{137}Cs concentration. Average measurement time was ca. 250,000s or ca. 3days. The count measurements were calibrated to a reference sample. The unit of ^{137}Cs concentration is the Bequerel (Bq), defined as 1 count per second. ^{137}Cs concentration within a sample of a given dry weight is expressed in units of Bq/kg, which is called ^{137}Cs activity. This measure was transformed into ^{137}Cs inventory (Bq/m^2), called total areal activity, using the following equation (Sutherland and de Jong (1990).

$$^{137}\text{Cs inventory} = {}^{137}\text{Cs mass} \times \text{BD} \times \text{D} \times 1000 \tag{6.1}$$

where ^{137}Cs inventory = total areal inventory (Bq/m^2)
^{137}Cs mass = concentration per unit mass (Bq/kg)
BD = bulk dry density (kg/m^3)
D = depth of sampling (m)

^{137}Cs spatial distribution

The ^{137}Cs inventories in Magada and Kongta were spatially mapped using kriging interpolation to reveal the spatial patterns of lower and higher ^{137}Cs values. These spatial patterns may give a first indication on possible erosion and sedimentation patterns within each hillslope. The corresponding soil redistribution rates to these ^{137}Cs inventory patterns are then estimated by the mass balance models. The intervals of the map legends for the ^{137}Cs inventory classes were set to indicate ^{137}Cs levels that are greater, smaller and nearly equal compared to the respective reference inventory values. These ^{137}Cs values, together with ancillary parameters were entered into the different mass balance models, which determined soil redistribution processes and estimated erosion and sedimentation rates.

6.2.5 Validation of estimated soil redistribution rates

The estimated soil redistribution rates from the mass balance models were validated to determine whether the simulated results are in congruence with other soil redistribution investigations. Two independent validation procedures were performed, involving the comparison of mass balance model results against 1) simulation results that were obtained by Water Erosion Prediction Potential Model (WEPP), which was applied to Magada hillslope only (Brunner et al., 2003) and 2) literature information from erosion studies that were carried out under similar environmental conditions within this region covering both hillslopes (Nakileza, 1992; Zake and Nkwiine, 1995; Mati, 1999).

6.3 Results and discussion

6.3.1 Potential to apply the ^{137}Cs approach in the humid tropics of Africa

Total variability of ^{137}Cs inventories

It is generally known that the ^{137}Cs amount in the lower latitudes such as in the humid tropics of Africa is relatively small, compared to those amounts in the mid-latitudes (Walling, 1998) (Figure 6.2). For Uganda, it can be further assumed that moderate to strong soil erosion has led to a marked soil loss since the deposition of ^{137}Cs from bomb fallouts more than 40 years ago (Oldeman, 1994). In addition considerable amounts of ^{137}Cs have meanwhile been lost by natural radioactive decay. These conditions made it uncertain as to whether the presently available ^{137}Cs amount in the selected hillslopes of Uganda is still adequate for successfully performing the ^{137}Cs approach.

The statistical distribution of the ^{137}Cs inventories is shown in Table 6.2.

Table 6.2: Descriptive statistics of ^{137}Cs inventories (Bq/m^2) in Kongta and Magada

Site	N	Mean	Minimum	Maximum	STD	CV
Kongta	30	202	87.3	449	87.2	43.1
Magada	52	382	95.4	905	155	40.7

Abbreviations: STD = standard deviation; CV = coefficient of variation.

The average ^{137}Cs inventories were ca. 200 to ca. 400 Bq/m^2 in Kongta and Magada, respectively. The variation between minimum and maximum values ranges between ca. 100 Bq/m^2 in both to ca. 450 and ca. 900 Bq/m^2 in Kongta and Magada, respectively. These values are within the range of the interpolated ^{137}Cs inventories in this region (Figure 6.2) (Walling, 1998) and are therefore regarded suitable for the application of the ^{137}Cs approach. The available ^{137}Cs inventory in Kongta is roughly half the amount in Magada. The absolute variation of ^{137}Cs inventories, characterized by the standard deviation, is relatively large for both sites, again Kongta showing smaller values than Magada. This may indicate that these ^{137}Cs inventories reflect a wide range of soil erosion and sedimentation rates. The standardized variance of ^{137}Cs inventories for the two sites is almost the same. The generally smaller ^{137}Cs values of Kongta most likely reflect hillslope specific processes on the steeper Kongta hillslope, which will be investigated in more detail in the following.

Total error of ^{137}Cs inventories

The total error of the measured ^{137}Cs inventories was based on the 2σ error. This error was quantified to assess whether this error is tolerable when applying the ^{137}Cs approach in areas like Uganda. The corresponding statistics are shown in Table 6.3.

Table 6.3: Statistics of the 2σ error for ^{137}Cs inventories in Kongta and Magada

Site	N	Relative Mean [%]	Absolute Mean (Bq/m^2)	Absolute Minimum (Bq/m^2)	Absolute Maximum (Bq/m^2)	STD	CV
Kongta	30	17.2	34.8	12.8	68.6	11.9	34.1
Magada	52	20.5	78.5	37.8	113	15.9	20.3

Abbreviations: STD = standard deviation; CV = coefficient of variation.

As Table 6.3 shows, the relative mean 2σ error of ^{137}Cs inventories is almost equal in both sites and amounts to ca. 20%. Similar error values of ^{137}Cs inventories were found in other soil redistribution studies using the ^{137}Cs approach (Walling and Quine, 1993). The absolute variations of 2σ error of ^{137}Cs inventories are relatively large compared to the ^{137}Cs inventories, though less so for Kongta. Given the partly low ^{137}Cs inventories in Table 6.2, these error statistics point out that the maximum range of ^{137}Cs inventories may be rather high. Based on the measurements of ^{137}Cs inventories, the estimated soil redistribution rates in t/ha of the mass balance models need therefore to be considered with this possible error in mind. However, relative soil redistribution rates within a spatial pattern on the hillslopes are more important in this study than the absolute soil redistribution rates at specific sample locations. These spatial patterns of ^{137}Cs inventories over the hillslopes are reported in the next section.

Spatial distributions of ^{137}Cs inventories

The patterns of lower and higher ^{137}Cs inventories after kriging interpolation are shown in Figure 6.7 a) and b).

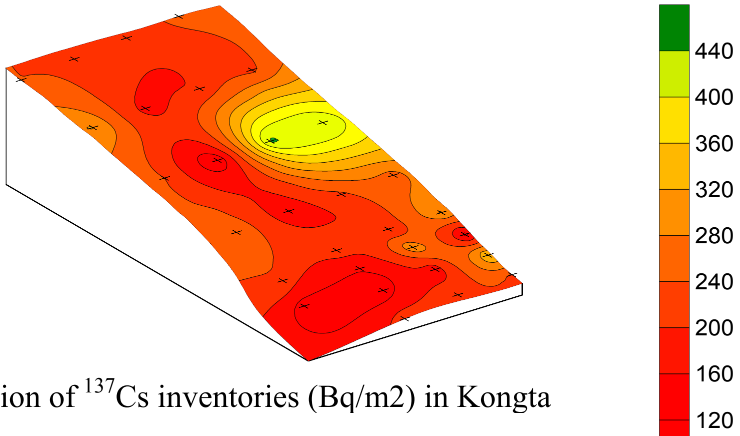

Figure 6.7 a): Spatial distribution of ^{137}Cs inventories (Bq/m2) in Kongta

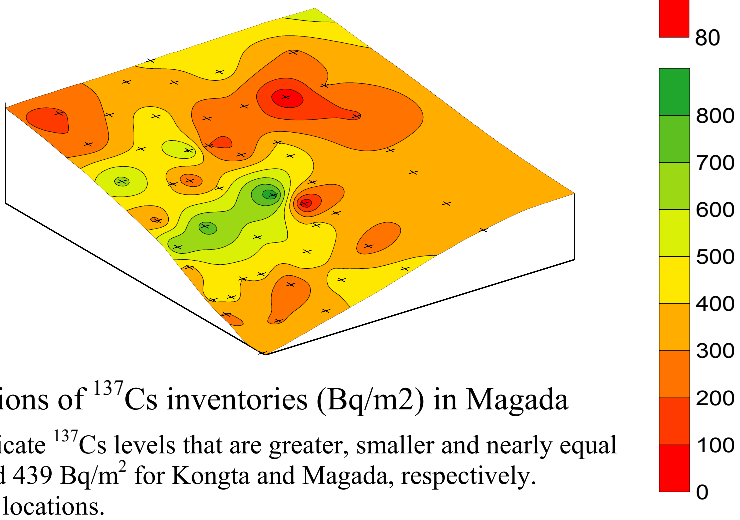

Figure 6.7 b): Spatial distributions of ^{137}Cs inventories (Bq/m2) in Magada

Note: The ^{137}Cs inventory classes indicate ^{137}Cs levels that are greater, smaller and nearly equal compared to the references of 392 and 439 Bq/m^2 for Kongta and Magada, respectively.
The crosses indicate the ^{137}Cs sample locations.

Figures 6.7 a) and b) show a pattern of ^{137}Cs inventories on both slopes, characterized by broad zones that are largely parallel to the elevation contours. These zones reflect ^{137}Cs inventories of higher or lower values than the values of the reference inventory. Within these zones, smaller islands are embedded representing peak values of considerably higher (dark to bright green color) or lower ^{137}Cs values (dark red color) compared to the reference inventory.

Most of the Kongta hillslope has spatial patterns of ^{137}Cs inventories that are much lower than the reference inventory as shown by the dominance of the dark red color. In these areas, values range between 80 and 200 Bq/m^2. Only one small patch in the middle slope position has ^{137}Cs inventories around the level of the reference site as displayed by bright greenish color. With the exception of this patch, a zonal pattern that follows largely the elevation contours, with alternating patterns of low and very low ^{137}Cs values can be discerned. This alternating pattern is most apparent in the ^{137}Cs changes that occur between the island patterns to the larger ^{137}Cs contour parallel zones.

The distribution of ^{137}Cs inventories of the Magada site exhibits a pattern with higher (displayed in greenish colors) and lower ^{137}Cs inventories (shown in different intensities of red) than the reference inventory. The spatial patterns of higher ^{137}Cs inventories occur in two relatively small elevation contour-parallel zones that are located in the middle of the east-west facing hillslope. The corresponding ^{137}Cs inventories of these zones reach up to ca. 900 Bq/m^2. The patterns of lower ^{137}Cs inventories are arranged around these high zones, largely following the elevation contours of the hillslope. The ^{137}Cs inventories of these patterns with lower values reach minimum values of ca. 100 Bq/m^2. These patterns of ^{137}Cs inventories may give a first indication of possible erosion and sedimentation areas, and the structure of these areas the possible causal processes within each hillslope. The zonal arrangement of ^{137}Cs inventories patterns may be caused by different terrain characteristics of the hillslope sections leading possibly to different soil erosion or sedimentation areas. The location of the higher and the lower ^{137}Cs inventory patterns represented by smaller patches as in Kongta or zones as in Magada may be due to different land use or land management systems that modify the major terrain-determined ^{137}Cs inventory patterns. The actual soil redistribution rates were estimated by the mass balance models below.

6.3.2 Estimation of soil redistribution rates, spatial patterns and processes

Three-dimensional spatial distribution of soil redistribution

Three-dimensional estimations of the soil redistribution rates were generated over the hillslopes using random sample inputs into the *mass balance model 2*. Table 6.4 shows the statistics of these estimated soil redistribution rates.

Table 6.4: Descriptive statistics of soil redistribution rates in Kongta and Magada assessed by the three-dimensional mass-balance estimation model

Site	Soil redistribution	N (count)	Mean	Minimum	Maximum	STD	CV (%)
			(t/ha/yr)				
Kongta	Soil loss	28	22.9	44.6	5.3	10.1	44.3
	Soil deposition	2	5.8	5.2	6.4	0.9	14.7
	Net soil redistribution	30	-21.0	-44.6	6.4	12.2	-58.1
Magada	Soil loss	36	9.3	36.3	0.2	7.6	81.6
	Soil deposition	16	6.3	0.0	25.0	7.3	116
	Net soil redistribution	52	-4.5	-36.3	25.0	10.4	-230

Note: Negative values indicate soil loss, whereas positive values indicate soil accumulation.
Abbreviation: STD = standard deviation; CV = coefficient of variation.

The soil redistribution rates in Table 6.4 indicate that both the Kongta and the Magada hillslope have experienced net overall soil losses. The average net losses from the hillslope in Kongta are ca. 21 t/ha/yr and in Magada ca. 4.5 t/ha/yr. Thus, Kongta has lost four times more soil than Magada. The sample location within the slope with the highest erosion rates in Kongta lost 44.6 t/ha/yr compared to 36.3 t/ha/yr in Magada. The location with the highest sedimentation rate in Magada gained 25 t/ha/yr soil, whereas the corresponding location in Kongta gained just 6.4 t/ha/yr. The soil redistribution rate at each sample location was interpolated over each site to visualize the pattern of soil redistribution (Figures 6.8 a) and b)).

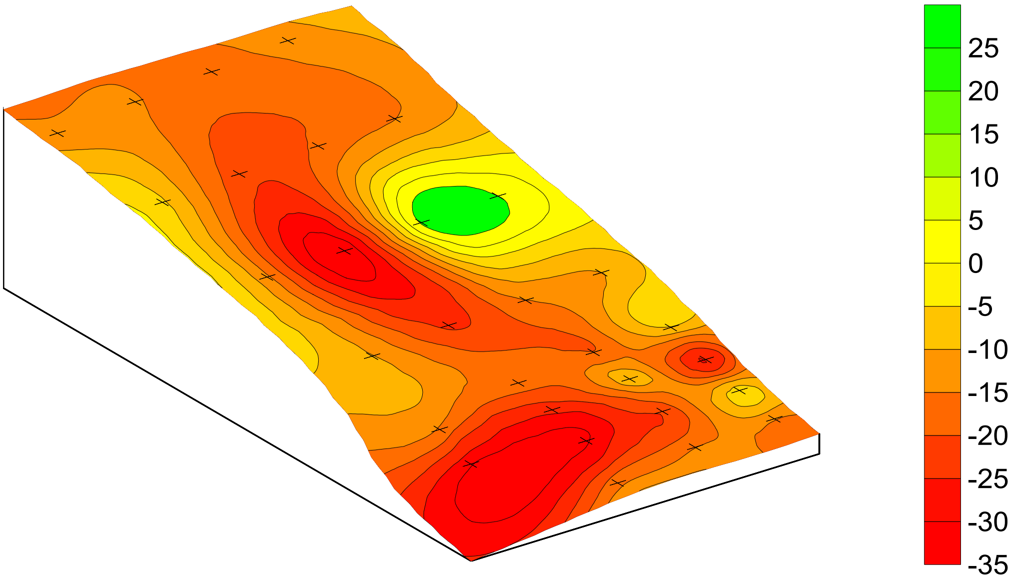

Figure 6.8 a): Spatial distributions of soil redistribution (t/ha/yr) in Kongta

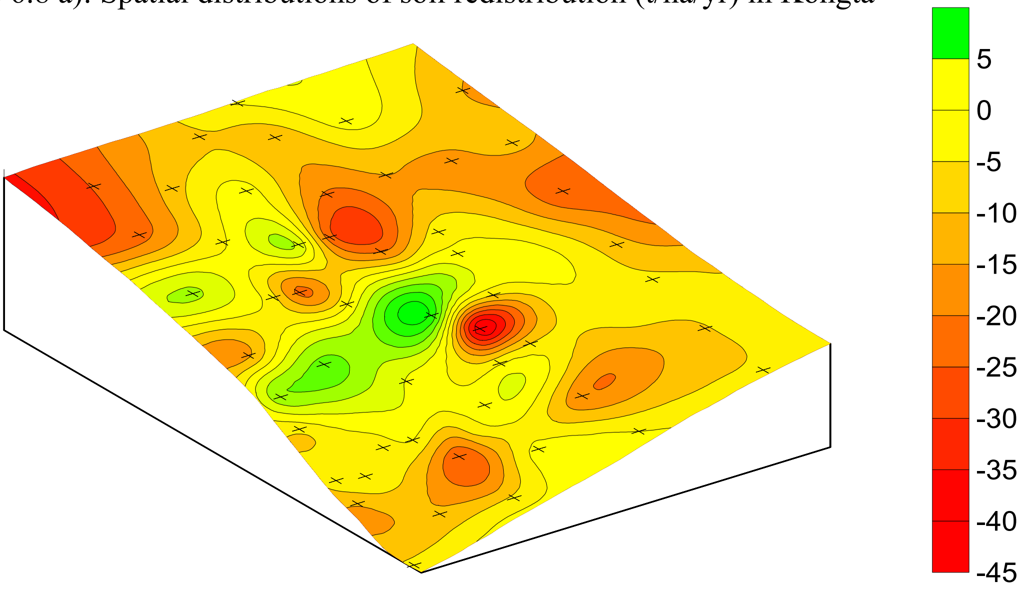

Figure 6.8 b): Spatial distributions of soil redistribution (t/ha/yr) in Magada

Note: The zones represent major erosion, deposition or balanced soil redistribution areas, indicated by reddish, greenish or yellowish map signatures, respectively. The crosses indicate the ^{137}Cs sample locations.

The Figures 6.8 a) and b) show that soil redistribution at both sites is generally arranged in broad zones, largely parallel to the elevation contours. These zones represent spatial patterns of soil loss and soil sedimentation of each hillslope. Within these zones smaller islands representing peak values of higher soil loss areas (dark red color) or higher soil sedimentation areas (dark to bright green color).

In Kongta the soil erosion patterns alternate. In the southern part of the hillslope relatively moderate erosion (ca. 15 – 20 t/ha/yr) appears on the upper convergent backslope. High to very high soil erosion (ca. 25 – 45 t/ha/yr) occurs on the middle and lower convergent backslope. Moderate soil erosion (ca. 15 – 20 t/ha/yr) is found further downslope connecting with the divergent backslope. High to very high soil erosion rates (ca. 30 – 45 t/ha/yr) are at the lower part of this divergent backslope. The northern part of this hillslope exhibits relatively moderate soil erosion (ca. 15 – 20 t/ha/yr) on the upper divergent backslope. Soil sedimentation (ca. 5 – 10 t/ha/yr) occurs in the middle part of the divergent backslope. Patches with relatively low as well as patches with relatively high soil erosion rates (ca. 5 – 30 t/ha/yr) appear on the footslope.

In Magada the zonal pattern of soil redistribution on the east-west facing hillslope occurs according to the following sequence: Relatively high soil erosion occurs on the upper divergent shoulder (ca. 12 - 25 t/ha/yr), moderate soil sedimentation is on the middle part (ca. 5 - 10 t/ha/yr), whereas moderate soil erosion is found on the lower part of this shoulder (ca. 5 - 12 t/ha/yr). The absolutely highest soil sedimentation rates over the total hillslope appear in a broad zone around the upper divergent backslope (ca. 17 - 27 t/ha/yr), little soil erosion is estimated for the lower divergent backslope (ca. 1 - 3 t/ha/yr) and high soil erosion is in the convergent footslope position (ca. 8 - 19 t/ha/yr). On Magada´s north-south facing hillslope section, spatial soil redistribution mainly occurred in one broad erosion pattern. This area extends from the divergent backslope to the convergent footslope and has moderate to high soil erosion rates (ca. 6 – 15 t/ha/yr). Magada´s north-west to south-east facing hillslope section has relatively high soil erosion rates in the upper and middle part of the convergent shoulder (ca. 12 - 25 t/ha/yr) and shows moderate soil sedimentation in the lower part of this shoulder (ca. 3 - 8 t/ha/yr). In the convergent backslope area one major patch reflecting the relatively highest soil erosion rates (ca. 20 – 35 t/ha/yr) in Magada is striking.

These alternating spatial patterns of soil erosion and sedimentation suggest that the processes are largely defined by terrain factors such as the higher and lower slope gradients, profile and plan curvature. These patterns of soil redistribution then determine landscape units and landscape elements.

The relation between slope and soil redistribution did not always fit intuitive notions. For example in Magada´s upper divergent shoulder position, slope gradient is relatively low and one might expect higher ^{137}Cs inventories and little soil erosion or even some sedimentation. However, this position has low ^{137}Cs inventories and moderate to high soil erosion. The divergent backslope sections at both sites have relative steep slope gradients and one may expect strong soil creep and lower ^{137}Cs inventories. However, maximum ^{137}Cs inventories and soil sedimentation were observed for this area in Magada and to some extent in Kongta. Another example is the footslope, where usually deposition of ^{137}Cs reflecting would be expected, but in these areas the ^{137}Cs inventory of the study site shows relatively low values, and soil erosion is dominant. From these results one would have to conclude that in some areas on the slope addition processes other than those related to terrain might be more dominant. Since Magada and Kongta sites are relatively small, homogeneous deposition of ^{137}Cs fallout can be assumed, thus spatially different ^{137}Cs deposition pattern can be safely rejected. Site-specific land use or land management may govern the occurrence of these smaller, but distinct ^{137}Cs inventories and soil redistribution patterns.

Soil redistribution considering different processes along transects

The influence of water and tillage processes on the spatial distribution patterns of soil was investigated for each hillslope in detail. This investigation was based on the transect model or *mass balance model 3* for the estimation of soil redistribution rates along linear slope transects. The advantage of this model lies in estimating the possible water and tillage processes separately from each other so as to identify the contribution of these processes and the resulting soil redistribution rates on soil erosion and sedimentation patterns. Furthermore, this process-oriented model was employed to reveal the possible causes that might have caused soil sedimentation in steeper and soil loss in flatter areas of the hillslopes. In Kongta the second and the third transect were used whereas in Magada the first and the third transect were selected as shown in Figure 6.6 a) and b), respectively. As a first step to revealing the influence of tillage and water processes on soil redistribution rates, the descriptive statistics of soil redistribution rates caused by these processes were analyzed for each transect at each site. Subsequently, the spatial soil redistribution due to water and tillage was determined along each transect. The results of the statistical analysis are presented in Table 6.5.

Table 6.5: Descriptive statistics of soil redistribution rates in Kongta and Magada estimated by the transect-based soil redistribution model

Site Transect Sample number	Soil redistribution process	Soil redistribution rate				
		Mean	Minimum	Maximum	STD	CV
		(t/ha/yr)				(%)
Kongta Transect2 N=8	Soil loss by tillage (Rt)	4.2	0.0	28.3	9.8	233
	Soil deposition by tillage (Rtd)	0.5	0.0	3.6	1.3	274
	Soil loss by water (Rw)	16.1	0.0	37.9	11.9	73.7
	Soil deposition by water (Rwd)	0.0	0.0	0.0	0.0	-
	Net soil loss (NR)	27.2	15.2	38.0	8.1	29.8
	Net soil deposition (NRd)	0.0	0.0	0.0	0.0	-
	Net soil redistribution	-27.2	-15.2	-38.0	8.1	-29.8
Kongta Transect3 N=8	Soil loss by tillage (Rt)	9.5	0.7	33.5	16.1	170
	Soil deposition by tillage (Rtd)	1.1	0.2	3.8	1.8	164
	Soil loss by water (Rw)	18.8	7.2	26.4	6.5	35
	Soil deposition by water (Rwd)	3.1	0.0	6.3	4.4	141
	Net soil loss (NR)	20.8	7.0	33.5	8.9	42.9
	Net soil deposition (NRd)	5.8	5.8	5.8	-	-
	Net soil redistribution	-17.5	-33.5	5.8	-	-
Magada Transect1 N=9	Soil loss by tillage (Rt)	3.1	0.0	26.6	8.8	289
	Soil deposition by tillage (Rtd)	0.1	0.0	0.7	0.2	267
	Soil loss by water (Rw)	4.8	0.0	15.3	5.5	114
	Soil deposition by water (Rwd)	3.6	0.0	18.2	7.2	200
	Net soil loss (NR)	9.9	0.8	26.6	8.2	83.3
	Net soil deposition (NRd)	15.9	14.1	17.7	2.6	16.2
	Net soil redistribution	-4.2	-26.6	17.7	13.7	-327
Magada Transect3 N=7	Soil loss by tillage (Rt)	1.2	0.1	7.8	2.9	235
	Soil deposition by tillage (Rtd)	0.1	0.0	0.6	0.2	265
	Soil loss by water (Rw)	3.2	0.0	18.4	6.8	216
	Soil deposition by water (Rwd)	2.3	0.0	9.6	3.7	160
	Net soil loss (NR)	7.5	0.7	17.8	6.5	86.9
	Net soil deposition (NRd)	5.2	4.4	9.5	2.8	53.5
	Net soil redistribution	-2.1	-17.8	9.5	8.9	-424

Abbreviation: STD = standard deviation; CV = coefficient of variation.

The mean soil loss rates (Rt, Rw, NR) at both sites are clearly higher than the corresponding soil sedimentation rates (Rtd, Rwd, NRd). This may indicate that larger soil masses have left the transect systems. Since these transects are representative for the two hillslopes, this finding reaffirms the earlier finding that that large quantities of soil material have left each of the hillslope systems.

The calculated mean and maximum soil redistribution rates by water processes (Rw, Rwd) are much higher than the corresponding rates due to tillage processes (Rt, Rtd). Thus, over the whole transect terrain factors generally determine the soil redistribution processes with water being more dominant than other possible drivers, such as tillage and other land use and land management practices.

Again, the calculated average net soil losses for the Kongta transects (TS2 = 27.2 t/ha/yr, TS3 = 15.3 t/ha/yr) are much higher than those for the Magada transects (TS1 = 7.7 t/ha/yr and TS3 = 4.3 t/ha/yr). In contrast, the Magada transect have much higher average net soil deposition (TS1 = 3.5 t/ha/yr, TS3 = 2.2 t/ha/yr) compared to the corresponding rates in Kongta (TS2 = 0.0 t/ha/yr, TS3 = 0.6 t/ha/yr). Similar conclusions are derived from the other statistics, such as maximum soil redistribution rates of the two sites.

The corresponding soil redistribution rates are visualized with slope gradient as one major terrain parameter and landscape elements in Figure 6.9.

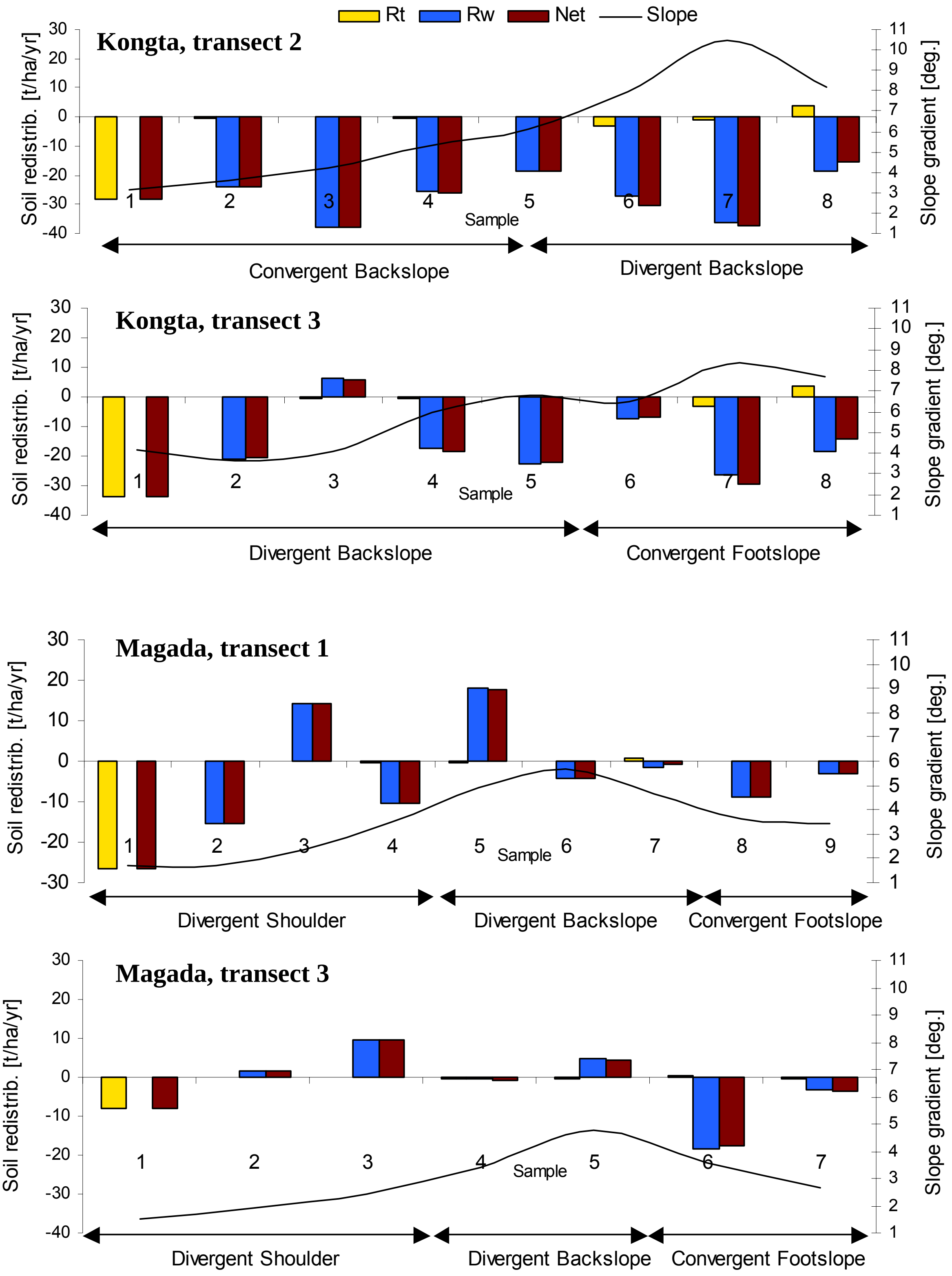

Figure 6.9: Spatial soil redistribution estimated along transects in Kongta and Magada in comparison to slope gradient and landscape elements

Note: Rt, Rw, Net = Soil redistribution by tillage, water, net processes, respectively. Negative soil redistribution values represent soil loss, positive values indicate soil sedimentation.

The different soil redistribution rates and patterns along transects of Kongta and Magada are described in the following sections.

Tillage induced soil redistribution rates and patterns

In nearly all landscape elements of the two sites, tillage impact on soil redistribution is uniform and almost balanced as indicated by generally near-zero tillage soil redistribution rates. However, the soil loss by tillage is considerably higher in the upper convergent and upper divergent backslope of Kongta (ca. –28 and –34 t/ha/yr, respectively) and in the two transects of the upper divergent shoulder of Magada (–7.8 and –26.5 t/ha/yr). In these upper landscape positions the topographic effect on soil redistribution may be weak due to low slope angles (Figure 6.9). Since these upper landscape elements are closer to settlements, these areas are traditionally the first farmers have been using for constructing the road infrastructure and settlement and were first taken into cultivation (Figures 5.2 a) and b)). In contrast, the areas further downslope and in the valley have been subsequently reclaimed to expand cultivation (Ssenyange, 2001). It can be assumed that soil which has been removed for construction of settlements and several decades of intensive tillage near farmers´ homesteads might have reduced the ^{137}Cs amount at these sites, which in turn may explain the soil loss estimated by the tillage component of the model.

Only relatively little soil was deposited (ca. 3.7 t/ha/yr in Kongta and ca. 0.7 t/ha/yr in Magada) in comparison to the average net soil redistribution. These sedimentation processes were mainly restricted to small areas in footslope positions.

Water induced soil redistribution rates and patterns

Water processes produced a greater range of soil redistribution rates and the spatial patterns along transects were more disaggregated than those generated by tillage-induced processes (Figure 6.9). On Kongta´s upper convergent and upper divergent backslope, a balanced soil redistribution rate was estimated. Some deposition occurred only on the middle backslope of transect 3 (6.2 t/ha/yr), whereas all other landscape positions experience moderate to very high erosion (-7.2 to -36.1 t/ha/yr).

Soil redistribution rate in the upper part of the divergent shoulder at Magada increases from balanced (0 t/ha/yr) to very high erosion rates (-15.2 t/ha/yr), followed by high sedimentation (14.2 t/ha/yr) in the middle part and high erosion (-10.2 t/ha/yr) in the lower part of this shoulder. In the upper part of the divergent backslope very high sedimentation rates (18.2 t/ha/yr) were calculated. Further downslope, erosion rates become moderate (-1.5 to –4.1 t/ha/yr). The convergent footslope is characterized by high erosion rates (-3.1 to 8.8 t/ha/yr). The soil redistribution patterns of Magada´s transect 3 follows the same pattern, but with less pronounced rates.

Again, soil redistribution rates and slope gradient for some landscape elements are counter-intuitive. Sedimentation occurs for example in medium to high slope gradient landscape elements (samples 5 in Magada transects 1 and 3) where higher erosion is usually anticipated (Figure 6.8). In addition, the footslope positions in Magada and Kongta have relatively low slope gradients but experience high erosion rates, while one would expect sedimentation in these areas. In the case of Kongta, a possible explanation may lie in the constructed stone lines with grass bunds that serve primarily as field demarcations (Figure 5.2 a)). Depending on the position within the hillslope and the maintenance of these stone lines, these structures may have a considerable impact on soil redistribution rates. This area is found in the divergent backslope position in front of a stoneline that is ca. 0.2-0.3 m high and partly planted with trees (Transect 3 in Figure 6.9, 5.2 a)). Although this stone line in Kongta was initially constructed on steep hillslopes, soil accumulation from upslope behind this line has smoothed slope gradient towards the lower terrace area, where higher ^{137}Cs inventories are also found.

Magada´s sedimentation pattern seems to be related to the natural vegetation pattern in the same locations. Thick bush and trees formerly covered Magadas´ hillslopes, before farmers settled and reclaimed land for cultivation (Ssenjange, 2001, Aggrey, 2002). However, some of these patches remain. These patches can for example be found within the area of the divergent shoulder and the divergent backslope and coincide spatially with the samples, which represent locations of soil sedimentation (compare the view on Magada hillslope with vegetation patches in Figure 5.2 b) and the location of Transect 1, Sample 3,5; Transect 3, Sample 3).

Soil profile investigations in Magada indicated that soil has accumulated within and in front of shrub locations (Brunner et al., 2003). These accumulations possibly originated from eroded soil material from upslope areas. Shrubs therefore represent a barrier against rapid soil mass transport by runoff water and dense shrubs may even reduce topsoil erosion in steeper hillslope sections. Such erosion reducing and sedimentation promoting processes of shrubs were confirmed in other ^{137}Cs studies under similar environmental conditions (Lindstrom et al., 2001; Schuller et al., 2003).

Validation of estimated soil redistribution rates

The soil redistribution rates that were estimated by the three-dimensional and the transect-based mass-balance models were validated against corresponding rates from independent studies in the same area or within the region.

In Magada, Brunner et al. (2003) estimated soil redistribution at the same Transect1 as investigated in this study by a forward simulation of the Water Erosion Prediction Potential Model (WEPP). The WEPP model used soil profile, terrain vegetation and land management data from 2001 and climatic records from 1990 to 1999 as inputs. The resulting WEPP estimation for the average soil loss of the entire transect amounted to 2 t/ha/yr compared to the 4.2 t/ha/yr of this current study. In some transect positions, soil loss modeled by WEPP amounted to ca. 3t/ha/yr in the interfluve position, whereas the ^{137}Cs model estimated ca. 8 t/ha/yr. At the steeper backslope position, WEPP modeling resulted in ca. 9t/ha/yr, whereas this study estimated ca. 17t/ha/yr soil loss. Soil deposition was modeled by WEPP on the hillslope bottom to amount to ca. 12t/ha/yr, whereas instead the ^{137}Cs model estimated 3.5t/ha/yr soil loss. Based on these comparisons, the relative soil redistribution rates over the whole transect are similar in both studies and the magnitudes are not unacceptably different. These comparisons show that the ^{137}Cs model provides soil redistribution values within the range of other soil erosion study techniques.

Brunner et al., (2003) argued that these losses in the WEPP model might be underestimated due to inability to account for tillage processes. This may explain why the ^{137}Cs model generated higher soil loss rates as tillage processes were included in this model. Furthermore, differences between the two model outputs might be caused by the different data and time-scales considered in the respective studies. The WEPP model combines climatic records of a past decade (1990-1999) with soil profile and other field information from a single season (2001) to run forward simulations of average annual soil redistribution. In contrast, the ^{137}Cs model considers the time-variant fallout ^{137}Cs input, the infiltration of ^{137}Cs into the soil profile, water erosion and tillage processes of more than four decades. Since the WEPP model runs are based on present soil, land use and land management conditions and shorter climatic dynamics, the resulting soil losses may be smaller than those from the ^{137}Cs model, which runs on a much longer time-period during which both water and tillage processes have been taken into account.

The results of this study were compared with other erosion studies within this region. For example, in the Ewaso Ngiro basin of Kenya, the site was characterized by loam-sandy to loam with multiple cropping systems, and thus was an environment similar to the Magada site. The applied Universal Soil Loss Equation in a GIS estimated an average soil loss of ca. 4.4 t/ha/yr (Mati, 1999), which is almost the same as what was found in this study. Soil loss estimations in standardized erosion plots in Wanale on the Mt. Elgon (Nakileza, 1992) for a sandy clay loam with maize crops amounted to ca. 6.4 t/ha/yr during one season in 1991. Other studies with the same soil and crop, but in the lowland of Kabanyolo in central Uganda, resulted in ca. 26t/ha/yr soil loss measured in non-standardized erosion plots for three seasons (Zake and Nkwiine, 1995). These comparisons show that the ^{137}Cs estimated soil redistribution rates are within the range of other studies. However, due to different methods of other studies in terms of spatial and temporal measuring interval, data and processes considered to estimate soil redistribution, a direct comparison with the ^{137}Cs approach is not possible.

6.4 Summary and conclusions

The ^{137}Cs modeling approach was evaluated to assess, whether this approach can be a suitable technique for estimating the spatial redistribution of soil on hillslopes in the humid tropics of Africa such as in Uganda. The selected sites for this evaluation included the Kongta and the Magada hillslopes, representing highland and lowland areas of Uganda, respectively. Following a positive evaluation, this approach was then used to estimate the spatial distribution of soil erosion and sedimentation by a three-dimensional hillslope and a transect-based mass balance model.

Although the Kongta and Magada sites represented areas of intensive cultivation on gently rolling to steep erosion-prone hillslopes, suitable ^{137}Cs reference inventories could be identified in undisturbed positions nearby. The average ^{137}Cs reference inventories were 392 and 439 Bq/m^2, for Kongta and Magada, respectively.

Under the conditions of generally low ^{137}Cs fallout deposition in this region, the min, mean and max ^{137}Cs inventories comprised 90, 200 and 450 Bq/m^2, respectively, in Kongta and 95, 380 and 900 Bq/m^2, repectively, in Magada. The average error of the ^{137}Cs measurements was ca. 20%.

The spatial pattern of ^{137}Cs inventories at both sites is in broad zones generally following the elevation contours. These zones represent ^{137}Cs inventories of higher or lower values than the values of the reference inventory. Within these zones smaller islands with considerably higher or lower ^{137}Cs values compared to the reference inventory are embedded. Kongta has mainly ^{137}Cs inventories of 80 to 200 Bq/m^2, thus much lower than the reference inventory. Magada has both, higher (up to ca. 900 Bq/m^2) and lower ^{137}Cs (down to ca. 100 Bq/m^2) inventories.

The soil redistribution rates that were estimated by the three-dimensional mass balance model indicate, for Kongta hillslope, -21 t/ha/yr and for Magada hillslope -4.5 t/ha/yr. Thus both sites experience net soil loss, with Kongta ca. four times higher losses than Magada. The overall soil erosion and sedimentation pattern at these sites follows mainly the sequence of landscape units with higher and lower slope gradients, while at a smaller scale the pattern follows the sequence of landscape elements, which change by profile and plan curvature.

Major soil losses in Kongta are on the upper convergent backslope (ca. 15 – 20 t/ha/yr) and on the middle and lower convergent backslope (ca. 25 – 45 t/ha/yr). High to very high soil erosion rates are dominant on the lower part of the divergent backslope (ca. 30 – 45 t/ha/yr). Soil sedimentation occurs in a small patch in the middle part of the divergent backslope (ca. 5 – 10 t/ha/yr). In Magada, higher soil erosion are on the upper divergent shoulder (ca. 12 - 25 t/ha/yr), on the convergent backslope area (ca. 20 – 35 t/ha/yr) and on the convergent footslope (ca. 8 - 19 t/ha/yr). The highest soil sedimentation rates are on the upper divergent backslope (ca. 17 - 27 t/ha/yr).

The influence of the different soil redistribution processes at each sample location within landscape elements of the hillslopes was estimated by the transect-based mass balance model. High soil loss by tillage was found in the upper convergent and upper divergent backslope of Kongta (ca. –28 and –34 t/ha/yr, respectively) and the upper divergent shoulder of Magada (–7.8 and –26.5 t/ha/yr). It was surmised that soil, which has been removed for construction of settlements and several decades of intensive tillage near farmers′ homesteads might have caused this soil loss. Only relatively little soil was sedimented (ca. 3.7 t/ha/yr in Kongta and ca. 0.7 t/ha/yr in Magada) in the footslopes.

The impact of water processes produced a greater range of soil redistribution rates and the spatial patterns along transects were more disaggregated than those generated by tillage processes. In Kongta′s upper convergent and upper divergent backslope, a balanced soil redistribution rate was estimated. Some deposition occurred only at the middle backslope (6.2 t/ha/yr), whereas all other landscape positions experienced higher erosion (-7.2 to -36.1 t/ha/yr). This sedimentation pattern seemed to be a result of the impact of stone lines in this area. These stonelines might have led to soil accumulation from upslope behind these lines as evidenced by the smoothed slope gradient and higher ^{137}Cs amount in this area.

The soil redistribution pattern of the Magada transects show an alternating sequence of lower and higher soil redistribution rates in the different landscape elements. Sedimentation occurred in areas of higher slope gradient where higher erosion is usually anticipated. This sedimentation pattern seems to be related with the spatial distribution of thick bushes and trees in these areas, which are remnants of formerly abundant natural vegetation. These bushes and trees are assumed to reduce the impact of upslope water erosion by a dense root system and ground cover, and contribute to soil accumulation in front and within this vegetation area.

The erosion patterns in Kongta′s and Magada′s footslope area may indicate that soil that has been eroded from upslope areas and temporarily deposited on the footslope, may be transported out of the hillslope system by river flooding during rainy seasons.

The possible interaction of the water erosion, tillage translocation and river flooding processes may therefore determine net soil redistribution rates and patterns on these hillslopes. Strong tillage erosion mainly governs the net soil redistribution on the upper hillslope. Water-induced processes, tempered by natural vegetation and stone-lines dominate net soil redistribution rates and distributions in the remaining landscape elements, while flooding process may be responsible for soil erosion in the footslope areas and out of the system.

Despite the difficulties of finding suitable ^{137}Cs reference inventories and acknowledging the moderate measurement error for ^{137}Cs, the ^{137}Cs modeling approach has the potential to estimate soil redistribution rates in the humid tropics of Africa. The strength of this approach is that only one field trip is necessary for sample collection compared to long-term observations for other erosion techniques. The estimation models allow comprehensive assessments of the spatial soil erosion and sedimentation patterns and their determining processes on hillslope and transect scales.

7 GENERAL DISCUSSION AND CONCLUSIONS

7.1 General discussion

Soil is the vital resource for many developing countries, such as for Uganda, where agriculture constitutes the economic backbone. However, Uganda's soil degradation problems, such as erosion and nutrient depletion have emerged to become a major concern and are threatening the food security of many small-scale farmers nowadays. Remedial action will require a better understanding of these problems so that site-specific land use and land management can be tailored for the region. This will first require description and quantification of the spatial variability of soils and the various soil forming factors. Unfortunately, development planners and policy makers often lack up-to-date and site-specific information on the spatial variability of soils and their influencing factors on the national-scale where regional soil improvement strategies are needed. Similarly, agricultural extension services are frequently unaware of the complex soil erosion and sedimentation variation that may occur within watersheds where farmers ask for advice on soil conservation and nutrient management strategies.

This research investigated the spatial variability of soils on a national- and a hillslope-scale and estimated the soil redistribution rates on hillslopes in Uganda. Specifically, this study stratified the whole area of Uganda into spatial domains as a pre-classification of the complex national-scale soil determining factors. On both national- and hillslope-scales, spatial variability characteristics of individual soil properties including pH, SOM, P, K, Ca and texture and their dominant determining factors were assessed and respective spatial patterns were demarcated. Spatially distributed soil erosion and sedimentation rates were estimated on hillslopes using a Caesium-137 approach.

7.1.1 Spatial stratification of Uganda

The GIS-based stratification model of Uganda produced 18 spatial domains of different factors comprising population density, market access, agricultural potential and elevation that may influence soil variability over Uganda according to pathways of development theory. The variance analysis showed that the spatial domains were largely homogeneous in terms of the socio-economic and the natural resource input factors. The main input factors as well as the factors July rainfall, annual rainfall potential, length of growing period and temperature potential that represented agricultural potential can be used to design improved land use and land management strategies to targeted regions, e.g. to use the information on the length of growing period and rainfall factors to identify suitable areas for drought resistant crop varieties; or to focus on these spatial domains with high agricultural potential and low market access for developing strategies that strengthen fertilizer distribution markets (Ruecker et al., 2003a). Based on this pre-classification, the number of soil samples for a representative national-scale soil variability assessment could be kept relatively small. In total 1050 soil samples were systematically collected from the classified domains covering the Southern, Eastern and Western regions of Uganda over two months. Due to this short sampling period temporal bias on soil data that were collected from such a wide study region was avoided. In addition, this spatial stratification helped to keep the costs of transportation reaching the soil sampling sites and of analyzing the soil samples to a minimum.

7.1.2 National-scale spatial variability of soils

The national-scale study was undertaken because presently available information on the spatial variability of soils in Uganda relies mainly on the national reconnaissance soil survey from the late 1950s (Chenery, 1960, p. 32). Since then, soil conditions may have changed due to the intensive agricultural use of these resources by farmers. This national-scale soil variability investigation was performed to reveal how the most important soil parameters that determine soil quality are spatially distributed in Uganda.

The average soil texture of sandy clay loam, the mean values of pH (5.3), SOM (5%) and phosphorus (50 mg/kg) all compared favorably with the critical soil fertility thresholds (Foster, 1971). However, the minimum soil parameter values represented certain areas of Uganda that are drastically lower than the critical levels, e.g. pH (3.9), SOM (0.6%) and P (0.24 mg/kg). Further variance analysis revealed that the soil nutrients P, K, and Ca had very wide ranges over Uganda stretching from ca. 1 to 800 mg/kg, 500 mg/kg and 700 mg/kg, respectively. This variability suggests a diverse spatial nutrient status of soils of Uganda, with some areas being more marginal and others more favorable for agriculture. These details are important, because in the past Chenery's (1960) summarized soil information "compared to other places in the tropics the soil of Uganda are on the whole fertile" was often used, while soil variability and soil problems were neglected (Ssali, 2000).

The soil correlation analysis indicated that most of the soil parameters are related to each other. For example, soil acidity (pH), had a high positive correlation with the soil nutrients P, K, and Ca. These coincidences usually occur on geologically old erosion surfaces where due to weathering few minerals remain and pH is relatively low. SOM, a major determinant of soil fertility in Uganda, was positively correlated with clay and silt as well as with different soil nutrients. In general erosion processes that redistribute fine earth-SOM complexes of the topsoil of cultivated land may have caused this relationship. Furthermore, coupled SOM and soil nutrient losses may be caused by farmers´ cultivation of fields over many decades, during which SOM has decayed and soil nutrients have been extracted by crop harvest without soil fertility replenishment (Ssali, 2001). The identified correlations can be helpful when quick field assessments of broad soil conditions are needed, such as on the major spatial patterns of nutrients within a water catchment. The magnitude of values of easier to measure soil parameters, e.g. soil texture by finger probe and acidity by portable pH meter can then be used to estimate the values of more difficult to measure soil parameters, e.g. P and SOM, respectively.

Detailed analysis of soil spatial variability along the hillslopes of the study communities showed that pH, SOM, sand and clay were homogeneously distributed within and heterogeneously distributed among each hillslope unit including upper and middle slope, lower slope and flat land. This shows that the certain terrain conditions of hillslopes may strongly influence the distribution of these parameters over the slope. These soil-terrain relationships have been found in many landscape-related studies (Conacher and Dalrymple, 1977; Moore et al., 1993; Park and Burt, 1999). However, for P, K, Ca and of silt it was surmised that other factors might have a more dominant influence on the spatial distribution as was subsequently confirmed in the hillslope-scale study in chapter 5.

The spatial structure investigation revealed that different soil parameters have different spatial dependencies. The sequence from highest to lowest spatial dependency, indicated by different range value is: P > clay > silt > SOM > K > sand > Ca. Further spatial structure indicators, such as the micro-variability, were ranked as: pH > clay > P

> sand > silt > SOM > K > Ca. A third indicator, the shape of the semivariance, showed that soil pH, clay, P, SOM, and K had much higher scattered semivariance than sand, silt and Ca. Although these geostatistics were based on a rather small dataset, they point out that different soil parameters may have very different spatial structure at a given spatial scale (Park and Vlek, 2002).

In a detailed assessment of the spatial structure it was found that the more mobile soil parameters, such as soil pH, clay, P, SOM, and K have a similar spatial structure different from the more stable soil parameters, such as sand, silt and Ca. These findings from Uganda are in accordance with general soil spatial variability theory. This theory claims that more mobile soil parameters, which change rapidly in both space and time, achieve equilibrium more quickly with local pedogenetic and human induced processes occurring on hillslopes than stable soil parameters (Park and Vlek, 2002). Therefore, local conditions, such as topography, land use and land management are more important in explaining the spatial variability of these mobile soil parameters than nationally prevailing conditions such as the homogeneous geology and climate, which may play a larger role in determining the more stable soil parameters. However, these local conditions are very difficult to capture in the required detail on the national-scale and were therefore analyzed for two selected hillslopes representing larger areas in the lowland and in the highlands of Uganda as shown in chapter 5.

Clearly different soil parameter patterns occur in the lowland area in central and western Uganda compared to the patterns in the eastern and southwestern highlands. Soil pH has spatial patterns with values that are markedly deficient for crop growth in the central area around Lake Kyoga, in southeastern Uganda along the shores of Lake Victoria, in the far west and in parts of the southwestern highlands. The level of pH increases generally towards the northeast and the western areas of the south-west. SOM showed contrasting patterns between the lowlands with values often close to the critical level of 3%. The overall distribution patterns indicated that SOM further decreased toward the North and East of the country where granite is the dominant parent material. The maximum values of SOM were found in the montane farming systems comprising the south western and eastern highlands where SOM levels reached levels of more than 11%. The soil nutrients P, K and Ca have lower values in a wide region covering northern, central and southern Uganda and parts of the south-western highlands. Higher levels of these plant nutrients occur in western Uganda and in the eastern highlands. The major area share of the survey region in the lowland has generally higher sand and lower clay content. These patterns are reversed in the eastern and the south-western highlands.

These patterns of soil parameters, which are displayed on national-scale maps, may give policy makers and regional planners of development initiatives or soil improvement projects a good estimate of the extent and the values of parameters determining soil quality in Uganda. Since these maps were based on 107 averaged community transect sample points that were spatially interpolated over the national-scale, the reliability of this map information in areas away from these sample points must be seen against the background that other environmental factors may be dominant over those captured with the presently available data.

Overall, the spatial variability of the investigated soil parameters was best explained by the geological and geomorphological conditions in Uganda comprising patterns with distinct geological age, geomorphologic erosion surfaces, parent material and elevation. These explained 9% of the differences in pH, 43% of SOM, 19% of K, 21% of Ca, 51% of sand, 45% of clay and 38% of silt. Land use and land management conditions, as expressed by the different farming systems, could explain 21% of the spatial variability of P over the national spatial extent. The strength of the correlation between climate/drought vulnerability and soil parameters was relatively low for most parameters. These different correlation powers of single stable predictors, such as geology, geomorphology and farming systems, were overall superior to the more dynamic predictors such as climate and drought vulnerability in explaining the spatial variability of soil parameters in Uganda. The more stable predictors were based on variables that were, in addition, more easily available as GIS maps for the whole of Uganda. In contrast, for climatic variables, one must rely on sparsely distributed meteorological stations.

The established spatial soils data base, the information on dominant factors determining soil quality and the soil redistribution patterns can help agronomists, policy makers and agricultural extension services to better target soil management strategies to the prevailing regional soil quality, especially taking soil organic matter into account, as a major constituent of soil quality. The use of these data and findings may also considerable reduce the efforts and costs of future soil surveys in Uganda.

7.1.3 Hillslope-scale spatial variability of soils

This hillslope-scale study was undertaken to investigate soil variability within landscapes. At this spatial scale, where farmers cultivate many small fields, spatial variability of soils was expected to be different from the national-scale patterns. The knowledge of the spatial distribution, the spatial patterns, the spatial structure and the dominant environmental factors determining soil spatial variability may be important for farmer communities and agricultural extension services, to tailor appropriate soil improvements to precise locations within landscapes.

Two hillslopes were selected for detailed soil variability studies from the national-scale sampling frame. These hillslopes, Kongta and Magada, represent landscapes within the densely populated areas of the eastern highlands and the Lake Victoria Region in Uganda, respectively. On both hillslopes soil resources are being rapidly degraded. However, due to the differing geographic positions, natural conditions such as climate, soil types, terrain, land use and land management are different between these hillslopes and may have an impact on the spatial variability of soils.

The analysis of the total variability of soil parameters on hillslope-scale revealed that the Kongta site, representing the eastern highlands soils (stratification domain #15), had generally more favorable conditions for crop cultivation than the marginal Magada site, which represented the lowland soils within the Lake Victoria Crescent (stratification domain #1) (Figure 3.4). This soil quality assessment was based on indicators that were evaluated against critical soil fertility levels of Foster (1971). For example the average SOM content reaches 5% in Kongta, compared to 3% in Magada. Furthermore, P, K, Ca in Kongta (41, 73, 113 mg/kg, respectively) had more than ten, four and three times the average levels than in Magada (3, 19, 45 mg/kg, respectively). Although some of the soil parameters exhibited a wide range between minimum and maximum values within each site, the identified soil quality classification holds, because most of the soil parameters in Kongta were much higher, while most of the corresponding parameters in Magada were at or below these critical levels. This soil quality classification can be used together with the information on the environmental and socio-economic conditions within these two domains (Table 3.2, Figures 3.2, 3.3) to improve soil fertility management. For example, to further improve crop yields in Kongta chemical fertilizer strategies may take advantage of the better market access of this area to nearby Kenyan markets (Kaizzi, 2002). On the contrary, strategies to improve crop production on the more marginal areas such as in Magada might consider strengthening organic fertilizer strategies using the more continuous rainfall distribution and favorable temperature potential within the Lake Victoria basin (Kaizzi and Wortmann, 2001; Esilaba, et al., 2002).

Each hillslope was delineated into coarser landscape units and more detailed landscape elements to test the influence of these terrain zones on the spatial variability of soils over these two sites. This delineation is based on the fundamental hillslope classification concept of Ruhe (1960), which states that similarly shaped hillslopes have similar spatial soil variability. Ruhe´s hillslopes had one ideal geometric shape over the whole spatial extent of the hillslope unlike the Kongta and Magada sites, which were more complex. Ruhe´s procedure was therefore applied to different zones within each hillslope and respective soil variability was studied within and between zones. The delineation of landscape units was based on slope gradient and upslope contributing area as terrain parameters that may usually represent major lateral pedological and hydrological processes on hillslopes. The landscape elements were separated using plan and profile curvature terrain parameters. Different threshold levels of these factors were applied on the assumption that the resulting zones represent areas with distinct processes that determine spatial variability of soils. The possible range of these threshold levels was based on published information, but the settings of these levels were adjusted to the specific terrain conditions in Kongta and Magada. Threshold values would need to be adjusted further if this approach would be extended to the very gentle hillslopes with low slope gradients in the northern part of Uganda.

The Kongta hillslope was delineated in a backslope and a footslope landscape unit. Further landscape units, such as an interfluve and a shoulder were not present. Kongta is located at the bottom of the Mount Elgon footslopes where these landscape units have not yet developed. The spatial variation of SOM and Ca in Kongta showed a catenary soil distribution over the hillslope. Other studied soil parameters did not follow this pattern. Magada comprised of a shoulder, backslope and footslope landscape unit.

The interfluve was only partly delineated in Magada due to the limited DGPS survey coverage within the hilltop that was covered by dense tree canopies. All soil parameters in Magada followed a catenary sequence. For a better representation of the spatial variability of soils in Kongta as well as in Magada, the hillslopes were subdivided into more detailed landscape elements. In Kongta this hillslope delineation resulted in a sequence of a divergent shoulder, convergent backslope, divergent backslope and convergent footslope. In Magada, the landscape elements included a divergent shoulder, divergent backslope and convergent footslope, convergent shoulder, convergent backslope and convergent footslope. At both sites, a catenary sequence of pH, SOM, P, K and clay in these landscape elements could be clearly recognized. This larger variation of landscape elements seemed to capture the terrain processes that determine spatial variability of soils better than the landscape units.

The demarcation of the hillslopes into landscape elements is relatively straightforward and can be performed by farmers and extension services directly in the field. In Magada, farmers were assistet in delineating and characterizing soil units and the spatial extent of erosion and sedimentation processes on the hillslope. The complete method description and the results of this participatory mapping are reported at Ruecker and Brunner (2001) and examples are shown in Figure 7.1.

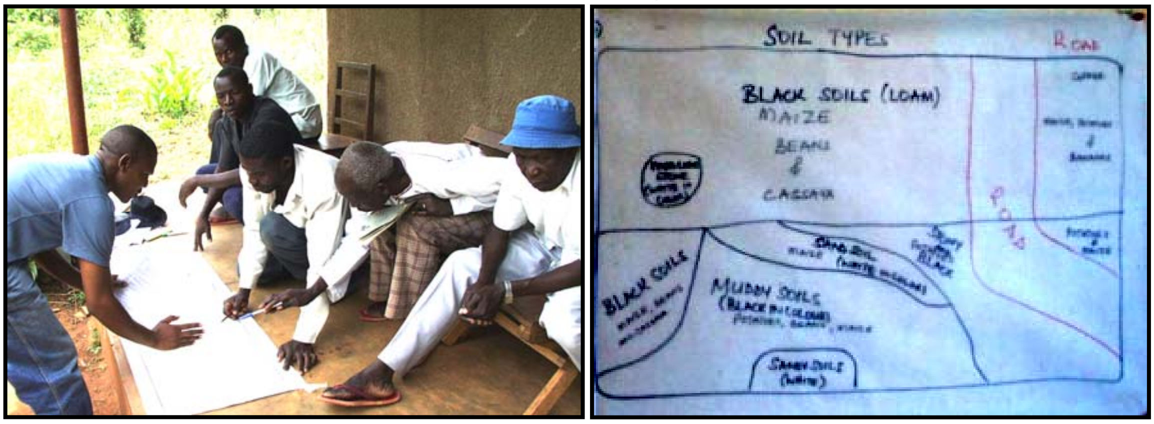

Figure 7.1: Participatory hillslope mapping and resulting spatial distribution map of soil types on one hillslope section in Magada

The resulting maps were largely in agreement with the applied scientific zonation and detailed soil profile investigations (Brunner, 2003) showing soil parameters similarly distributed in hillslope zones. This participatory method may be further refined to guide farmers in the identification of landscape elements. Agricultural extension services and farmers could use this approach for identifying the spatial patterns of soils in order to develop soil fertility improvement and soil and water conservation strategies that are best suited to improve soil quality in the different landscape elements.

The more mobile soil parameters, such as soil pH, clay, P, SOM, and K showed a much more scattered semivariance in Magada than the stable soil parameters, such as sand, silt and Ca. However, just the opposite was found in Kongta with generally more stable soil parameters showing more scattered semivariance than the more mobile parameters. This contradiction was assumed to be caused by local conditions, such as the different interactions of topography, land use and land management that have determined these spatial structure patterns.

The spatial patterns of the soil parameters pH, P, Ca, sand, clay and A-horizon thickness in Kongta and Magada showed a series of contour bands along the elevation gradients stretching from upslope to footslope. The patterns of SOM and K are more scattered. The values of pH, Ca, K and clay are higher in the upper slope positions, whereas sand has lower values there. Highest P and lowest A-horizon thickness values were found in the midslope position. Lower pH, Ca, K, clay and higher sand and SOM values were characteristic for the footslope position.

Terrain had the strongest power to explain the spatial variability of most of the soil parameters on both hillslopes, accounting for ca. 35% and 41%, respectively of the variability in pH in Kongta and Magada. These were for SOM in Kongta (ca. 38%), Ca in Kongta and Magada (ca. 39% and 35%, respectively), sand in Magada (ca. 39%), clay in Kongta and Magada (ca. 20% and 48%, respectively) and A-horizon thickness in Magada (ca. 27%). Land management explained the spatial variability for SOM in Magada (ca. 31%), P in Kongta and Magada (15% and 8%, respectively), K in Kongta (ca. 24%), sand in Kongta (ca. 10%) and A-horizon thickness in Kongta (ca. 10%). Land use played a role in explaining K variability in Magada (ca. 22%).

This dominance of terrain in explaining the spatial variability of many soil parameters was mainly caused by different slope gradients, upslope contributing areas and by different geometric shapes of landscape elements that in turn influence pedohydrological processes. In the case of the spatial variability of SOM, higher values were found in several steeper slope sections, where usually more intensive erosion is expected to reduce topsoil and SOM content. However, stonelines in Kongta and selectively maintained bushes and trees in Magada may have interfered with erosion processes and seem to have provided input to the SOM at these sites. Vegetation and stoneline structures that are positioned within landscape elements where specific soil degradation processes, such as erosion, usually occur may be promising strategies for maintaining soil quality at these locations. In fact, these affect the entire hillslope.

The identification of the spatial landscape elements, the corresponding spatial patterns of soils and the pedological determining factors and processes may help farmers, agricultural extension services and researchers to design integrated nutrient management and soil and water conservation strategies targeted to landscape elements on a hillslope (Ruecker et al., 2003). These stakeholders can be taught to inventory their own landscapes to this end. This spatially explicit landscape management may thus facilitate better utilization of available soil nutrient stocks and application of additional nutrients to plots within landscape elements based on the respective pedological factors and processes (Dumanski and Craswell, 1996; Ruecker et al., 2001).

7.1.4 Hillslope-scale soil redistribution processes and rates

For this study the suitability of the ^{137}Cs approach to estimate soil erosion and sedimentation was tested on the Kongta and Magada hillslopes sites in Uganda. The selected sites were representative areas for the humid tropics of Africa where this approach has not yet been applied to date. Based on the potential usefulness of this approach, the spatial distribution of mid-term erosion and sedimentation rates and corresponding patterns were estimated. Furthermore the main processes determining these soil erosion rates and patterns and the underlying factors that have been determining these processes in specific landscape positions were elaborated.

Mean ^{137}Cs values on these hillslopes were 200 and 380 Bq/m^2, for Kongta and Magada, respectively. The mean error of the ^{137}Cs measurements was relatively high at ca. 20%. However, using these values to estimate the soil redistribution over the hillslopes by mass balance models provided rates, which were within the range of other soil erosion studies on the same hillslope or within the same region (Zake and Nkwiine, 1995; Mati, 1999; Brunner et al., 2003). Therefore, it was concluded that these values and the error are acceptable for soil redistribution estimations on these hillslopes.

The soil losses were estimated to be four times higher in Kongta than in Magada (21 t/ha/yr and 4.5 t/ha/yr, respectively). The soil erosion and sedimentation patterns in these sites closely followed the sequence of landscape units, which broadly changed with higher and lower slope gradients. The more detailed pattern followed the sequence of landscape elements, as a result of changes in profile and plan curvature. Thus, major soil losses in Kongta were on the upper convergent backslope (15 – 20 t/ha/yr), on the middle and lower convergent backslope (25 – 45 t/ha/yr) and the lower part of the divergent backslope (30 – 45 t/ha/yr). Soil sedimentation was in Kongta marginal and occurred only in a small area in the middle part of the divergent backslope (5 – 10 t/ha/yr). Higher soil erosion appeared in Magada on the upper divergent shoulder (12 – 25 t/ha/yr), the convergent backslope area (20 – 35 t/ha/yr) and the convergent footslope (8 – 19 t/ha/yr). The highest soil sedimentation occurred in Magada on the upper divergent backslope (17 - 27 t/ha/yr).

This hillslope separation into landscape elements may be used as a preliminary assessment of soil erosion and sedimentation patterns. However, transect-based estimations revealed the impact of different processes on the spatial redistribution rates. High soil losses by tillage processes were found in the upper convergent and the upper divergent backslope of Kongta (28 and 34 t/ha/yr, respectively) as well as in the upper divergent shoulder of Magada (8 and 27 t/ha/yr). These losses were most likely due to soil removal by house construction and several decades of intensive cultivation. In contrast, water processes at both sites produced a greater range of soil redistribution rates and the spatial patterns along transects were more disaggregated than those generated by tillage processes. The sedimentation pattern in Kongta seemed to be a result of the impact of stonelines in this area. These stonelines might have led to soil accumulation from upslope resulting in a smoothed slope gradient and higher ^{137}Cs inventory in this area. In Magada, the sedimentation patterns seemed to be related to the presence of thick bushes and trees in these areas, which may have reduced the impact of run-off water on soil removal. On the footslope soil loss was indicated at both sites. It was assumed that soil, which has been eroded from upslope, and temporally sedimented on the footslope, was transported out of the hillslope system by occasional river floods. Overall, the upper hillslope parts were mainly characterized by soil loss due to tillage, the middle hillslope parts lost soil by water erosion, but partly accumulated soil due to bushes, trees and stonelines, while the footslopes lost soil by river floods.

These findings demonstrate that the ^{137}Cs approach was successful for soil redistribution studies on the study hillslopes. An application of this approach to other areas of the humid tropics of Africa may be possible, provided that suitable ^{137}Cs reference inventories can be identified. Compared to traditional soil erosion technologies, e.g. run-off plots, that may require time-consuming observations and several expensive constructions to capture the spatially distributed soil redistribution over hillslopes, the strength of the ^{137}Cs technology is that only one field trip is necessary to collect relatively few soil samples for estimating mid-term soil erosion and sedimentation rates and processes over the same spatial extent.

7.2 Conclusions

The national-scale stratification was useful to classify Uganda, a complex area with heterogeneous natural resource and socio-economic conditions influencing soil quality into larger spatial domains. Based on this stratification representative communities and hillslopes for national-scale research on soil spatial variability could be selected. This national-scale investigation revealed the overriding influence of geology and geomorphology in explaining the spatial variability of most soil quality parameters. Land use, land management and climate factors played secondary roles. Combining all predictors together, the explanatory powers ranked from highest to lowest prediction were: Silt (58%) > SOM (54%) > sand (52%) > clay (43%) > P (37%) > K (33%) > Ca (23%) > pH (22%). The spatial interpolation GIS-maps clearly revealed Uganda´s regional soil disparities, thus highlight deficient, nearly deficient and favorable soil quality areas. Planners and policy makers can use these maps to focus soil improvement programs on specific soil regions in Uganda.

On the hillslope-scale, terrain, as a composite of various land qualities, was the dominant factor explaining the spatial variability of most of soil parameters in the selected sites, comprising Kongta in the highlands and Magada in the lowlands. The factors land use and land management could explain mainly the spatial distribution of SOM and soil nutrients. The land management structures of bush and tree vegetation in Magada and the stonelines in Kongta were found to affect, in specific areas, much of the

SOM and the textural patterns. The prediction powers of the combined variables for different soil parameters were for Kongta and Magada, respectively pH (37%, 41%), SOM (41%, 42%), P (24%, 9%), K (27%, 27%), Ca (42%, 41%), sand (16%, 43%), clay (36%, 50%), A-horizon thickness (8%, 31%).

The ^{137}Cs approach for spatially distributed estimations of erosion and sedimentation rates was found to provide realistic results, thus may be considered a promising method for soil redistribution studies in other areas of the humid tropics of Africa. The estimated soil redistribution rates were -21 and -4.5 t/ha/yr for Kongta and Magada, respectively. The spatial patterns of soil redistribution rates follow easily discernable landscape elements that are characterized by terrain factors, whereas the bush vegetation and the stonelines caused sedimentation locally.

Overall, this study showed the dominant influence of geomorphology on national-scale and of terrain and land management on the hillslope-scale in determining the spatial variability of soils in Uganda. The importance of land management points to opportunities for influencing future developments of soils in the region using management techniques that are tailored to the characteristics of the landscape elements. With some experience or training, these elements are easily discernable in the field.

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9 APPENDICES

Appendix 1: Spatial distribution of some national-scale environmental variables

The maps of the stratification of Uganda (chapter 3) and the following maps were applied for the national-scale environmental correlation of soil parameters (chapter 4).

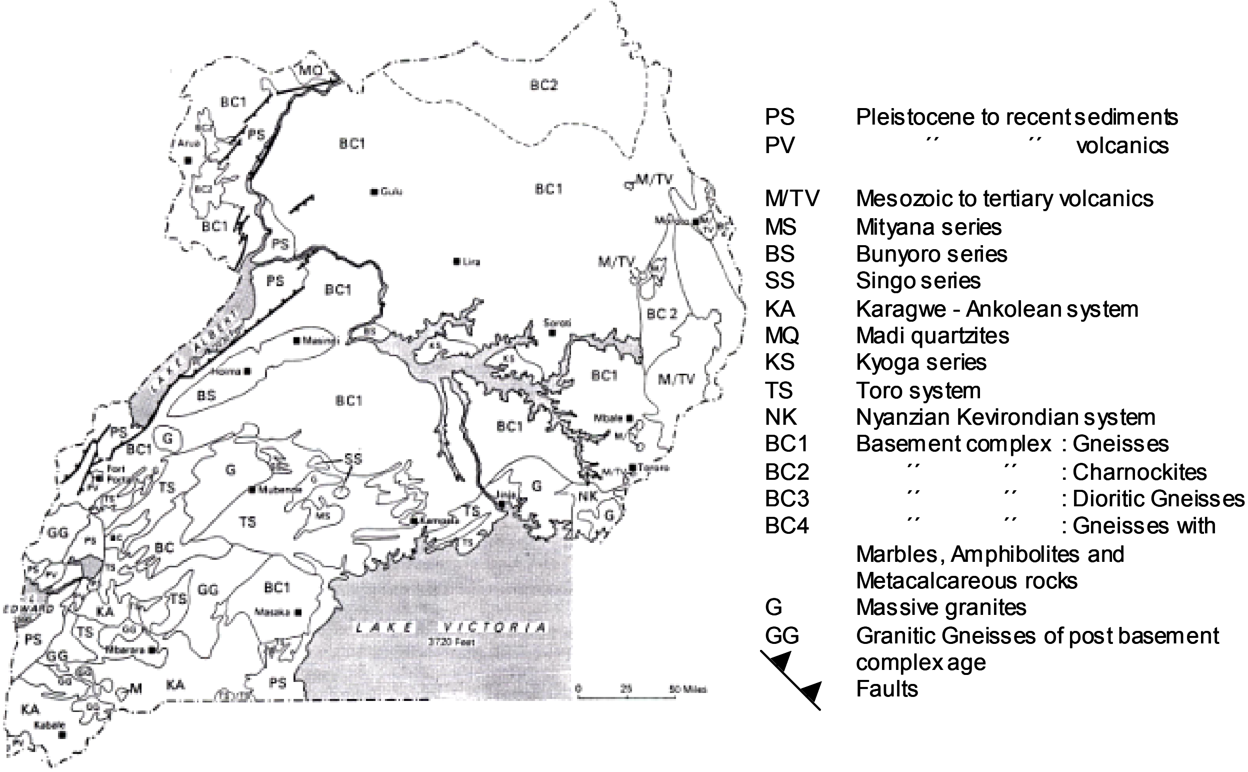

Figure 9.1: Geomorphology of Uganda (modified after Harrop, 1970)

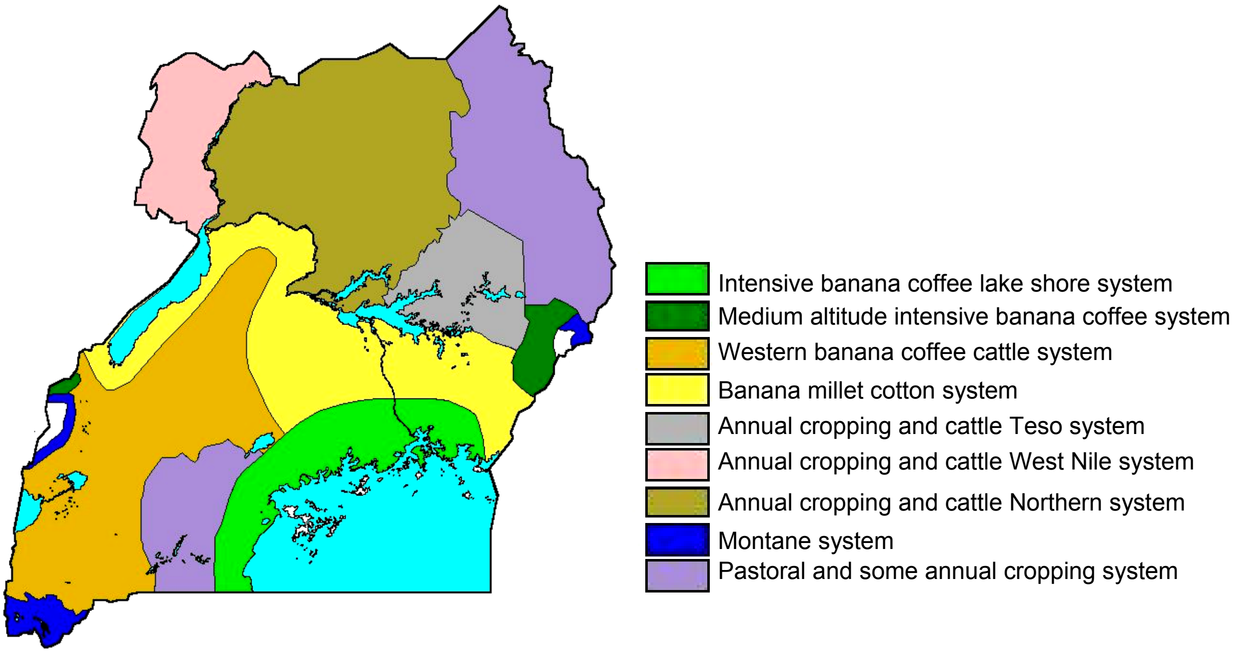

Figure 9.2: Farming systems of Uganda (after Parsons, 1960)

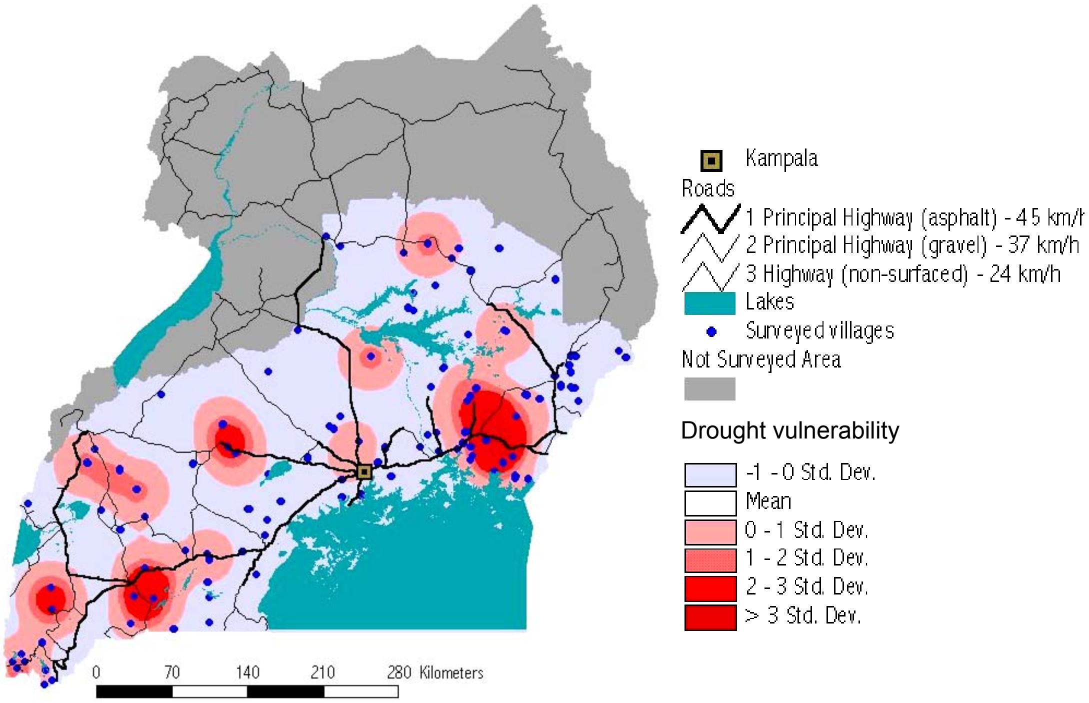

Figure 9.3: Drought vulnerability in Uganda

Note: High positive standard deviations indicate high, while high negative standard deviations indicate low drought vulnerability

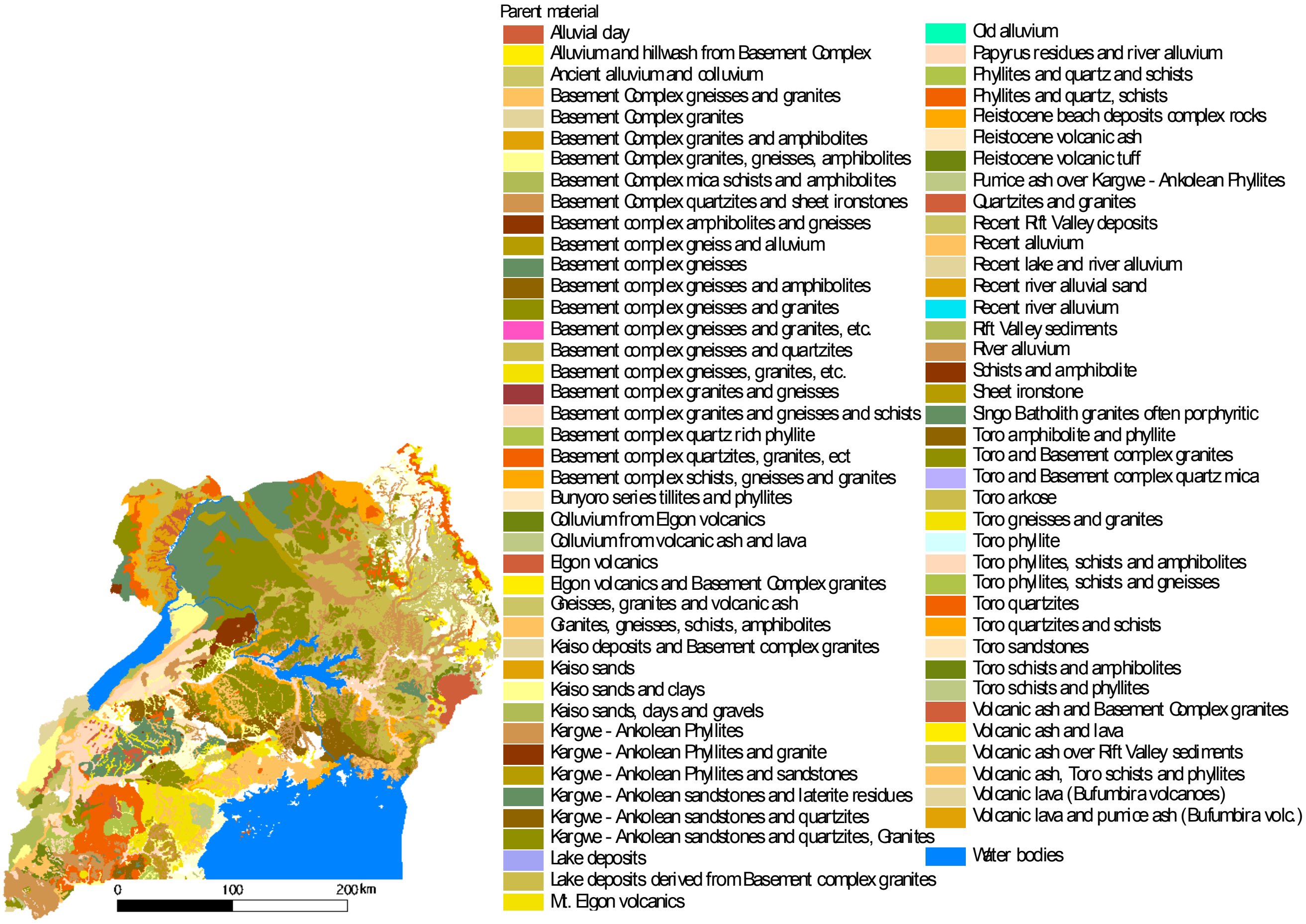

Figure 9.4: Parent material in Uganda (modified after Chenery, 1960)

Appendix 2: Description of ancillary parameters for ^{137}Cs mass balance models

- **Temporal distribution pattern of ^{137}Cs fallout.** It characterizes the global amount of ^{137}Cs fallout that was deposited in the northern hemisphere from 1954 to 1988 (Cambray et al., 1989);
- **Proportional factor (y)**, representing the proportion of ^{137}Cs receipts that are removed in runoff before incorporation in the plough layer. Max value of 1.0 in the hypothetical case of all erosive rainfall occurring immediately prior to tillage. In practice, it can be estimated as the proportion of annual erosive rainfall. This value was set to 0.7 to reflect high intensity rainfall events as occurring in the study sites (Schuller et al., 2003);
- **Relaxation mass depth (H)** is the depth to which ^{137}Cs initially infiltrates when first delivered to the soils surface. It is expressed as mass depth (kg/m^2). According to He and Walling (1997) empirical values of H are 3.8 kg/m^2 for cultivated soil, which has been adopted for this study;
- **Mass depth of the plough layer**. Tillage in Magada is performed by hand hoe, which penetrates ca. 0.12 m into the soil. The average density of soil in the plough layer is 982 kg/m^3. In Kongta ox-ploughs are used for tilling, thus tillage depth amounts to ca. 0.18 m and average density of soil in the plough layer is 855 kg/m^3. The mass depth of the plough layer is estimated as the product of tillage depth and soil density, 118 kg/m^2 and 154 kg/m^2 for Magada and Kongta, respectively;
- **Tillage constant** varies with type of tillage and was set to 50 to account for hand hoe tillage in Magada and to 100 to represent ox-plough tillage in Kongta;
- **Particle size correction factor (P)** recognizes preferential entrainment and deposition of particles dependent on their size, and is a function of the soil textures. Given the restricted range of soil textures in the study sites, and the empirical observation, that in situ soils and colluvium have essentially the same textures, this factor is not considered relevant, and has been set to unity.
- **Length of slope transect segment incorporating the sample point (m);**
- **Input and output angles to and from that slope segment (°);** (description of the latter two parametes are in Appendix 4).

Appendix 3: Description of ^{137}Cs "mass balance model 2" equations

In this model, a sampling point with a total ^{137}Cs inventory A (Bq/m^2) less than the local reference inventory A_{ref} (Bq/m^2) is assumed to be an eroding site, while a point with a total ^{137}Cs inventory greater than the local reference inventory is assumed to be a depositional site. *For an eroding point* ($A(t) < A_{ref}$), the change in the total ^{137}Cs inventory $A(t)$ with time can be expressed as:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) - (\lambda + P\frac{R}{d})A(t) \tag{1}$$

where:

$A(t)$ = cumulative ^{137}Cs inventory per unit area (Bq/m^2);

R = erosion rate (kg/m^2/yr);

D = cumulative mass depth representing the average plough depth (kg/m^2);

λ = decay constant for ^{137}Cs (1/yr);

$I(t)$ = annual ^{137}Cs deposition flux (Bq/m^2/yr);

Γ = percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer;

P = particle size correction factor.

Considering an exponential distribution for initial ^{137}Cs fallout distribution at the surface of the soil profile (He and Walling, 1997), Γ can be represented as:

$$\Gamma = P\gamma(1-e^{-R/H}) \tag{2}$$

where γ is the proportion of the annual ^{137}Cs input susceptible to removal by erosion, and H (kg/m^2) is the relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile. Because the deposition of ^{137}Cs from the atmosphere is primarily associated with wet precipitation, a fraction of the annual ^{137}Cs input may be removed from the soil surface by water erosion associated with surface runoff before being incorporated into the plough layer by cultivation. γ is therefore dependent on the timing of cultivation and the temporal patterns of the local rainfall regime and has a maximum value of 1.0. Let t_0 (yr) be the year when cultivation started, from Equations 1 and 2, the total ^{137}Cs inventory $A(t)$ at year t can be expressed as:

$$A(t) = A(t_0)e^{-(PR/d+\lambda)(t-t_0)} + \int_{t_0}^{t}(1-P\gamma(1-e^{-R/H}))I(t')e^{-(PR/d+\lambda)(t-t')}dt' \tag{3}$$

where $A(t_0)$ (Bq/m^2) is the ^{137}Cs inventory at t_0 (yr):

$$A(t_0) = \int_{1954}^{t_0} I(t')e^{-\lambda(t'-t_0)}dt' \tag{4}$$

The erosion rate R can be estimated by solving Equation 3 numerically, when the ^{137}Cs deposition flux and values of the relevant parameters are known. The ^{137}Cs concentration of mobilised sediment $C_e(t')$ can be expressed as:

$$C_e(t') = \frac{I(t')}{R}P\gamma(1-e^{-R/H}) + P\frac{A(t')}{d} \tag{5}$$

For a depositional point ($A(t) > A_{ref}$), assuming that the excess ^{137}Cs inventory A_{ex} (Bq/m^2) (defined as the measured total inventory $A(t)$ less the local direct fallout input A_{ref}) at an aggrading point is due to the accumulation of ^{137}Cs associated with deposited sediment, the excess ^{137}Cs inventory can be expressed as:

$$A_{ex} = \int_{t_0}^{t} R'C_d(t')e^{-\lambda(t-t')}dt' \tag{6}$$

where R' (kg/m^2/yr) is the deposition rate and $C_d(t')$ (Bq/kg) is the ^{137}Cs concentration of deposited sediment. $C_d(t')$ reflects the effect of the sediment and its associated ^{137}Cs concentration mobilised from all the eroding areas that converge on the aggregation point. $C_d(t')$ comprises two components, the first of which is associated with the removal of the freshly deposited ^{137}Cs, and the second is associated with erosion of the accumulated ^{137}Cs stored in the soil. Again, $C_d(t')$ can be estimated from the ^{137}Cs concentrations of the mobilised sediment from the upslope eroding area S:

$$C_d(t') = \frac{1}{\int_S RdS}\int_S P'C_e(t')RdS \tag{7}$$

From Equations 6 and 7, the mean soil *deposition rate R′* can be calculated:

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}dt'} \tag{8}$$

Appendix 4: Description of ^{137}Cs “mass balance model 3” equations

This model represent the most complex equations of the series of mass balance models, because it includes in addition to soil redistribution by water erosion also soil translocation by tillage processes.

The influence of tillage in redistributing soil may be represented by a downslope sediment flux F_Q (kg m^{-1} yr^{-1}) from a unit contour length. That sediment flux may be expressed as

$$F_Q = \phi \sin \beta \tag{9}$$

where β (°) is the steepest slope angle, and ϕ (kg/m/yr) is a constant.

Considering a flow line down a slope that is divided into several sections, then for the ith section (from the hilltop), the net soil redistribution induced by tillage R_t (kg/m^2/yr) can be described as:

$$R_t = R_{t,out} - R_{t,in} = (F_{Q,out} - F_{Q,in}) / L_i = \phi(\sin \beta_i - \sin \beta_{i-1}) / L_i \tag{10}$$

where $R_{t,out}$ (kg/m^2/yr) and $R_{t,in}$ (kg/m^2/yr) are net tillage output and input, respectively. $F_{Q,out}$ and $F_{Q,in}$ represents sediment lost and gained, respectively form section i. L_i (m) is the slope length of the ith segment, ϕ is a constant and β_{i-1} is input slope angle, whereas β_i is output slope angle (in °) (Figure 9.5).

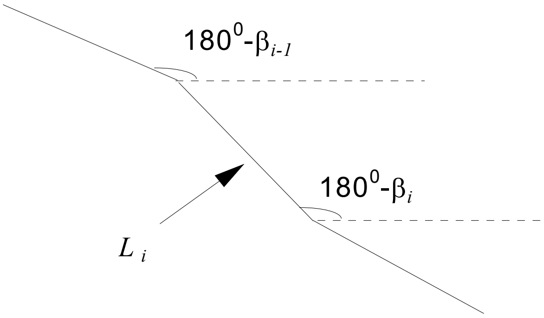

Figure 9.5: Part of slope transect with section L_i, input angle β_{i-1} and output angle β_i (modified after Walling and He, 2001).

The constant ϕ can be estimated from the erosion rate $R_{t,out,1}$ for an eroding point from the first segment at the hilltop, assuming water erosion can be neglected and there is no tillage input into that point:

$$\phi = \frac{R_{t,out,1} L_1}{\sin \beta_1} = \frac{R_1 L_1}{\sin \beta_1} \tag{11}$$

The necessary R_1 value can be calculated from the measured total ^{137}Cs inventory $A_1(t)$ of that point according to:

$$A_1(t) = A_1(t_0) e^{-(R_1/d+\lambda)(t-t_0)} + \int_{t_0}^{t} I(t') e^{-(R_1/d+\lambda)(t-t')} dt' \tag{12}$$

For a point experiencing water erosion R_w, change of total ^{137}Cs inventory $A(t)$ with time t can be expressed as:

$$\frac{dA(t)}{dt} = (1-\Gamma) I(t) + R_{t,in} C_{t,in}(t) - R_{t,out} C_{t,out}(t) - R_w C_{w,out}(t) - \lambda A(t) \tag{13}$$

where Γ is the proportion of ^{137}Cs that is removed by rainfall prior to incorporation into the plough layer. It can be expressed as:

$$\Gamma = P\gamma(1 - e^{-R/H}) \tag{14}$$

where P is particle size correction factor, γ is proportion of annual ^{137}Cs input susceptible to pre-tillage removal, and H is cumulative mass depth of initial ^{137}Cs infiltration (kg/m^2).

$C_{t,in}$, $C_{t,out}$ and $C_{w,out}$ are the ^{137}Cs concentrations of the sediment associated with tillage input, tillage output and water output respectively. R_w is water erosion rate. The net erosion rate R (kg/m^2/yr) is:

$$R = R_{t,out} - R_{t,in} + R_w \tag{15}$$

For a point experiencing deposition from water induced processes (rate R'_w, (kg/m^2/yr)), change of the total ^{137}Cs inventory with time may be expressed as:

$$\frac{dA(t)}{dt} = I(t) + R_{t,in} C_{t,in}(t) - R_{t,out} C_{t,out}(t) + R'_w C_{w,in}(t) - \lambda A(t) \tag{16}$$

where $C_{w,in}$ (Bq/kg) is the ^{137}Cs concentration of the sediment input from water-induced deposition. The net erosion rate R is:

$$R = R_{t,out} - R_{t,in} - R'_w \tag{17}$$

The ^{137}Cs concentration of the soil within the plough layer $C_s(t')$ (Bq/kg) can be expressed for a net erosion site as:

$$C_s(t') = \frac{A(t')}{d} \tag{18}$$

and for a net depositional site as:

$$C_s(t') = \frac{1}{d}[A(t') - \frac{|R|}{d}\int_{t_0}^{t-1} A(t'')e^{-\lambda t''}dt''] \tag{19}$$

where $|R|$ ($R<0$) is the net deposition rate. The relationships between C_s and $C_{t,in}$ and $C_{t,out}$ are as follows:

$$C_{t,in}(t') = C_{t,out}(t') = C_s(t') \tag{20}$$

The concentration of ^{137}Cs in water eroded sediment $C_{w,out}(t')$ in Bq/kg can be expressed as:

$$C_{w,out}(t') = PC_s(t') + \frac{I(t')}{R_w}P\gamma(1 - e^{-R_w/H}) \tag{21}$$

while the ^{137}Cs concentration of water-derived deposited sediment $C_{w,in}(t')$ (Bq/kg) can be expressed as:

$$C_{w,in}(t') = \frac{1}{\int_S RdS}\int_S P'C_{w,out}(t')RdS \tag{22}$$

with S as upslope contributing area.

For a given point, the tillage-induced erosion or deposition can be estimated from equations 10 and 12, wheras the water erosion or deposition rate can be calculated by solving equations 13, 15, 21, and 22.

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