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# Gamma-ray spectrometry as auxiliary information for soil mapping and its application in research for development

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## Summary

Sustainable yield increase is desperately needed for enhancing global food security, in particular, in Sub-Saharan Africa. There population growth and resulting land degradation accompany with extreme weather events. As a consequence, famines frequently occur. For planning result-oriented agricultural research for development (R4D) like in the Trans-Sec project (www.trans-sec.org), in which this thesis was embedded, local environmental, as well as social realities must be taken into account prior to any cropping experiment. Only this way, cost-efficient and adapted solutions for local subsistence farmers, but also conclusive outcomes for researchers, can be obtained. For this purpose, methods that work quick and cost-efficient are a prerequisite.

In this respect, gamma-ray spectrometry as rapid soil survey method is reviewed in the first part of this thesis. Soil or geological exploration are easily accomplishable, in either airborne (with helicopters, airplanes or drones) or proximal (stationary or on-the-go) surveys. Gamma decays of the naturally occurring isotopes 40-potassium ($^{40}K$), 238-uranium ($^{238}U$) and 232-thorium ($^{232}Th$) that appear in sufficient amounts and decay energies for field measurements are counted per time. The counts are then transferred to the respective element contents. Water and soil organic matter attenuate gamma signals, on one hand hampering signal interpretation, on the other hand indirectly enabling soil water content and peat mappings. Gamma-ray signatures of soils depend on (1) mineral composition of the bedrock, as well as (2) weathering intensity and related soil forming processes, that, in turn, influence the environmental fate of $^{40}K$, $^{238}U$ and $^{232}Th$. Hence, due to soil formation heterogeneity at the landscape scale, resulting gamma signatures are locally specific and make soils readily distinguishable.

In two villages in central Tanzania, participatory soil mapping in combination with gamma-ray spectrometry served as rapid and reliable approach to map local soils for later cropping experiments. Local farmers indicated major soil types on satellite images of the village area, which were the basis for further mapping steps. Fingerprint gamma-ray signatures of reference soil profiles were collected. Subsequent gamma-ray surveys on transect walks accelerated soil unit delineation for the final soil map. Challenges were misunderstandings related to language issues, variable soil knowledge of individual farmers and erosion leading to staggered soil profiles and non-distinctive signatures in some places. The combination of indigenous knowledge and gamma-ray spectrometry, nevertheless, led to a quick overview of the study area and made laboratory soil analyses largely redundant.

The gained gamma-ray signal information were further statistically evaluated. For this purpose, distinction of major local soil types via K/Th ratios were graphically and statistically tested. The results showed that gamma-ray spectrometry is a sound method to distinguish certain local clay illuviation soil types by their K/Th ratios.

The last part of the thesis covers the Trans-SEC approach of testing innovations for sustainable agricultural yield increase. Pearl millet (*Pennisetum glaucum* (L.) R.Br.) as the typical staple food in the study region was used as example crop. The process was scientist-led but local farmers selected the innovations that they considered adequate to their needs. Tied ridging for enhancing the water storage and placed fertilizer for increasing fertilizer efficiency was offered for their choice. Transferability of results from on-station experiments and demonstration plots in the village to farmers' plots and trans-disciplinary issues are discussed. The number of factors that influence the result, as well as data insecurity increased with every level of spatial aggregation (on-station, demonstration plot and on-farm plots in the village). Soil type, position of the plot in the landscape (lateral water flow, distance to homesteads and, hence, fertility status) were the major influencing factors. In particular, the data insecurity related to on-farm trials due to low control intensity suggests to only conduct such experiments if large numbers of replicates (large N-trials) are feasible in future approaches.

In conlusion, the thesis shows, that local knowledge combined with modern science is beneficial for agricultural R4D projects. Shortcomings within the transdisciplinary experimental approaches are pointed out. In particular, with respect to knowledge gained from the linkage of local experience and scientific approaches, there is still high potential. For this purpose, social and applied natural sciences should both strive for more interdisciplinary collaboration.

## Zusammenfassung

Eine nachhaltige Steigerung der Erträge zur Verbesserung der globalen Ernährungssicherung ist dringend notwendig, insbesondere in Subsahara-Afrika. Dort gehen starkes Bevölkerungswachstum und daraus resultierende Bodendegradation mit extremen Wetterereignissen einher. Als Folge treten gehäuft Hungersnöte auf. Die Planung ergebnisorientierter landwirtschaftlicher Forschungsprojekte mit Entwicklungsansätzen wie beim Trans-SEC-Projekt (www.trans-sec.org), in das diese Arbeit eingebunden war, erfordert die Berücksichtigung lokaler Umweltbedingungen, aber auch soziokultureller Gegebenheiten vor dem Beginn jeglicher Feldversuche. Erst so ist man in der Lage, kostengünstige, adaptierte Lösungen für ansässige Subsistenzbauern, aber auch aussagefähige Ergebnisse für Forscher zu erzielen. Kostensparende wissenschaftliche Methoden, die zu schnellen und verlässlichen Ergebnissen führen, sind hierzu die Voraussetzung.

Eine solche Methode zur raschen Bodenkartierung, die Gammaspektrometrie, wird im ersten Teil dieser Arbeit vorgestellt. Anwendbarkeit und Grenzen für die bodenkundliche Anwendung werden diskutiert. Bodenkundliche oder geologische Erkundungen sind mit dieser Methode entweder luftgestützt (mit Helikoptern, Flugzeugen oder Drohnen) oder bodengestützt (stationär oder in Bewegung) in kurzer Zeit durchführbar. Gammazerfälle der natürlich vorkommenden Isotope 40-Kalium, 232-Thorium und 238-Uran ($^{40}$K, $^{238}$U und $^{232}$Th), die mit ausreichender Zerfallsenergie und Menge zur Messung im Feld vorkommen, werden pro Zeiteinheit erfasst. Die spezifischen Zählraten werden dann in Elementgehalte umgerechnet. Wasser und organische Bodensubstanz schwächen das Signal, was einerseits Signalinterpretationen erschwert, andererseits indirekt Wassergehalts- und Torfkartierungen ermöglicht. Die Gammasignaturen von Böden hängen von (1) der mineralischen Zusammensetzung des Ausgangsgesteins, sowie (2) der Verwitterungsintensität und den damit verknüpften bodenbildenden Prozessen ab, die wiederum das Umweltverhalten von $^{40}$K, $^{238}$U und $^{232}$Th beeinflussen. Somit sind Gammasignaturen wegen der heterogenen Bodenbildung für lokale Umwelten spezifisch und machen Böden direkt unterscheidbar.

Zur Bodenkartierung zweier Dörfer in Zentraltansania bewährte sich die Kombination aus partizipativer Bodenkartierung und Gammaspektrometrie. Ansässige Landwirte zeichneten die lokal vorkommenden Hauptbodengruppen als Basis für weitere Kartierungsschritte auf hochaufgelösten Satellitenbildern der Gegend ein. Die spezifischen Gammasignaturen von Referenzbodenprofilen wurden gemessen. Die Abgrenzung der Bodeneinheiten für die finale Bodenkarte erfolgte durch Transektkartierung unterstützt durch gammaspektrometrische

Messungen. Unterschiedliche Kenntnisse der ansässigen Landwirte zu den lokalen Böden, sprachliche Unklarheiten, sowie Bodenüberlagerungen aufgrund von Erosion und resultierende schlechter unterscheidbare Bodensignaturen erschwerten den Kartierungsprozess. Der Ansatz führte dennoch zu einem raschen Überblick über das Untersuchungsgebiet und machte aufwändige Laboranalysen der Bodenproben größtenteils überflüssig.

Die gammaspektrometrisch gemessenen K/Th-Verhältnisse der lokal vorkommenden Hauptbodengruppen wurden grafisch und statistisch näher untersucht. Die Ergebnisse zeigten eine gute Unterscheidbarkeit einiger lokal vorkommender Tonverlagerungsböden aufgrund der herangezogenen K/Th-Verhältnisse.

Der letzte Teil der Arbeit behandelt den Trans-SEC Projektansatz zur nachhaltigen Ertragssteigerung. Perlhirse (*Pennisetum glaucum* (L.) R.Br.) wurde als typisches Grundnahrungsmittel im Untersuchungsgebiet für diese Untersuchungen genutzt. Wissenschaftler leiteten den Prozess, die ansässigen Landwirte wählten jedoch die zu testenden Innovationen bzgl. des Feldmanagements, angepasst an ihre Bedürfnisse aus. Als Optionen wurden „tied ridging“ als Maßnahme zur Erhöhung der Wasserspeicherung und „placed fertilizer“ zur Erhöhung der Düngereffizienz angeboten. Die Übertragbarkeit der Versuchsergebnisse einer Versuchsstation mit kontrollierten Bedingungen, auf Demonstrationsflächen im Dorf und Versuchsflächen „on-farm“ unter Aufsicht der Landwirte wird diskutiert. Es zeigte sich, dass die Anzahl der Faktoren, die einen Einfluss auf das Versuchsergebnis haben und die Datenunsicherheit mit jeder räumlichen Aggregierungsebene (Versuchsstation, Demonstrationsfelder und on-farm Felder im Dorf) ansteigen. Als wichtige Faktoren wurden Bodentyp und Position des Versuchsfeldes in der Landschaft (Zuflusswasser, Distanz zu Siedlungen und damit Trophie) identifiziert. Insbesondere die Datenunsicherheit on-farm aufgrund niedriger Kontrollintensität legt nahe, solche Versuche nur durchzuführen wenn große Wiederholungsanzahlen möglich sind (large-N-trials).

Insgesamt zeigt die vorliegende Arbeit, dass die Kombination aus lokalem Wissen und moderner Forschung von Vorteil für landwirtschaftliche Entwicklungsprojekte ist. Schwächen innerhalb der transdisziplinären Versuchsansätze werden aufgezeigt. Gerade hinsichtlich des Wissensgewinns durch Verknüpfung lokalen Wissens mit wissenschaftlichen Ansätzen kann potenziell noch viel getan werden. Hierzu sollte - von beiden Seiten - mehr interdisziplinäre Zusammenarbeit der Sozial- und angewandten Naturwissenschaften angestrebt werden.

# 1. General Introduction

## 1.1. Preamble

Land degradation is incrementally threatening ecosystems. Sub-Saharan Africa's (SSA) subsistence farmers particularly struggle with soil degradation initiated by erosion and nutrient deficiency. Food security, especially in SSA, is directly linked to the agricultural productivity of soils. Climate constraints are further hampering yield stability. To stop further degradation, actions for sustainably enhancing plant performance and yield increase with respect to site amelioration are urgently needed. Thereby, approaches that adapt to farmers' reality and possibilities are indispensable.

Soil properties variability related to soil type and landscape position is complicating the identification of adequate approaches. The World Reference Base for Soil Resources (WRB; IUSS Working Group, 2015), which serves as international soil classification system, already distinguishes 32 Reference Soil Groups according to morphogenetic soil formation. Further distinctions relate to over 120 additional qualifiers. Farmers in the whole world, as well, know very well about the diversity of soils, especially according to fertility and plant performance (Barrera-Bassols and Zinck, 2003).

In consequence, agricultural research for development (R4D) must address specific site conditions, i.e. soil properties, adapted to socio-cultural circumstances. Gamma-ray spectrometry as rapid soil mapping method together with participatory involvement of local farmers revealed an improved approach for soil science in R4D.

## 1.2. Thesis embedment in the project Trans-SEC

The project Trans-SEC (Innovating strategies to safeguard food security using technology and knowledge transfer: a people-centred approach), in which this thesis was embedded, aimed at safeguarding food security by means of scientific and participatory approaches in two regions in rural Tanzania, i.e. the semi-arid Dodoma region and the sub-humid Morogoro region The project was funded by the initiative "Securing the Global Food Supply – GlobE" in the framework program "National Research Strategy BioEconomy 2030". The project approach was covering the whole food value chain, from primary production to consumption, and the involvement of local people for participatory research.

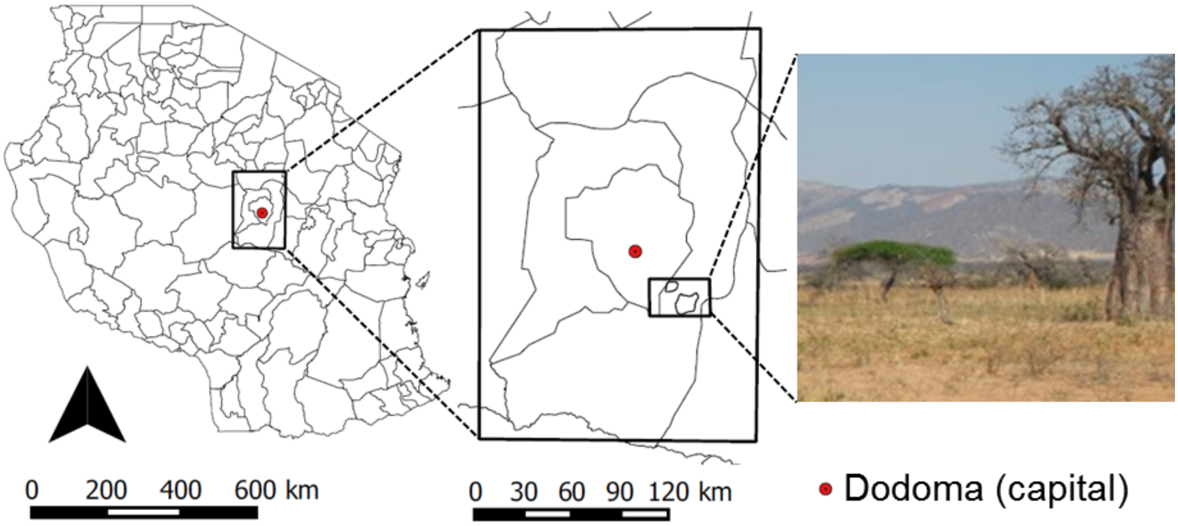


**Figure 1-1** Study area (QGIS Lyon, Version 2.12; own photo)

Addressed food value chain sectors were natural resources, food production, processing, waste management, markets and consumption. The project followed an action research approach involving the key stakeholders, i.e. farmers and farmers' organizations, governmental and non-governmental organizations, research institutes, and dedicated researchers. Seven German research institutes[a], five Tanzanian institutions[b] and two CGIAR (Consultative Group on International Agricultural Research) centers[c] were involved.

This thesis deals with the sector of natural resources in the semi-arid region (Figure 1-1), in particular soils related to crop production. Data collection and field work were carried out in the dry seasons from 2013 to 2016.

## 1.3. The history of land degradation and its prevention attempts in central Tanzania

Land degradation is characterized by loss of soil-related ecosystem services. Origins of degrading soils are mainly anthropogenic, either indirectly due to climate change or with direct impact from overpopulation.

[a] Leibniz-Centre for Agricultural Landscape Research (ZALF), University of Hohenheim, Leibniz University Hannover, Humboldt University Berlin, German Development Institute (DIE), Potsdam Institute for Climate Impact Research (PIK) and German Institute for Tropical and Subtropical Agriculture (DITSL)

[b] Sokoine University of Agriculture (SUA), Agricultural Research Institutes (ARI), Tanzania Federation of Cooperatives (TFC), Agricultural Council of Tanzania (ACT) and a network of small-scale farmers' groups (MVIWATA)

[c] International Food Policy Research Institute (IFPRI; USA) and the International Centre for Research in Agroforestry (ICRAF; Kenya)

First noted erosion measurements were carried out in 1933 in central Tanzania (Staples, 1934). Already those times, erosion cause was identified to be loss of vegetation cover by overgrazing which even got worse, when herd density per area increased along with population growth. Successively, decreasing arable land area along with decreasing yields due to land degradation and less water retention capacity of soils arose.

During the colonial era during the 1940s, soil conservation measures like ridging, contouring, gully control, rotational grazing and reforestation were undertaken to prevent erosion (Kalineza et al., 1999). Unfortunately, the conserving measures were used for punishing the disobedience against chiefs and tax evasion, leading to negative associations with land conservation. Colonialists often did not accept existing local erosion prevention systems and forced people to adapt to the "imported" ones. This mainly contributed to their abandonment after Tanzania's independence in 1961 (Mbegu and Mlenge, 1984, in Eriksson et al. 2000). From then on, soil conservation and erosion prevention was seen as "nasty colonial habit" and was no longer promoted by politicians until the 1970s (Holtland, 2007).

Free grazing of cattle was regarded as a major reason for soil degradation. During the Hifadhi Ardhi Dodoma (HADO) program near Mvumi Mission, where this study was located, in 1986 (Lamboll, 2000), people were forced to evict their herds from village terrains. Holtland (2007) studied the background of HADO. He reported more than 100.000 cattle were banned from 2.000 $km^2$ bearing over 100.000 inhabitants. He described the HADO destocking as "traumatic experience" as the livelihood of the local people depended on livestock keeping. Loss of many cattle due to mismanagement and great distances between cattle and village area were throwing back farmers. Nevertheless, destocking resulted in regeneration of vegetation cover. HADO together with population pressure led to a higher share of cropping in the area.

One solution for yield increase in agriculture that performed adequately in Asia and South America, the Green Revolution in the 1960s and 70s, bypassed Africa. The following aspects might account for its failure:

- High yielding varieties, needing high fertilizer inputs and irrigation, are not adapted to the old, nutrient poor soils in most parts of Africa in contrast to rather fertile soils in e.g. Asia.

- Local farmers cannot afford the high inputs of mineral fertilizer, also due to the risk of losing everything related to droughts, weather events or pests, next to low accessibility of adequate fertilizer.
- Soils in parts of Africa might not even respond to mineral fertilizing, e.g. due to high sand contents not being able to hold back nutrients.
- Hybrid plants are not adapted to local circumstances and might react extremely sensitive.

### 1.4. Actual situation of rural subsistence farmers in central Tanzania

Despite shifting from herding to cropping, land degradation, nowadays, has remained enormous and is still going on. The pressure on natural resources is expected to further increase (FAO, 2009), especially in Africa, where, according to the United Nations (2017), 16% of the world's population lives (1.2 billion). This number is expected to increase to over 50% until 2050.

Still, overgrazing is a prominent issue. More people have more cattle – on the one hand for food, i.e. dairy products or meat, on the other hand as capital to safeguard their families in times of financial shortages. More animals need more fodder, the stocking rate gets too high for low-productive soils, and bare soil is the result making the land susceptible to wind and water erosion (Holtland, 2007).

Besides, land clearing from deforestation occurs as more people require more food, and hence, expansion of agricultural land to feed the growing population is needed. Often the last forests to cut for adding cropland are located on steep slopes (Biamah, 2005). Erosion makes this "additional cropland" useless for agriculture within few years, if not even within months. Top soils including organic matter are either blown or washed away, fertility status of soils further decreases.

As land resources run scarce, fallow periods of agricultural fields become shorter or are even omitted (Holtland, 2007) with the consequence of soil fertility decline (Osbahr and Allan, 2003). Input of organic matter and land regeneration drops out not only because of missing fallow, but also due to removing harvest residues, and hence, soil nutrient status as well as soil structure stability decreases. This, again, leads to increased erosion susceptibility (Blume et al., 2002). Decomposition rates of organic matter in the tropics and subtropics are accelerated by climatic conditions, further decreasing the soil organic matter stock. Consequently, cation exchange capacity declines, especially in sandy soils, and consequently, soil nutrients progressively leach.

Mineral fertilizer is expensive, especially in SSA. Crop failure due to droughts or crop pests is probable, and so is investment loss. In consequence, subsistence farmers cannot invest their rare financial capital in fertilizer. Next to un-affordability, fertilizer accessibility is bad due to inadequate market access and infrastructure in rural central Tanzania.

### 1.5. Soil heterogeneity vs. blanket fertilizer recommendations

For decades, fertilizer recommendations have been set as blanket and universal rates (Giller et al., 2011) for agro ecological zones, whole countries or vast areas with diverse soil conditions. These recommendations are disputable with regard to soil heterogeneity (IUSS working group, 2015) and related response to nutrient input (Blume et al., 2002).

Next to natural soil heterogeneity due to parent material, relief, climate and vegetation, Zingore and Vanlauwe (2011) reported on soil heterogeneity between and even within plots in Sub-Saharan African (SSA) subsistence agriculture, due to diverse land use histories and distance from settlements. Fields near homesteads generally receive more nutrient inputs from household waste or manure than outlying field. This generates a gradient of soil fertility and yield potential with distance from homesteads (Zingore et al. 2007).

Vanlauwe et al. (2016) highlighted non-responsive soils as special cases that often occur in high population density areas in SSA. Those soils develop from old soils, mismanagement practices like continuous cropping, or erosion. They are characterized by salinization, compaction or tremendous nutrient deficiencies, leading to missing crop response on fertilizer input. Their rehabilitation is elaborate. Best is to apply manure as organic matter input containing nutrients like nitrogen and phosphate (Zingore et al. 2007). For remote fields, however, this is nearly not feasible for local subsistence farmers. Up to 15% of Africa’s soils do not respond adequately to fertilizing due to degradation (Bossio, 2015; https://wle.cgiar.org) due to micro-nutrient deficiency, acid pH values or low organic matter content (Vanlauwe and Zingore, 2011).

### 1.6. The linkage of research to development

Agricultural R4D is defined by the European Initiative on Agricultural Research for Development (EIARD, 2008), as “a multi-dimensions research that addresses the agricultural development challenges of developing and emerging countries” and “includes crop production and animal husbandry, agro-forestry, fisheries and aquaculture, agribusiness and related enterprises, animal and human health related issues, as well as the sustainable management of the natural sources on which farming depends and the socio-cultural and bio-diverse landscapes, food systems and ecologies in which it is embedded.”

But how to combine science and development? Research in the development context must be based on local reality, knowledge and constraints. The sustainable improvement of agricultural productivity to make more efficient use of fragile natural resources is the focal point. Particularly, in subsistence agriculture, numerous individual factors are integrated in manifold combinations (Reinhardt et al., 2019). Control of factors or universality are absent. Reality on farms is highly complex and, hence, must be studied in detail to understand driving factors.

For reliable and quick outcomes in agricultural R4D, modern scientific methods must be combined with existing knowledge. Giller et al. (2011) modeled a whole-farm-approach with data from manifold countries of SSA resulting in tailored, “best fit” management options. They included internal and external drivers, used system analysis tools as well as experiments. Local knowledge from farmers together with agricultural education and knowledge of new technologies from extension workers could already result in efficient site-adapted farm management. Multilateral (local farmer, extension worker, and researcher) determination of key factors helped to find the best suited technology for major tasks, and not to be lost in details. Land, labor and cash were identified to be the main internal influences; major external influences are climate or population growth leading to the well-known hazards.

For agricultural R4D, given pre-conditions must be captured ex ante, accepted and dealt with in research. For this purpose, it is first of all necessary to determine, what those pre-conditions are in a cost-efficient, quick and reliable way. Next step is to determine the actual tasks in agriculture on the ground, which have to be faced – as well at low cost and quick. The third step again requires to be achievable with low budget and, most important, with long term impact. This third step directly addresses the yield increase with locally feasible techniques and at the same time keeping the connection to local farmers, their habits, habitat, problems, opportunities, and real needs. Vanlauwe et al. (2016) issued the warning of missing transferability of innovative cropping methods from controlled conditions on experimental stations to farmers due to lacking match to the tasks and preferences of farmers.

Digital soil mapping is a promising discipline in soil science that can help to establish high resolution soil maps needed for successful agricultural R4D related to cropping. With improved computational power and increasing existence of spatial data via satellite images and geographical information systems (GIS), digital soil mapping has been incrementally used for soil science (Minasny and McBratney, 2015). Digital soil mapping sensors employ certain parts of the electromagnetic spectrum (Herrmann, 2015). Proximal or remote sensing of land surfaces can exhibit differences in lithology or soil type (e.g. gamma-ray sensors), water contents (e.g. radar sensors), natural vegetation via Normalized Difference Vegetation Index (infrared sensors) or visual exploration by satellite imagery (e.g. WorldView satellites). Its advantages are compelling: complete and non-invasive land surface overview, rapid data collection, investigations at low-cost, and the possibility to record several aspects during one survey by including different sensors. Drones have introduced the opportunity for smaller, less complicated surveys. Multiple investigations are now accomplishable with digital soil mapping, rather than with time-consuming and exhausting field trips.

Gamma ray spectrometry is an especially promising and rapid technique for soil science to estimate soil properties or differentiate soil units (Reinhardt and Herrmann, 2018). The method relies on counting gamma decays of the naturally occurring isotopes 40-potassium ($^{40}K$), 232-thorium ($^{232}Th$) and 238-uranium ($^{238}U$). Those count rates are then transferred to their element contents and result in specific signatures. A major advantage of the method is the recording of not only the land surface but several decimeters beyond, depending on the surface material (Beamish, 2014). Whereas visible (VIS) or infrared (IR) wavelength sensors are unable to produce results when vegetation or clouds are in place, gamma-rays are only attenuated by these (Herrmann, 2015). Especially in difficult to access terrain, the method is a sound auxiliary. This exactly meets the requirements of R4D approaches where a quick, low-cost and simple mapping approach is needed, e.g. for site-specific amelioration recommendations.

### 1.7. Objectives of the thesis

Main goals of the thesis were to establish soil maps of the study area in a rapid approach in order to evaluate innovative cropping experiments with regard to subsistence farmer opportunity adapted methods. For this purpose, gamma-ray spectrometry as non-invasive technique was applied together with participatory soil mapping.

The specific objectives were to:

(1) Review gamma-ray spectrometry critically as a method to employ in mapping, identify its limitations and its applicability in soil science;

(2) Generate two soil maps at village scale of the Trans-SEC intervention area with participative methods and gamma-ray spectrometry as rapid approach, involving local soil nominations as well as scientific soil classification;

(3) Test gamma-ray spectrometry as tool to distinguish clay illuviation soil types in the intervention area;

(4) Assess the concept of yield increasing management strategies on different research levels in the project context (researcher-controlled on-station and demonstration plot in the village, and farmer-managed on-farm trial).

## 1.8. Outline of the thesis

This dissertation is devised as a cumulative thesis. In Chapter 2, gamma-ray spectrometry application in soil science is introduced and reviewed. Chapter 3 describes the soil mapping process in Tanzania, i.e. testing a method combination of participatory mapping with gamma spectrometry as rapid mapping approach. Chapter 4 gives a deeper insight into data analysis of gamma-ray spectrometric surveys by means of bivariate mixed models. Chapter 5 reviews the project-related procedure according to innovative yield increase strategies and related to soil type and landscape position. Besides, the concept of on-station experiments in relation to demonstration plot and farmer managed trials for agricultural R4D is discussed. Chapter 6 is a general and concluding discussion of thesis related topics.

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## 2. Gamma-ray spectrometry as versatile tool in soil science: a critical review

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### 2.1. Abstract

Gamma-ray spectrometry is an established method in geo-sciences. This article gives an overview on fundamentals of gamma-ray spectrometry that are relevant to soil science including basic technical aspects, and discusses influencing factors, inconsistencies, limitations, and open questions related to the method. It relies on counting gamma quanta during radionuclide decay of $^{40}K$, $^{238}U$ and $^{232}Th$, but secular equilibrium for the decay series of U and Th must be given as decays of their respective daughter radionuclides are used for determination. Secular equilibrium for U and Th decay series, however, is not always given leading to e.g. anomalies in U concentration measurements. For soil science, gamma-ray spectrometry is of specific value since it does not only detect a signal from the landscape surface, but integrates information over a certain volume. Besides, different spatial scales can be covered using either ground-based or airborne sensing techniques Together with other remote sensing methods, gamma signatures can provide completive information for understanding land forming processes and soil properties distributions. At first, signals depend on bedrock composition. The signals are in second order altered by weathering processes leading to more interpretation opportunities and challenges. Due to their physico-chemical properties, radionuclides behave differently in soils and their properties can be distinguished via the resulting signatures. Hence, gamma signatures of soils are specific for local environments. Processes like soil erosion can superimpose gamma signals from in situ weathering. Soil mappings, available K and texture determination, or peat and soil erosion mapping are possible applications being discussed in this review.

**Key words**: Digital soil mapping, soil sensing, radionuclide, $^{40}K$, thorium, uranium

## 2.2. Introduction

During the decay of radionuclides, the resulting gamma signatures enable to determine the absolute concentrations of several elements. Among these, potassium (K), uranium (U), thorium (Th), and cesium (Cs) occur in soil in concentrations that allow their determination directly in the field. In consequence, in situ detection of their spatial distribution can be rapidly accomplished. Already in the late 1940s, gamma-ray spectrometry was used for U exploration (IAEA, 2003). Meanwhile, the method has undergone improvements regarding sensitivity, applicability as well as handiness. Gamma-ray spectrometry is a passive, ground-based or airborne, non-invasive method capturing a certain measurement depth in half-space geometry of surface-near material, and is perfectly implementable for soil science. In contrast to other remote or proximal (within, on or less than 2 m above the soil body; Viscarra Rossel et al., 2010) sensing methods, soils can be inspected down to 1 m depth under certain conditions, even if vegetation cover is present (McBratney et al., 2003). Penetration depths of more than 1 m are achievable in peaty dry soils with high porosity, low bulk density and low gamma attenuation potential (Beamish, 2013). However, exact and reliable calculations and assumptions concerning measurement depths are disputable.

Applicability of gamma-ray spectrometry to soil investigation works due to initial compositions of radionuclides in bedrock minerals (K, U, Th) or to human impacts (Cs). With natural weathering and soil erosion processes, this causes a different distribution of radionuclides over particle sizes and subsequent different environmental behavior leads to redistribution processes at various spatial scales. Gamma-ray measurements, thus, can help to differentiate between bedrock and soil, and detect weathering intensity, textural properties and nutrient status of the latter (Cook et al., 1996). Gamma-ray spectrometry has emerged as a helpful tool for rapid soil mapping (Schuler et al., 2011), soil map refinement (Reinhardt and Herrmann, 2017), soil characterization (Beamish, 2013), and precision farming (Van Egmond et al., 2011).

Cesium-137 originates exclusively from anthropogenic activity and, consequently, can be applied for soil erosion and soil organic carbon (SOC) loss determination, equipment calibration or as contamination indicator after nuclear accidents. It was widely distributed through the atmosphere by nuclear bomb testing, power plants, nuclear disasters or industry processing/accidents and has a half-life of 30.2 years (IAEA, 2003).

Labour input as well as financial expenses can be reduced by the use of gamma-ray spectrometry as laboratory analyses become partly redundant (Heggemann et al., 2017). Gamma-ray spectrometry can add soil information to other covariate data layers like parent rock or topography as used in digital soil mapping (Bierwirth, 1996; Dickson and Scott, 1997; Taylor et al., 2002). Combination with other (3D-) methods like electromagnetic measurements (Hyvönen et al., 2005), but also participatory mapping (Reinhardt and Herrmann, 2017) make gamma-ray spectrometry even more expedient.

Although gamma-ray spectrometry is increasingly applied in soil science, some important aspects need further discussion: (1) attenuation of gamma radiation by environmental compounds (e.g. soil water), (2) soil radiation models without inclusion of depth-depending property changes, having an influence of the detected soil volume, (3) unproven assumptions about the volume contributing to the radiation signal, as well as (4) the use of parameters that are reported in the literature based on theoretical assumptions but that have never been confirmed under field conditions. Having this in mind, the focus of this review will be on possibilities and limitations of gamma-ray spectrometry in soil science.

## 2.3. Fundamentals

### 2.3.1. Natural gamma radiation

The naturally occurring radioelements $^{40}$K and daughter nuclides in the decay chains of $^{232}$Th and $^{238}$U (Pickup and Marks, 2000) emit sufficient gamma radiation for in situ detection in the environment, due to their abundant average content in the earth crust. Gamma radiation originates from excited nuclei sending out high-energy gamma rays for de-excitation. Radioactive decay has a statistical character; every radionuclide disintegrates with a certain probability within unequal time intervals and independently from other decays. The gamma-ray emission is directly proportional to the amount of decaying radionuclides. Radiation is particle-free, isotropic, electromagnetic, travelling at the speed of light, with energies reflecting the respective characteristics of the parent nuclei. Table 2-1 gives an overview about half-lives (IAEA, 2003), natural

**Table 2-1** Half-lives, natural crustal abundances (adapted from IAEA, 2003) and conversion factors to specific activities for $^{40}$K, $^{238}$U and $^{232}$Th (adapted from IAEA, 1989)

| | Half-life [years] | Natural crustal abundance [%] of element | Conversion from concentration to specific activity |
|---|---|---|---|
| $^{40}$K | $1.3\times10^{9}$ years | 0.012 | 1%[a] in rock ≙ 313 Bq kg$^{-1}$ |
| $^{238}$U | $4.46\times10^{9}$ years | 99.27 | 1 ppm[a] in rock ≙ 12.4 Bq kg$^{-1}$ |
| $^{232}$Th | $1.39\times10^{10}$ years | 100 | 1 ppm[a] in rock ≙ 4.1 Bq kg$^{-1}$ |

[a]Usual denotation for $^{40}$K given in %, $^{238}$U and $^{232}$Th in ppm.

crustal abundances of the radioisotopes (IAEA, 2003) and conversion factors from specific activity to concentrations (IAEA, 1989).

Using this information, natural radioactivity data can be transformed into K, U and Th concentrations. Becquerel (Bq), an SI unit, describes the radioactive activity, i.e. decay counts of an isotope per second [s$^{-1}$]. In geo-sciences, activity per mass is usually measured, i.e. the number of decays per second [Bq kg$^{-1}$].

### 2.3.2. Gamma-ray spectrometry – technical aspects

*Detectors*

Different detector systems are available (Table 2-2); however, most spectrometers make use of thallium activated sodium iodide (NaI(Tl)), cesium iodide (CsI(Tl)) or high-purity germanium (HPGe) crystals. Measurement time depends on required measurement accuracy, detector type and crystal size (Hendriks et al., 2001). The longer the measurement period, the more accurate are the results (Gilmore, 2011). The so-called dead time is the preferably exiguous time a detector and the attached data acquisition system needs to process a single photon. For detailed information about detection of gamma-rays, please refer to Gilmore (2011), IAEA (1991; 2003), Syntfeld et al. (2006). NaI(Tl) (and CsI(Tl)) detectors are superior for field applications as they do not need cooling (Wilford and Minty, 2006). CsI detectors exhibit a greater absorption coefficient due to their higher density, are less brittle and less hygroscopic than NaI detectors (Gilmore, 2011). HPGe detectors have advantageous sharp peaks, i.e. high energy resolution. In former times, HPGe detectors could only be applied in laboratory measurements due to compulsory liquid nitrogen cooling. Today, the pulse tube cooling makes them also applicable in field surveys. The high efficiency scintillation Bismuth Germanate crystal (BGO) allows for lower counting times

**Table 2-2** Commonly used detectors for gamma-ray spectrometry in soil science (IAEA, 1991 and 2003; Syntfeld et al., 2006; Van Egmond et al., 2010¸ Gilmore, 2011; Giaz et al., 2013)

| Detector substance | Type | Volume | Field of use | Efficiency | Energy resolution | Dead time | Density [g $cm^{-3}$] |
|---|---|---|---|---|---|---|---|
| BGO | Scintillator | $cm^3$ | field surveys | high | poor | n.a. | 7.13 |
| CsI(Tl) | Scintillator | $cm^3$ to $dm^3$ | field surveys and laboratory | high | poor | $10^{-9}$ s | 4.51 |
| HPGe | Semi-conductor | $cm^3$ | laboratory (vacuum, cooled to -196 °C) or field | low (need long time) | high | n.a. | 5.32 |
| NaI(Tl) | Scintillator | $cm^3$ to $dm^3$ | field surveys and laboratory; commonly used for airborne surveys | ~100% for low energies, a bit lower for high energy gamma-rays | poor | $10^{-7}$ s | 3.67 |

(Hendriks et al., 2001) but is more expensive than the NaI(Tl) detector. Recently, a lightweight cadmium zinc telluride detector has become available, e.g. for unmanned aerial vehicle (UAV) surveys (Martin et al., 2015).

*Gamma-ray spectra*

Gamma-ray spectra usually display energies between 0.04 and 3 MeV (Hyvönen et al., 2005). Potassium-40 decays in 10.55% to $^{40}Ar$ without intermediate steps and is directly measured (rest decays via beta-decay to $^{40}Ca$). Thorium-232 and $^{238}U$ measurements rely on daughter radionuclide decay (Fig. 2-1) that emit sufficient gamma radiation for detection. Therefore, data are commonly denoted as eU and eTh (e for equivalent). These measurements are based on $^{214}Bi$ to $^{214}Po$ (eU) and $^{208}Tl$ to $^{208}Pb$ (eTh) decay rather at the end of the respective decay series. Hence, the prerequisite for a secular equilibrium that allows to transfer counts into element concentrations is hard to prove.

The frequently reported total counts (TC) sum up counts usually for energies between 0.4 and 3 MeV. Window analysis and full spectrum analysis (FSA) are the two main methods regarding spectra interpretation for gamma-ray spectrometry in soil science, next to the summed spectra method (Xhixha, 2012) and moving window analysis (Brundson et al., 1996), which is not dealt with in this review.

Most field spectrometers run by means of window analysis, i.e. they analyze pre-defined regions of interest (ROIs) around the relevant peaks of the specific nuclides. The peaks follow a Gaussian distribution, their width is defined by full width at half maximum (FWHM) in relation to energy or channel number (Gilmore, 2011). According to IAEA (1991) standards, the defined energy levels for the respective decays are 1.46 MeV for $^{40}K$ (window: 1.370−1.570 MeV), 1.76 MeV for eU (window: 1.660−1.860 MeV) and 2.62 MeV for eTh (window: 2.410−2.810 MeV). They slightly differ between studies, e.g. Carroll (1981) used 1.36 to 1.56 MeV for $^{40}K$ detection.

Full spectrum analysis (FSA) as described by Hendriks et al. (2001) provides an expedient, cost-efficient method. In contrast to window analysis it uses almost the full spectrum to obtain more sensitive results (Hendriks et al., 2001). Standard spectra (1 Bq $kg^{-1}$ spectrum for a radionuclide) are then applied for computing the concentration of any individual radionuclide of interest within the measured range

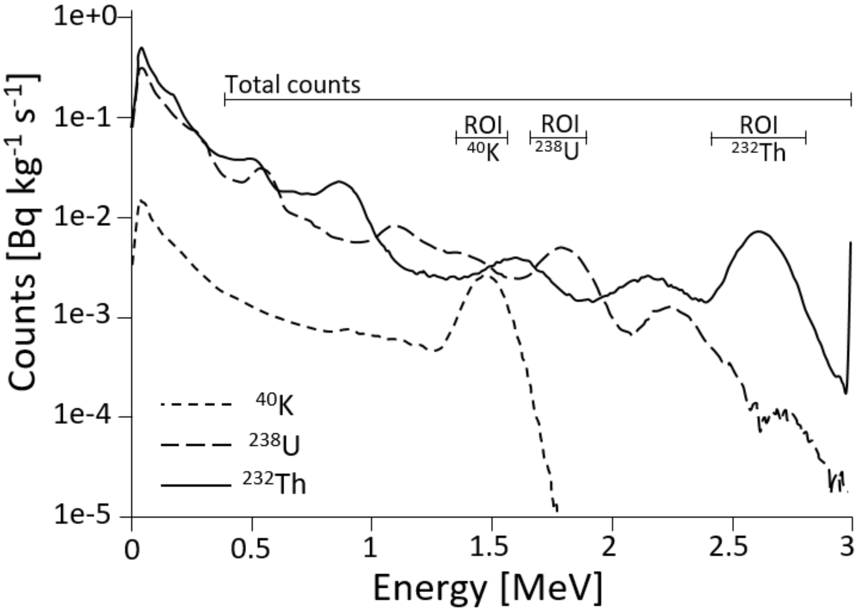


**Figure 2-1** Gamma decay spectra of $^{40}K$ (1.46 MeV), $^{238}U$ (daughter nuclide $^{214}Bi$, 1.76 MeV) and $^{232}Th$ (daughter nuclide $^{208}Tl$, 2.62 MeV). Regions of interest (ROI) indicate the counts per second (cps) within the respective measurement window, total counts (TC) are measured over the indicated region (adapted from Hendriks et al., 2001; IAEA, 2003)

(after background subtraction). The windows analysis is simpler but less accurate than the FSA, the latter creating more operating expense. Spectrum shapes depend on radioelement concentration and source geometry; their intensity, i.e. peak heights, depends on magnitude of attenuation by non-radioactive overburden (Minty, 1997). Stripping factors are applied to eliminate secondary radiation from other elements in energy windows. In particular, interfering radiation from $^{238}U$ is removed from the $^{40}K$ ROI, $^{232}Th$ radiation from the ROIs of $^{40}K$ and $^{238}U$. In contrast, influences from $^{40}K$ or from $^{238}U$ radiation on $^{232}Th$ spectra are expected negligible (Killeen, 1979). In Figure 2-1, the super-imposed character of the different spectra is displayed.

Stripping factors, but also respective concentrations as well as device sensitivity coefficients are determined by spectrometer calibration over calibration pads with defined $^{40}K$, $^{238}U$ and $^{232}Th$ contents. The IAEA (2003) standards for calibration are: identical pads with 1 m × 1 m × 0.3 m edge length, identical geometry for the measurement and a similar matrix composition.

### 2.3.3. Gamma radiation influencing factors

*Uranium-238 disequilibria and the radon influence on measurements*

Uranium-238 disequilibria are the most relevant for soil science as they change eU signals. After Killeen (1979), in theory, more than 8 times the longest half-life of the daughter nuclides are obligatory for the required secular equilibrium, i.e. 40 years for $^{232}$Th, and >1.5 million years for $^{238}$U. Hence, disequilibria inevitably occur (Dickson and Scott, 1997) due to dislocation of decay products via selective leaching (e.g. $^{226}$Ra), gaseous $^{222}$Rn diffusion from soils (Minty, 1997), or due to $^{226}$Ra containing groundwater (Bierwirth, 1996). Wind (Bierwirth, 1996), diurnal differences of $^{222}$Rn in air (Grasty, 1979) as well as atmospheric pressure and temperature changes affect $^{222}$Rn gas diffusion in or from soils (Grasty, 1979; De Jong et al., 1994; Minty, 1997). Seasonal variations in gamma recordings arise from gradual soil warming (Grasty, 1997) and follow drying patterns. Darnley and Grasty (1970) detected an average contribution of 70% from $^{222}$Rn in air to the airborne eU signal. After rainfall events, measured eU ground concentrations can rise up to 2000% (Charbonneau and Darnley, 1970) via raindrops combing out $^{222}$Rn and $^{218}$Po, $^{214}$Pb or $^{214}$Bi attached to aerosols (Minty, 1997). A precaution is to wait with measurements for at least 3 hours after a rain event (Minty, 1997) or until the soil has dried up as diffusion is lowered in wet soil (Grasty, 1997), i.e. best is dried soil until measurement depth.

A further potential source of erroneous eU measurements are fertilized plots. Saueia and Mazzilli (2006) showed that the secular equilibrium of eU and eTh in phosphate fertilizers is disrupted due to harsh fertilizer production processes leading to an increase of up to 1158 Bq kg$^{-1}$ $^{238}$U and up to 521 Bq kg$^{-1}$ $^{232}$Th in the fertilizer. Whereas Saueia and Mazzilli (2006) do not consider fertilizer to raise U levels over security thresholds, there are several reports stating an increasing contamination risk due to enhanced U contents in mineral fertilizers and its accumulation in cropland soils (e.g. Schnug and Lottermoser, 2013).

In conclusion, especially eU measurements are intrinsically defective and should be cautiously interpreted. Several authors (De Meijer and Donoghue, 1995; Rawlins et al., 2007; Schuler et al., 2011) judge $^{40}$K and eTh as reliably detectable. TC measurements give less information on element content, but can be used as indicator where the signal intensity e.g. of $^{238}U$ and $^{232}Th$ is low (Hyvönen et al., 2005).

### 2.3.4. Attenuation

*Theory*

In general, gamma-ray attenuation is assumed to follow the Lambert-Beer-law:

$$I = I_0 \times e^{-\mu_l \times x} \quad (2.1)$$

where I is the attenuated incident ray [eV], $I_0$ the initial incident ray [eV], $\mu_l$ depicts the matter specific linear attenuation coefficient [length$^{-1}$] and x the thickness of absorbing matter [length]. However, in the strict sense the Lambert-Beer-law in this form is only applicable to point radiation sources, non-radiating absorbers, and a measurement situation without constant background noise. All these conditions are not fulfilled during measurements in natural environments.

Linear attenuation coefficients $\mu_l$ depend on bulk (or material) density, atomic number of the attenuating material and initial incident ray energy $I_0$. Consequently, Cook et al. (1996) ordered the attenuation capacity of soil constituents as follows: soil (mineral and organic matter) > water >> air. The resulting linear bulk attenuation coefficient of soil, water and air together, $\mu_t$ can be expressed as:

$$\mu_t = \mu_{soil} + \mu_{water} + \mu_{air} \quad (2.2)$$

Mass attenuation coefficients $\mu_m$ [area×mass$^{-1}$] are linear attenuation coefficients divided by the material or bulk density (ρ). In this way, attenuation factors become independent of ρ.

The following processes induce gamma-ray attenuation (Fig. 2-2):

(1) Compton scattering is the most frequent process at low to moderate energy levels, mostly in interaction with low atomic number elements, i.e. atomic numbers from 2 to 30; hydrogen is an exception (Grasty, 1979; Løvborg, 1984). It happens when a gamma quant collides with a loosely bound outer-shell orbital electron of an atom and partially transmits its energy to this electron. The gamma quant recoils from the electron in an altered scattering angle with lower wavelength, hence, with lower energy. Compton scattering within the detector creates the so-called Compton edge and the Compton continuum (Løvborg, 1984).

(2) The photoelectric effect is the total absorption of a gamma quant by the outermost electron of the attenuating atom, and the accompanied emission of that

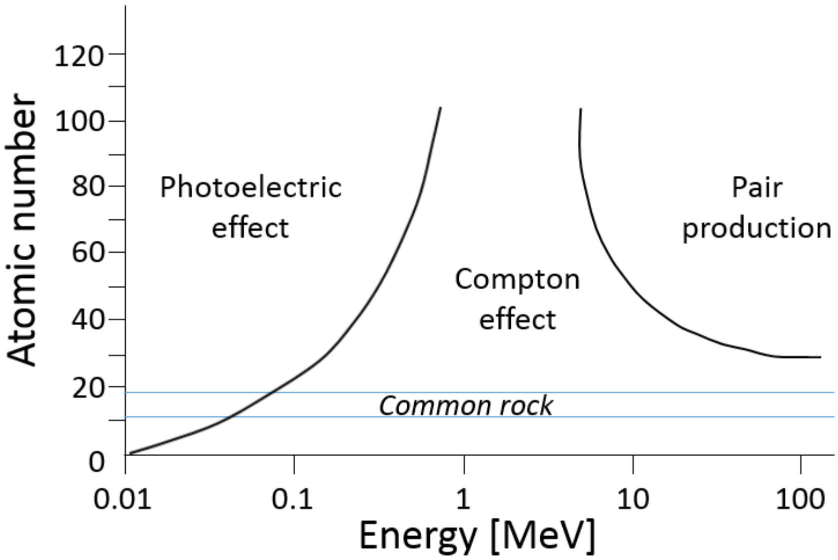


**Figure 2-2** Attenuation effects according to energy ranges and typical behaviors of gamma-rays as to interaction with matter of different atomic numbers (adapted from Killeen, 1979)

electron (Cook et al., 1996). It is dominant in lower energy ranges and usually relevant after a previous attenuation via Compton scattering.

(3) Pair production at high energy levels occurs only with high atomic numbers at energies exceeding 1.02 MeV. Part of the energy generated during decay is used for the formation of an electron/positron pair, which is then emitted (Gilmore, 2011).

Under practical conditions in soil science, Compton scattering is the predominant process, and gamma radiation from soils is predominantly attenuated by water, soil and organic matter.

*Soil environment*

Specific aspects that need to be considered when applying gamma-ray spectrometry to soil are the radioactivity and attenuation of the soil material itself, but also the dynamic fluctuation of soil water content in space and time. Commonly used attenuation coefficients follow the work by Hubbell and Berger (1968) who calculated collimated beam attenuation coefficients of diverse materials, mainly based on theoretical considerations. Grasty pointed already in 1979 to the issue that gamma-rays in nature are not collimated but scattered. Zotimov (1971) carried out elaborate tests with regard to the attenuation potential of soil water. The article deals with an important approach; however, neither Grasty (1979) nor Zotimov (1971) attempted to verify the attenuation coefficients of Hubbell and Berger

(1968). For water, the following mass attenuation coefficients were established by Grasty (1979), based on Hubbell and Berger (1968): $^{40}K$ 0.059 $cm^2$ $g^{-1}$, $^{238}U$ 0.053 $cm^2$ $g^{-1}$ and $^{232}Th$ 0.043 $cm^2$ $g^{-1}$. Due to the energy dependence of attenuation coefficients, $^{40}K$ radiation is more attenuated than those of $^{238}U$ and $^{232}Th$. Cook et al. (1996) assumed that 1% soil water content lowers gamma signals by approximately 1%. This rule of thumb meanwhile serves as common practice (e.g. Minty, 1997; Priori et al. 2013).

Still open questions are the radiative properties of soil air, soil water and soil organic matter (and their interaction), as well as experimental procedures for their proper determination. Normally, these soil constituents are thought to be composed of attenuating rather than radiating elements (except when $^{222}Rn$ in soil air is present in relevant amounts). Accepting this hypothesis makes the determination of e.g. soil moisture or peat thickness by gamma radiation feasible (Keaney et al., 2013; Beamish, 2015).

*Measurement depth*

Various assumptions have been made with regard to the depth/volume that contributes to the gamma-ray signals at the soil surface. Assumed depths for signal contribution range from 30 to 100 cm (Grasty, 1975; Cook et al., 1996; Dickson and Scott, 1997; Taylor et al., 2002; Hyvönen et al., 2005; Wilford and Minty, 2006; Rawlins et al., 2007; Van Der Klooster et al., 2011). Following Grasty (1997), eTh radiation from mineral soils with a bulk density of 1.5 g $cm^{-3}$ originates to 90% from a depth of 22 cm, to nearly 100% from a depth of 50 cm, following a saturation curve.

The following equation (2.3) is given by Grasty (1997) to calculate the gamma radiation per time using the so-called King’s function (2.4) (King, 1912, in Grasty 1997):

$$N = nA\varepsilon/2\mu_g \times E_2(\mu_a h) \quad (2.3)$$

$$E_2(\mu_a h) = \int_1^{\infty}(e^{-\mu_a hx}/x^2)dx \quad (2.4)$$

with N being the number of unscattered photons detected per time, n primary photons per unit volume per time, A the cross-sectional area of the detector, $\varepsilon$ photopeak efficiency, $\mu_g$ linear attenuation coefficient of the ground, $\mu_a$ linear attenuation coefficient of air and h height. $E_2$ is the exponential integral of the second kind (equation 2.4) with x being thickness [cm]. This function is applicable for homogenously distributed radioelements as radioactive sources. These conditions are, however, rare in particular in soils and sediments that are characterised by their stratification and inhomogeneity in space and time.

Duval et al. (1971) stated bulk density had the biggest influence on the captured soil volume, as the higher soil bulk density, the higher is the attenuation, and the smaller the measured volume. Attenuation also increases with moisture content due to effective density increase. However, soil minerals in contrast to soil water also emit gamma radiation. Therefore, the concept of a bulk linear attenuation coefficient composed of the constituents solids, water and air has to be reassessed.

In theory, soil moisture and soil bulk density do not affect the spectrum shape. De Groot et al. (2009) applied Monte-Carlo simulations and ascertained the influence of soil bulk density and water content changes onto the captured volume. Despite the great usefulness of these simulations, practical field checks should always proof theoretical findings. To our knowledge, this gap is still to be closed.

*Change of natural isotope ratios*

In practical work, gamma counts are transferred to total element content by calculations inter alia based on constants that represent the natural isotope/element ratios. Therefore, consistency of these ratios is a prerequisite. The $^{40}K$ fraction of total K ($K_t$), for instance, is considered to be 0.012% (IAEA, 2003). However, as known for isotopes of other elements (e.g. $^{16}O$, $^{18}O$) gravitational separation is possible. Consequently, we can assume that marine deposits like sylvine (KCl) have another nuclide composition than magmatic rocks. If these sediments are then applied to soils, e.g. as fertilizer, they might be able to alter the isotopic ratio over time and, thus, the measured signal at the soil surface. This has, however, to be tested in future studies.

Fujiyoshi et al. (2014) screened the $^{40}K/K_t$ ratio in forest soils in Japan and Slovenia comparing gamma-ray spectrometry and x-ray fluorescence data. Potassium-40/$K_t$ values varied with depth in both, carbonaceous and siliceous soils. Equisetum hyemale L. plants in Sapporo showed significantly reduced $^{40}K/K_t$ ratios of 0.0042 (± 0.0001)%, its litter even showed ratios of 0.0059 (± 0.0002)%, leading to the assumption of $^{40}K$ discrimination by certain plants. Determined soil $^{40}K/K_t$ ratios were between 0.009 and 0.013% in the study of Fujiyoshi et al. (2014). For the relation pH-$^{40}K/K_t$ -ratio, correlation coefficients of r = 0.9 were determined. Treatment of respective soil samples with 1 M hydrochloric acid led to further increased $^{40}K/K_t$ ratios. Only few articles could be found regarding changes of $^{40}K/K_t$ ratios related to land use and soil formation. Wetterlind et al. (2012) observed different $^{40}K/K_t$, eU/total U and eTh/total Th ratios from airborne gamma data and soil chemical analyses (hydrofluoric and perchloric acids, and inductively coupled plasma mass spectroscopy (ICP-MS)) comparing forest and arable soils in France. Measured Th ratios did not significantly differ, but gamma counts for $^{40}K$ and $^{238}U$ increased in comparison to chemically determined contents in arable soils. The authors explained these trends by bulk density and water content differences but could not prove their hypotheses. Arable soils are - in contrast to forest soils - frequently fertilized. Type and location of mineral sources as well as fertilizer processing might lead to shifted $^{40}K/K_t$ ratios. Chauhan et al. (2013) and Alharbi (2013) investigated several fertilizers. Their data indicated shifted $^{40}K/K_t$ ratios in fertilizers via variable radiation for similar weight % of $K_t$. This was, however, not in the focus of their publications. For precise statements regarding $^{40}K/K_t$ ratio shift, the method has to be refined. In unpublished studies in Thailand and SW-Germany, the authors of this review found a correlation of plant available potassium with total potassium as measured by gamma-ray spectrometry in forest stands but not in fertilized land. If this finding is true, long-time heavily fertilized areas might need a correction factor for fertilizer input. To our knowledge, no specific studies concerning this topic exist. Shifted isotopic ratios in fertilizers and fertilized soils as well as in plants and litter should be of high interest for further investigations.

*Source-detector geometries*

Source-detector geometries highly influence measured count rates. Problems arise if geometries like in Figures 2-3c ($<4\pi$, i.e. valleys) and d ($>2\pi$, i.e. mountain ridges) occur, as no unique geometry conversion factor can be assigned (Fig. 2-3, Fig. 2-4). Terrain characteristics like hills, valleys, quarries or buildings can influence measured radioelement concentrations up to tens of per cent (IAEA, 2003). Already during calibration procedures, measurement geometries need to be taken into account (Killeen, 1979). Recording the environment including landscape position is of absolute importance during airborne as well as ground-based gamma

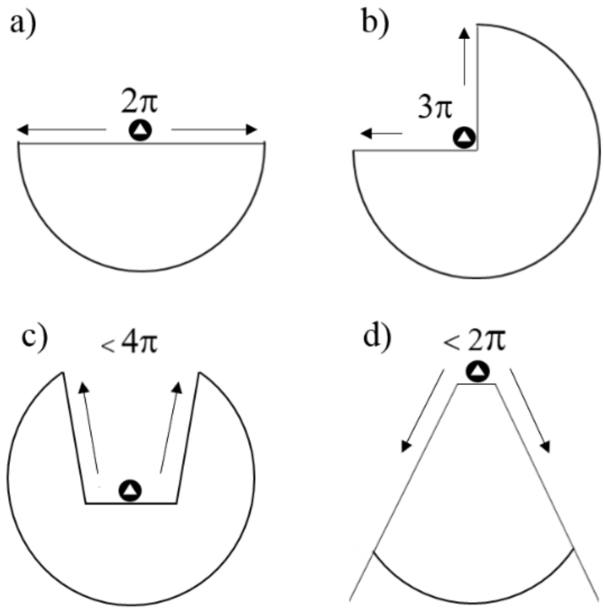


**Figure 2-3** a) 2π geometry (illustrates gamma-ray recordings in flat terrain), b) 3π geometry (referring to e.g. recordings in incipient mountainous areas), c) < 4π geometry (referring to recordings in valleys), d) < 2π geometry for ground-based measurements (referring to mountains; adapted from Killeen, 1979)

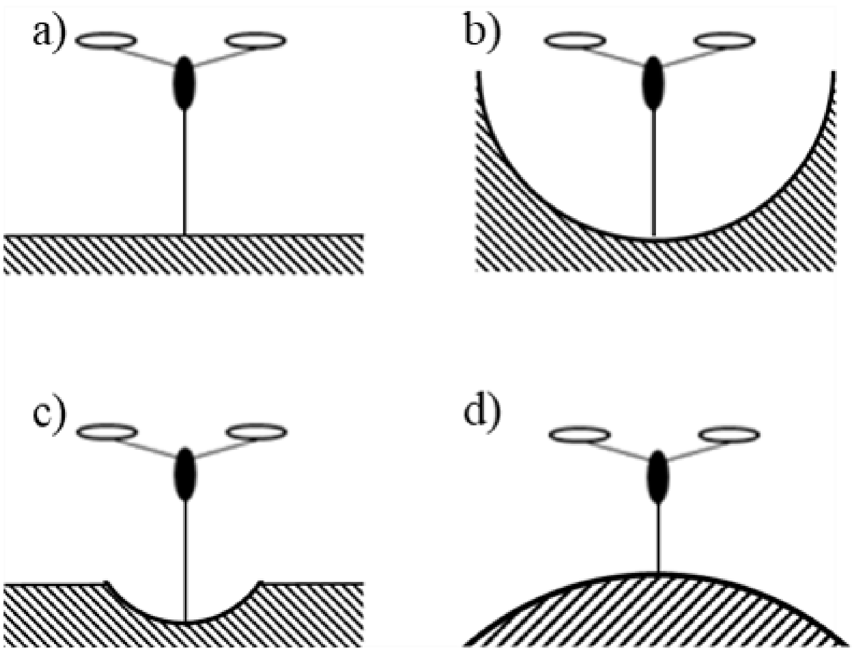


**Figure 2-4** Source-detector effects on airborne gamma-ray surveys: recordings in a) flat terrain, b) valleys, c) areas with depressions, d) undulating area. (adapted from Grasty, 1976)

spectrometric surveys. Usually, flat calibration pads in 2π geometries are used, i.e. flat geometry (Fig. 2-3a, 2-4a). Borehole measurements, where the detector is surrounded by the source should experience 4π geometry calibration.

Figure 2-4 is related to airborne survey source-detector geometries. Count rate changes occur due to the different landscape shapes. Depressions can increase (Fig. 2-4b) or decrease (Fig. 2-4c) signals. As well, during horizons-wise soil pit measurements (Herrmann et al., 2010), changing geometry with depth is biasing the results. Doig (1968, in Killeen, 1979) confirmed a signal increase of 50% changing from 2 π to 3 π geometry. Schwarz et al. (1992) calculated a decrease of 10-30% in airborne count rates over mountains in the Swiss Alps. The authors examined signal adjustment opportunities with 2D and 3D models related to terrain geometry, i.e. gamma signals from rugged terrain are recalculated into signals that would derive from a 2 π geometry. Fortin et al. (2017) reviewed airborne gamma-ray spectrometry and discussed current methods of data acquisition in rugged terrain, e.g. the 3D inversion method by Minty and Brodie (2016), which incorporates topography, altitude of the detector and the directional sensitivity of rectangular detectors and calculates elemental concentrations.

*Ground-based and airborne data acquisition*

Gamma-ray surveys operate either ground-based or airborne. Common ground-based surveys are conducted proximal, i.e. on or less than 2 m above the surface (Viscarra Rossel et al., 2010), either on-the-go - using backpacks, quads, cars or tractors - or stationary on the surface, in soil pits or boreholes. Airborne investigations run by means of airplanes, helicopters or, as latest achievement, with unmanned aerial vehicles (UAVs).

*Stationary ground-based surveys*

Stationary surveys serve as reliable method for point scale measurements. Transect measurements can broaden the scale but still yield detailed and small-scale surveys, e.g. for soil mapping (Reinhardt and Herrmann, 2017). Advantageous is the accuracy due to a very small circle of investigation – or footprint - and minor influence of background radiation. In cases of low gamma radiation, stationary measurements result in more distinct spectra due to less statistical noise (Rouze et al., 2017). Stationary gamma-ray investigations can serve as point validation of large-scale airborne surveys. However, the results are difficult to correct for continuously shifting measurement geometry (2-4$\pi$) related to topographic variability in the landscape if the device is not completely shielded, which is normally not the case.

During stationary investigations, the measurement device is usually placed directly onto the soil surface or in near proximity, up to approximately 1 m above the ground (e.g. Dierke and Werban, 2013; Reinhardt and Herrmann, 2017). Adequate counting times depend on signal intensity, detector type and crystal size. As an example, a 0.35 l NaI(Tl) detector needs 2 min for high and 6 min for low signal intensities from rocks with 10% error (IAEA, 2003).

Borehole investigations for geological purposes, e.g. U exploration (Xhixha, 2012), record gamma radiation within the borehole. For this purpose, the testing probe is lowered into the ground. The advantage of the latter is that topographical effects are excluded. Captured measurement radius is assumed to be 0.1 to 0.3 m in rock (IAEA, 2003). Due to the mainly geological application, the borehole mode will not be discussed in detail in this review.

*Mobile surveys*

This section includes ground-based on-the-go investigations together with airborne gamma spectrometric surveys, because many conditions apply for both procedures. The detection frequency is commonly 1 Hz, sometimes higher frequencies are applied (Martin et al., 2016). Appropriate velocities depend on demanded resolution, next to signal intensity, detector, and crystal size. Rouze et al. (2017), for instance, chose 63 m $s^{-1}$ for their airborne survey using a 50.3 dm3 NaI detector crystal. Loonstra and van Egmond (2009) recommended a speed on the ground of 2.8 m $s^{-1}$ for a 70 × 150 mm CsI crystal, Heggemann et al. (2017) went at 0.7-1.4 m $s^{-1}$ with two 4 l NaI(Tl) detectors. Flying heights are, depending on vehicle and demanded accuracy, up to 30 m for UAVs (Martin et al., 2015) and the standardized 120 m for helicopters and aircrafts (IAEA, 1991).

Minty (1997) gave an overview about airborne gamma-ray spectrometry and summed up total gamma counts as the radiation of $^{40}$K, eU and eTh nuclides, but also aircraft (or vehicle), cosmic and $^{222}$Rn derived background radiation, so-called noise. Hence, data have to be pre-processed for noise elimination. Cosmic radiation increases with altitude (Grasty, 1979) and is commonly determined via survey flights in different altitudes over a large water expanse (Carroll, 1981). During the survey, the airplanes should not tilt but keep its position to carry out perpendicular measurements, i.e. keep the same geometry condition.

Multi-temporal airborne surveys are an opportunity to eliminate blank areas on maps, observe variation measurements of the water budget, or of forest areas but surveys are costly. UAV surveys are a promising approach (van der Veeke et al., 2017), also for precision agriculture.

*Aspects of spatial resolution*

Rawlins et al. (2007) deduced from their airborne gamma measurements in England that radiometric properties relating to thematic soil maps can produce map scales up to 1:50,000. Beckett (2007) concluded that airborne spectrometry can achieve a spatial resolution of 1:25,000 depending on height and velocity of the aircraft. Cost efficiency calculations resulted in an advantage of ground-based measurements below a limit of 500 line-km (that equals 1250 ha with 25 m line spacing). Ground-based surveys were able to generate map resolutions of 1:10,000 with an accuracy of ± 7 m in Beckett's study (2007). In areas with highly differing signatures between soil units, even resolutions up to 1:2,500 were achievable. Therefore, for precision agriculture, ground-based surveys are to prefer. Pracilio et al. (2006) concluded that gamma-ray spectrometry is precise enough to explore yield variations related to soil properties at farm scale.

*Circle of investigation*

The so-called "footprint" is the circle of investigation contributing to the detected radiation. It depends on sensor integration time and the velocity of the aircraft or vehicle, next to detector height above ground (Pickup and Marks, 2000). The IAEA (1991) described the footprint extent as an ellipse due to the movement during recording. As a rule of thumb, 66% of the counts originate from an area covering twice the altitude wide and twice the altitude plus the travelled distance long (Ward, 1981, in Wong and Harper, 1999). Consequently, altitude is the most relevant factor for the footprint area, which is, next to ground conditions, determining the measured volume (Duval et al., 1971). Figure 2-5 gives an impression of altitude influence on the footprint and measured volume, i.e. infinite source yield.

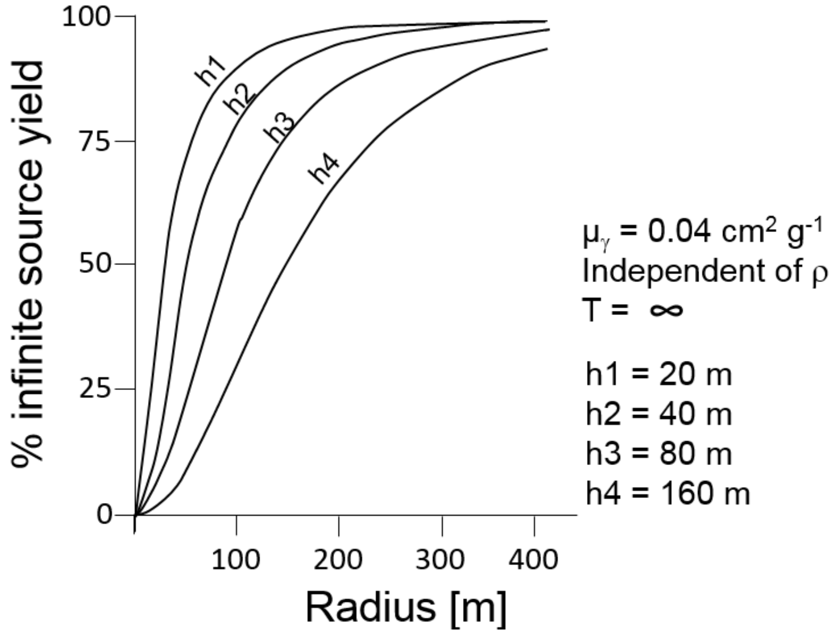


**Figure 2-5** Percentage of captured volume (infinite source yield) vs. circle of investigation (radius r) for different altitudes h (adapted from Duval et al., 1971)

Signals in highly variable landscapes become blurred as the collected signals represent "pseudo-averages". Wilford and Minty (2006) added flight-line spacing and time sample interval as precision determinants. They emphasized that appropriate detection heights and velocities had to be chosen according to expected spatial heterogeneity

*Airborne vs. ground-based data collection*

As long as factors of gamma signal generation in a terrain are not fully understood, ground-based methods should be preferred due to higher spatial accuracy (Wong and Harper, 1999). Ground validation is indispensable for airborne surveys, on one hand by proximal gamma-ray spectrometry, but as well by laboratory analyses (Keaney et al., 2013).

Kock and Samuelsson (2011) found strong Pearson correlation for airborne vs. ground-based $^{40}K$ and eTh ($r^2 > 0.9$) but not for eU signals ($r^2 = 0.68$) due to higher radiation in some spots that was smoothed out in airborne measurements. A comparison of an airborne with a conventionally produced soil map by Cook et al. (1996) showed consistent results in general.

*Data processing*

In particular, airborne gamma data need to be processed and corrected due to additional factors. Interferences like geometric position and height of the detector above ground, cosmic and background radiation occur. It is impossible in rugged terrain to fly at a constant height (Schwarz et al., 1992). Other mentioned aspects are the footprint, anomalies for $^{222}Rn$, dead time of the signal processing unit, water vapor and gases between detector and ground depending on temperature and barometric pressure. Consequently, the airborne system needs, apart from the spectrometer, additional equipment (barometric and/or laser altimeter, GPS etc.). Information on the meteorological conditions during the flight as well as on land cover are indispensable.

Complete data processing comprises the following steps: transformation of GPS information into the intended mapping coordinate system, determination of the detector height above ground and vegetation height, energy calibration, noise reduction, correction for background radiation, for atmospheric $^{222}Rn$ radiation, for Compton scattering, for landscape $\pi$–geometry, to standard flight height, outlier analysis, spectral analysis, application of stripping factors, calculation of radionuclide content, correction for attenuation by vegetation, trend correction based on ground-based data, correction for soil water content and attenuating surface layers (e.g. O-horizons), spatial interpolation, pattern recognition, (thematic) map development and data storage (compare Minty, 1988, Viscarra Rossel et al., 2007). Not all of these can be dealt with here. We concentrate on those that pose problems and need further research.

There are two main problems that reduce the interpretation abilities for airborne gamma data. These are (i) a number of assumptions instead of measured data for data correction, e.g. vegetation correction and soil moisture, and (ii) the missing process/factor-based correlation of aerial with ground-based data. These problems will be exemplified in the following:

(1) Meteorological conditions: Apart from barometric pressure, hardly any meteorological data are collected during the flight. However, temperature and relative air humidity are relevant for calculating the attenuation between the ground and the vehicle. Instead of measurements, in most cases data from the nearest meteorological station are applied, which are not necessarily corresponding to the

situation in the intervention area, e.g. areas of local precipitation or fog accumulation in local depressions. Consequently, these information need to be observed during the flight. Inclusion into the data set and respective application for correction remains expert-based.

(2) Radon-222 concentration in the air is subject to large fluctuations influenced by topography, barometric pressure differences and meteorological influences. Upward aligned detectors that separately measure cosmic and ground-based radiation can be used for correction (IAEA, 2003). However, due to weight reasons, large crystals used in airborne surveys are rarely shielded against e.g. lateral radiation biasing the correction procedure. In addition, the average $^{222}Rn$ content during the flight is assumed to represent actual conditions, which is not the case during windy days. In order to check for potential $^{222}Rn$ anomalies, it is recommendable to consult geological maps for the inspection of potential rock sources like magmatic rocks prior to the flight campaign.

(3) Correction for vegetation influence: Vegetation cover plays a major role in attenuation of airborne gamma data. Kogan et al. (1971) calculated that 50-100 kg $m^{-2}$ organic material from a forest stand equals a 40-80 m thick air layer with respect to attenuation. However, vegetation also emits radiation. According to Kogan et al. (1971) the radiation of forest stands reaches 15% of soil signals for K, and 10% for U and Th. Ahl and Bieber (2010) established a correction procedure using a laser-altimeter for measuring the vegetation height as proxy for biomass during the flight. The authors selected lithological units that were large enough to compare forested and non-forested areas on the same unit. Linear biomass attenuation coefficients were derived that are, however, only valid for the studied coniferous forest (Tab. 2-3).

(4) Correction for soil variables: Soil water content is the major influence on the interpretability of environmental gamma-ray data (Grasty, 1997). Available radar data (e.g. AVHRR) that regularly deliver soil water content information could be used for correction procedures, however, data are not available in the same spatial resolution. Choice of adequate climatic conditions for the survey are helpful, i.e. after extensive rains when soils in a given area are either saturated to field capacity, or droughts when soils dried down to the permanent wilting point. Developing correction algorithms for soil moisture content is one of the most urgent tasks for gamma-ray spectrometry research in the near future.

**Table 2-3** Estimated attenuation of gamma radiation by different vegetation types as stated in different publications

| Authors | Attenuation of gamma radiation by vegetation in % | Vegetation type |
|---|---|---|
| Pereira and Nordemann (1983) | 40-60 | Tropical rain forest |
| Schwarz et al. (1997) | 5-25 | Forest |
| Aspin and Bierwirth (1997) | 13-22 | "Vegetation" |
| Ahl and Bieber (2010) | 20-24 | Coniferous forest |

Depending on the aim of the study, organic horizons demand correction, especially when wet. Since organic matter is a weak emitter (for potassium), it mainly acts as attenuator. Detection of these horizons needs inspection on the ground. Until now, correction algorithms for this feature have not been developed.

(5) Other processing steps: Due to drifts of peaks during the survey, energy calibration is carried out first. Dead time corrections are of importance as next step, especially in areas with high radiation. For this purpose, the measured count rates are extrapolated to the measurement cycle of one second based on recommendations of the IAEA (2003):

$$N_R = n_R \times 10^3 / t_L \quad (2.5)$$

with $N_R$ being the corrected count rate, $n_R$ the measured count rate and $t_L$ the live time [ms].

Inappropriate signal/noise ratios require pre-processing for more distinct spectra. Principal component analysis (PCA) can be applied for this purpose. Procedures are the Noise-Adjusted Singular Value Decomposition as examined by Hovgaard and Grasty (1997) or Minty and McFadden (1998), and Minimum Noise Fraction for spectral smoothing.

Another topic is spatial interpolation, since gamma data are recorded along flight/driving lines with constant distance. Brundson et al. (1996) applied geographically weighted regression, Hengl et al. (2004) regression kriging. Multivariate linear mixed models in combination with regression tree analysis were used by Pracilio et al. (2006).

Besides, pattern recognition and explanation is necessary. Clustering or tree analysis represent helpful tools. Rawlins et al. (2009) significantly reduced the mean square errors for SOC prediction in an airborne survey in Northern Ireland

by clustering in mineral, organo-mineral and organic soil data. Inter alia Beckett (2007), Schuler et al. (2011) or Priori et al. (2014) used tree analysis to group soil-derived gamma spectra. Without grouping in different parent materials Priori et al. (2014) underline the lack of reliability of a general regression model as it is the case in many other studies. Heggemann et al. (2017) successfully overcame the necessary grouping of parent material using Support Vector Machine models.
In general, data processing bears the risk of loss of relation to reality in the field. Therefore, the IAEA (2003) recommends limiting spectral components to 8. Validation of airborne data with ground-based measurements of gamma radiation is essential. Models should always have more validation than calibration points; otherwise predictions are biased. Unfortunately, in most published studies, this relation is inverted (often 1:2).

### 2.4. Applications in soil science

In general, every process and resulting soil property can be inferred by gamma-ray spectrometry. The most basic application of this technology in soil science is to support parent rock determination via detection of the total element content. The influence of soil formation processes, like weathering, on element redistribution, allows to infer soil properties used for soil type classification, e.g. after the WRB (World Reference Base for Soil Resources; IUSS Working Group, 2015). Some soil components can be determined via their attenuation effects (e.g. soil water or soil organic matter), using a reference signal like dry soil in situ. Others show an indirect statistical relationship to gamma radiation (e.g. pH) due to their correlation to other soil properties (e.g. base saturation and the potassium component contributing to it). Finally, soil erosion mapping can be conducted, particularly based on undisturbed reference profiles of an anthropogenic radionuclide (i.e. $^{137}Cs$).

#### 2.4.1. Parent rock characterization

Dickson and Scott (1997) gave an overview of $^{40}K$, $^{232}Th$ and $^{238}U$ distribution in parent rocks of Australia. Parent material radionuclide content explains the major part of gamma signal variation at the land surface, they conclude. More quantitatively, Rawlins et al. (2012) reported from an airborne gamma-ray survey that parent material accounted for 52% of gamma radiation variability in the whole

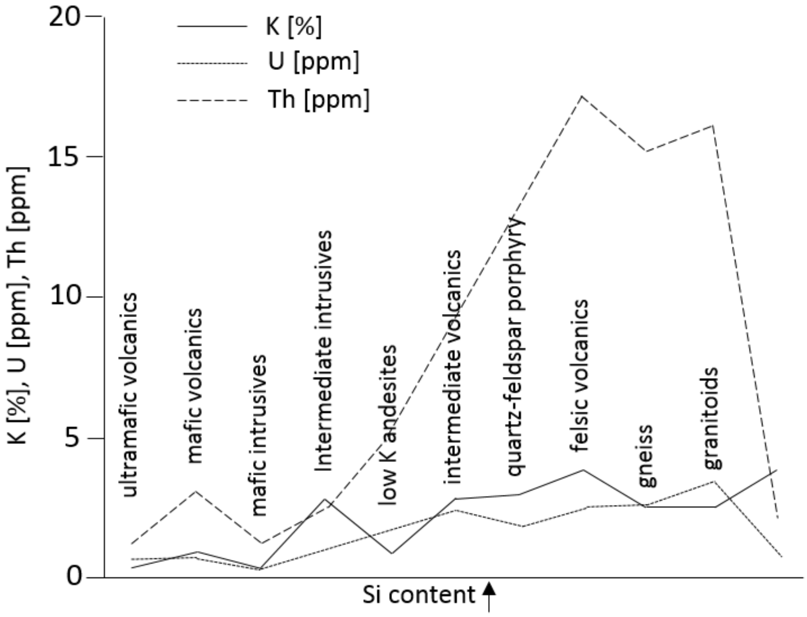


**Figure 2-6** Variation of average K, U and Th content in igneous rocks with increasing Si content (adapted from Dickson and Scott, 1997, investigated in Australia)

of Northern Ireland (13,542 km²). Generally, the more felsic rocks are, the higher their K, U and Th content (Rawlins et al., 2007). Dickson and Scott (1997) concluded from their data that metamorphism does not change radionuclide content and sedimentary rocks mirror gamma signatures of the source rock. The authors reported calcrete to be low in radionuclide content relative to the parent material, and iron-rich pisoliths or ferricretes to accumulate U and Th but not K. Residual quartz and sand contain little radionuclides (Taylor et al., 2002). Figure 2-6 (Dickson and Scott, 1997) shows K, U and Th contents in several rock types.

Dickson and Scott (1997) emphasize large variations within rock classes, e.g. granites do not exhibit one unique fingerprint. Therefore, local rock (and soil) signature reference measurements are needed (Wilford and Minty, 2006). Table 2-4 shows from a ground-based survey in Thailand that limestone, in particular freshwater limestone, silicate rocks and related soils can be distinguished via their element content as well as ratios.

**Table 2-4** Element content sensed by gamma-ray spectrometry in rocks and derived soils in Northern Thailand (condensed from Herrmann et al., 2010)

| Rock/soil | N | K [mg g$^{-1}$] | eU [µg g$^{-1}$] | eTh [µg g$^{-1}$] |
|---|---|---|---|---|
| Limestone | 21 | 2 ± 1 | 2.0 ± 0.9 | 4.0 ± 2.7 |
| Alisols | 42 | 18 ± 9 | 4.5 ± 1.4 | 15.4 ± 4.1 |
| Acrisols | 105 | 6 ± 2 | 7.1 ± 2.2 | 27.8 ± 5.1 |
| Ferralsols | 27 | 4 ± 2 | 7.4 ± 1.9 | 25.2 ± 5.5 |
| Umbrisols | 21 | 8 ± 2 | 6.4 ± 2.1 | 23.1 ± 4.2 |
| Freshwater limestone | 3 | 1 ± 1 | 0.7 ± 0.4 | 1.4 ± 0.7 |
| Chernozems | 39 | 7 ± 3 | 1.9 ± 1.0 | 5.0 ± 3.0 |
| Claystone | 6 | 25 ± 2 | 3.8 ± 1.7 | 12.9 ± 1.2 |
| Luvisols | 90 | 21 ± 5 | 4.0 ± 1.4 | 16.0 ± 2.5 |
| Alisols | 258 | 22 ± 5 | 4.5 ± 1.7 | 16.4 ± 3.2 |
| Umbrisols | 75 | 28 ± 7 | 4.7 ± 1.5 | 15.4 ± 4.1 |
| Latite | 1 | 17 | 0.9 | 13.1 |
| Cambisols | 19 | 21 ± 8 | 1.2 ± 0.6 | 3.4 ± 1.1 |
| Luvisols | 30 | 16 ± 4 | 1.6 ± 0.7 | 3.9 ± 0.9 |

### 2.4.2. Environmental behaviour of potassium, thorium and uranium

Soil property detection via gamma-ray spectrometry is possible because the elements (and their sensed radionuclides) show a different environmental behaviour.

Potassium is prevalent in primary mass minerals like alkali-feldspars and micas in felsic rocks whereas mafic and ultramafic rocks contain less, carbonate rocks hardly any. Main secondary minerals containing K (and therefore $^{40}K$) are illite, vermiculite, chlorite and smectite (Blume et al., 2016). Due to a lack of specific sorption places, K is rather mobile and tends to absolute loss over time in humid to sub-humid environments and silicate rocks (Dickson and Scott, 1997, Herrmann et al., 2013).

Thorium-bearing minerals like zircon, monazite, allanite, xenotime, apatite and sphene (Wilford and Minty, 2006) are rare and show generally low dissolution rates. Th is rather immobile, but better soluble in acid solutions (Langmuir and Herman, 1980). Consequently, it does not move in carbonaceous soils. However, it can form phosphate, sulphate or carbonate anion complexes (Xhixha, 2012).

Together with organic compounds, Th appears soluble at neutral (Chopin, 1988, in IAEA, 2003) to basic pH values, where it totally adsorbs on clay particles (Von Gunten et al., 1996). However, higher affinity to humic organic solids than clays was reported from a ground-based study in Germany (Dierke and Werban, 2013). Bednar et al. (2004) indicated Th affinity to metal oxide fractions. This is supported by findings of Taylor et al. (2002) with respect to hematite, or Wilford and Minty (2006) with respect to aluminum oxides. Vertical leaching in soil profiles was assumed minimal. Herrmann (2015) reported from ground-based data for N-Thailand soils increasing Th content with decreasing grain size (clay and silt > sand) and about one third stored in the free oxide fraction of silt and clay.
Uranium is mainly found in a number of so called "heavy" minerals that also contain Th (Wilford and Minty, 2006). Like Th, it is rather immobile and often associated with anions. One difference is its redox sensitivity. As it forms complexes with carbonates, sulfates or phosphates in the more soluble form $U^{6+}$ (Uranyl, $UO_2^{2+}$ as prominent form in soils), its mobility is enhanced relative to Th. Uranium-238 complexes adsorb on hydrous iron oxides like hematite (Taylor et al., 2002), aluminum oxides (Wilford and Minty, 2006) as well as on clay minerals and colloids (Dickson and Scott, 1997).

### 2.4.3. Soil texture mapping

Soil textures often show reliable correlation with soil gamma radiation because radionuclides form part of the mineral structure (K in clay minerals), part of the adsorption complex (K, Th), or are occluded in oxide minerals (e.g. U in goethite). In order to understand the effects in detail, we need to differentiate between the clay size fraction (share of particles <2 µm in diameter) and clay minerals, often the major share of particles in the clay size fraction.
Taylor et al. (2002) found a significant linear relationship ($r^2 = 0.71$, $p<0.001$) between clay content and TC for the top 10 cm in Western Australia during an airborne study due to the affinity of Th and U contents to the clay size fraction. In a ground-based study in the Netherlands (Van Egmond et al. 2011), $^{232}$Th was evaluated as the most predictive nuclide predicting the clay size fraction with a coefficient of determination of $r^2 =0.78$.
In calcareous soils with vertic soil properties in Sicily, Italy, relevant Spearman correlation coefficients were observed for gamma radiation and clay content (Fig.

2-7) as well as for the sand, but not for the silt content during a ground-based investigation (Priori et al., 2013). In a follow-up study regarding clay and stone contents in diverse parent materials, the statistical challenge for Priori et al. (2014) was that parent material composition explains a higher share of the signal variability than clay content variation. In response, the authors did data pre-grouping based on parent material with explorative PCA in (1) feldspatic sandstone with high TC, (2) calcareous flysch with very low TC and (3) other parent materials with low to medium TC values. Signature variability within these groups was then referable to clay content ($r^2$ between 0.64 and 0.74). Stoniness prediction was worse ($r^2$ between 0.49 and 0.58) and related to local conditions. Similar conclusions were drawn from the radiometric map for Tuscany for which gamma spectrometry was carried out in a laboratory (Callegari et al., 2013).

Heggemann et al. (2017) tested the potential of ground-based stop-and-go gamma-ray spectrometry for site-independent texture prediction by means of non-linear Support Vector Machine models (including all ROIs as well as TC) on 10 arable fields with varying parent rocks in Germany. The majority of prediction errors for soil texture was <5%. When the sand fraction contained a certain amount of

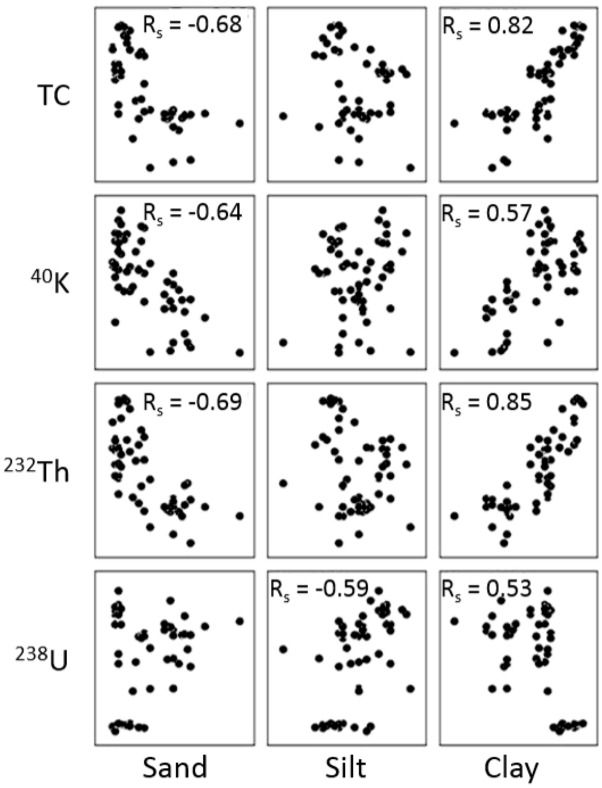


**Figure 2-7** Scatterplot matrix between gamma ray signals and soil data of experimental fields (N= 55) in Sicily, Italy. Rs: Spearman correlation coefficient for $p < 0.01$, only relevant correlations are indicated (adapted from Priori et al., 2013)

radionuclide-bearing feldspars and micas instead of non-radioactive quartz, difficulties arose due to extra counts instead of signal dilution by quartz.
Higher Th affinity to non-swelling clays like illite or kaolinite was revealed in studies by Bierwirth et al. (1996) and Taylor et al. (2002). However, both pointed to the possibility of erroneous results due to outgassing daughter nuclides in the $^{232}$Th (e.g. $^{220}$Rn) and $^{238}$U decay chains through cracks in swelling clay soils.
In conclusion, gamma radiation can be quite easily used to predict soil texture in areas with homogeneous parent rock. In areas of heterogeneous lithology, more sophisticated statistical processing for data grouping is necessary to derive textural information. In principle, it appears possible to indirectly infer other physical properties that depend on clay content and type, like water infiltration, waterlogging potential, water retention or repellence (Beckett, 2007) applying pedotransfer functions.

### 2.4.4. Plant-available potassium

The hypothesis behind detection of the plant-available K (paK) fraction of soils via gamma-ray spectrometry is an assumed equilibrium between Kt content, mainly stored in primary silicate minerals (e.g. mica), the liberation of K via chemical weathering, and plant uptake or leaching losses. However, this equilibrium might be askew in agricultural landscapes due to high input of mobile K via fertilizers. It appears reasonable that processed fertilizer show different isotopic ratios, as indicated in Chauhan et al. (2013) and Alharbi (2013) in laboratory studies. In own investigations (unpublished) in Thailand and Germany, no relation between paK and the gamma signal could be established for fertilized soils in contrast to non-fertilized soils, leading to the assumption of shifted $^{40}K/K_t$ ratios. This, however, has to be investigated in detail.
Wong and Harper (1999) found a strong log-linear correlation ($r^2 = 0.94$) between $K_t$ and the $^{40}$K gamma signal in a ground-based survey on 5,000 ha cultivated land in Australia. In addition, a high linear correlation ($r^2 = 0.93$) between paK as extracted by the Colwell procedure (sodium bicarbonate extraction), and the $^{40}$K gamma signal was detected. Therefore, the authors state that, for the study area, gamma-ray spectrometry based determination of paK is a promising, rapid and cost-efficient application in (precision) agriculture. Yet, they did not mention any

fertilization influences, and the question of $^{40}K/K_t$ ratios remains unsettled. With respect to the observation that below 100 mg $kg^{-1}$ paK correlation disappeared ($r^2$ = 0.05), the authors did not give an explanation for this. The generally high correlations from this study might depend on dry conditions during the survey (i.e. no signal variability induced by water content) and an intervention area that was not heavily fertilized.

Dierke and Werban (2013) investigated the same topic with ground-based measurements at field scale in Germany. Particle size distribution was homogenous, but their site was continuously fertilized. In contrast to Wong and Harper (1999), Dierke and Werban (2013) did not find any correlation between paK content and $^{40}K$ (Pearson's correlation coefficients for 4 sub-fields between -0.08 and 0.14). Values were for the most part above the mentioned value of 100 mg paK $kg^{-1}$, which Wong and Harper (1999) set.

In conclusion, paK is allocable by gamma-ray spectrometry in mineral soils under quasi-natural land use (no mineral K fertilization, forest, grassland). On arable land, the applicability has to be tested, for two reasons: (1) potential shift in the $^{40}K/K_t$ ratio, and (2) shift in the paK/Kt ratio.

### 2.4.5. Soil pH

It is difficult to establish a general hypothesis, how soil pH and gamma radiation are coupled - although it is related to parent material constituents as well as soil development - since pH is a rather labile value and can be influenced in agricultural landscapes by a number of management measures.

In the long term, base leaching is causing acidification depending on mineralogy and age of the land surface, i.e. pH value determination with gamma-ray spectrometry is an indirect effect (Bierwirth et al., 1996). If leaching of K and other neutral cations (mainly Ca, Mg) is congruent, the $^{40}K$ signal is an indicator for pH. However, this is only true in non-carbonaceous systems. On marl or carbonate rocks, the K-signal is first increasing and the pH decreasing during soil development due to residual enrichment of silicate minerals, while carbonate is leached from the system (Herrmann et al., 2013).

In the airborne study of Bierwirth et al. (1996) in Australia, a relationship between pH (in $CaCl_2$) and $^{40}K$ [%] in A horizons could be established following a data grouping based on geomorphological units: (1) piedmont terraces/sloping plains,

(2) lower footslopes of metasediments, (3) granites and (4) inactive alluvial areas. However, inspecting the data in detail shows that this relationship mainly works for the unit piedmont terraces/sloping plains but not for the lower footslopes of metasediments. Geochemical variability of the parent material might be the reason for the latter fact.

Wong and Harper (1999) assumed ground-based gamma K counts to be log-linearly correlated to pH values ($r^2 = 0.69$) for deeply weathered soils from granite in Western Australia. The detected spatial gradients were explained by decreasing eolian cover sheets consisting of parna (carbonate-rich, similar to loess, but particles are small clay mineral agglomerates), leading to decreasing K and carbonate contents with distance from the source. Hence, $^{40}K$ radiation might be applicable for topsoil pH-prediction, but only in petrographically homogeneous areas and without regular pH-influencing measures like liming.

### 2.4.6. Soil organic carbon and peat mapping

Some studies evaluate SOC through gamma-ray spectrometry. In theory, this is possible, given the overall attenuating effect. However, the gamma-ray signal does not respond very sensitively to solely SOC concentration changes due to the relative high signal/noise ratio. However, it is not only the SOC attenuation effect but other related changes in soil organisation (pore volume → water content → detected soil volume; exchange places for K) that impact on the global effect of SOC on the gamma-ray signal. Martz and De Jong (1990) found a positive correlation between organic carbon and radiometric data, but only because organic carbon was strongly bound to clay-humus-complexes, and clay was the real emitter.

The anthropogenic radionuclide $^{137}Cs$ can efficiently indicate SOC in soils. After its deposition, $^{137}Cs$ readily adsorbs onto clay particles and taken up by vegetation due to its similar properties to K (Van den Bygaart and Protz, 2001). The authors found $^{137}Cs$ contents to be most prominent in the top 5 cm together with the organic matter and clay size fraction of the investigated sandy soil in Canada. Correlation coefficients (not indicated whether Pearson or Spearman) accounted for $r = 0.73$ for clay and $r = 0.68$ for organic matter content ($p = 0.05$) as a whole in four soil profiles. Downward movement or distribution of the nuclide does not happen as solute but via e.g. bioturbation (Takahashi et al., 2015) or clay illuviation (Hao et al. 2000). Van den Bygaart and Protz (2001) further highlighted the fact that $^{137}Cs$ enters the nutrient cycling via litter. Specific transfer factors for soil-to-plant assimilation exist.

Peat areas are generally low emitters with respect to gamma radiation. First of all, peat (and soil organic matter in general) contains low concentration of emitting elements. Second, peat areas are normally (if not drained) saturated by water, efficiently attenuating the potential emission from underlying mineral sediments. Gamma-ray spectrometry is, thus, suitable for mapping peat areas. Rawlins et al. (2009) improved prediction accuracy for SOC in an airborne study in Northern Ireland by using $^{40}K$ radiation and altitude information as well as grouping soils into mineral, organo-mineral and organic soils. Misclassifications could be reduced by adding bulk density as data layer for better recognition of peat areas.

Beamish (2013) calculated the radiation transmissibility of two soils in Ireland with different bulk densities and water contents, based on attenuation coefficients derived from Minty (1997) (Tab. 2-5). According to his calculations, in drained peat areas, the gamma signal can originate from more than 1 m depth. This is congruent with ground-based findings of Billen et al (2015). However, the transmissibility is proportional to the signal strength of the underlying material. Inhomogeneities with respect to the materials underlying the peat need also to be taken into account as possible source of error.

With a rather coarse approach, Hyvönen et al (2005) detected peat reserves for industrial exploitation during an airborne survey in Finland. The latter indicated that with 90 vol.% water content up to 0.6 m peat thickness could be differentiated. In consequence, detected radiations close to zero indicate peat layers of greater thickness. Unfortunately, correlation coefficients between radiation and peat thickness are missing.

Finally, the applicability of gamma-spectrometry to peat mapping depends on: (1) the signal strength of the underlying mineral material (the higher, the more peat thickness can be differentiated), (2) the uniformity of underlying sediments, and (3) a known drainage scheme (due to the major attenuating effect of water) that allows to apply different algorithms depending on drainage intensity. Best results can be expected either in completely undrained systems or in drained systems after a long dry period (own unpublished data).

**Table 2-5** Half-space reach of gamma radiation in mineral soils and peat (bulk density 0.1 g cm-3) from Beamish (2013)

| | Mineral soil | | Peat | |
|---|---|---|---|---|
| | Bulk density [g $cm^{-3}$] | | Water content [%] | |
| | 1.1 | 1.6 | 20%[a] | 80%[a] |
| 90% gamma radiation from distance [m] | 0.6 | 0.4 | >>1.0 | 0.6 |

[a] No indication of either weight or volume % was given.

### 2.4.7. Soil type mapping

*Weathering*

During weathering in a leaching environment (humid to sub-humid climate), the mobile K fraction diminishes over time relative to Th and U. This weathering behaviour was confirmed by a study of Carrier et al. (2006) who mapped chemical erosion processes and progressive K loss from unweathered micaschist to saprolite applying airborne gamma-ray spectrometry in France and cross-checked these data with laboratory results. Chemical erosion or weathering indicates disintegration of rocks or soils via chemical processes like hydrolysis or oxidation. In the sensed environment, the average chemical weathering rate of K was estimated to be $17 \pm 2$ kg $km^{-2}$ $a^{-1}$ and the total average net export to be $422 \pm 50$ kg $m^{-2}$ compared to unweathered micaschists, i.e. an estimation accuracy of 12% in both cases.

The Th/K ratio of soil material in comparison to the parent rock commonly provides good information about the weathering status. On this basis, Wilford et al. (2007) developed a weathering index (WI) to refine existing soil/regolith maps for their 1,600 $km^2$ study region in Australia:

$$WI = 0.405443 + 0.007304 \times relief - 0.069814 \times Th/K + 0.017819 \times TC \qquad (2.6)$$

Therein, the relief represents the relative elevation difference within 150 m distance. Based on the index, the authors separated their study area into three classes, which were slightly, moderately and highly weathered regolith. Low relief, low TCs, and high Th/K ratios indicated highly weathered regoliths. This was explained by low water erosional activity for soils in low relief; the effects of weathering in situ were, thus, predominant. Field checks resulted in an $r^2$ of 0.89.

*Soil type distinction*

The relative difference of gamma signatures allows to potentially classify soil types. It is not possible to globally relate one soil type to one quantitative signature since different combinations of factors and processes can lead to the same result. Nevertheless, in an area where different soil types are present and reference measurements of each soil type were done, soil type mapping with in situ gamma-ray spectrometry is promising and efficient (Reinhardt and Herrmann, 2017).
Beamish (2013) described soil type mapping with airborne gamma data in Northern Ireland. He used spectra shapes of TC to distinguish brown earth, mineral gley, and peat (soil classification following Gauld et al., 1984; Fig. 2-8). Organic layers on top of mineral soils exhibited spectra, which were comparable to peat regarding skewness. Additionally, he found that the investigated Brown Podzol spectra with organic surface layer showed bimodal distributions. The studied Podzols without organic surface layer exhibited high and low value TC peaks and a shoulder peak,

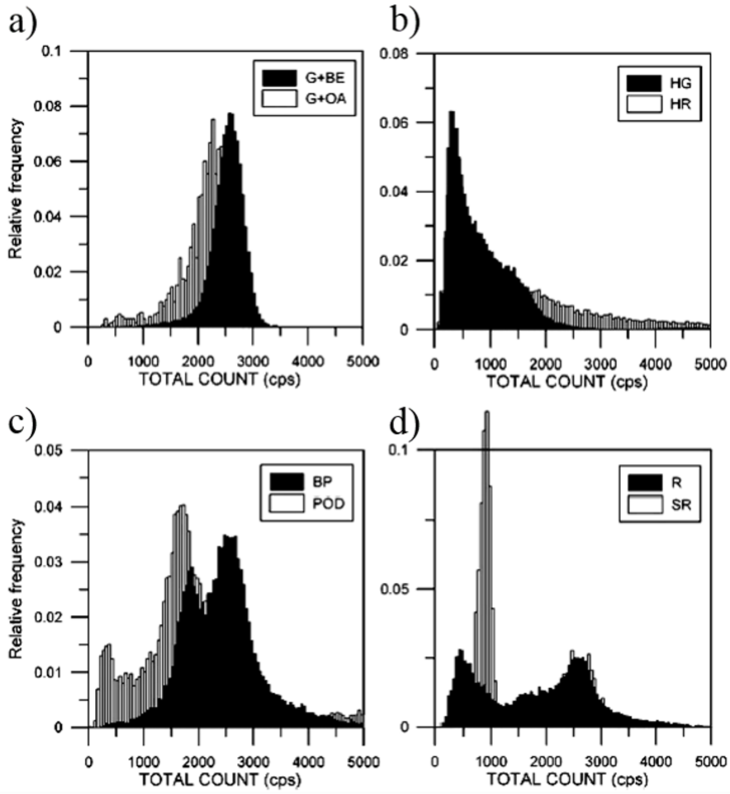


**Figure 2-8** Normalized distributions of TC data for 8 soil types from Northern Ireland: a) Mineral gley (G) + brown earth (BE) and mineral gley + organic (OA), b) groundwater humic gley (HG) and humic ranker (HR), c) brown podzol (BP) and podzol (POD) and d) ranker (R) and sand ranker (SR) (Beamish, 2013)

i.e. a different spectra shape (Fig. 2-8c). In conclusion, spectra shapes in addition to element content and element ratios can be used to map certain soil types.

Martelet et al. (2014) worked on silty plateaus in central France. They found the following Reference Soil Groups in a toposequence: (Luvic) Cambisol, Haplic Luvisol, Albeluvisol, Luvic Planosol, Stagnosol-Gleysol, Haplic Planosol. While for the first three a similar airborne gamma signature was detected, the radiation was tremendously lower for the latter in all energy channels. The authors related this finding to weathering and judged gamma-ray spectrometry as suitable to explore weathering stages of those soil type sequences. The authors waited “several hours after rainfalls” to let the soil dry before their measurements. However, for soils with hardly permeable layers and stagnating water like Planosols and Stagnosols, the higher topsoil water contents might better explain the generally lower radiation in all channels. However, water content was not indicated in the publication by Martelet et al. (2014) – as it is in many articles but would help in interpreting the results.

Van den Bygaart and Protz (2001) studied podzol profiles horizon-wise in Canada. Potassium-40 and $^{232}$Th gamma radiation was measured in the laboratory. The authors found lower Th abundance in relation to global averages and referred this fact to the coarse particle size (Megumi and Mamuro, 1977). Within the profile $^{40}$K and $^{232}$Th radionuclides were translocated in the course of the podzolization process and $^{232}$Th was adsorbed to the Fe and Al oxides in the Bf and Bfh horizons, where radiation levels were increased.

WRB clay illuviation type soils, namely Luvisols, Lixisols, Alisols and Acrisols (IUSS Working Group, 2015) have formerly not been distinguishable in the field, due to their separation based on chemical criteria that need to be analysed in the laboratory. Schuler et al. (2011) introduced ground-based gamma-ray spectrometry in combination with conservative field pH measurements for an in situ distinction in Northern Thailand. While the Th/K ratio was used as surrogate for CECclay and, thus, clay mineral composition, the pH indicated the base saturation. Acrisols could be discriminated from Alisols by the Th/K ratio (Fig. 2-9) since Acrisols mainly contain K-free kaolinite whereas Alisols are characterised by K-bearing illite in general.

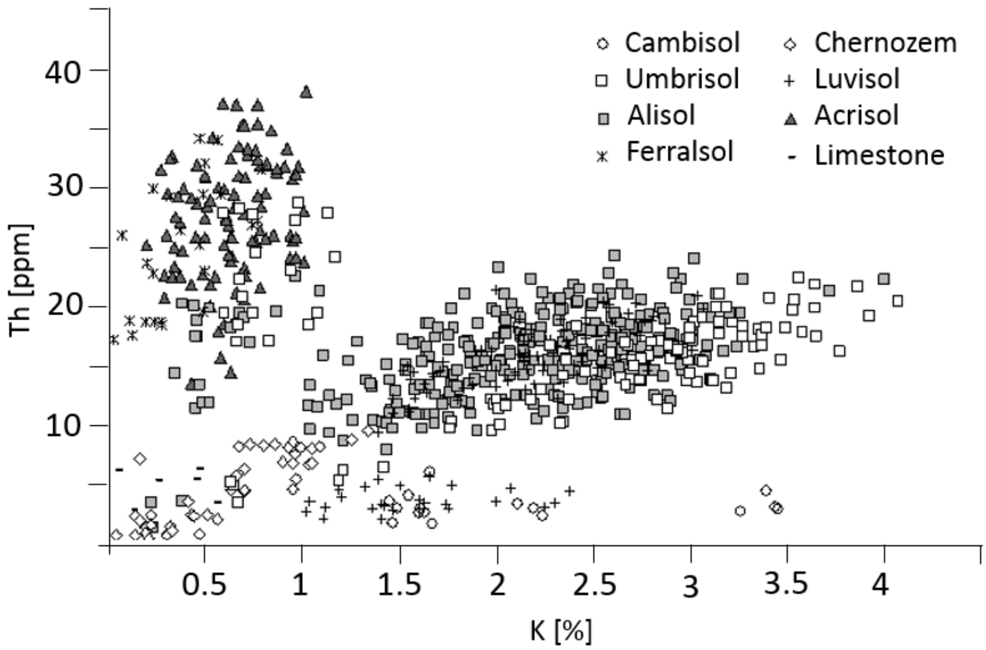


**Figure 2-9** Binary plot of K vs. Th in several soils in a catchment in Thailand (adapted from Herrmann et al., 2010)

Schuler et al. (2011) could generally detect the difference from surface measurements but more accurate results were obtained by subsurface measurements.

The published studies show that gamma data can be used in various ways: absolute data, relative changes with respect to the parent material, element ratios, spectral shapes etc. It is worthwhile to investigate in more detail, which approach is feasible under which environmental conditions.

*Soil erosion mapping*

Soil erosion and deposition influence soils and their radiation properties. In areas of soil translocation, soils do not necessarily reflect the radionuclide composition of the rock or in situ weathering, but topography and past landscape processes as well. In consequence, erosional truncation and sources of deposited soil material can potentially be traced by gamma radiation.

Bierwirth et al. (1996) mapped an area in north-western Australia with airborne gamma-ray spectrometry. Figure 2-10 from their study shows that $^{40}K$ signals depend on relative elevation, mountain ridges representing the highest values. This fact is explained by exposition of the parent material, while the weathered soil was deposited farther downslope.

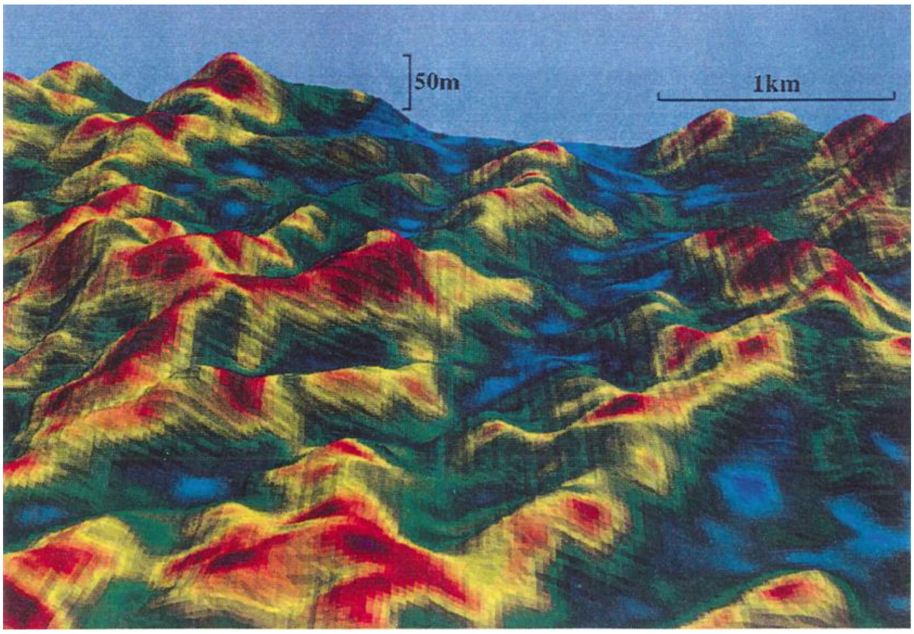


**Figure 2-10** Digital elevation model with radiometrically determined K concentrations. K concentrations range from 0.9% (blue) to 3% (red). Higher concentration is regularly related to high landscape positions and soil erosion, excavating bare rock and lowering soil burden depth (Bierwirth et al., 1996)

Martz and De Jong (1990), who sampled their sites for analyses in the laboratory, and Pickup and Marks (2000) using airborne data showed rising $^{40}K$ contents towards the valley floors. Downslope accumulations of finer fractions (mainly clay) that contain higher shares of $^{40}K$ explain these findings. Pickup and Marks (2000) further differentiated depositional behaviour depending on rock type: Landscapes from basalt rocks showed topography related element gradients to a lesser extent than those from granite or metamorphosed sediments because soil material weathered from basalt shows a lower spread of grain sizes with a majority of particles from finer fractions that are less erodible in aggregated form. Martz and De Jong (1990) were able to differentiate between eolian and alluvial sediments, due to different effects of the transport processes on grain size sorting; eolian materials in their case being coarser and consequently lower in gamma radiation. Spatial distribution of $^{137}Cs$ is used for soil erosion mapping as well. Cesium-137 is predominantly found in the top 10 cm of soil (IAEA, 2003) in the northern hemisphere. General assumptions for soil erosion mapping with $^{137}Cs$ are that the nuclide has been homogeneously distributed in an area and that it is hardly vertically reallocated in the soil profile by whatever process. However, both assumptions are in most cases not completely valid depending on size of the area (depositional patterns depend on rainfall patterns at the given time) and land use (redistribution through surface flow). Pre-requisite for spatial soil erosion estimation is an undisturbed reference profile serving as comparison for truncated (lower $^{137}Cs$ signal) or depositional (higher $^{137}Cs$ signal) sites. Reference profiles usually show an exponential decrease of $^{137}Cs$ activity with depth (e.g. Schoorl et al., 2004). Normally, only one sampling campaign is necessary to gain the needed samples. As a standard, analyses are carried out with a laboratory gamma-ray spectrometer in order to achieve sufficient counting rates (Walling, 1998). The quantification of SOC loss by soil erosion using $^{137}Cs$ signature measurements is easily accomplishable due to the adsorption of both matters onto mineral particles and similar translocation processes (Ritchie and McCarty, 2003).

Haering et al. (2014) applied this approach for the assessment of SOC loss via soil erosion after land use change in a mountainous region of Vietnam. However, Fang et al. (2012) studied "Black Soils" in China and could not detect any relationships between slope position and $^{137}Cs$ signal. They explained this fact by tremendous gullies serving as major sediment carriers, interrupting the regular sediment redistribution along the slope.

Advantages and limitations of $^{137}Cs$, $^{7}Be$ and $^{210}Pb_{ex}$ measurements for soil erosion assessments are given by Chappell (1999) and Mabit et al. (2008). A definite advantage is that a medium term average (50 years) soil erosion evaluation is enabled based on only one field visit for sampling. As limitations, the authors mention the problem of polluted areas caused by the Chernobyl accident, which complicates the spatial homogeneity assumption with regard to original deposition rates. In contrast, areas in the southern hemisphere often contain too little 137Cs for application of this method. For event-based soil erosion assessments, i.e. single storm or rainfall, 137Cs determination is not appropriate due to the needed assumption of spatial homogeneity. For this purpose, Mabit et al. (2008) recommend the use of the 7Be radionuclide, which is not dealt with in this review.

## 2.5. Conclusions

Gamma-ray spectrometry enables rapid and informative surveys but requires deliberate application, terrain knowledge and data interpretation. Optimal sensing conditions are dry soil, low standing biomass, stable weather and in situ developed soils at places with low geomorphic activity. Strong signals result in higher signal to noise ratio and more distinct spectra for better interpretability. Consequently, higher spatially resolved data can better serve interpretation of weak signals from soils for mapping. Direct correlation of soil properties and gamma signatures can lead to wrong assumptions if effects of certain variables (e.g. water content) are not known. Element ratios can be interpreted with respect to weathering intensity. The TC spectrum can be used for soil type mapping. Single or multiple absolute and relative values can be related to a number of soil properties.

In particular, airborne studies need ground validation and a sufficient number of checks by laboratory data. Number and choice of ground sampling points, their geographical matching with measurement data, sampling depth, stratification of the terrain, data processing or ratio of calibration to validation point numbers are essential.

Advantageous for soil science applications is the depth-integrated signal of gamma-ray spectrometry capturing the plant main rooting depth. In contrast to other remote or proximal sensing methods (e.g. VIS-NIR) that only “see” the surface or some millimeters in depth, gamma-ray spectrometry can provide information down to 1 m in peaty soils, and 30 to 60 cm in mineral soils. Particularly, in difficult to access or fragile terrains like forests, nature reserves, planted agricultural fields and peat areas, airborne gamma-ray spectrometry (airplane or UAV) can provide valuable data sets.

Airborne application has advantages as to costs and efficiency, but also higher inaccuracy potentially due to non-transparent or not properly processed correction algorithms and lower spatial resolution than ground-based surveys. In order to reduce spatial noise it is advisable to sample water content and bulk density at ground truthing sites at the same time.

Next to classical soil science, potential applications are the investigation of sites contaminated by sewage sludge, mining waste or radioactive accidents. In the latter respect, drones and recently available light gamma detectors can be deployed. Also in precision agriculture, gamma-ray spectrometry is suitable for exploring soil texture, water logging, or spots with elevated radiation from e.g. fertilizers. Generally speaking, via airborne gamma-ray spectrometry, contaminated areas can be discovered and their dimensions defined without posing a human being at risk.

It is essential that the researcher has a sound knowledge on the technical aspects influencing the gamma signal. This refers, in particular, to the assumptions made to convert gamma counts into element contents, to equilibrium aspects in the decay chains (e.g. $^{222}$Rn loss, secular equilibrium), to the major processes introducing noise (e.g. soil water content, organic surface layers). In addition, the effect of soil (e.g. clay translocation) and landscape processes (e.g. soil erosion) on the surface signal should be known. Adequate data interpretation is often not possible without basic knowledge in petrography, mineralogy and geo-chemistry.

There is still need for research. Experimental proof under field conditions (scattered radiation) of attenuation coefficients calculated from theoretical application of the Lambert-Beer law (collimated beam condition) is still missing. Neither in situ investigations concerning applicability of the calculated attenuation coefficients nor effective monitoring of volume contributing to the signal exist. In particular, the geometric correction of signals measured in non-2$\pi$ geometries, i.e. rugged terrain, needs further inputs. Discrimination of $^{40}K$ during plant uptake is of interest in order to enable correction algorithms for the vegetation in airborne studies. The nuclide composition of fertilizers (K-fertilizer, P-fertilizer for the associated U component) should be studied, too, in order to evaluate the potential effect of fertilization in agricultural landscapes on $^{40}K/K_t$ ratios in respective soils.

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# 3. Fusion of indigenous knowledge and gamma spectrometry for soil mapping to support knowledge-based extension in Tanzania

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## 3.1. Abstract

Food shortages often threaten central Tanzania. Sustainable action adapted to local environmental conditions is desperately needed. In the framework of the Trans-SEC project, two food value chains in the Dodoma region of Tanzania were inspected in order to make propositions for improvement, spanning from soil preparation to product consumption. Therefore, soil mapping approaches were required to obtain rapid and reliable information. This would enable local farmers to participate in the development of upgrading strategies and extensionists to develop recommendations that take local soil conditions into account. In this study, a combination of participatory soil mapping and gamma ray spectrometry assisted transect mapping was applied to establish local soil maps of two villages in the Dodoma region. Participatory mapping included key informant interviews, group discussions and transect walks. Local farmers indicated reference profiles for local soil types. Their gamma radiation signatures delivered base information for further soil exploration and soil unit delineation in the field. Finally, high resolution satellite images were used to establish the village soil maps. This approach allows capture of the major soil differences within a village territory and reduction of the costs of chemical analyses. Challenges were soil unit separation with gamma ray spectrometry due to erosional redistribution processes at the surface, correct translation of specific terms from local tongues as well as variable individual soil knowledge of local participants. Ultimately, the combination of local soil knowledge with innovative scientific mapping yielded quick results with sufficient spatial resolution for extension work.

**Keywords**: Local soil knowledge, participatory research, rapid soil mapping approach, soil radiative properties

## 3.2. Introduction

Central Tanzania frequently suffers from food shortages (Liwenga, 2013). In this region, low and unreliable rainfall, as well as degraded soils and poor agricultural practices, lead to unsatisfactory yields (Sledgers, 2008; Mwalyosi, 1992). As the population continues to grow (Central Intelligence Agency, 2014), it is necessary to invest in more agricultural research that delivers recommendations for site-adapted cropping. This includes the necessity for soil information as well as the development of upgrading strategies that are adapted to the soil types and respect the socio-economic conditions of the local population (Norton et al., 1998).

Plant performance in the widely distributed subsistence cropping systems found in the Dodoma region of Tanzania mainly depends on soil properties and their management (Blume et al., 2016; Letey, 1985). Therefore, soil information at a sufficient spatial resolution is required to enable extension staff to make sound proposals on where to apply specific management measures (AbdulRahim et al., 2008). In addition, a soil map based on the relevant local soil units will allow the development of innovation-testing schemes that deliver sufficient information about where a certain management measure might be successful. This way, blanket recommendations, such as for fertilizer application, can be avoided. Unfortunately, soil mapping is a laborious and cost-intensive measure as Schuler et al. (2010) and van der Klooster et al. (2011) have pointed out. However, many approaches and methods have emerged in recent decades which facilitate mapping at village scale, which is the spatial scale of interest for development action. Methods such as digital soil mapping and remote sensing are promising approaches for the simplification of soil mapping (Werban et al., 2013.). Other proximal sensing methods (i.e. sensing in contact or close proximity to the soil surface) exist. These include infrared spectroscopy or ground based gamma spectrometry. In this study the combined use of two easy-to-apply methods, i.e. local soil knowledge and gamma ray spectrometry, to develop local soil maps in a development orientated environment, was examined.

The incorporation of local knowledge on soils appears as part of an optimal research approach at village scale if participatory development action is planned. This approach has already been applied by many, including Clemens et al. (2010), Schuler et al. (2010) and Lippe et al. (2011). Evidently, local farmers know best about the terrain characteristics in their home region. Therefore, immediate overviews about soil units and their specific characteristics relevant to cropping can be easily collected from key informant interviews. In particular, plant growth deficits as well as opportunities to enhance crop yields at given sites with related soil properties may be revealed (Barrios and Trejo, 2003; Cools et al., 2003). Often farming families live at a given site for generations. Consequently, they have developed and inherited strategies to deal with the constraints posed by the natural environment such as low soil fertility status or water scarcity (Oudwater and Martin, 2003). Scientists and extensionists should explore this rich knowledge in their own interest, since it can speed up their own knowledge generation processes (Schuler et al., 2010). Nevertheless, individual knowledge cannot be directly generalized; farmer opinions and expressions need to be verified in the field using scientific methods. In consequence, a combination of approaches and methods promise rapid and reliable results.

Gamma ray spectrometry is a rapid and easy application that immediately provides total element concentrations in the field that are indicative of nutrient stocks and weathering processes (Dierke and Werban, 2013;Wilford et al., 2007). Gamma spectrometry can be applied remotely or on the ground, and it is non-invasive. It measures the nuclear decay of $^{40}$K, $^{232}$Th and $^{238}$U radionuclides (IAEA 2003). The measured gamma quant counts per unit time are transferred into concentrations via calibration procedures. $^{40}$K decay can be directly measured. $^{232}$Th and $^{238}$U concentrations can only be determined via daughter nuclides that emit sufficient gamma quants. The $^{232}$Th and $^{238}$U concentrations are therefore commonly designated as eTh and eU. The e stands here for equivalent. The eU signal has to be interpreted with caution, since equilibrium conditions are seldom reached in soils. Therefore, Schuler et al. (2011) identified $^{40}$K and eTh concentrations as "most relevant to distinguish some Reference Soil Groups".

Rock-borne minerals containing $^{40}$K, $^{232}$Th and $^{238}$U are natural gamma ray emitters. Soil forming processes alter the inherited mineral composition. Thus, different soils result in specific gamma signatures (Herrmann et al., 2013). These can be used to map soil types (Herrmann et al., 2010; Wilford and Minty, 2006). Since several chemical and physical soil properties influence the gamma signal, they can be assessed using inverse calibration. Applications include estimation of soil water content (Caroll, 1981) or peat thickness (Beamish, 2013) from air-borne gamma spectrometry. Soil texture, plant available K, total P and organic C seem to be detectable via gamma spectrometry as well (Pracilio et al., 2006; Wong and Harper, 1999), offering plenty of applications in agriculture. These applications can help to reduce costly laboratory analysis and support the direct classification of soils in the field (Herrmann et al., 2013).

The present study was conducted within the framework of Trans-SEC (Innovating Strategies to Safeguard Food Security using Technology and Knowledge Transfer: A People centered Approach, www.trans-SEC.org), which is a research-for-development project with a special focus on action research and sustainable food security in collaboration with local stakeholders (Graef et al., 2014). It concentrates on the participatory improvement of food value chains in the Dodoma and Morogoro regions of Tanzania. These regions serve as models for semi-arid and sub-humid environments, respectively. All case study sites (CSS) have a relief dependent soil-type distribution. The soil properties range from sandy to clayey and from acid to basic. Consequently, crop and soil management strategies will have different effects, depending on the site. For the Trans-SEC project to reasonably distribute on-farm trials in space and to stratify the results, a village soil map was a pre-requisite. To allow for better spatially-restricted recommendations within the project that are understandable by farmers, the intention was to use a local soil classification. The aim of this work was to establish soil maps for the two CSS in the Dodoma region by testing the combination of local soil knowledge and gamma radiation measurements as a soil mapping approach.

## 3.3. Materials and Methods

### 3.3.1. Study area

The present survey was conducted in two villages, Ilolo and Idifu, in Chamwino district, Tanzania (E35°59´11″ S6°25′13″and E35°54′50″ S6°20′26″, respectively). The village areas are about 26 km$^2$ for Ilolo and 90 km$^2$ for Idifu. The local climate is semi-arid with an average annual precipitation of 594 mm and an average annual temperature of 23°C at Dodoma airport (1980 to 2010, TMA, 2013). The land is extensively used for herding and for rainfed crop agriculture. The natural vegetation is dry savanna. Cropping is feasible only during the rainy season from November to April. The most commonly cultivated crops are pearl millet (*Pennisetum glaucum* (L.) R.Br.), sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) as staples. Sunflower (*Helianthus annuus* L.), groundnut (*Arachis hypogaea* L.), bambara nut (*Vigna subterranea* (L.)Verdc.) and sesame (*Sesamum indicum* L.) are planted as cash crops but also for personal use (unpublished data from project household surveys; Institute for Environmental Economics and World Trade, Hannover, Germany). Sporadically, grape cultivation is done, including field preparation with deep furrows, filled with dung as fertilizer. This was more frequently observed in Idifu. Main agricultural constraints are the short cropping period, spatially and temporally variable rainfall, as well as a high share of eroded soils and soils with low chemical fertility, in particular low amounts of plant-available P and low N.

### 3.3.2. Topography, geology and soils

Ilolo exhibits elevations between 1050 m and 1190 m above sea level (asl). The area is more undulating than the Idifu area (which has elevations from 990 m to 1050 m asl). Soil surfaces are usually bare in the dry season. Thus, as in other semiarid areas (Herrmann et al., 1996), water- and wind-erosion play important roles. Geology is variable, reaching from unconsolidated sorted Quaternary sediments over Tertiary intermediary metamorphic rocks to felsic and intermediary Precambrian volcanic rocks (own observations). Geological maps from 1953 and 1967 (Geological Survey of Tanzania, Dodoma) indicate so-called “contaminated granite” as the dominant rock type. However, the resolution of these maps is too low (1:100.000 and 1:125.000) to provide reliable baseline information. These maps declare that about 60% of the Ilolo area and nearly 80% of the Idifu area have “undifferentiated soils”. This information does not coincide with our own observations, which show clear topography-related sequences (catenas), including rocky hilltops, intermediate sandwashed plains and clayey depressions. Additionally the available geological maps were rated as not reliable as they assigned geological units as soils, partly with local soil names and in this way did not provide information about parent rocks.

In quasi-endorheic basins, the accumulation of fine clastic material together with secondary solute-derived accumulations (e.g. carbonate) are found. These basins turn to swamps during the rainy season. Severe erosion is evident in most places arising from overgrazing and deforestation for firewood or additional agricultural land. Soils, except those from the basins, are mostly of low nutrient status and organic matter content. The United Nations Soil Survey Report (1983) specified inadequate moisture availability, low soil fertility status and soil erosion as the major soil-related constraints in the Dodoma region.

### 3.3.3. Population and cropping

The village people in the intervention area almost entirely belong to the Gogo tribe. They were resettled in village communities by the government in 1986 (Liwenga, 2013) in order to decrease overgrazing and land degradation in the Dodoma Region (HADO program, 1973). Most farmers rely on subsistence agriculture, having several fields spread widely over the village area. They remain agro-pastoralists, but to a lesser extent than 50 years ago (Liwenga, 2013).

Sorghum and pearl millet, as staple crops, are grown everywhere. Soil fertility is occasionally intentionally improved by fallowing, application of manure, crop rotation and/or intercropping. For intercropping, bambara nut, chickpea, groundnut or cowpea are planted together with sunflower, sorghum, millet or maize. Planting of staple crops together with legumes, sunflower or vegetables such as cucumber or pumpkin was frequently observed during data collection for this study. Mineral fertilizers are hardly used due to three reasons: i. limited access; ii. limited financial resources; iii. risk of financial loss due to insecure return on investment. Tillage is done with oxen and plough or by hand and hoe. In the latter case, only sowing holes are prepared at appropriate distances according to the grown crop. When available, farmers use oxen and plough. Sometimes oxen are rented. Cattle (mainly oxen or cows) or goats serve as resource capital for hard times. Only better-off households keep herds. The number of animals per farm varies from one up to 20 cows or oxen, or one up to 30 goats as was observed during data collection.

### 3.3.4. Participatory approach

In general, the participatory approach followed methods described in Chambers (1992). Field work was accomplished from November 2013 until March 2014 and during April and May 2015 in Ilolo. In Idifu, it was conducted from September until November 2014 and then in April to May 2015.

First, focus group discussions with people considered to be knowledgeable about the physical village setting were carried out in both CSS for the elaboration of the local soil map. Focus group participants were chosen by the village head. In Ilolo, 11 people including four women from the 11 sub-villages took part in the discussion; 16 participants including two women came from the 16 sub-villages in Idifu. Figure 3-1 displays the scheme used in the mapping process.

In each village, three focus group discussions took place. The first one was dedicated to the introduction of local famers to the objectives of the joint effort and the compilation of known local soil types as well as their delineation on a satellite image. A high resolution (0.6 m * 0.6 m on the ground) satellite image of the village area (size DIN A1 corresponding to 84 cm × 119 cm), printed as a color image, was introduced to the focus groups as a spatial resource.

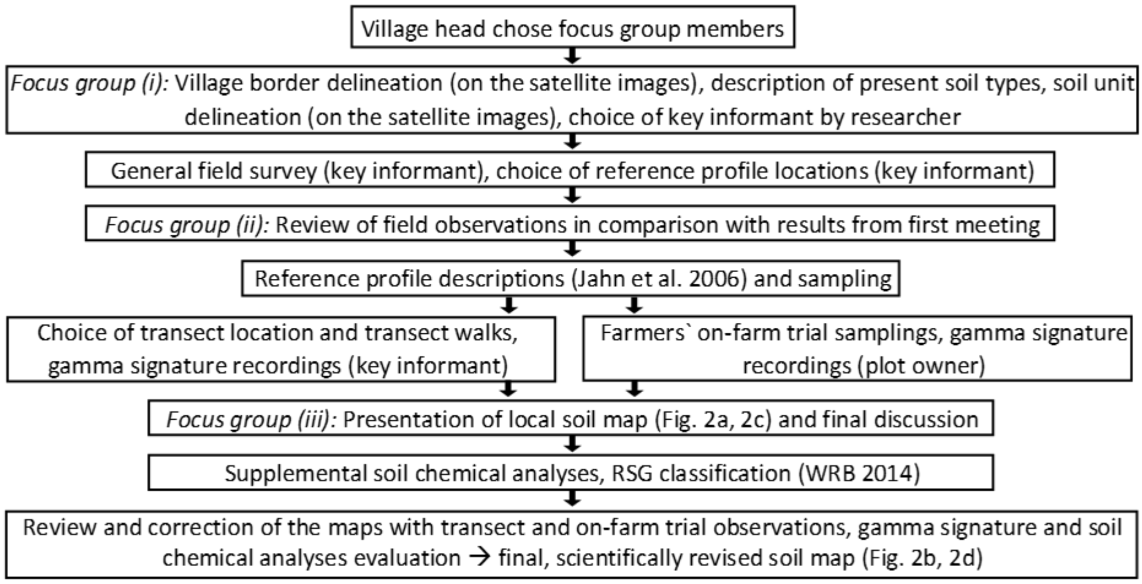


**Figure 3-1** Scheme of the mapping process used in Chamwino, Tanzania, including participatory action, field work and map creation. Information on the stakeholder that assisted during the specific steps is in brackets

The satellite images were taken with a Worldview-2 (WV-2) 4-band sensor for both areas. The recordings of Ilolo were taken on 23/9/2010 and 21/4/2012; those for Idifu on 18/8/2010 and 23/9/2010. To help the orientation of participants, known fix points such as mountains, streets or ephemeral riverbeds were located together on the printout. Guided discussions concerning soil properties and soil unit allocation were held. In this first meeting, the later key informants for assistance in the field and for queries outside of the focus groups were chosen. Selection was done based on observations about knowledge as well as respect from the other focus group members towards the person. During the following field survey with the key informants, the village terrain was overviewed and typical locations for the previously-described local soil types were assigned together with the key informants. A GPS device (GPSmap 62 s, Garmin) was used to record the geographical coordinates. The second group meeting was timed after the first general field survey with the key informants.

It focused on a clarification of terminology as well as map refinement. Afterwards, the reference profiles of the local soil types, chosen with the key informants before, were described (Jahn et al., 2006) and sampled. For map validation and its further refinement, six transect walks with key informants were carried out in each CSS before a final group meeting. Farmers' on-farm trial samplings were carried out concomitant with the transect sampling period. They were done without key informants but in collaboration with the owners of the fields.

**Table 3-1** Overview of participatory soil mapping and sampling actions in Chamwino, Tanzania

| | [a]N | Background | Location | Involved |
|---|---|---|---|---|
| Soil profiles | 5; 5 | Discussions/satellite image, field visits | Farmer-indicated spots for reference soils | Focus group, key informants during visits |
| Transects | 82; 92 | Participatory map/ satellite image | After Graef (1999) and Milne (1935) | Key informants |
| On-farm trial sites | 32; 58 | Workshops with Trans-SEC involved farmers | Farmers' fields | TransSEC farmers |
| Random spots | 10; 12 | Field visits | Randomly | Key informants |

[a]N depicts the number of sampling points for Ilolo; Idifu

These point measurements were used for further refinement and validation of the map. Using information obtained during the transect walks with key informants, on-farm trial sampling and consequent map adjustments, a last meeting was held with the focus group members for final agreement on the jointly-elaborated map.

### 3.3.5. Soil sampling

The reference profiles were described following FAO guidelines (Jahn et al., 2006) and classified after the World Reference Base of Soil Resources (IUSS Working Group WRB, 2015). Soil samples were analyzed in the laboratory (see section Laboratory analyses). Transect locations were chosen using the following rules: (i) they should lead through different map units, (ii) they should at best be located perpendicular to changes in soils and/or landscapes, and (iii) represent more or less straight lines (following Graef, 1999 and the catena concept in Milne, 1935). Additional to transects, soils at the on-farm trial sites of the TransSEC project were described and sampled from 0 to 20 cm and 21 to 60 cm depth. In Ilolo, 32 farmers' field plots were sampled; in Idifu 58 plots. On the transects, augerings to depths of approximately 80 cm (depending on soil hardness to less than 80 cm) were done at sampling locations every 50, 100 or 150 m depending on terrain heterogeneity. Topsoils down to 30 cm were sampled. Soil texture was estimated in the field (Jahn et al., 2006), soil colors were determined using a Munsell soil color chart (Munsell, 2009). The surrounding area was described in a 25 m circumference covering vegetation, elevation and surface characteristics. On-farm trial sites were 10 m X 10 m. Samples were pooled from four augers within the plot. An overview of the participative soil sampling actions is given in Table 3-1.

### 3.3.7. Gamma ray mapping

Gamma ray signatures were measured vertically with the device placed on the bare soil surface using the ground based, handheld spectrometer Gamma Surveyor GRM-260 (Gf Instruments, s.r.o. Geophysical Equipment and Services, Czech Republic) containing a NaI-crystal detector (4 cm3). It was calibrated over calibration pads following IAEA guidelines (IAEA 2003) by the producer. In contrast to airborne gamma ray spectrometry, background radiation does not play a significant role during ground-based measurements. The radiation of $^{40}K$ (1.46 MeV), eU (1.76 MeV) and eTh (2.82 MeV) was determined at each point with a sampling time of three minutes and four repetitions. Gamma ray measurements were done for the reference soil profile spots, transect sampling points and on-farm trial sites. Random spots in the landscape were recorded with the spectrometer during field trips. Reference profile gamma measurements were conducted in a circumference not more than 50 cm away from the profile. During transect walks, the measurements were done at the sampling points described above. Gamma radiation measurements in farmers' testing sites were made in the middle of the 10 m X 10 m plot. Soil moisture and organic matter attenuate gamma radiation but were not relevant in this study as measurements were carried out in the dry season and on soils typically showing very low organic matter contents. Differing soil bulk densities slightly influence captured soil volumes for gamma ray spectrometry (de Groot et al., 2009) but were not considered to be large as only top soils were captured during gamma ray measurements.

### 3.3.8. Laboratory analyses

For reference profile characterization, laboratory analyses concerning pH in water (Landon, 1984), electrical conductivity (Herrmann et al., 1996), total C and N (Elementar Macro, Heraeus, Germany), plant available P and K (Bray and Kurtz, 1945), carbonate content (gasometric method after Scheibler, DIN 18129-G - ISO 10693), cation exchange capacity and exchangeable base cations (Chabra et al., 1975), bulk density (Blake and Hartge, 1986) and texture (pipette method after Köhn, DIN ISO 11277) were carried out in the laboratories of the University of Hohenheim in Germany. The resulting scientifically-revised participatory soil maps were generated with QuantumGIS Version Lyon 2.12.

## 3.5. Results and discussion

### 3.5.1. Local soil map

Initially focus group farmers had difficulties in orienting themselves on the "birds-eye" perspective satellite image, since this was a new experience for them. However, due to the high resolution of the satellite image that allowed them to identify each single tree and farm house, participants quickly acquainted themselves. The delineation of the village boundaries caused lively discussions since these might be defined differently by village members and state authorities. Farmers in both villages pointed out that there have been reallocations of land over the years but could finally and commonly agree on village boundaries. These were mostly related to easily identifiable landmarks such as streets, ephemeral riverbeds or mountains. They were checked on later field trips and confirmed to be located in the expected places.

The next intended step was to identify the existing soils and their properties. This was a delicate step since terms and concepts are not the same in all languages and translation might consequently alter the original statement (Herrmann, 2013). At a very early stage in the discussions, the Swahili word "udongo" (that literally means soil) and further expressions like "kichanga" /sand or "mfinyanzi" /clay appeared. This implied that the term and concept of soil also appears in the Gogo language of the participants and that translation did not lead to great mis-representation of participant statements. The main criteria to distinguish local soil types were topsoil colour and texture, fertility, workability and water holding capacity, in that order. This finding corresponded with the experience reported by Barrera-Bassols and Zinck (2003) in their overview about ethno-pedology. Three of these terms describe intrinsic soil properties and one each relates to a soil function or cultivation practices, and as such are anthropocentric. Across the two villages, soil properties were conformably attributed to the local soil types. Table 3-2 shows soil denominations and related property descriptions given by members of the focus groups as well as the corresponding WRB Reference Soil Groups (the latter based on analyses of reference profiles).

Already during the first focus group meeting, farmers were able to delineate the borders of soil units within their particular village territory. In both CSS, key informants drew the soil units on the satellite images during an animated discussion. Color differences of the images served as major points of adjustment

**Table 3-2** Local soil denomination of comparable soils and their respective properties in Ilolo and Idifu villages, Dodoma region, Tanzania, with corresponding WRB Reference Soil Groups

| Local soil denomination | | WRB classification | Locally stated soil properties |
|---|---|---|---|
| Ilolo | Idifu | (2014) | |
| Mbuga (swamp) | Mbuga (swamp) | Sodic Vertisol (hypereutric) | Black, surface cracks and very hard when dry, very sticky when wet, fertile, hard to plough or cultivate, retains water for a long time, some areas salt affected |
| Mfinyanzi (clay) | Kichanga mwekundu (red sand) | Chromic Lixisol (hypereutric)[a] | Red, breaks into aggregates, sticky when wet, retains water if infiltration happens, high run off, fertility adequate, plough-able with hoe or plough, fertility improvable with fertilizer |
| Tifu tifu (dust) | Kichanga mwekundu nyika (red mixed sand) | Chromic Lixisol | Reddish, dusty, fertility adequate, easy to plough or cultivate, low moisture retention |
| Kichanga (sand) | Kichanga mweupe (white sand) | Haplic Acrisol | White/reddish, sandy, loose, high infiltration rate, low moisture retention, least fertility |
| Ikanganyika (mixed soil) | - | Cutanic Stagnic Luvisol (hypereutric) | Grey, surface cracks, hard when dry, good fertility, similar to Sodic Vertisol (hypereutric) but easier to cultivate, water logging after rain |
| - | Kichanga nyika (mixed sand) | Chromic Lixisol (loamic) | Reddish, sandy, fertility adequate, similar to Chromic Lixisol above but coarser texture |

[a]This soil was found as Chromic Lixisol (hypereutric, profondic) in Ilolo

for delineation, but the group scrutinized nearly every line. Only swamp areas were identified without questioning due to a distinct dark grey topsoil colour, which was also clear on the printouts. The farmers in Ilolo quickly listed the main soil units. Only the spatially restricted Luvisol was mentioned after some time of further reflection and discussion. Participants from Idifu had more problems to recall the relevant soil units and their spatial distribution. There were some differences of opinion. Hilltop soils were not mentioned during the discussions in both CSS. On prompting, farmers offered no explicit denomination for these soil units. They stated that hilltop soils were not relevant for cropping and, therefore, they did not need a name for them. The resulting preliminary local soil maps of both villages are shown in Figure 3-2a (for Ilolo) and 3-2c (for Idifu).

Two cases of language disorientation occurred during the focus group discussion in Ilolo, apparently because the translator had insufficient command of the local Gogo language, and was fully conversant only in Swahili and English. In the first case, group members used Swahili and Gogo words for the same soil unit. Hence, two soil units were noted. This misunderstanding was clarified later during the delineation of the soil unit boundary. In the second case, the Gogo expression “nghuruhi” was misleadingly translated to “mfinyanzi”/red clay in the first focus group discussion. Because a reddish soil of different texture (“tifu tifu”/dust) was found during field trips, this misapprehension was noticed. In the second clarification meeting, the distinction between the soil units was discussed. The initial “nghuruhi” unit was finally divided into the “tifu tifu”/dust and the “mfyinyanzi”/clay unit. In Idifu, in part due to this experience, no such language confusion occurred.

Follow-up field surveys were done to get a general idea of the soils in the study area and their distribution across the landscape. During the field survey, one soil unit was discovered in Ilolo which was not mentioned in the first group meeting. Subsequently, reference profile locations were defined in the field after inspection of the first draft map and consulting the key informant.

During the field stay for data collection, it turned out that people are compelled to cover large distances to cultivate all their fields, leading to comprehensive knowledge about their land. Farmers plant crops related to their understanding of soil fertility or other attributes, e.g. groundnut in well-aerated shallow soils, and vegetables mainly in the seasonal swamps with available irrigation water at shallow depth and with high chemical soil fertility. It was striking that local farmers in Ilolo were more aware of the soil unit locations than were focus group farmers in Idifu. In Ilolo the recognized additional soil unit was discussed and then added to the local map. Since farmers in Idifu seemed to know less about soil locations, the second discussion was necessarily more detailed. Locations and dimensions of several soil units had to be changed, even though all the soil units found to occur in Idifu had been mentioned during the first discussion. Both local soil maps were improved afterwards using the knowledge gained from field surveys and extra discussions.

Use of the reference profile classification, transect walks and on-farm trial visits revealed the need to correct the map unit delineations. No new soil types were discovered during the final mapping phase. In the third group meeting, all changes to the local maps were agreed on by the focus group members. Final corrections to the maps were based on the listed activities, soil analytical results and gamma signature measurements. Figure 3-2b (for Ilolo) and 3-2d (for idifu) represent the scientifically revised soil maps and include reference profile, on-farm-trial and transect locations.

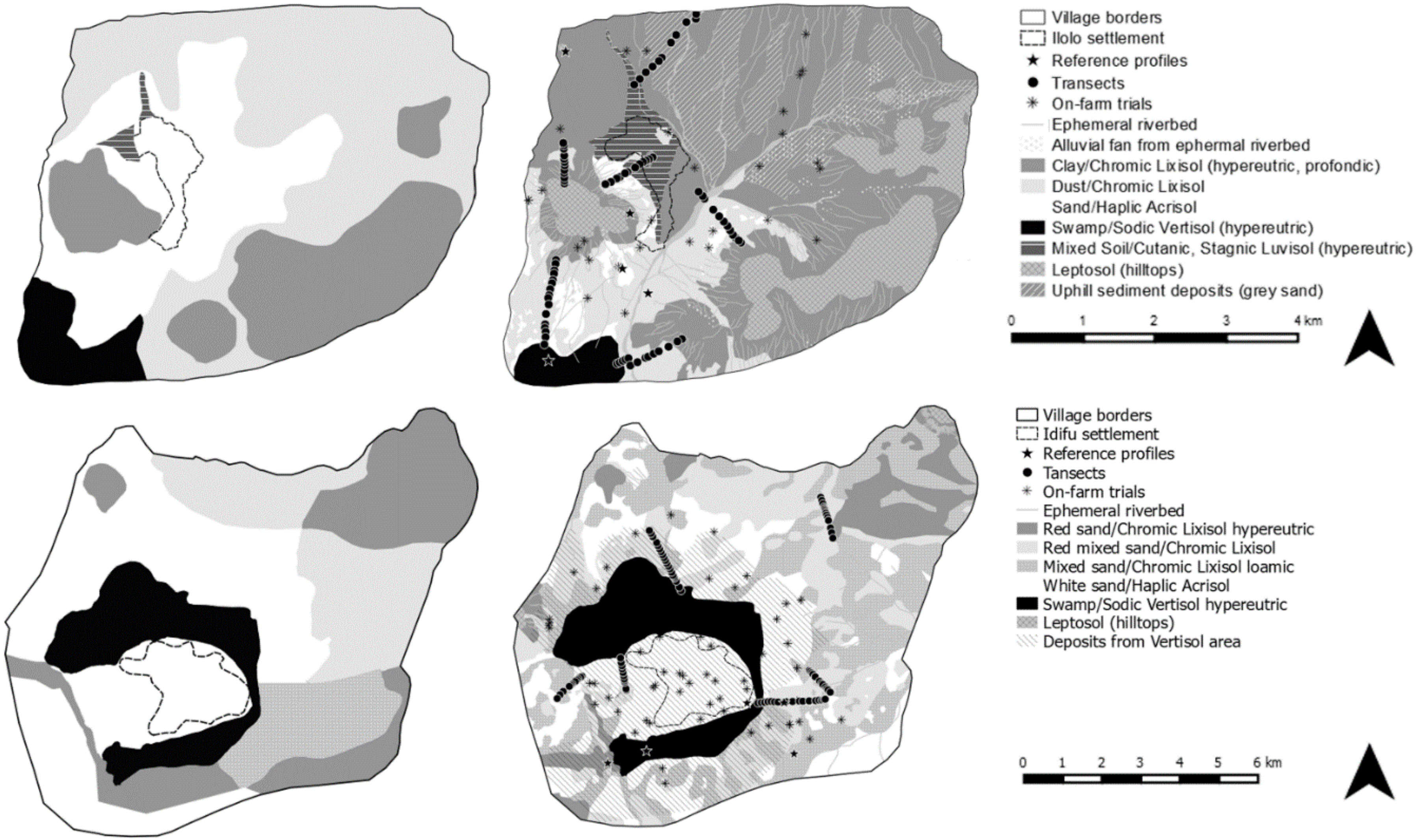


**Figure 3-2** Preliminary local soil maps of Ilolo and Idifu in Chamwino, Tanzania, on the left (a, c) and the final maps on the right side (b, d) after the field visits, reference profile, transect and on-farm trial assessment with gamma ray spectrometry

### 3.5.2. Soil characterization according to WRB 2014

The main soil forming process observed in both CSS was clay illuviation. Lixisols on slopes and Acrisols in flat areas covered the major parts of the village territories. Typical catenas were Leptosol–Lixisol–Acrisol–Vertisol, especially distinct in the undulating landscape of Ilolo. The lower landscape positions appeared as depressions with restricted surface drainage. During heavy rainfall events, finer particles together with solutes are transported to these depressions. In consequence, Vertisols have developed from these clayey substrates. In the rainy season, the depressions transform to swamps. In the early dry season they allow for vegetable cropping under irrigation. The available geological maps (Geology Survey of Tanzania, sheet Dodoma and Mpwapwa, 1:100.000 and 1:125.000, 1967 and 1953, respectively) depict a considerable area classified as Mbuga, which is the local soil name for the swamp area with its dark and heavy soils (Liwenga, 2013). However, the obtained mapping results did not spatially coincide with the geological map units. Instead, mainly Lixisols and Acrisols were detected. A particularity in Ilolo was the presence of a Cutanic Stagnic Luvisol (hypereutric). This is characterized by higher chemical fertility than the more common soils in the study area. The assumption, based on the gamma radiation measurements (Fig. 3-3), was that it developed from another parent material. However, this is not supported by the geological map (Geological Survey of Tanzania, sheet Dodoma, 1:100.000, 1967 and sheet Mpwapwa, 1:125.000, 1953). Hilltop soils in both CSS were identified in the field as Leptosols. They were not investigated in detail since they are not relevant for cropping. According to farmers, substantial deforestation occurred between 2003 and 2005 to clear land for extra cropping areas. Severe water-based erosion, but also aeolian erosion was the consequence, and obvious signs of this were visible in the terrain. Gillman (1930) already identified erosion to be substantial in these areas from the beginning of the twentieth century. In the United Nations "Soil Survey Report of Dodoma Capital City District" (1983), erosion was noted to be a threat for agriculture in the study region, mainly as sheet erosion and splash erosion. In contrast, Eriksson and Christiansson (1997), who published several reports about erosion in central Tanzania, identified severe gully erosion. Both forms of erosion were observed in the study area. Several villagers reported that Idifu generally receives less rainfall than Ilolo. Project-compiled rainfall data of the last two seasons support this statement. Other weather data were not available. A mountain range located in the south east of Idifu prevents rain clouds from passing over the village territory. In Ilolo, fatal gully erosion with depths of 10 m or more was monitored throughout over the village area. Eroded hilltop soil from a mountain range to the North, outside the village area, was transported to the northern area inside the village and covered the Chromic Lixisols (hypereutric, profondic) on the slopes (Fig. 3-2b). In Idifu, fewer gullies were found. Nevertheless, erosion processes were obvious even for Vertisol topsoil material, which was transferred by wind erosion (Fig.3-2b). Idifu exhibited a smaller relief gradient and, thus, planar dislocation was present to a higher extent.

In general, across the two villages, the WRB Reference Soil Groups were similar with respect to classification and fertility, but noticeably different for texture. Generally, the sand content was higher in Idifu.

### 3.5.3. Gamma ray spectrometry

The first gamma ray measurements were made on the reference soil profiles. The collected signatures served as a reference for spatial and classificatory correlation. During transect walks, soil type transitions were recognized via signature changes. The $^{40}K$ signal appeared as the best proxy to indicate changes in soil type in the study area. A pre-requisite here is the absence of mineral K fertilization, since the application of K fertilizer might change the gamma ray signature (Nisar et al., 2015). Figure 3-3 shows the change of $^{40}K$ and $^{40}K/eTh$ ratios along a slope in Ilolo. Both values decreased down the slope. The expected main reason for this is the redistribution of soil material through water erosion. Due to erosion, the fresh parent material was located closer to the surface on hill tops (high K concentration and high $^{40}K/eTh$ ratio). In this case, the eroded sandier material was deposited downslope, covered the bedrock and thus suppressed its signal. Since the eroded material has experienced weathering, a share of the K was leached, leading to lower overall K concentration and, in consequence, lower $^{40}K/eTh$ ratios. Decreasing $^{40}K/eTh$ ratios down the slope were also observed in a study by Wilford and Minty (2006) near Cowra, New South Wales, Australia. These authors described the loss of K during weathering and its leaching in a soil profile. Thus, low $^{40}K/ eTh$ ratios point to weathered soils.

In Figure 3-3, section A refers to a Leptosol, section B to a Chromic Lixisol (hypereutric, profondic). Section C was identified as a Chromic Lixisol. In section D an exceptional soil for the study area (a Luvisol) was found; it occurred only at this location in Ilolo. The difference between a Lixisol and a Luvisol is the composition of clay minerals. These are dominated by so-called low-activity clays

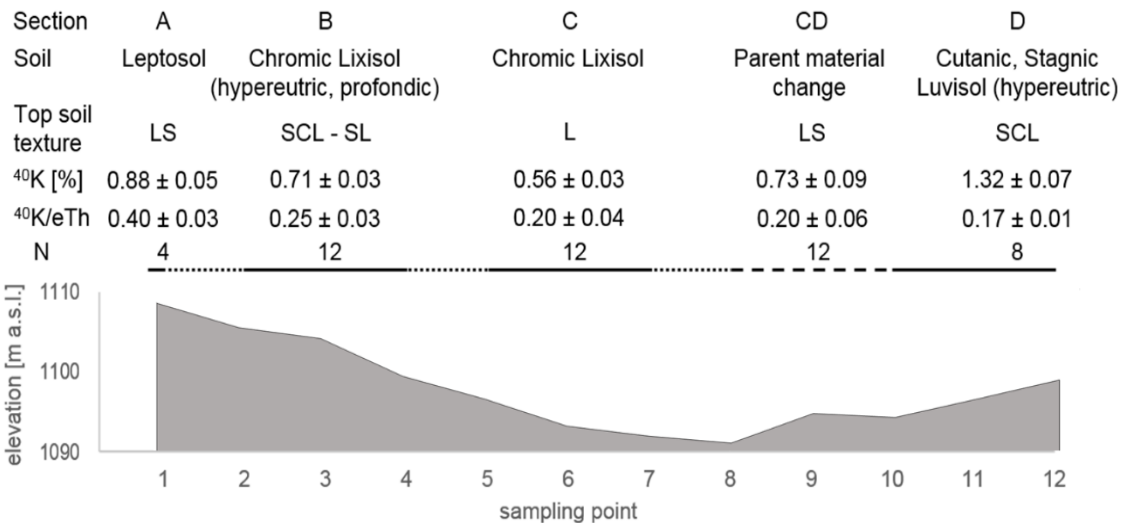


**Figure 3-3** Example of a transect cross-section through Ilolo with corresponding gamma ray $^{40}K$ signature means ± standard deviations as well as $^{40}K/eTh$ ratios. N depicts the number of samples. Sampling point distance was 50 m. Means and standard deviations were taken from specific points within one soil type. Continuous bars integrate all sampling points of one soil type. Dotted bars mark transitions between soil types. The dashed line stands for a slow transition from section C to D. A = Leptosol, B = Chromic Lixisol (hypereutric, profondic), C = Chromic Lixisol, D = Luvisol.

in Lixisols (e.g. kaolinite) indicating advanced weathering status, whereas Luvisols are characterized by high activity clays (e.g. illite, smectite). The difference in clay mineral assemblage as well as the high K concentration at simultaneous low $^{40}K/eTh$ ratios indicated a change in parent material. Schuler et al. (2011) found a $^{40}K/eTh$ threshold for distinguishing high activity clays from low activity clays. Because in the study area nearly exclusively low activity clay soils were present, this threshold could not be proven. Nevertheless, similar findings with low K and relatively high Th concentrations in Acrisols were observed. In both of the studied villages, Acrisols and Chromic Lixisols (both containing low activity clays) were found to have low $^{40}K/eTh$ ratios. In contrast, nearly un-weathered sediments from uphill locations exclusively shared $^{40}K/eTh$ ratios greater than or equal to 0.27 (upper quartile). Leptosols were also found to have $^{40}K/eTh$ ratios from 0.25 upwards, with one exception. The parent material of this exceptional Leptosol was highly-weathered saprolithic gneiss.

### 3.5.4. Local versus scientific knowledge

Since farmers consider other classification variables compared to those used by scientists, farmer soil classifications follow different rules. In particular, our farmers used observable topsoil properties, i.e. those in the first 15 cm. In Idifu, people also mentioned subsoil color and texture as separation criteria. This goes back to their experience with grape cultivation that includes digging soils down to 50 cm depth for ridging.

All farmers used topsoil colors to delineate soil units, but not exclusively. Additionally they were able to further differentiate soils according to their texture and fertility, based on their tillage and cropping practices. According to WRB, the soils in both villages were nearly identical by classification, whereas the local denominations differed. Local farmers used soil texture as a distinctive soil property. Ilolo farmers were able to distinguish the local soil types “kichanga”/sand, “tifu tifu”/dust and “myinyanzi”/clay, based on their soil texture. Idifu, in general, has sandier soils. This was proven by textural analysis. In consequence, the additional distinction of sandy soils by colour played a more important role, e.g. “kichanga mweupe”/white sand, and “kichanga mwekundu/red sand. For the Reference Soil Groups in question, the WRB classification does not consider absolute texture but instead relative textural changes within the vertical horizon sequence, except in the case of Vertisols.

Soil texture and water holding capacity ratings were properly indicated by local farmers and scientifically comprehensible. Local farmers judged the chemical soil fertility status of their soils as unsatisfactory but still suitable for cropping. Plant available K was found to be high in all sampled locations (rated after Landon, 1984). Deficits were determined for P and N contents. The higher P contents in Idifu arise from grape cultivation and associated field preparation with dung as fertilizer. Electrical conductivity, as well as pH values, were found unremarkable with the exception of high values for Vertisols. Vertisols were considered to be exceptionally fertile in farmer discussions as well as from interpretations of the soil analyses.

However, the physical properties of Vertisols were identified to present problems in both participatory and analytical investigations since these soils are hardly

**Table 3-3** Means and standard deviations (SD) for major nutrients in on-farm trials in Ilolo and Idifu, Tanzania

| | Depth [cm] | $N_t$ [%] | SD | $C_t$ [%] | SD | Bray P [mg kg$^{-1}$] | SD | Bray K [mg kg$^{-1}$] | SD |
|---|---|---|---|---|---|---|---|---|---|
| Ilolo | 0-20 | 0.04 | 0.01 | 0.37 | 0.07 | 6.0 | 4.2 | 195 | 50 |
| (N = 32) | 21-60 | 0.02 | 0.01 | 0.26 | 0.04 | 1.9 | 2.4 | 152 | 55 |
| Idifu | 0-20 | 0.03 | 0.01 | 0.41 | 0.07 | 12.9 | 6.9 | 216 | 70 |
| (N = 58) | 21-60 | 0.03 | 0.01 | 0.33 | 0.06 | 3.7 | 2.3 | 162 | 55 |

N depicts number of samples, $N_t$ total N, $C_t$ total C, P and K plant available potassium. Outliers were eliminated using the Grubbs test (5%) (Microsoft xlsat, Version 2016.02.27913). (Since no carbonate was detected $C_t$ equals $C_{org}$)

cultivable during the rainy season. Farmers described these soils as not possible to walk on after heavy rains. An overview of soil basic nutrient contents from on-farm trial locations is given in Table 3-3. Lixisols, as a major soil group, are the most common soils in Ilolo. In focus group discussions, farmers indicated them to be adequately fertile and good to farm; accordingly many of the on-farm trials were located there. Acrisols were described to be the least fertile. These assessments are supported by scientific analysis.

After finalizing actions in the field related to participatory mapping and the comparison of local and scientific findings, further refinements to the map were necessary in both CSS. Shorter distances within a smaller village area and, thus, less unfamiliar territory was one reason why the local soil map of the smaller village (Ilolo) was more coherent than the one from the bigger village area (Idifu). Moreover, eye-catching soils like red clay or black swamps were pinpointed most precisely in contrast to less characteristic soils and their boundaries such as the brighter Acrisols or Lixisols. Concurrently, the eye-catching soils were the more fertile soils in the region.

Particular soils in areas with little agricultural activity had to be rearranged on the maps. In Ilolo, these were rather remote from the village centre. There, a map refinement gradient was observed from densely populated areas to less frequented regions like the north of Ilolo, which is a mountainous territory, unsuitable for agriculture. Consequently, farmers rarely visit their plots there, farmers commented in the final discussion. Many deep erosion gullies and only a few crop fields were found there. During the first discussion, farmers just assumed the soil types in this area since no focus group member was familiar with the area. Furthermore, the investigated “myfinyanzi”/clay in this area could easily be mixed up as deposits from hilltops made the topsoils dustier and brighter, similar to the “tifu tifu”/dust that was indicated in theparticipatory discussion. Gamma signatures, supported by supplemental laboratory results, showed the presence of “myfinyanzi”/clay. Furthermore, gamma spectrometry measurements indicated a larger extent of the participatorily identified “ikanganyika”/mixed soil area. Consequently, this was changed on the map. The big area of “kichanga”/sand was changed to “tifu tifu”/dust. The reason for the different indication could not be identified in the meeting but participants agreed that the renaming of the soil type was correct. In Idifu, the soils directly around the center of the village but outside the swamp-belt were less known by focus group members. Those were the less fertile soils within Idifu, whereas the relatively fertile “kichanga mwekundu”/red sand at the northeastern border was well known. Sandier soils make roads more exhausting to move on. In consequence, people in Idifu visit their fields less frequently for management.

### 3.5.5. Risks, strengths and weaknesses of the method

Formation of the focus groups posed the first problem for the research team. In an unknown area and society, researchers do not have the experience to identify apt co-operators. Extension staff often change in such remote areas, so they do not either. The normal choice is therefore to consult the village head and let him choose experienced people from the study region. In our case, the only condition was to invite people from all sub-villages that were familiar with the village territory. As the village heads were elected by the local people, the latter respected and trusted the advice of the former to participate. To conclude, the village head was the only person who could find the right persons to elaborate the soil map.

Women were present during the focus group discussions. With two exceptions, they appeared shy and not self-confident. In Ilolo, two of the four women were recognized to be active and highly respected during discussions. In Idifu, however, this was not the case; the two women who were sent as representatives for their husbands did not share their opinions. This led to the necessary map corrections in the southeastern part of Idifu later on. Females remain highly disadvantaged with education and capital although they take over a big share of agricultural activities (Osorio et al., 2014).

Language barriers posed a further constraint. Cross-checks concerning denomination, completion of present soil units and delineation should always be carried out, and repeated. Translators that are versed with local tribal languages or group members having English skills are favorable. Researchers with local experience are of great advantage as people develop more trust and respect for them. Researchers living in the village gain experience of local livelihoods making mutual understanding easier. Especially in remote areas, local networks make it possible to get additional and more valuable information, e.g. about land use history from neighbors or other people.

Choice of the translator and local field assistant is of greatest importance. Local language skills, knowledge of local terrain and high profile of the key informant help facilitate the work. During the first focus group discussion, it became recognizable who had a good overview about the territory and whose opinion was respected.

In both villages, people tired after a two-hour meeting which resulted in decreased concentration and participation. Group meetings should be limited in time and breaks included (NOAA Coastal Services Center, 2009). Main tasks like the allocation of village boundaries and soil unit boundary mapping should be completed at the beginning of the discussion; easier tasks like the description of soil properties at the end. Great advantages were the rapidness of the land overview via group discussions as well as the capacity to draw on decades of experience. A satellite image and discussions with local participants led to a draft map and created fast initial orientation in the area. Residents could pass their experience, including land changes influencing soil forming processes like resettlements or deforestation, to the scientists leading to a better and quicker understanding of the terrain.

Gamma radiation approaches included weaknesses and strengths. Whereas the $^{40}K$ (on unfertilized plots) and eTh signal are stable and reliable, the eU signal should be used with caution for direct interpretation. Several interferences like $^{222}Rn$ disequilibria influence the eU signature and make interpretation barely feasible (IAEA 2003). Signals for eU have been reported to show diurnal patterns of emanation from the top soil (Schubert and Schulz, 2002). This was not verifiable as different soil locations were tested during the day. Schuler et al. (2011) carried out a classification tree analysis and underlined the use of $^{40}K$ and eTh signals for further interpretation. For the interpretation of gamma signals, first it was necessary to record gamma radiation from the reference soil profiles to get an idea of specific signatures. Nevertheless, it was not possible to strictly follow these reference signatures. A unique fingerprint cannot always be identified with gamma signatures which profoundly depend on radionuclide composition, i.e. on soil weathering stage and parent material (van der Klooster et al., 2011). Texture (Petersen et al., 2012), bulk density (Taylor et al., 2002), water content (Hubbell and Berger, 1968), organic matter (Beamish, 2013) and additional radiation signals from large stones (IAEA, 2003) can all affect the local gamma signature. As organic matter content and soil moisture were very low, these did not play a role. Changes in radionuclide compositions were easy to determine in situ. Recognizing soil unit changes in the field was uncomplicated. The $^{40}K$/eTh ratio was able to give information about the relative age and leaching stage of the soil on the spot. Even so, different soil forming processes had to be considered before drawing conclusions. Eroded and colluvial domains manipulated the signatures from autochthonous undisturbed soils. Augerings showed deeper soil horizons sometimes to differ, creating signatures other than those expected from topsoil appearance alone. This is why closer area monitoring was necessary. Diurnal top soil moisture differences can be excluded in this environment in the dry season.

It is still not clear from which depths gamma rays are recorded in soils. Theoretical assumptions by Beamish (2013) suggest depths of about 40 cm. Wilford and Minty (2006) have worked with 35 cm depth, others with 30 cm (van der Klooster et al., 2011). All these are based on a publication from Hubbell and Berger (1968) theoretically investigating rock without quant scattering (again reviewed by Grasty (1979)). In summary, soil signal depth assumptions are inexplicit. Under the conditions of this study, expectably, gamma ray measurements have delivered information from at least the top 40 cm, i.e. the active rooting zone. Thus, some of the soil units could not have been adequately related to map units if gamma radiation signatures were unavailable. Gamma ray spectrometry was found to be a good way to bypass complex mapping procedures or elaborate analyses.

### 3.5.1. Application in the Trans-SEC project

The following description of Ilolo soil sampling results serves as an example for both case study sites. Reference profile locations are pictured in Figure 3-2b and 3-2d. Table 3-4 summarizes the importance of soil differentiation for extension using Ilolo reference profile data consisting of weighted averages of values for various soil properties from topsoil to 30 cm depth. Only $C_{org}$ and $N_t$ values were rated very low (Landon, 1984) throughout the sampled soils. Farmers remove plant residues from their fields for diverse reasons or let animals feed on them. These practices are widespread in the tropics (Bot and Benites, 2005).

**Table 3-4** Means for various soil properties of sampled reference profiles in Ilolo, Tanzania (weighted averages related to horizon thickness, number of observations per horizon N = 2)

| | **pH** ($H_2O$) | **EC** [µS $cm^{-1}$] | **$N_t$** [%] | **$C_C$** [%] | **$C_{org}$** [%] | **P Bray** [mg $kg^{-1}$] | **K Bray** [mg $kg^{-1}$] | **BS** [%] |
|---|---|---|---|---|---|---|---|---|
| **Haplic Acrisol** | 5.0 | 71 | 0.06 | n.d. | 0.31 | 6.6 | 148 | 49 |
| **Chromic Lixisol** | 5.5 | 84 | 0.05 | n.d. | 0.27 | 5.3 | 230 | 57 |
| **Chromic Lixisol (hypereutric, profondic)** | 6.5 | 92 | 0.06 | n.d. | 0.33 | 0.3 | 115 | 72 |
| **Cutanic, Stagnic Luvisol (hypereutric)** | 8.6 | 158 | 0.05 | 0.1 | 0.29 | 11.7 | 289 | 76 |
| **Sodic Vertisol (hypereutric)** | 8.7 | 1501 | 0.08 | 0.3 | 0.62 | 0.3 | 234 | 81 |

EC was unremarkable, values are not shown here, $N_t$ total N, $C_C$ carbonate C, $C_{org}$ organic C, P Bray is plant available phosphate and K Bray plant available potassium. BS is base saturation. All means were calculated from weighted averages for the top 30 cm (n.d. = not detectable)

All other values were divergent among the soil types. pH plays an especially important role for nutrient availability. pH increased to critically alkaline values in the sampled Cutanic, Stagnic Luvisol (hypereutric) and Sodic Vertisol (hypereutric). Available K was rated medium for Haplic Acrisols and Chromic Lixisols (hypereutric, profondic) and high for all other soils (Landon, 1984). Phosphate contents differed but were all rated very low (Landon, 1984) except for the Cutanic, Stagnic Luvisol (hypereutric). Here, pH values must be included in site adapted cropping recommendations. Base saturation, and thus the amount of nutrients like K, Ca or Mg, serves as a good indication of differences in soil fertility. Why should it be reasonable to suggest only one universal soil amelioration strategy for different soil units with different properties then? The results show the need for recommendations that are adapted to variation in soil fertility. Extensionists should avoid general suggestions about fertilization strategies so as not to waste the limited capital of local farmers. Using local soil knowledge together with gamma spectrometry can help extensionists to carry out soil evaluation and hence give farmers recommendations that are adapted to individual soil units with local denomination. Overall, globally there is need for more local soil characterization to reduce land degradation and improve food security.

### 3.6. Conclusion

The applied soil map creation process described in this article, involving the combination of local soil knowledge investigation and gamma ray spectrometry, was rapid and simple. Satellite images served well as a start. Discussions with local farmers resulted in accelerated terrain orientation, an overview of soil diversity and map creation. Persons with a sound knowledge of properties of the physical terrain are essential for efficient progress. Focus group members, translators and key informants must be chosen carefully. Cross checks are, however, inevitable to avoid map inaccuracies. Despite the need for a considerable amount of circumspection and revision, the participatory action approach expedited field work and map creation. Together with gamma ray spectrometry as a facilitating method for the distinction of soils directly in the field, these methods can quickly establish soil maps at sufficient resolution for their use by extensionists in developing countries. Satellite image costs fall below expenditures for traditional scientific mapping approaches. Additionally, part of the laboratory work for the distinction of soil types became redundant. Thereby, map inaccuracies could be eliminated. Further development of gamma ray spectrometry will make it more useful for rapid soil mapping by increasing signal interpretation abilities. Additional applications such as the mapping of soil nutrient deficiencies are imaginable.

Gamma ray spectrometry will be especially useful in difficult-to-access terrains, where soil mapping in the traditional way might not be feasible. Airborne gamma ray spectrometry will deliver results for even larger areas in a faster way. Nevertheless, some ground validation will still be necessary where variable interferences like organic matter content, soil or air humidity are present as approaches to correct these are underdeveloped. Gamma ray spectrometry (both air-borne and in situ), is to be further tested for the description of soil properties.

### 3.7. Acknowledgements

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# 4. Application of $^{40}K/^{232}Th$-ratios for clay illuviation Reference Soil Group distinction – a case study

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## 4.1. Abstract

There are indications that gamma-ray spectrometry can serve WRB Reference Soil Group (RSG) distinction - in particular for those which developed from clay illuviation as major soil forming process (i.e. Luvisols, Lixisols, Acrisols, Alisols). This case study used the $^{40}K$/eTh ratio to separate RSGs in two villages in central Tanzania. For this purpose, gamma-ray measurements of reference profiles, transects and randomly selected farmers' plots were conducted. Bivariate mixed models were applied after graphical pre-analysis. They distinguished 47 out of 82 soils correctly. Soils that were not distinguishable by $^{40}K$/eTh ratios were, however, easily discriminable in the field due to topographic location in the catena, and visual and haptic appearance. In conclusion, gamma-ray measurements can only be a supportive tool for soil mapping. Gamma-ray data alone do not provide sufficient information for consistent mapping.

**Key words**: soil mapping, bivariate mixed model, gamma-ray spectrometry

## 4.2. Introduction

In developing countries, high resolution soil maps are generally lacking. In certain environments, map generation is difficult due to inaccessibility and lacking laboratory facilities. However, soil information is of high importance for different stakeholders like farmers, extension services, non-governmental organizations, researchers and even governments in order to recommend site-adapted amelioration strategies.

Soils are usually heterogeneous within short distances, and different WRB Reference Soil Groups (RSG) intergrade into each other. In Sub-Saharan Africa countries, soil heterogeneity is, next to parent material, climate, relief and biota, specially connected to anthropogenic influences, i.e. fertilization with manure or household waste and irrigation near homesteads, particularly in subsistence farming environments (Zingore et al. 2007). Clay illuviation RSGs after WRB (IUSS working group, 2015), i.e. Luvisols, Lixisols, Acrisols and Alisols are differently classified, only according to exchange capacity and base saturation. For instance, an Acrisol can change to a Lixisol by base saturation increasing nutrient input.

Soil mapping is known as laborious task (Schuler et al., 2011). Laboratory analyses make it even more cost-intensive. Nowadays, modern scientific methods simplify soil mapping. Gamma-ray spectrometry, as such a method, was identified to have great potential for soil properties prediction and RSG allocation refinements (Bierwirth et al., 1998; Schuler et al., 2011; Wilford and Minty, 2006). It is a non-invasive technology, determining the natural radionuclides 40-potassium ($^{40}K$), 232-thorium ($^{232}Th$) and 238-uranium ($^{238}U$), which are differing in dependence on (1) mineral composition of the parent material, and (2) soil forming processes (Rawlins et al., 2012). Current field gamma-ray spectrometers measure $^{40}K$, $^{232}Th$ and $^{238}U$ concentrations by counting gamma decays of a certain soil volume per time. Soil moisture or organic matter attenuate gamma radiation from soils. Potassium-40 directly decays to $^{40}Ar$, $^{232}Th$ and $^{238}U$ contents, however, require indirect determination via the decay of their daughter nuclides $^{214}Bi$ to $^{210}Tl$ (denoted as eU) and $^{208}Tl$ to $^{208}Pb$ (denoted as eTh). Secular equilibria within those decay series are, thus, of importance for reliable measurements, especially in the case of eU.

So-called fingerprinting, i.e. connecting specific gamma signatures to local reference soils, helps to identify soil types in the landscape (Loonstra and Van Egmond, 2009). Gamma ray spectrometry can as well serve for map refinement (Schetselaar et al., 1999), weathering stage (Wilford, 2012) and erosion pattern determination (Martz and De Jong, 1990). Established measurement modes are (1) stationary in near proximity to the soil surface, (2) proximal and mobile attached to vehicles or in backpacks, and (3) airborne in airplanes, helicopters, or drones as remote sensing method.

The present study was carried out in the framework of the Trans-SEC project (Innovating strategies to safeguard food security using technology and knowledge transfer: a people-centred approach). For this purpose, village soil maps were generated with participatory means and gamma-ray spectrometry (Reinhardt and Herrmann, 2017). In this case study, distinction of major clay illuviation RSGs in the intervention area by graphical and statistical analysis of $^{40}K/^{232}Th$ ratios is investigated in detail.

## 4.3. Material and Methods

### 4.3.1. Study area

The study area is located in central Tanzania, Chamwino district. Two villages were mapped and investigated: Ilolo (E35°59´11” S6°25´13”, approx. 26 $km^2$, 1050-1190 m above sea level) and Idifu (E35°54´50” S6°20´26”; approx. 90 $km^2$, 990-1050 m above sea level). Climate is semi-arid with annual average rainfall of 594 mm and average temperature of 23°C at Dodoma airport weather station (1980 to 2010, TMA 2013). Next to herding, local farmers depend on rain fed agriculture. Cropping of pearl millet (*Pennisetum glaucum* (L.) R.Br.), sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) as main staple crops, and sunflower (*Helianthus annuus* L.), groundnut (*Arachis hypogaea* L.), bambara nut *(Vigna subterranea* (L.)Verdc.) and sesame (*Sesamum indicum* L.) as cash crops and for self-consumption is common.

Geology is diverse; on field surveys, unconsolidated sorted Quaternary sediments, Tertiary intermediary metamorphic rocks, as well as felsic and intermediary Precambrian volcanic rocks were identified. Typical soil units are Leptosols on eroded hill tops, Lixisols on slopes and Acrisols in lower landscape positions. In quasi-endorheic basins, Vertisols have developed. Aeolian and water erosion are widespread phenomena that are caused by high population pressure and overgrazing leading to uncovered soils. A more detailed area description is given in Reinhardt and Herrmann (2017).

### 4.3.2. Gamma-ray surveys

Soil mapping was carried out as described in Reinhardt and Herrmann (2017). A preliminary map was generated together with local farmers in focus group discussions using high resolution color print satellite images (0.6 m × 0.6 m resolution on the ground, size DIN A1 corresponding to 84 cm x 119 cm¸ Worldview-2 (WV-2) 4-band sensor) of the two village areas. Reference profiles of major soil types, five in each village, were described following the FAO guidelines (Jahn et al., 2006). The gamma fingerprints were measured using a handheld Gamma Surveyor GRM-260 (Gf Instruments, s.r.o. Geophysical Equipment and Services, Czech Republic) vertically on the surface, in near proximity to the soil profile (not exceeding 0.5 m distance). During transect walks, every 50 to 150 m – depending on terrain heterogeneity – auger samplings and gamma-ray measurements were carried out similar to reference profile measurements. From those results, in agreement with local farmer information, a final soil map was generated (Reinhardt and Herrmann, 2017).

Transect measurements served as calibration data sets. For validation, on-farm trial sites were measured which were chosen by participating farmers in the project for cropping experiments (Reinhardt et al, 2019). Those farmers provided self-selected sites belonging to their land. The on-farm trials are therefore treated as randomly sampled. Gamma radiation measurements from transect walks and on-farm trials were graphically and statistically analyzed.

Due to the semi-arid environment and realization of the sampling during the dry season, gamma-ray attenuation by soil moisture is not expected to have disturbed signaling. Further, attenuation by soil organic material could be excluded due to very low contents of less than 0.5% organic carbon (Reinhardt and Herrmann, 2017).

### 4.3.3. Statistics

The aim of the analysis was to develop decision rules using two variables (i.e. $^{40}K$ and eTh) sensed by gamma-ray spectrometry data to predict the RSG of farmers' fields. For this, the two datasets taken from transects and from a random sample of farmers' fields were evaluated. For all observations of both datasets the two variables $^{40}K$ and eTh were derived from the same gamma-ray measurement and therefore represent samples with paired observations. The RSG was determined independently from gamma-ray spectrometry data by personal inspection during soil sampling. Both datasets were limited to contain four different soils (Chromic Lixisol, Chromic Lixisol (loamic), Chromic Lixisol (hypereutric) and Haplic Acrisol) by dropping samples with rare RSGs (i.e. Sodic Vertisol (hypereutric) and Stagnic Luvisol (hypereutric)) before statistical analysis. Furthermore, missing data e.g. if sample points lay on a street or vineyard, were dropped. This reduced the number of observations taken from transects from 166 to 129 and the number of farmer fields from 89 to 82. As residuals for both variables increased with increasing variance, both variables were transformed logarithmically.

In the transect dataset, $^{40}K$ and eTh data as well as the respective soil characteristics were taken from 11 to 19 sample points of each of 12 transects located along gradients of RSG changes in two villages (Idifu and Ilolo, Tanzania). Taking data from more than one sample point per transect causes a covariance between these samples. Thus, a proper analysis has to account for both, covariance between $^{40}K$ and eTh measures of one sample and between samples of the same transect.

The transect data set was taken from Ilolo and Idifu together for calibration, because soils were considered similar as described in Reinhardt and Herrmann (2017). The paired observations require that the analysis should account for covariances between $^{40}K$ and eTh values. A bivariate model directly fits these covariances and therefore this approach for analyzing the transect dataset was chosen. In this model fixed effects for soil and random effects for location, transect within the location and a first order autocorrelation between sample points within a transect were assumed. The latter try to account for the covariances between samples taken from the same transect. The model for each single sample point can be described by:

$$\begin{pmatrix} y_{K_{ijkl}} \\ y_{ETH_{ijkl}} \end{pmatrix} = \begin{pmatrix} \mu_K \\ \mu_{ETH} \end{pmatrix} + \begin{pmatrix} \tau_{K_l} \\ \tau_{ETH_l} \end{pmatrix} + \begin{pmatrix} l_{K_i} \\ l_{ETH_i} \end{pmatrix} + \begin{pmatrix} t_{K_{ij}} \\ t_{ETH_{ij}} \end{pmatrix} + \begin{pmatrix} e_{K_{ijkl}} \\ e_{ETH_{ijkl}} \end{pmatrix}, \tag{4.1}$$

where $y_{K_{ijkl}}$ and $y_{ETH_{ijkl}}$ are the values of $^{40}K$ and eTh at sample point *k* in transect *j* of location *i*. $\mu_K$, and $\mu_{ETH}$ are fixed general effects. $\tau_{K_l}$ and $\tau_{ETH_l}$ are fixed effects of the *l*th soil. $l_{K_i}$ and $l_{ETH_i}$ are random location effects of the *i*th location. Thus, $\begin{pmatrix} l_{K_i} \\ l_{ETH_i} \end{pmatrix}$ had a $2\times 2$ variance-covariance structure which can be written as $\begin{pmatrix} \sigma^2_{l_K} & \sigma_{l_k,l_{ETH}} \\ \sigma_{l_k,l_{ETH}} & \sigma^2_{l_{ETH}} \end{pmatrix}$, where $\sigma^2_{l_K}$ and $\sigma^2_{l_{ETH}}$ are the variances of locations for parameters $^{40}K$ and eTh and $\sigma_{l_k,l_{ETH}}$ is the covariance between location effects of the same location for different parameters, respectively. $t_{K_{ij}}$ and $t_{ETH_{ij}}$ are random transect effects of the *j*th transect in the *i*th location. Again, $\begin{pmatrix} t_{K_{ij}} \\ t_{ETH_{ij}} \end{pmatrix}$ had a $2\times 2$ variance-covariance structure which can be written as $\begin{pmatrix} \sigma^2_{t_K} & \sigma_{t_k,t_{ETH}} \\ \sigma_{t_k,t_{ETH}} & \sigma^2_{t_{ETH}} \end{pmatrix}$, where $\sigma^2_{t_K}$, $\sigma^2_{t_{ETH}}$ and $\sigma_{t_k,t_{ETH}}$ are the variances of and the covariance between transect effects of parameters $^{40}K$ and eTh. $e_{K_{ijkl}}$ and $e_{ETH_{ijkl}}$ are the two error effects with a variance-covariance structure analogous to location and transect effects. The single sample point model was extended to all sample points by assuming independence between location effects und transect effects within a parameter. Furthermore, for each parameter a first order autoregressive variance-covariance structure was assumed between errors of sample points within one transect, while sample points from different transects were independent. To model such a variance-covariance matrix for all error effects, a Kronecker product of the direct sum of 12 first-order variance covariance matrices and a $2 \times 2$ unstructured variance-covariance described above was used. With this model, mean vectors of means for $^{40}$K and eTh are estimated for each soil.

These mean vectors were used afterwards to assign sample points from transect data or farmer field data to RSGs. To do so, for each sample point and each soil vector the Mahalanobis distance between gamma-ray spectrometry data of the sample point (vector $p$ with parameter values for $^{40}$K and eTh) and the soil mean vectors ($s$) was calculated. The Mahalanobis distance is given as

$$\sqrt{(p-s)^T \Sigma^{-1} (p-s)} \,, \quad (4.2)$$

where $\Sigma^{-1}$ is the inverse of the estimated error variance covariance matrix of $p$, thus it is the inverse of variance-covariance matrix of $\begin{pmatrix} e_{K_{ijkl}} \\ e_{ETH_{ijkl}} \end{pmatrix}$. $s$ and $p$ are $2 \times 1$ vectors of $^{40}$K and eTh values. Predicted soils are chosen so that the Mahalanobis distance is minimized. To validate the decision rule developed from transects dataset, data (soil, $^{40}$K and eTh) from the second dataset, the 82 farmer fields located in the same two location, were used. Predicted soil from $^{40}$K and eTh values of farmer fields were compared to the soil determined by personal inspection including laboratory analysis in some cases of insecurity.

To show the profit from accounting for correlations between sample points within a transect, a model analogous to the one described above was fitted, but independence between error effect of sample points within a transect was assumed. For both models, including or excluding the first order autoregressive variance-covariance structure, the AIC (Akaike Information Criteria; Wolfinger, 1993) value was calculated and compared.

## 4.4. Results

### 4.4.1. Graphical analysis

Gamma-ray spectrometry measured $^{40}$K concentrations were plotted against eTh signals (Figure 4-1; OriginPro 2018). Figure 4-1a shows Ilolo transect measurements, Figure 4-1b on-farm trial measurements; Figure 4-1c shows transect measurements and Figure 4-1d on-farm trial measurements in Idifu.

In Ilolo, it was possible to separate Chromic Lixisols (hypereutric) from Haplic Acrisols and Chromic Lixisols using this approach (Figure 4-1a and b). Plotting of $^{40}$K vs. eU resulted in similar patterns (data not shown). Idifu, in contrast, featured

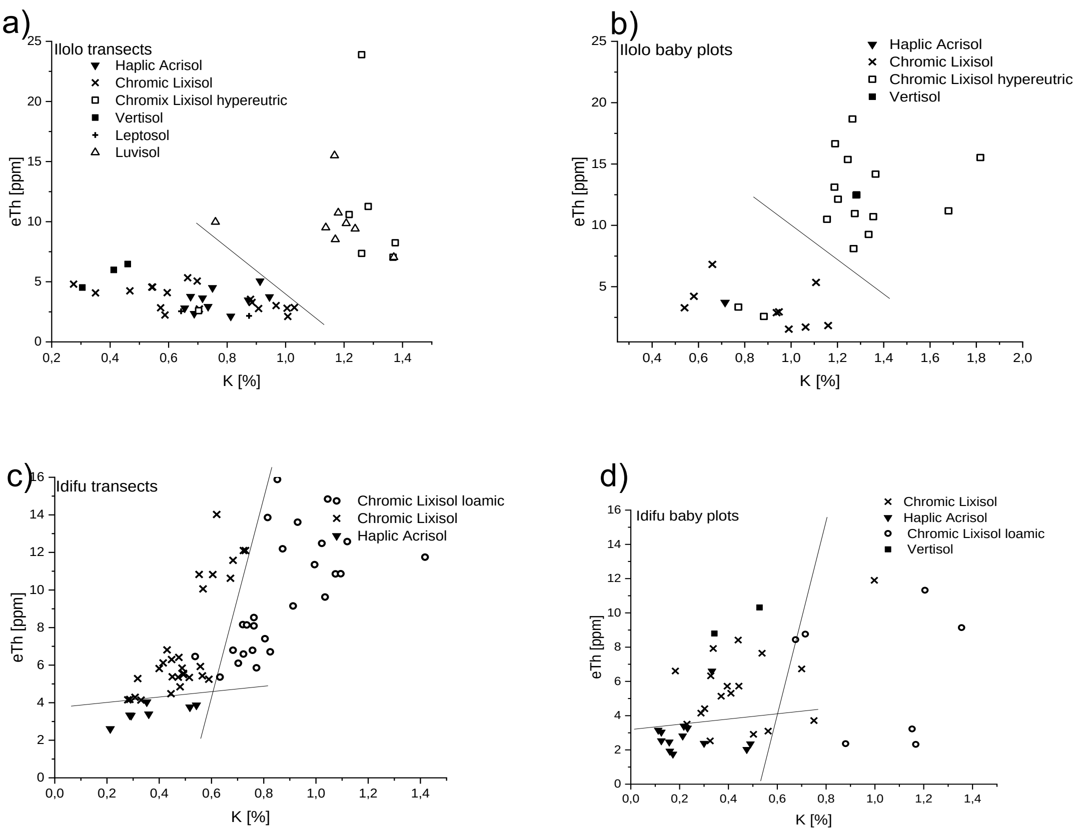


**Figure 4-1** $^{40}K$ vs. eTh scatterplots for a) Ilolo transect sampling points, b) Ilolo on-farm trials, c) Idifu transect sampling points and d) Idifu on-farm trials

different gamma-ray division patterns. (Figure 4-1c and d). Validation via on-farm trial sampling was less distinct.

### 4.4.2. Statistical analysis

The first order autocorrelation results in a much better model fit ($\Delta$AIC = -46.9 – 7.3 = -54.2). The correlation between neighboring sample points within transect was 0.6339, while the correlation between error effects from both parameters within a sample point was 0.0878.

The $\chi^2$test of independence is significant ($p<0.0001$) for both datasets (calibration with transect data and validation with farmers´ fields), meaning that the predicted RSG is not independent from the correct soil. The correct soil is predicted in 72 out of 129 cases (56%) and 47 out of 82 cases (57%) for calibration and validation data, respectively. While the identification of Chromic Lixisol (hypereutric) and Haplic Acrisol works well (a proportion of 0.9375 and 0.7391 was correctly identified within the validation dataset), it is hard to statistically distinguish Chromic Lixisols and Haplic Acrisols. Most Chromic Lixisols (loamic) were predicted to be Chromic Lixisol (hypereutric), even in the calibration dataset. The prediction of the

**Table 4-1** Soils, their number and share of correctly predicted RSGs.

| RSG | Calibration N | Calibration Predicted as right soil | Validation N | Validation Predicted as right soil |
|---|---|---|---|---|
| **Haplic Acrisol** | 19 | 17 | 23 | 17 |
| **Chromic Lixisol** | 25 | 6 | 34 | 14 |
| **Chromic Lixisol (hypereutric)** | 25 | 23 | 16 | 15 |
| **Chromic Lixisol (loamic)** | 60 | 26 | 9 | 5 |

present soils by $^{40}$K/eTh ratios by means of the bivariate mixed model results are shown in Table 4-1.

### 4.5. Discussion

From graphical analysis (Figure 4-1), a conflict related to $^{40}$K/eTh ratios of Chromic Lixisols (hypereutric) and Chromic Lixisols (loamic) was observed. In Ilolo, this did not play a role due to the absence of Chromic Lixisols (loamic). Nevertheless, the similarity in $^{40}$K/eTh ratios led to miss-prediction in Idifu: Chromic Lixisols (loamic) were predicted as Chromic Lixisols (hypereutric) in 5 of 9 observations. However, the two soils were found in completely different landscape positions and could thus be separated.

Chromic Lixisols were predicted as Chromic Lixisols (hypereutric) in 50% of the cases, probably due to their neighbouring location in the catena, where uphill sediments from Chromic Lixisols (hypereutric) mixed to the topsoils of the below lying Chromic Lixisols. Here, as well, the soils were easily distinguishable in the field by visual and haptic appearance (i.e. soil colour and texture).

Stagnic Luvisols (hypereutric) could not be distinguished from Chromic Lixisols (hypereutric) solely via gamma spectrometric signals (Figure 4-1). In the field, however, the Luvisols were easily identifiable due to their greyish color, cracked surface, finer texture as well as higher pH values than Lixisols.

Chromic Lixisols and Haplic Acrisols were hardly discriminable in the field; both were dusty, color was sometimes similar, and they were situated next to each other in the landscape (catena). Here, topographic position did not differ as significant as between Chromic Lixisols vs. Chromic Lixisols (hypereutric); the latter developed on steep slopes, exclusively. Gamma-ray spectrometry served well as auxiliary and uncomplicated method for distinction via $^{40}$K/eTh ratios (Figure 4-1) also proven by statistical analysis.

In Idifu, catenas were less distinct due to less undulation. Chromic Lixisols (loamic) were sometimes that similar to Chromic Lixisols from visual observations that even local farmers were hardly able to make the difference. Via gamma-ray spectrometry and $^{40}$K/eTh ratios, this separation is possible as statistically proven. Chromic Lixisols (loamic) seemed less weathered which is reflected in the higher $^{40}$K signal (Wilford, 2012).

Several points, which did not fit into the division concept, were checked for anomalies: (1) Some areas within Chromic Lixisols (hypereutric) in Ilolo were exhibiting extraordinary low gamma-ray signals, already identified in the field as locations with extreme conditions, i.e. in areas with saprolithic, highly weathered spots. Wilford (2012) as well identified saprolithic areas as very low in radiometric signals due to leached minerals.

(2) In the Idifu data set, several discrepancies appeared. In Figure 4-1d, two Chromic Lixisol (loamic) data points exhibited lower eTh signals than others. Their surficial texture was loamy sand which was the coarsest texture found in the studied villages. As $^{232}$Th shows higher affinity to the clay fraction (Bednar et al., 2004), here the eTh signal was lower than in other locations.

(3) The three Chromic Lixisols (loamic) with eTh signals below 4 ppm and $^{40}$K signals between 0.5 and 0.8% (Figure 4-1d), were measured in the same area where the soil was eroded resulting in less weathered top soils with different $^{40}$K/eTh ratio (Wilford 2012). Genuine parent rock as well occurred.

Generally, soils with higher clay contents, i.e. Chromic Lixisols (hypereutric) and Stagnic Luvisol (hypereutric), emitted higher eTh signals than soils with coarser texture, i.e. Haplic Acrisols and Chromic Lixisols (Figure 4-1), which confirms findings from Wilford et al. (2007). The authors described an accumulation of Th in soils which were more weathered with higher clay contents.

During on-farm trial samplings the Sodic Vertisol (hypereutric) with pure clay texture showed the expected high signals. Here, despite findings from Bierwirth et al. (1996) and Taylor et al. (2002) who indicated outgassing of one daughter isotope ($^{220}$Rn) within the $^{232}$Th decay series and a lower affinity of $^{232}$Th to swelling clays, the measured radiation was high. In contrast, during transect samplings in Ilolo, Sodic Vertisol (hypereutric) spots were found to exhibit low signals. Because of overburdens due to erosional processes, Chromic Lixisol sediments covered the finer textured Vertisol, which lied below in the catena, with sandy loam; the material on top diluted the gamma-ray signal. Gamma-ray spectrometers measure soil depths of up to 0.5 m in half-space geometry (Grasty, 1997). Thereby, upper layers contribute to a higher extent to the measured radiation due to (1) probability, i.e. the gamma quant with a shorter way will meet the detector with a higher probability, also because (2) the general attenuation by soil. Hence, soils that are covered by different material are not properly definable by gamma-ray spectrometry alone.

The soil map could be corrected by combining field observations and satellite images with gamma-ray spectrometry in several cases of misinterpretation. Signaling was influenced by surficial stones or sediments from other soils via erosion (aeoilian and water erosion).

## 4.6. Conclusion

With pre-knowledge of soils and terrain, and high resolution imagery, gamma-ray spectrometry is a useful and rapid technology for soil mapping, especially, combined with preliminary soil maps from local knowledge. The latter can be refined with regard to soil boundaries with little effort, particularly, hardly discriminable soils. Airborne gamma-ray spectrometry can even detect bigger terrains. However, not all gamma radiation signals are explicitly attributable to specific soils neither are they globally applicable. Reference soil calibration, i.e. fingerprinting, as well as ground truth are of paramountcy for reliable and exact maps. For better distinction in situ, e.g. pH measurements could be applied next to gamma-ray spectrometry.

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## 5. Soil and landscape affecting technology transfer targeting subsistence farmers in central Tanzania

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### 5.1. Abstract

This article deals with technology transfer from science to agriculture with pearl millet (*Pennisetum glaucum* (L.)R.Br.) in central Tanzania as example. The major question is which validity recommendations from different types of field experiments have and how geo-information (i.e. soil and landscape position) can lead to more site-specific recommendations. Tied ridging and reduced amounts of placed fertilizer during sowing were tested to increase yields on researcher-managed plots on-station, demonstration plots in villages, and farmer-managed plots on-farm. While on-station trials provided potential yield effects, physical distance to the station and differing conditions led to a higher informational value of village plots that mirror the context of local farmers. The treatments often resulted in significant yield increase. Soil and relief information and distance to settlements (i.e. gradient of management intensity) are key factors for data variability in on-farm trials. Unexplained variability is introduced through leaving degrees of freedom with respect to management to the farmer. Apart from soil and physiographic information, the latter should be part of a detailed data collection procedure in agronomic large N-trials addressing Sub-Saharan smallholder farming. Balanced data sets with dispersed trials on crucial soil and relief units is essential for future research.

**Keywords**: Placed fertilizer, tied ridging, landscape position

## 5.2. Introductory statement

In many developing countries, recommendations distributed by public agricultural extension are still assumed to apply for entire countries or agro-ecological zones. This concerns, in particular, fertilizer use, cultivar choice (often so-called improved varieties), and tillage practices. This extension approach contradicts the obvious variability of site conditions within landscapes, village territories and even individual farms or fields (Vanlauwe et al., 2016). Soil types and properties usually change along topographic position. Based on respective field observations in Tanzania, Milne (1935) developed the catena concept that is widely used in soil science. Surface and subsurface flows redistribute particulate as well as dissolved soil matter, e.g. nutrients. In consequence, notably subsistence agriculture that mainly depends on soil conditions as natural resource, and is limited by available area or labor, needs site-adapted recommendations considering environmental gradients. Further aspects to be considered in agricultural extension are climatic constraints (e.g. intra-seasonal droughts, spatial variability of rainfall), as well as limited access to inputs (e.g. fertilizer) and production risk. Multi-year experiments are, therefore, of highest importance to evaluate inter-annual influences on crop yield (Herrmann et al., 2013).

In Tanzania, agricultural policy emphasized the need for extension services to primarily support subsistence farmers. The number of extension staff indeed increased over the last years (Elifadhili, 2013). However, extension services rather addressed livestock related problems than cropping (Elifadhili, 2013), even in regions, which suffer from high population pressure that results in soil degradation. Droughts leading to famines are still frequent threats for subsistence agriculture in central Tanzania.

The Trans-SEC project (Innovating strategies to safeguard food security using technology and knowledge transfer: a people-centered approach) participatorily investigated the transfer and distribution of knowledge along whole food value chains in Tanzania in order to improve the different steps from land preparation to consumption. In the project framework, the need appeared to better integrate all stakeholders reaching from scientists and extension services over farmers' organizations to farmers. A crucial aspect was to include soil information as explanatory variable. For this purpose, three different types of field trials were conducted reaching from researcher managed on-station trials and researcher-managed demonstration plots in the village to farmer managed on-farm trials on variable soil units.

Emphasis in this paper is put on the questions, (1) which type of experiments can support which kind of recommendation, (2) which explanatory power soil information has in this respect and (3) what other aspects need to be considered. This topic is discussed taking fertilizer and tillage experiments as examples.

## 5.3. Materials and methods

The research was conducted on a research station and in two villages in central Tanzania. With respect to the research, the traditional top-down approach was applied and combined with participatory methods, i.e. international and national scientists selected potential innovations based on previous experience and literature research and discussed with farmers in the intervention zones applicability and constraints. Based on these discussions, the scientists adapted chosen technologies to their best knowledge to local conditions.

### 5.3.1. General description of the study area

All field trials were conducted in the semi-arid Dodoma region of Tanzania. Average rainfall amounts to 594 mm and average temperature is 23°C at Dodoma airport (1980 to 2010; TMA, 2013). Evaporation reaches ca. 1,600 mm per year (Kahimba et al., 2014). The rainy season lasts from December to April. This is when subsistence farmers extensively grow rain-fed crops like pearl millet (*Pennisetum glaucum* (L.)R.Br.), sorghum (*Sorghum bicolor* (L.)Moench) and maize (*Zea mays* L.) as staples. Milne's catena concept (1935) applies for the study area, reaching from rock outcrops and low pH at hilltops to fine grain sizes and alkaline conditions in valley bottoms. Rainfall scarcity and variations within short distances as well as water redistribution by lateral flow along slopes are common.
Elevations in the study area range between 990 and 1190 m asl. On geological maps from 1953 and 1967, obtained from the Geological Survey of Tanzania in Dodoma, so-called "contaminated granite" (i.e. incorporation of foreign petrographic material) appears as major rock type. Due to low spatial resolution (1:100,000 and 1:125,000, respectively), and own field observations, those maps were not considered adequate. In fact, variable petrography was found during field trips, reaching from unconsolidated sorted Quaternary sediments over Tertiary intermediary metamorphic rocks to felsic and intermediary Precambrian volcanic rocks.

Soils are variable reaching from highly weathered and nutrient deficient ones (e.g. Acrisol), over those degraded by overgrazing and erosion (e.g. Leptosol), to temporally inundated Vertisols rich in nutrients. Soil surfaces have been observerd to be bare during the dry season.

Most farmers practice subsistence agriculture, growing pearl millet, sorghum and maize as staple crops during the rainy season. As inter- and cash crops, peanuts (*Arachis hypogaea* L.), bambara nuts (*Vigna subterranea* (L.)Verdc.), pigeon peas (*Cajanus cajan* (L.)Millsp.) or cow peas (*Vigna unguiculata* (L.)Walp.) were found. On more fertile Vertisols, vegetables are grown. Either hand hoes, or, in better off households, ox-ploughs are used for tillage. If available, manure is applied, while hardly any mineral fertilizer is used.

### 5.3.2. Study sites, soil mapping and information

The research station of the Agricultural Research Institute (ARI) Makutupora (E35°46´7" S5°46´7", ca. 1100 m a.s.l.), is located in Mjini district of Dodoma, approximately 20 km north of Dodoma. According to the World Reference Base for Soil Resources (WRB, IUSS working group, 2015) the soils of both fields were classified as Rhodic Luvisol (loamic, ochric) characterised by clay illuviation as major soil forming process. Previous soil surveys showed the following nutrient content for the top 0.15 m, evaluated after Landon (1984):

Field A: 0.06% N – very low, 16.7 mg $kg^{-1}$ P – medium, 414 mg $kg^{-1}$ K - high

Field B: 0.09% N – very low, 96.6 mg $kg^{-1}$ P – high, 582 mg $kg^{-1}$ K - high

Soil mapping in the villages Ilolo (E35°59´11" S6°25´13") and Idifu (E35°54´50" S6°20´26) approx. 45 km to the southeast of Dodoma followed a mixed approach, beginning with participatory mapping (including local denomination of major soil units) and adding information from transect mapping, gamma spectrometry and remote sensing. The mapping approach is detailed in Reinhardt and Herrmann (2017).

In both villages similar Reference Soil Groups occurred. Leptosols were found on eroded hilltops, Chromic Lixisols (hypereutric) on middle slopes, Chromic Lixisol (loamic in Idifu) on foot slopes, Haplic Acrisols (loamic) in flat terrain, and Sodic Vertisols (hypereutric) in depressions. Cutanic Stagnic Luvisols (hypereutric) were solely found in a small area in Ilolo in the same topographic position as Chromic Lixisols. Chromic Lixisol (hypereutric) units were rare in Idifu. The dominating soils in both villages are those characterized by clay illuviation (Luvisol, Lixisol, Acrisol) representing a typical soil forming process in seasonal climates. The occurrence of the soils within the landscape is a function of the underlying rock (large variability of magmatic, metamorphic and volcanic parent materials) and the topographic position. The latter is important due to lateral redistribution of soil materials mainly through water erosion. While the hilltops are strongly eroded (Leptosols), sand accumulation belts are found at the foot slopes (Acrisols) and finest material (clay) and solutes are accumulated in the endorheic depressions (Vertisols). Soil properties of reference soil pits are presented in Table 5-1.

Texture spreads from loamy sand to pure clay. Organic matter content is generally low. The pH values show a wide spread from acidic to alkaline (pH 5.0 to 8.7 in Ilolo and 5.5 to 7.1 in Idifu). Electrical conductivity was unremarkable, except higher values for the Vertisol in Ilolo that are only relevant for sodium sensitive plants.Primary limiting nutrients are phosphorus and nitrogen. Plant available phosphate is rated low to very low (0.3-11.7 mg $kg^{-1}$), nitrogen very low on nearly

**Table 5-1** Means for various soil properties of sampled reference profiles in a) Ilolo and b) Idifu. All means were calculated from weighted averages for the top 30 cm (n.d. = not detectable). EC: electrical conductivity; BS: base saturation, pa: plant available

| a) Ilolo | **pH ($H_2O$)** | **EC [µS $cm^{-1}$]** | **$N_t$ [%]** | **$CO_3^{2-}$ [%]** | **$C_{org}$ [%]** | **paP [mg $kg^{-1}$]** | **paK [mg $kg^{-1}$]** | **BS [%]** | **Tex-ture** |
|---|---|---|---|---|---|---|---|---|---|
| Haplic Acrisol (loamic) | 5.0 | 71 | 0.06 | n.d. | 0.3 | 6.6 | 148 | 49 | SL |
| Chromic Lixisol | 5.5 | 84 | 0.05 | n.d. | 0.3 | 5.3 | 230 | 57 | SCL |
| Chromic Lixisol (hypereutric, profondic) | 6.5 | 92 | 0.06 | n.d. | 0.3 | 0.3 | 115 | 72 | SCL |
| Cutanic, Stagnic Luvisol (hypereutric) | 8.6 | 158 | 0.05 | 0.5 | 0.3 | 11.7 | 289 | 76 | SCL |
| Sodic Vertisol (hypereutric) | 8.7 | 1501 | 0.08 | 1.5 | 0.6 | 0.3 | 234 | 81 | C |

| b) Idifu | **pH ($H_2O$)** | **EC [µS $cm^{-1}$]** | **$N_t$ [%]** | **$CO_3^{2-}$ [%]** | **$C_{org}$ [%]** | **paP [mg $kg^{-1}$]** | **paK [mg $kg^{-1}$]** | **BS [%]** | **Tex-ture** |
|---|---|---|---|---|---|---|---|---|---|
| Haplic Acrisol (loamic) | 5.5 | 55 | 0.02 | n.d. | 0.3 | 3.6 | 63 | 37 | LS |
| Chromic Lixisol | 5.9 | 134 | 0.04 | n.d. | 0.3 | 0.3 | 120 | 50 | SL |
| Chromic Lixisol (loamic) | 6.3 | 132 | 0.04 | n.d. | 0.4 | 3.4 | 112 | 53 | SL |
| Chromic Lixisol (hypereutric) | 7.1 | 174 | 0.06 | n.d. | 0.5 | 2.0 | 85 | 74 | SL |
| Sodic Vertisol (hypereutric) | 6.7 | 190 | 0.10 | n.d. | 1.0 | 3.5 | 348 | 77 | C |

all sampled plots. Vertisol sites are subject to seasonal inundation. Rated after Landon (1984), plant available potassium was high with few exceptions.

Given this variability of soil conditions, it cannot be expected that crops on all sites respond to management measures in the same manner. This is particularly true for both tested innovations i.e. fertilization (given the spread of plant available P) and soil tillage (work load depending on texture). Vertisols were ex ante exempted from field trials due to their special character, i.e. good nutrient status and inundation risk.

During focus group discussions, local farmers distinguished the major soil types due to colour, texture, water holding capacity and crop performance. Acrisols were designated suitable for plants with low nutrient demand like pearl millet, white sorghum, peanuts, cow peas or cassava (*Manihot esculenta* Crantz). On more fertile soils like Lixisols, sunflowers, grapes (*vitis vinifera*) or sesame (*Sesamum indicum* L.) were grown. Plants having higher nutrient requirements like vegetables or sugarcane were exclusively grown on Vertisols (and the Luvisol in Ilolo).

### 5.3.3. Innovations tested in pearl millet cropping

Tested innovations that deal with the actual production constraints water scarcity and soil nutrient status were tied ridging as tillage and water conservation practice, and placed fertilizer application in order to restrict fertilizer input and increase fertilizer efficiency at the same time.

**Tied ridges (TR)** increase soil moisture by decreasing surface flow and enhancing infiltration *(*Kilasara et al., 2015*)*. Ridges in combination with ties act as water erosion barriers, thus conserving fertile topsoil and rainwater. However, the establishment of TRs is work demanding in comparison to flat cultivation and requires about 266 labor hours per hectare (measurements in situ). General TR design recommendations were as follows: Ridge distance 0.75-0.80 m, ridge height 0.2 m, ties every 1.5 m and 0.15 m high, and fixed in a staggered way (Trans-SEC factsheet, 2016).

**Placed fertilizer (PF)** application has multiple goals. It enhances fertilizer efficiency and leads, in consequence, to reduced nutrient losses, in the case of mobile K and N, and less fertilizer demand in comparison to broadcast application. This, in turn, results in lower investment, decreases the risk for loss of investment, while increasing the yield potential (Bielders and Gerard, 2015). However, as it is true for tied ridging, the workload is increased. Application was recommended as follows: a full screw cap from a water bottle, i.e. 2 g (resulting in 7.5 kg P $ha^{-1}$) of triple superphosphate (TSP) fertilizer was placed into each planting hole and covered with some soil before the seeds were sown right next to the fertilizer spot. Pearl millet (*Pennisetum glaucum* (L.)R.Br. cv. *okoa*) as test crop was chosen since it represents a major staple crop in the semi-arid areas of Tanzania. The average grain yield in Tanzania according to Kamhambwa (2014) is 0.77 t $ha^{-1}$; in Chamwino district, however, it only reaches 0.36 t $ha^{-1}$. Responsible for low crop performance is poor soil fertility and insufficient precipitation in combination with erosion and low soil water retention capacity (Kimenye, 2014).

### 5.3.4. One dimensional testing: The on-station researcher- managed trial

**On-station field trials** were conducted on two fields at ARI Makutupora from January to May in 2015 and 2016. In this context, we call these experimental conditions **one-dimensional (1D)**, since only the treatments are expected to mainly influence the crop yield. Climate and soil conditions are regarded constant at this spatial level. The experiment was designed to reveal the maximum potential of TR. A researcher designed, supervised, and conducted the experiments in a controlled environment (i.e. on-station in randomized block design).

A weather station (WS-GP1, Delta-T) was installed close to the experimental site on-station. The observed precipitation substantially differed between the two seasons (Table 5-2) and between the research station and intervention villages.

Pearl millet was grown on two experimental fields (field A and B) during the rainy seasons 2015 and 2016 from January until beginning of May. Hereby, rainfed plots with TR were compared with rainfed flat plots (R) without any alteration of the soil. A fully irrigated (FI) treatment was part of the experiment on field A in order to explore the potential yield under the prevailing environmental conditions. These plots were connected to a drip irrigation system and irrigated whenever the rainfall amount was not sufficient to meet the crop water requirements. The weeding frequencies and input of fertilizer was identical among the mentioned treatments. Each treatment was tested with 4 replicates on both fields.

Plots were 4.0 m × 5.7 m in size, every treatment was installed with five rows, each containing 18 plants. Border plants were not harvested and not included in yield calculations.

On-station, all plots received a mixture of fertilizers at the recommended rate (Kanyeka et al., 2007; Khairwal et al., 2007): 60 kg N $ha^{-1}$, 13.1 kg P $ha^{-1}$, 24.9 kg K $ha^{-1}$ via Yara Mila complex fertilizer (23-10-5), potassium nitrate (13-0-46), triple super phosphate (0-44.5-0) were placed into each planting hole during sowing and

**Table 5-2** Mean rainfall data ± standard deviation [mm] collected from the weather station in Makutupora (i.e. on-station) and by local farmers in Ilolo and Idifu for the cropping periods 2015 and 2016, N is the number of observations

| | Total rainfall [mm] in season 2015 (mean) | N | Total rainfall [mm] in season 2016 (mean) | N |
|---|---|---|---|---|
| **Makutupora** | 252 | 1 | 794 | 1 |
| **Ilolo** | 171.0 ± 5.1 | 6 | 280.4 ± 3.6 | 11 |
| **Idifu** | 98.6 ± 6.0 | 7 | 384.1 ± 5.8 | 18 |

covered with some soil before the seeds were added. Urea (46-0-0) was side dressed 4-6 weeks after emergence over all treatments. Adequate nutrient supply of millet with N, P and K can therefore be assumed.

The TR geometry was based on general recommendations (Trans-SEC factsheet, 2016) and adjusted to the irrigation set up: the ridges were 0.8 m apart and 0.25 m high. They were connected via cross ties in 0.6 m distance and with a height of 0.15 m. Seeds were sown on top of the ridges.

### 5.3.5. Two- and multiple-dimension experiments in the local environment: Mother and baby trials

As next step, the experiments were expanded to the intervention areas, i.e. the two villages llolo and Idifu. The experiments on mother (demonstration plots) and baby trials (on-farm) started in the end of 2014. The distance between these and Makutupora-station amounts to approximately 60 km linear distance. Mother trials served as researcher-managed demonstration plots, whereas baby trials reflected real farm environments managed by the plot owners.

Mother trials took place on one field per village that was provided by local farmers. Soil properties did not play a primary role during the site selection process. Instead, availability, i.e. farmers' disposition to provide their land was decisive. In consequence, the mother trials differed between each other and from the on-station fields in their RSG. This way, variability with respect to soil as well as meteorological variables (rainfall and its distribution) were introduced into the experimental error. Due to the limited variability of experimental factors and the management still being in the hand of the researcher, we call this experimental approach **two-dimensional** (2D). Plot size per repetition was 21.6 m²; each treatment was repeated 5 times in Ilolo in 2015 and three times in both villages in 2016. The Idifu mother trial failed to produce any yield in 2015 due to deficient precipitation. In order to reduce the risk of repeated crop failure, the experiment was shifted from the highly degraded site to an area with better water holding capacity. Therefore, from Idifu, only data for the season 2015 are available. Reference Soil Groups were Haplic Acrisol (loamic) in Idifu at the new plot and Chromic Lixisol in Ilolo in both seasons. On the mother trials, 3 different fertilizer rates were applied. The "full rate" is based on recommendations of Kanyeka et al. (2007): (1) recommended rate, i.e. 60 kg N $ha^{-1}$ and 13.1 kg P $ha^{-1}$; zero K (di-ammonium phosphate and calcium ammonium phosphate). The two other applied rates were: (2) 25% of treatment 1, and (3) control plots without fertilization (i.e. common farmers' practice). The furrows related to tied ridging followed the given recommendations. The seeds were sown on top of the ridges. Control plots were left flat.

Project staff guided the installation of the on-farm experiments (baby trials) by explaining the principal setup, but finally, farmers themselves managed the land. Baby trial treatments were to the farmers' independent choice. Within their fields, one 10 m*10 m plot was assigned as treatment plot and one as control. Rainfall was also measured by some farmers. The amounts between the two consecutive seasons 2015 and 2016 differed tremendously (Table 5-2).

For the analytical work, only data from plots within village borders, and from one of the major Reference Soil Groups (except Sodic Vertisol (hypereutric)) were taken into account to grant a sufficient number of repetitions. The number of yield data for analyses was n = 141.

Apart from the variability of environmental conditions (soil, topography etc.), this approach incorporates one further uncertainty for data analysis, i.e. management control in the hands of the farmers. Consequently, transferred information on management practices per site might not be complete. In addition, certain yield explanatory environmental factors like rainfall or pest occurrence often remain unknown. Due to these added uncertainty components we call these experimental conditions **multi-dimensional** (multiD).

### 5.4. Statistical analysis

#### 5.4.1. On-station trials (1D)

The following linear mixed effects model was used to evaluate on-station trials.

$$y_{abil} = \mu + s_a + j_b + (sj)_{ab} + r_{abl} + \tau_j + (s\tau)_{ai} + (j\tau)_{bj} + (u\tau)_{abj} + e_{(a)bjl} \quad (5.1)$$

where $y_{abil}$ are the square root-transformed millet yields in site *a*, at year *b*, in replicate *l* within year and site and treatment level *j*. $\mu$ is the intercept; $s_a$ is the fixed effect of the *a*-th site; $j_b$ is the fixed effect of the *b*-th year; $(sj)_{ab}$ is the fixed year specific site effect; $r_{abl}$ is the effect of the *l*-th replicate within the combinations of site and year; $\tau_j$ is the effect of the *j*-th treatment; $(s\tau)_{aj}$, $(j\tau)_{bj}$ and $(sj\tau)_{abj}$ are the interactions of treatment with site, year and their combination. $e_{(a)bjl}$ are the residual error terms. In order to account for heterogeneity of variance between the two sites, separate error variances were estimated with expected mean of zero and variances $\sigma_{e1}^2$ and $\sigma_{e2}^2$: $e_{(1)bjl} \sim N(0, \sigma_{e1}^2)$ and $e_{(2)bjl} \sim N(0, \sigma_{e2}^2)$.

#### 5.4.2. Mother trials (2D)

The following linear mixed effects model was used to evaluate on-site mother trials. We renounced to a joint analysis with multiD due to the enormous increase in factor variability from mother to baby trials (e.g. soil type, climate, management). Information about the blocks in mother trials is missing, therefore the data were analyzed as a completely randomized design. The following model was used.

$$y_{abjkl} = \mu + s_a + j_b + \tau_j + \phi_k + (\tau\phi)_{jk} + (s\tau)_{aj} + (s\phi)_{ak} + (s\tau\phi)_{ajk} + (j\tau)_{bj} + (j\phi)_{bk} + (j\tau\phi)_{bjk} + e_{(ab)jkl} \quad (5.2)$$

where $y_{abikl}$ the log-transformed millet yield on the *l*-th plot in site *a* and year *b*, with the combination of the water harvesting-type *j* and fertilizer level *k*. $\mu$ is the intercept, $s_a$ ist the effects site *a*, $j_b$ is the effect of year *b*. $\tau_j$ is the effect of the *j*-th water harvesting system, $\phi_k$ is the effect of the *k*-th fertilizer level, $(\tau\phi)_{jk}$ their interaction. $(s\tau)_{aj}$, $(s\phi)_{ak}$, $(s\tau\phi)_{ajk}$, $(j\tau)_{bj}$, $(j\phi)_{bk}$ and $(j\tau\phi)_{bjk}$ are the interactions of site, season and both treatment factors as well as their combination. $e_{(ab)ikl}$ are the residuals error terms. In order to account for heterogeneity of variance between environments, separate error variances were estimated: $e_{(11)bjl} \sim N(0, \sigma_{e11}^2)$, $e_{(12)bjl} \sim N(0, \sigma_{e12}^2)$ and $e_{(22)bjl} \sim N(0, \sigma_{e22}^2)$.

### 5.4.3. On-farm trials (multiD)

The following linear mixed effects model was used to evaluate yield data from the two-site/two-season on-farm data. The treatment combination tied ridges without fertilizer was not sufficiently often chosen by farmers for statistical evaluation. Therefore, a single treatment factor variable with three levels (FTF0, FTPF and TRPF) was used in the model.

$$y_{abijl} = \mu + s_a + j_b + (sj)_{ab} + \eta_i + \tau_j + (\eta\tau)_{ij} + (s\eta)_{ai} + (s\tau)_{aj} + (j\eta)_{bi} + (j\tau)_{bj} + (sj\eta)_{abi} + (sj\tau)_{abj} + (sj\eta\tau)_{abij} + e_{bi(aj)l} \quad (5.3)$$

where $y_{abijl}$ is the log-transformed millet yield on the *l*-th farmers plot of soil type *i*, in site *a* and year *b* and treatment *j*. $\mu$ is the intercept, $s_a$ is the fixed effect of site *a*. $j_b$ is the fixed effect of season *b*. $\eta_i$ is the fixed effect of the *i*-th soil type, $\tau_j$ is the fixed effect of the *j*-th treatment, , $(\eta\tau)_{ij}$, $(\eta\tau)_{ij}$ is the two-way interactions of soil and treatment. $(sj)_{ab}$, $(s\eta)_{ai}$, $(s\tau)_{aj}$, $(j\eta)_{bi}$, $(j\tau)_{bj}$, $(sj\eta)_{abi}$, $(sj\tau)_{abj}$ and $(sj\eta\tau)_{abij}$ are the random site and year specific effects of soil and treatment. $e_{bi(aj)l}$ are the residual error terms, whereby individual variances for each combination of site and water treatment were allowed to achieve homogeneity of variance. Independence of soil type and treatment factors was perceived to be a prerequisite in order to formulate model (3). The allocation of the factor soil is not randomized. Participating farmers themselves chose which treatment combination to use for their plot. Hence, possibly the selection of treatment could be guided by farmers' assumption which treatment might turn out favorable on different soils. Such selection would distort any conclusions drawn from an analysis of performance of treatment combinations on different soils. To control for such bias before applying model (3), association of treatment and soil type was tested for each site and season combination. Independence of soil and treatment allocation was tested in contingency tables. As the expected frequencies in the tables were very low, p-values for the $\chi^2$-test were estimated by resampling from the contingency table 10,000 times.

### 5.4.4. Model fitting

The model parameters were estimated using the software SAS 9.4. Variance components were estimated by restricted maximum likelihood method (REML). Model assumptions normal distribution of residuals and homogeneity of variance were assessed by inspecting plots of standardized residuals. For the former assumption quantile-quantile-plots were used, for the latter the scatter plots of residuals against predicted values. If assumptions were not fulfilled, response variables were transformed and heterogeneous variances were used until assumptions appeared. Random effects were tested for significance using likelihood-ratio tests and non-significant effects were removed from the model. Fixed effects were tested for significance by sequential Wald-type F-test. Non-significant fixed effects were removed from the model. Denominator degrees of freedom and standard errors were adjusted using the method of Kenward and Roger (Littell et al. 2006). The levels of factors found significant in the F-test were compared by pairwise t-tests and other linear contrasts. Throughout the entire statistical analysis, a significance level of 5 % was used.

## 5.5. Results and discussion - treatment effects on different levels

### 5.5.1. One-dimensional testing: The on-station researcher managed trials - potential yield of and tied ridging effect on pearl millet grain yield

When model (1) was fitted to the pearl millet yields obtained from the on-station trials, the F-test showed a significant interaction of season and treatment ($p < 0.0001$, Tab. 5-S1) while the three-way interaction of site, season and treatment, as well as the two-way interaction of site (here field A and B) and treatment were not significant ($p = 0.95$ and $p = 0.56$, respectively, Table 5-S1).

Estimates of treatment levels within each season and estimates of seasons within each treatment level were compared by pairwise t-tests. Median estimates and test results are reported in Figure 5-1. The yield ranking between the treatments was the same in both cropping seasons, i.e. FI >TR >R. Consequently, water availability during the rainy season was identified as production constraint. Based on the guidelines of the FAO-56 methodology (Allen et al., 1998), evapotranspiration of pearl millet under the local conditions is 524 mm. However, only 252 mm of rainfall occurred between sowing and harvest in 2015 (Table 5-2). Consequently, solely rainfed crops in flat terrain suffered from drought stress and hardly produced any grain. Highest susceptibility to water shortage was observed during the reproductive stage, i.e. at flowering.

In contrast, the FI-treatment revealed the yield potential under ideal water supply on-station, i.e. 3.6 ± 0.7 t ha-1 (Fig. 5-1), but showing N-deficiency being common in semi-arid areas. Exchangeable P and K were present in sufficient amounts. Micronutrients were not analyzed. As to be expected, the FI grain yields did not statistically differ between the two growing seasons. Pearl millet in TR treatments

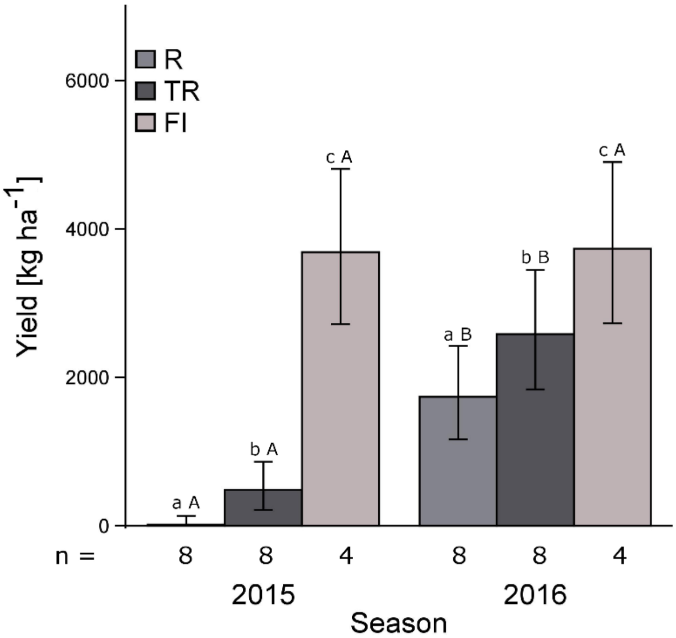


**Figure 5-1** Median estimates and 95% confidence intervals of different water harvesting treatments in the on-station trials at Makutupora research station (Tanzania) in 2015 and 2016 averaged over two sites. Treatment medians within each year are compared by pairwise t-tests. Medians of treatments within one season that share a common small letter do not differ significantly at α = 5%. Medians of two seasons within the same treatment factor level that share a capital letter do not differ significantly at α = 5%. Median estimates are based on model (1) fitted to square-root-transformed data and back-transformed for graphical display. Legend: R: rainfed, TR: tied ridging, FI: full irrigation

performed significantly better than under rainfed conditions. R and TR treatments differed between the seasons, most probably due to water availability. The efficiency of TR in 2016 is underlined via approximation of yields to those of the FI treatment.

The generally higher yields on TR plots compared to R plants was probably attributed to reduced run-off as often argued in literature. However, farmers stated that they could apply this technology only to one acre per season, due to the extra-ordinary workload. In contrast, several reports state that only little maintenance is necessary in following seasons. (UNEP, undated). In this respect farmers stated that erratic high intensity rain events cause enormous efforts to repair tied ridged fields.

In conclusion, under the given soil conditions (Rhodic Luvisol (loamic, ochric)) TR increased yield compared to rainfed conditions. No information was produced how TR would perform under other soil conditions (e.g. low nutrient levels, different texture), and whether this technology is economically feasible given the high workload. The on-station trials revealed the importance of water availability in

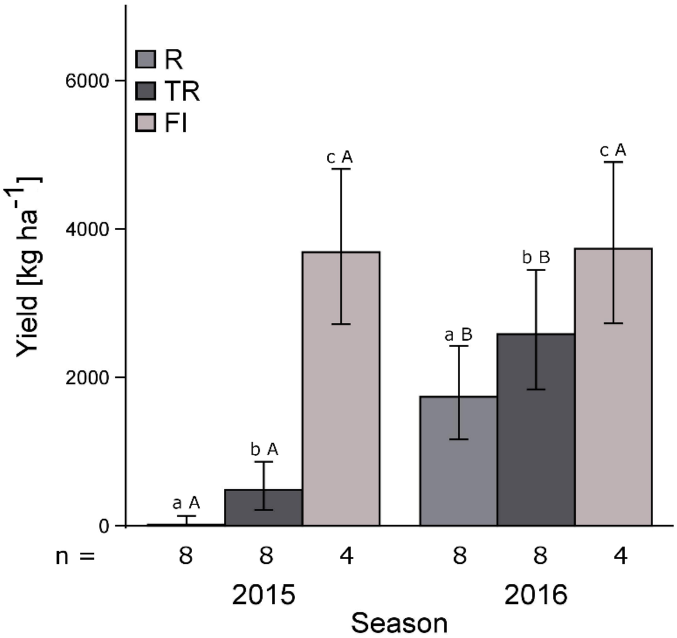


**Figure 5-2** Median estimates and 95% confidence intervals of different water harvesting treatments in the on-station trials at Makutupora research station (Tanzania) in 2015 and 2016 averaged over two sites. Treatment medians within each year are compared by pairwise t-tests. Medians of treatments within one season that share a common small letter do not differ significantly at $\alpha = 5\%$. Medians of two seasons within the same treatment factor level that share a capital letter do not differ significantly at $\alpha = 5\%$. Median estimates are based on model (1) fitted to square-root-transformed data and back-transformed for graphical display. Legend: R: rainfed, TR: tied ridging, FI: full irrigation

certain growth stages, especially in the reproductive stage of pearl millet. On-station plots were not useable for technology transfer to farmers, mainly due to the distance of 60 km from the villages and diverging soil and climate conditions.

### 5.5.2. Two-dimensional testing: Researcher managed trials in the investigated villages – tied ridging and placed fertilizer effect on pearl millet grain yield

When model (2) was fitted to mother trial yields, the F-test showed a significant three-way interaction of water harvesting, fertilizer and site (p = 0.0017, Tab. 5-S2), while the same interaction with season was not significant (p = 0.2316, Tab. 5-S2) but the season main effect (p = 0.002, Tab. 5-S2).

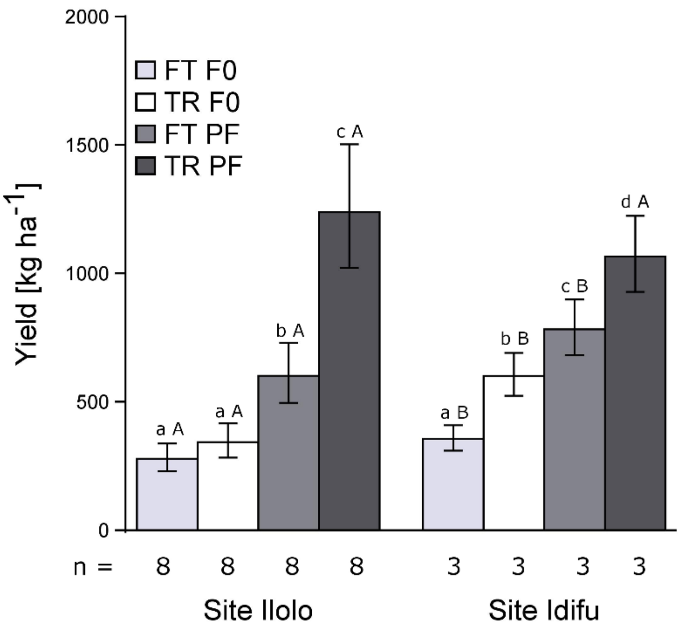


**Figure 5-3** Median estimates and 95% Confidence intervals of combinations of water harvesting systems and fertilizer regimes at Illolo and Idifu villages (Tanzania). Medians at Ilolo are averaged over two years. Medians of treatment combinations which share a common small letter do not differ within each site at α = 5% significance level. Medians of the same treatment combination that share a common capital letter do not differ between sites at site at α = 5% significance level. Medians are estimated from model (2) fitted to log-transformed data and back-transformed for graphical display. Mean comparisons based on pairwise t-tests. Legend: FT: flat ties, F0: no fertilization, TR: tied ridging, PF: placed fertilizer

Figure 5-2 shows the pearl millet yield means of fertilizer regimes and water harvesting systems on mother trials in the two intervention villages. Crop failure in the first experimental season on the mother trial in Idifu was caused by highly degraded soil in combination with erosion on-site and severe drought. This is, however, reality in the village. In 2015, farmers in both villages lost most of their crop due to drought (Table 5-2).

The order of treatment effects on pearl millet grain yield over the years and sites is consistently the same: Combined water harvesting and fertilizer > fertilizer > water harvesting > control. The control yields are with 0.3-0.4 t $ha^{-1}$ exactly in the range that are reported to be average on local farms in the district (i.e. 0.36 t $ha^{-1}$, Kimenye, 2014). Given the low rainfall in 2015, this year can be taken as worst-case scenario with an average yield in the control of 0.31 ± 0.1 t $ha^{-1}$ and an observed minimum yield of 0.14 t $ha^{-1}$. Thus, the yield range at the chosen sites with low input conditions is 0.1-0.4 t $ha^{-1}$ and serves as a reference for treatment effects

Indifferent from the site and whether water harvesting was used, fertilizer always increased yields. The difference between fertilized and unfertilized plots did not differ in magnitude between flat and ridged plots ($p = 0.1763$). On both sites water harvesting together with fertilizing increased the yield significantly. However, the effect was significantly higher in Idifu compared to Ilolo as found in an additional contrast ($p = 0.011$).
Yields in Idifu were – except for the combined treatment – higher than in Ilolo. The ranking of treatment effects as well as the general significant effect of fertilizing shows that nutrients might be more limiting than water in the village environment, where irrigation is far beyond farmer means, and fertilizer access and affordability are limited. Nevertheless, water deficiency can reinforce nutrient deficiency as only water can dissolve and transport nutrients to the plant roots.
The maximum average yield achieved by combined treatments reaches only about 40% of the potential yield determined on-station. Combined stresses in the villages (water availability: less than 400 mm rainfall and depending on sowing date; nutrient availability: limited fertilization; biotic stresses: not recorded) can explain this result. The effect of combined tied ridging and placed fertilizer (TRPF) on pearl millet grain yield was significant in all cases.
The interlinkage of water deficit due to scarce precipitation, surface run off and low infiltration, worsened by sealed soil surfaces and low water holding capacity in local sandy soils, together with nutrient deficiency led to low grain yields in both intervention villages.
Demonstration plots in the village served for training purposes as well as for showing the potential success of the applied technologies. In conclusion, the experiments clearly show that the placed fertilizer and tied ridging treatments are also effective in the village environment. However, the absolute yield level and relative yield increase differ from on-station results. In consequence, their economic returns - as most relevant information for the farmer - differ.

## 5.6. Multi-dimensional testing

### 5.6.1. Spatially dispersed farmer-managed trials in the case study sites – tied ridging and fertilizer effect on pearl millet grain yield

Due to absent significant inter-annual differences, statistical analyses consider all baby trial yield data for 2015 and 2016 together. The soils were grouped with regard to: (1) Reference Soil Groups (RSG, IUSS Working Group, 2015), (2) and - where reasonable - landscape position, e.g. in flat (Acrisol (flat)) or undulating terrain (Acrisol (slope)). Only RSGs with a sufficient number of repetitions were considered, therefore, the pure placed fertilizer treatment and the Sodic Vertisol (hypereutric) were not evaluated.

An independence tests for each environment revealed no indications for a systematic association of soil types and treatments by farmers in the resampling-based $\chi^2$-tests. Monte-Carlo estimates (and confidence intervals) for p-values were 0.51 (0.503; 0.529) for Idifu in 2015, 0.9211 (0.9142; 0.9280) in 2016. In Ilolo, a p-value of 0.6296 (0.6172; 0.6420) was estimated for 2015 and 0.8571 (0.8481; 0.8661) in 2016. We concluded that it is therefore justifiable to draw conclusions from the evaluation of the factor soil in the baby trial experiment.

When model (3) was fitted to the yield data obtained from the farmer-managed baby trials a significant interaction of treatment and soil ($p = 0.0033$, Tab. 5-S3) was found. Figure 5-3 shows the estimates treatment factor levels on different soils.

Treatments were subsequently compared within each soil-type by pairwise t-tests. Yields on the control plots (FTF0) over all RSGs ranged within reported ones

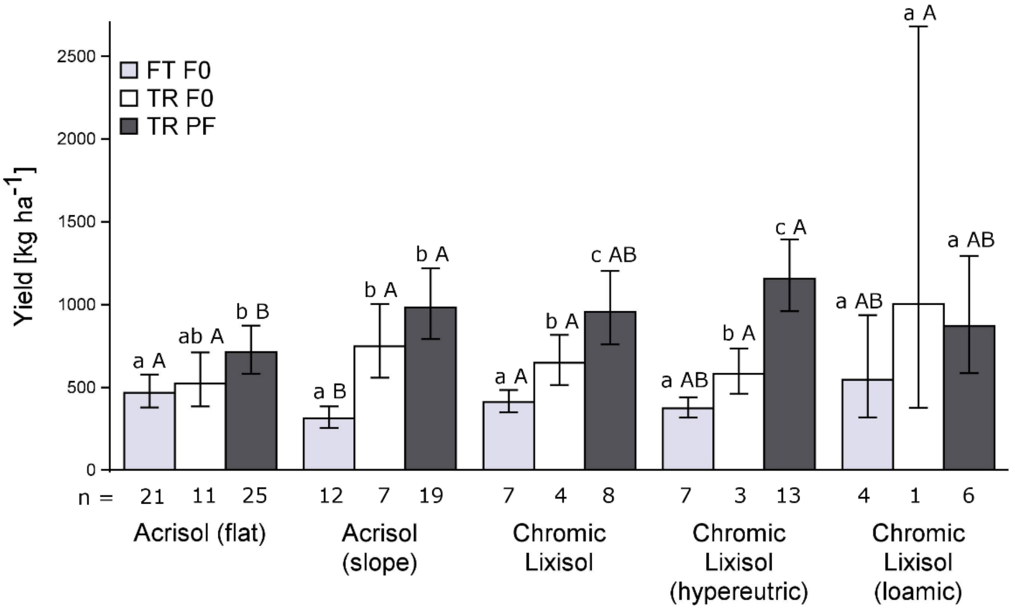


**Figure 5-4** Median estimates and 95% Confidence intervals of combinations of water harvesting systems and fertilizer in on farm babyplots averaged over Illolo and Idifu sites (Tanzania) and years. Treatment combination medians within one soil type that share a common small letter do not differ at α = 5% significance level. Medians between soil types with the same treatment that share a common capital letter do not differ at α = 5% significance level. Medians are estimated from model (3) fitted to log-transformed data and back-transformed for graphical display. Mean comparisons are based on pairwise t-tests. Legend: FT: flat ties, F0: no fertilizer, TR: tied ridging, PF: placed fertilizer

(Kamhambwa, 2014), i.e. between 203 and 1,239 kg $ha^{-1}$ (arithmetic mean: 518 ± 262 kg $ha^{-1}$; n = 54). Yield differences between RSGs are not overall significant here (Fig. 5-3). The mean grain yield is 515 ± 212 kg $ha^{-1}$ on Acrisols altogether, 336 ± 47 kg $ha^{-1}$ on Lixisols, both being lower compared to 550 ± 261 kg $ha^{-1}$on Chromc Lixisols (loamic). Farmers evaluated the latter in focus group discussions as rather fertile with adequate infiltration. Their advantages are their position in rather flat landscape, promoting infiltration, a higher base saturation and at the same time a similar plant available P content compared to Acrisols. Per definition, Lixisols have a higher base saturation, i.e. a higher saturation of cations like $Ca^{2+}$, $Mg^{2+}$, and $K^+$ at the exchange complex than Acrisols (IUSS Working Group, 2015). This indicates a higher chemical fertility status in this respect. The reference soil profile properties (Tab. 5-1) indicate that Lixisols (except the loamy one) have generally a lower plant available P-status. Statistical analysis of P contents in baby trials showed that those on all Lixisols (5.2 ± 4.5 mg $kg^{-1}$, n = 32; except the loamic variant) are significantly lower than those of Acrisols (12.9 ± 13.2 mg $kg^{-1}$, n = 29), the latter being closer located to the village centers with a higher chance of organic wastes being deployed. Plant available P - as usual in non-fertilized terrestrial ecosystems - is rated decisive for yield in the control plots. Those Acrisols with highest yields are situated close to the swamps in the depressions and profit from eolian redistribution of the fertile swamp deposits (Reinhardt and Herrmann, 2017) as well as lateral sub-surface water flow (own observations). In addition, capillary rise from the shallow groundwater can positively influence these Acrisol sites. The plant performance gradient was obvious during field visits at the end of the rainy season.

TR resulted in significantly increased pearl millet yields in the cases of Acrisol (slope), Chromic Lixisol on foot slopes and Chromic Lixisol (hypereutric) situated on middle slopes. It appears that with TR in sloped terrain increased water infiltration led to better plant performance. In contrast, Chromic Lixisols (loamic) and Acrisols (flat) were solely found in levelled terrain where less surface flow but more lateral subsurface flow can be expected, hence TR should have less effect. The number of observations for Chromic Lixisol (loamic) and treatment TRF0 was only one and can hardly be interpreted.

Combined fertilizer and water harvesting treatments revealed significantly higher yields compared to controls except for Chromic Lixisols (loamic). On Lixisols, affected by P-deficiency, TRPF resulted in significant yield increase as well in comparison to TR. Chromic Lixisols (loamic) baby trials exhibited already adequate plant-available P-content without fertilizing which was 13.6 ± 17.7 mg $kg^{-1}$ on baby trials (n = 11) which as well correlate with the distance from settlements and higher P-input from manure and household waste near settlements (Vanlauwe et al., 2016), i.e. fertilization impacted to a lesser extent.

Average yield gains with respect to treatment were the following:

- Acrisols in plains: TRF0 +21%, TRPF +66%
- Acrisols on slopes: TRF0 +59%, TRPF +142%
- Chromic Lixisols: TRF0 +19%, TRPF +102%
- Chromic Lixisols (hypereutric): TRF0 +55%, TRPF +215%
- Chromic Lixisols (loamic): TRF0 +76% (n = 1), TRPF +66%

The treatment effects (Fig. 5-3) allow the following conclusions: (1) water availability is less a constraint on Acrisols in flat landscape positions but on slopes where run-off can be expected. (2) Lixisols (except Chromoc Lixisol (loamic) near the settlement) are more limited by nutrients (in particular P) than water (higher additional yield gain in TRPF treatment). (3) Loamic Lixisols respond mainly to additional water input. (4) The yield on plots with both treatments exceed the control yield more than twofold. (5) Highest yields in the control treatment are near the swamp and the settlement in Idifu, benefiting from additional water due to low landscape position. With the TRPF treatment, highest yields were achieved in proximity to the swamp in Idifu in undulating terrain.

In summary, nutrient status (in particular P), and water availability in dependence of RSG, slope position and distance to settlements mainly control the pearl millet crop yield. Landscape position influences soil development. It can interfere with soil type specific features, e.g. run off reducing infiltration on relatively fertile slopes, and in turn leading to less yield. Combined treatments have the best effect (except for loamic Lixisols). The relative low yield level in the combined treatments (ca. 1000 kg $ha^{-1}$) reveals that further undiscovered limiting factors exist.

On-farm plots could have performed better with a higher share of supervision from researcher to farmer. For smallholder farmers, local experiments are more valuable due to conditions influencing plant performance in their respective environment. In conclusion, a typical problem of on-farm trials in large numbers is an unbalanced data set that influences the statistical significance evaluations.

### 5.6.2. Pros and cons of different research dimensions

Yields from on-station experiments were major compared to those from village level, most probably due to constant fertilization, higher overall precipitation and the highest level of control. Plot size also differed, which was a bit over 20 m² for on- station and demonstration plots and 100 m² for baby plots on farm. The increasing complexity with increasing research dimensions is obvious. Even on station, factors vary despite an envisaged controlled environment, e.g. sowing time and related water received from rain. From on-station to village mother trials, complexity increases by addition of the factors relief, RSG, soil fertility, meteorology, and external forces. At the same time, the possibility of control decreases leading to a higher necessary number of replicates. This, however, could not be managed within the Trans-SEC framework due to communication and resource constraints as well as disadvantageous timing of activity planning.

External forcing can i.a. occur in the form of intermediate trampling and browsing by animals, local inundations, fire, intended influence or destruction by humans etc. These are not necessarily reported, since the managing person can hardly constantly observe the mother trials. Particular care is necessary for the choice of the demonstration plot locations (mother trials) also in the sense of local acceptance and availability. The local population often chooses degraded terrain for such experiments (and on-farm trials) resulting in non-representative outcome. Degraded sites pose a low risk of non-expected crop loss. Risk aversion can also lead to non-participation (Guttormsen and Roll, 2014) or low responsibility taken. Therefore, lack of adequate plot care is frequently observed.

Mother and baby trials experience in a general sense similar environmental conditions in the same landscape. However, for the baby trials again factor diversity and weight increases. Next to soil fertility variability related to landscape position and distance from home stead, socio-cultural factors (e.g. wealth status or gender related plot quality; Franke et al., 2016) and management skills (i.e. education) are added. But also RSG diversity (by their intrinsic properties) impact on the most important site conditions, i.e. potential rooting depth, chemical soil fertility, and water infiltration/budget. Baby trials were at most visited three times by scientific staff: before planting for preparation of the trials, at some sites for intermediate control, and after harvest for data collection. In 2015, many participating farmers shifted the beforehand indicated baby trials to other locations. Since soil sampling for analysis already had been carried out on the foreseen baby trials, a spatial mismatch between soil analytical information and plot setting occurred. Therefore, distances between new baby trials and sampled locations were calculated, and within the same soil unit, distances of 100 m were tolerated to relate yields to laboratory soil analyses. However, soil properties variability can be tremendous within short distances even within small farms as in our work (Vanlauwe et al., 2016).

The advantage to introduce those additional factors is that they offer more possibilities to draw conclusions on applicability of innovations in the farmer’s environment. The mother trials allow farmers a first insight into the potential performance of a technology, into its constraints and necessary adaptations in their environment. In most cases, if the technology does not perform during the first season, farmers lose interest. Therefore, mother trials need to be well prepared in time, i.e. at the end of the preceding season.

Lacking communication of mandatory conditions for the baby trials led in our example to increased data uncertainty: control plots were partly not installed (i.e. no reference yield) and some plots were installed too late (i.e. different rainfall experienced in control and treatment). In consequence, for further experiments, either a better supervision of baby trials has to be implemented, or, ex ante, the number of replicates needs to be fixed at higher numbers.

It must be stated that in this case the soil map accuracy was never tested due to time constraints. In consequence, an unknown level of inaccuracy contributes to the spread of data within one "theoretically pure" RSG. This means that (1) all treatments need to be present in a sufficient (not necessarily equal; Vanlauwe et al. 2016) number for statistical evaluation and that (2) the normal cropping sites are represented in a sufficient number, since farmers tend to offer their worst sites for such kind of tests. Table 5-3 summarizes pros and cons of the research levels.

**Table 5-3** Properties of the different research dimensions with tasks and conclusion for each

| | Opportunities and benefits | Shortcomings |
|---|---|---|
| **1D - on-station trials** | one person (researcher) in charge - restricted communication challenges | lack of transferability to subsistence environment: social and management factors are excluded |
| | climate and soil homogeneity simplifies data interpretation and detailed investigation of occurring issues | artificial conditions, particularly high nutrient status |
| | potential yield under given circumstances achievable (full irrigation, pest control, weeding = controlled conditions) | explanatory results but constraints in famer environment not identified |
| | constant observation and maximum control, biotic and abiotic stress factors are identifiable | |
| | ideal prerequisites to serve statistical analysis, e.g. randomization, balanced number of samples, reliable and detailed data (e.g. weather data) | |
| **task** | mapping of biotic and abiotic stresses and detailed soil analytical data required | |
| **conclusion** | small-N trials are useful - due to intense and constant control,- to identify the processes behind the functioning of a technology | |
| **2D - mother plots** | one person (researcher) in charge - restricted communication challenges | restricted transferability to farmers' practice: social and management factors are excluded |
| | subsistence environment given with regard to climate, soil nutrient status, relief | increasing external influences, e.g. drought, cattle destroying the crop |
| | homogenous conditions regarding climate and soil variables | |
| | fertilization impact is measureable | |
| | local yield range and potential yield in village reality determinable | design constraints: demonstration plots have to be lucid for local farmers |
| | locally existing limitations identifiable, e.g. (ex post) possibility to identify biotic and abiotic stresses | |
| | | social nets influence decision on the farmer providing the mother plot land |
| **task** | prepare timely several plots on major terrain (i.e. soil, relief) types | |
| **conclusion** | adequate conditions for statistical analysis with small sample numbers, balanced number of samples, restricted reliability of data due to external influences and overall decreasing control intensity | |

| | | |
|---|---|---|
| multiD - baby plots | multi-actor approach: high number of farmers involved leads to high diversity of management practices/habits | increase in complexity, decreasing data quality |
| | identification of so far not realized factors | complex to identify the driving factor of certain results |
| | complete factor variability with respect to micro-climate, soil properties, landscape position, farmers practice and socio-cultural factors | |
| | | sporadic time-consuming controls due to spatially distant plots |
| | | communication challenges in the researcher - intermediate - farmer continuum |
| | | lower control intensity leads to unidentified influences, e.g. pests |
| | factor variability allows for more specific site- and socio-economically adapted recommendations | missing knowledge about individual crop management |
| **task** | use large-N trials respecting site variability (e.g. based on the SOTER approach) and socio-cultural factors | |
| **conclusion** | relation to farmers' reality increases, but data insecurity, too; more site- and socially adapted recommendations become possible | |

### 5.6.3. How to prepare for a balanced trial scheme on-farm?

With respect to the baby trials, it is fundamental to establish a spatially distributed testing scheme, in which a sufficient number of repetitions per relevant terrain condition is present. The term "terrain condition" is chosen by intention in order to reflect the finding that apart from RSGs (or "soil types") also landscape position, and distance from settlements play a role in the response function. In fact, such a mapping approach was introduced since long aiming at lower resolution scales by ISRIC, i.e. the SOTER approach (Herrmann et al., 2001) that considers terrain units that respond similarly to management and are usually defined by soil and relief variables.

However, in a local subsistence context it appears more feasible to rely on an indigenous knowledge approach in order to ease communication and later technology adaptation. In addition to the map unit geometry information, it is wise to collect a reduced data set on soil variables in order to ease later yield data interpretation. For this purpose a mixed sample of the topmost tilled horizon, sampled before the season starts, is sufficient. The following (analytical) data are recommended:

- location i.e. GPS position (please make sure that all data are collected in the same format, i.e. respect projection, map datum, grid etc.).
- slope inclination (as indicator for water budget and erosion)

- local soil/terrain type name
- texture (allows for conclusions on nutrient stock and available water capacity)
- pH value (as indicator for nutrient availability or toxicities)
- organic matter content (as indicator for N and P stocks)
- plant available (potassium and) phosphate contents (since phosphate is limiting in most subsistence environments; Vanlauwe and Giller, 2006))

For adequate initial terrain unit information, Reinhardt and Herrmann (2017) carried out an innovative approach: local knowledge based mapping is advantageous due to decade old experience of local farmers leading to a rapid terrain and terrain unit overview. The following checks were executed using in situ ground-based gamma-ray spectrometry with preliminary reference soil profile descriptions and transect walks, as well as subsequent randomly distributed gamma-ray measurements. For the following on-farm trials, it is advantageous to plan an adequate number of plots per terrain unit in advance. For this purpose, a statistical power analysis which includes factor variability would be appropriate. Guidance of farmers in the first experimental year could lead to results which afterwards can induce further experimental progress.

## 5.7. Conclusions

Referring to research question (1), on-station trials rarely reflect conditions of subsistence farms due to nutrient-rich soils on-station related to previous fertilization and diverging conditions compared to the village (climate, relief, soil type). Factor complexity tremendously increases from 1D researcher-managed plots on station over 2D demonstration plots in the village to multiD farmer-managed plots that are spatially spread over the village area. Transferability of on-station results to smallholder environments was, hence, hardly possible. On-station trials, however, enable to determine the maximum yield under a given management and detailed observation in a quasi-controlled environment.

Related to research question (2), management adaption to soil type is one possible strategy to perform site-adapted agriculture for efficient use of available resources, especially in Sub-Saharan agriculture. However, this did not completely match in this approach. Landscape position (swamp proximity and correlated subsoil water reserves), distance to settlements (soil fertility gradients due to manure and household waste application near homesteads), as well as differing sowing dates (amount of received rainfall in certain plant growth stages), emerged as important influences on pearl millet performance in the village. Water and P deficiency were attributed as limiting factors for pearl millet yields in the study area.

According to research question (3), multiple limitations have to be considered that impede food security in rural central Tanzania, e.g. investment ability in fertilizer, and variable rainfall patterns with intermediate droughts. Tied ridging and placed fertilizer in reduced amounts was proven successful on-station and in the villages, on demonstration plots (mother trials) as well as on-farm and farmer-managed plots (baby trials). Nevertheless, not only financial capital but also labor is restricted making tied ridging only possible on a limited area of farmers' land. With appropriate supervision, mechanized preparation could be an adequate way to overcome this constraint.

Researchers should work together with local farmers, at first, to learn from their experience related to needs and barriers in the local environment and, secondly, to jointly develop strategies for overcoming those barriers and fulfill the needs using technologies adapted to local environmental and social conditions. This was targeted in the Trans-SEC approach; however, shortcomings related to communication issues appeared.

The only way of transferring technologies to smallholder farmers is the demonstration of technologies in situ, i.e. the introduction of demonstration plots for training. Therefore, farmers should be supervised on their own plots in establishing adapted and sustainable technologies for yield stabilizing or increase. Plots should not be located far away from each other to work with comparable initial conditions on all research levels, i.e. soils with similar nutrient deficiency and related zero fertilization experiments on-station, or rainfall in similar amounts, should apply in future studies to be able to draw more revealing conclusions from the different types of field experiments.

## 5.8. Supplementary material

**Table 5-S1** Sequential F-test for fixed effects for a model fitted to pearl millet yield in on-station trials

| Effect | Description | Numerator DF | Denominator DF | F-value | p-value |
|---|---|---|---|---|---|
| $\mu$ | Intercept | 1 | 12 | 451.81 | < 0.0001 |
| $s_a$ | Site effect | 1 | 10.6 | 0.02 | 0.8873 |
| $j_b$ | Season effect | 1 | 12 | 51.67 | < 0.0001 |
| $u_{ab}$ | Season-specific site effect | 1 | 9.71 | 5.58 | 0.0405 |
| $r_{abl}$ | Block effect | 12 | 11.9 | 1.26 | 0.3470 |
| $\tau_i$ | Treatment effect | 2 | 14.1 | 80.73 | < 0.0001 |
| $(s\tau)_{ai}$ | Site-specific treatment effect | 1 | 9.09 | 0.31 | 0.5586 |
| $(j\tau)_{bi}$ | Season-specific treatment effect | 2 | 14.1 | 20.3 | < 0.0001 |
| $(u\tau)_{abi}$ | Site- and season-specific " " | 1 | 7.61 | 0.004 | 0.9520 |

F-tests are based on model (1). Response variable was square root-transformed. Random effects: $\sigma^2_{e1}$ = 211.62 and $\sigma^2_{e1}$ = 36.98. Denominator degrees of freedom are adjusted with the Method of Kenward and Roger.

**Table 5-S2** Sequential F-test for fixed effects for a model fitted to millet yield in on-site mother trials

| Effect | Description | Numerator DF | Denominator DF | F-value | p-value |
|---|---|---|---|---|---|
| $\mu$ | Intercept | 1 | 26.2 | 33249.2 | <0.0001 |
| $s_a$ | Site effect (Si) | 1 | 10.5 | 13.81 | 0.0037 |
| $j_b$ | Season effect (Se) | 1 | 26.1 | 11.83 | 0.0020 |
| $\tau_j$ | Water harvesting (WH) | 1 | 22.1 | 41.29 | <0.0001 |
| $\phi_k$ | Main effect fertilizer-regime (F) | 1 | 22.1 | 175.39 | <0.0001 |
| $(\tau\phi)_{jk}$ | Interaction of WH and F | 1 | 22.1 | 4.99 | 0.0360 |
| $(s\tau)_{aj}$ | Interaction of Si and WH | 1 | 28.1 | 0.21 | 0.6499 |
| $(s\phi)_{ak}$ | Interaction of Si and F | 1 | 28.1 | 10.44 | 0.0031 |
| $(j\tau)_{bj}$ | Interaction of Se and WH | 1 | 25.3 | 2.63 | 0.1171 |
| $(j\phi)_{bk}$ | Interaction on Se and F | 1 | 24.3 | 0.77 | 0.3893 |
| $(s\tau\phi)_{ajk}$ | Interaction of Si, WH and F | 1 | 27 | 12.10 | 0.0017 |
| $(j\tau\phi)_{bjk}$ | Interaction of Se, WH and F | 1 | 23.3 | 1.51 | 0.2316 |

F-tests are based on model (2). Denominator degrees of freedom are adjusted with the Method of Kenward and Roger. Response variable was log-transformed. Residual variances: $\sigma^2_{e11}$ = 0.0889, $\sigma^2_{e12}$ = 0.0384, $\sigma^2_{e22}$ = 0.0076

**Table 5-S3** Sequential F-tests for fixed effects for a model fitted to millet yield in on-farm trials

| Effect | Description | Numerator DF | Denominator DF | F-value | p-value |
|---|---|---|---|---|---|
| $\mu$ | Intercept | 1 | 107 | 35176.0 | <0.0001 |
| $s_a$ | Main effect of Site (Si) | 1 | 121 | 13.35 | 0.0004 |
| $j_b$ | Main effect of Season (Se) | 1 | 61.7 | 3.29 | 0.0746 |
| $\eta_i$ | Main effect of soil (S) | 4 | 75.3 | 1.27 | 0.2888 |
| $\tau_j$ | Main effect of treatment | 2 | 56.2 | 56.78 | <0.0001 |
| $(\eta\tau)_{ij}$ | Interaction of S and treatment | 8 | 41.4 | 3.54 | 0.0033 |

F-tests are based on model (3). Denominator degrees of freedom are adjusted with the Method of Kenward and Roger. Response variable was log-transformed. Random effects were found to be simultaneously non-significant in a likelihood ratio test (DF = 7, $\chi^2$ = 9.73, p = 0.2046) and therefore removed from the model.

## 5.9. Acknowledgements

We thank the German Federal Ministry of Education and Research for funding.

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# 6. General discussion and conclusions

## 6.1. Thesis context

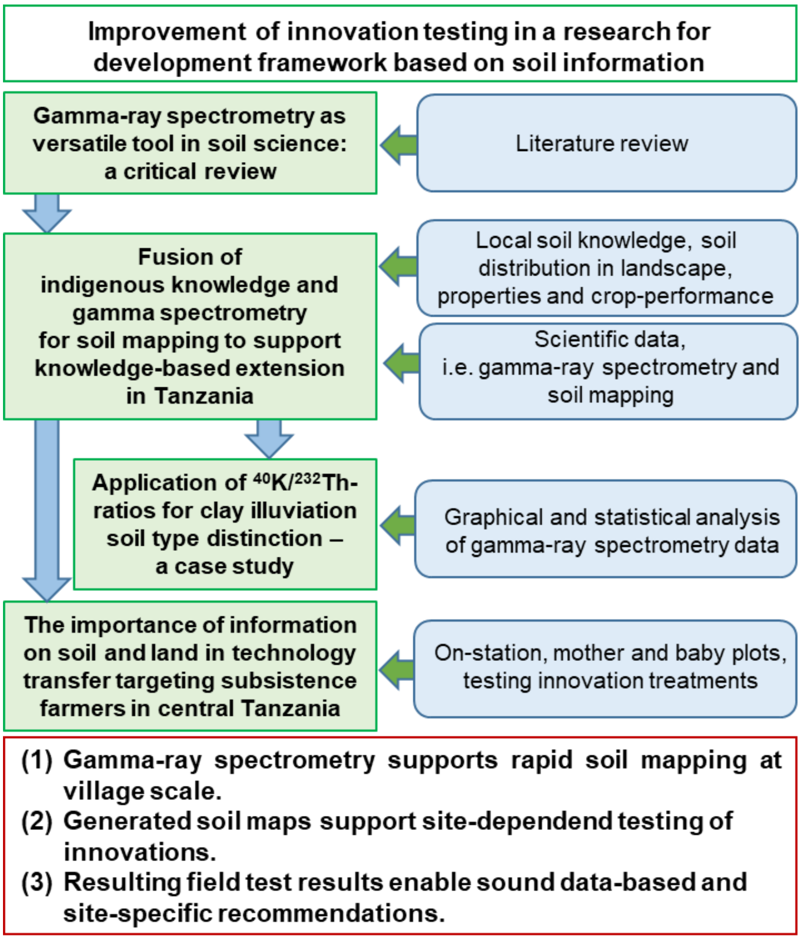


**Figure 6-1** Thesis progress including the title on top, the developed articles in green boxes and means for their development in blue boxes, main conclusions are shown in the red-framed box

Figure 6-1 sketches the thesis entitled "Improvement of innovation testing in a research for development framework based on soil information". It deals with gamma-ray spectrometry as an innovative mapping tool in soil science, which could be proven adequate for soil type distinction and rapid soil mapping in combination with local soil knowledge in an agricultural R4D context. The tested cropping-related innovations on the different spatial and conceptional research levels (on-station, mother and baby plots), i.e. tied ridging and placed fertilizing, led to an overall yield increase on all these levels. Soil type and catena position explained a great share of their varied success in the terrain.

The main findings in the course of this thesis were:

(1) Local terrain knowledge is valuable for initial orientation in new areas and overview about occurring soil types including their properties and uses. Mutual understanding and trust between actors is of high importance.

(2) Gamma-ray spectrometry serves well for soil mapping if its limitations are well-understood. It offers, in particular, the opportunity to distinguish WRB Reference Soil Groups that are otherwise hardly distinguishable in the terrain.

(3) Involving the local population in agricultural R4D initiatives is crucial for exploitation of local experience and for assessing innovations in real farm environments. The tremendous increase of environmental and socio-cultural factors on trial results makes large numbers of farmer-managed plots indispensable for solid assertions and statistical findings.

(4) Sub-soil is often not regarded during rapid soil surveys leading to incomplete assessment of site properties. Often, influences from soil depths beyond 20 or 30 cm are of high importance, in particular with respect to soil water budgets as remarked in this study close to swamps.

(5) Presumed that gamma-ray mapping makes laboratory analyses redundant, or minimizes the sample number to only inconclusive spots where detailed inspection is needed, this approach is cost-effective.

## 6.2. The connection of social and soil science in research for development

Agricultural R4D projects require on the one hand the knowledge of actual environmental conditions for estimating the potential of cropping innovations, on the other the hand the interaction with socio-cultural circumstances influencing agricultural management. The combination of both exposes the interests and needs of the local society and their available means, which R4D has to address. For this purpose, the participatory involvement of experienced residents is high-priority with regard to project efficiency. Figure 6-2 depicts several aspects in the course of a cropping season. Soil is the basic resource for farmers, in particular, in underprivileged regions. Thus, soil knowledge, including their properties related to landscape position, is crucial for R4D for amelioration and sustainable yield increase. As well, in the course of a cropping season, soil scientists can assist. Nevertheless, using participatory methods, social sciences could not only contribute to such approaches, but moreover benefit with regard to data collection.

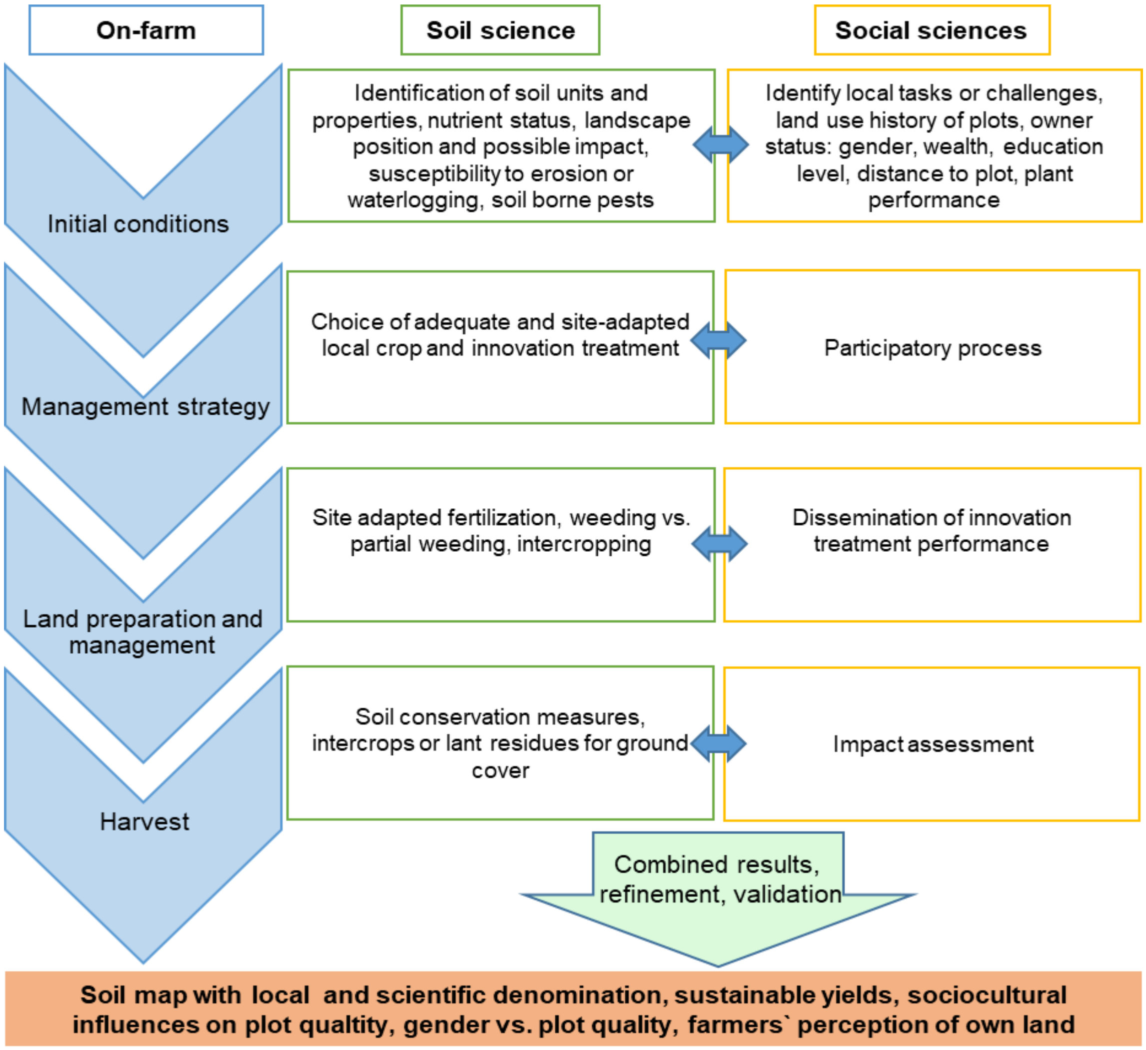


**Figure 6-2** Possible interactions of soil science and social science for valuable outcomes in agricultural R4D

Several activities have been carried out in earlier studies which connected local soil knowledge to mapping activities (Lippe et al., 2011; Osbahr and Allan, 2003; Barrios and Trejo, 2003), resulting in adequate means for rapid data collection and solid data sets. Comparison of scientific and local denomination was reviewed by Talawar and Rhoades (1998). They concluded from their research, that for development progress, scientific denomination or explanation of physico-chemical soil properties are of less value for action research than involving local perception of the terrain and related management adaption in both ways, agro-ecological and socio-cultural. Studies like the one by Birmingham (2003) can help to understand differences in soil perception, or descriptions by local population due to differences in knowledge, articulation issues and in individual interests in agricultural land. Barrera-Bassols and Zinck (2003) recommend to put the emphasis on the “cosmovision” of indigenous people for improving outcomes of R4D.

## 6.3. Shortcomings in the project related to thesis components

To present knowledge, some project or thesis aspects could have been accomplished in an easier, more efficient or effective way:

- Timeliness: Conflicts of interest arose during the Trans-SEC study. Questionnaires for the villagers were too exhaustive and surveys were undertaken during busy periods, when farmers had the priority to work the land for cropping. Non-timely decisions led to insecure household survey results. Agricultural R4D projects must identify labor peaks and act accordingly. Otherwise, research is rather hampering development.
- Labor, next to land, environmental and financial capital, is a limiting factor for subsistence farmers in the study area (Liwenga, 2013). It is one of the main factors distracting farmers from adopting a certain technology. Researchers should as well consider this aspect. Especially in the study area, fields are widespread, and elaborate preparation techniques like tied ridging can only be applied to fields near the homestead. In discussions with farmers and field assistants, mechanizing, i.e. oxen plough, was mentioned to be possible and requested. Tied ridges as well as planting distances should then be wider, to co-opt for this possibility.
- Adoption of the introduced innovation technologies is uncertain in the study area due to the bad performance of the demonstration plots and farmers' trials (Reinhardt et al., 2019). Nevertheless, on field trips, several farmers stated, they and some of their neighbors will keep preparing tied ridges on the home fields. One way researchers could have improved data outcome was longer stays in the village for better assistance during the cropping experiments. Only this way, trust on both sides, farmers and researchers, is achievable. Local culture and linked habits, e.g. in cropping, then become clearer for researchers. Communication between researchers and farmers would improve, leading to a more successful outcome.
- During field studies in the research area, several extension workers one by one quit their jobs due to manifold personal restrictions: deficient general agricultural education, limited financial resources and lacking motivation to work in remote and harsh environments like central Tanzania (personal communication). This led to unsatisfactory mentoring of the farmers who repeatedly requested help of an extension worker. In Idifu, extension staff was not present for several months. For the project Trans-SEC, this circumstance constrained participatory action.

## 6.4. The way forward

How to tailor adoptable techniques for land conservation? In R4D, as a first step, researchers have to adapt to local needs linked with local circumstances. Their intention cannot be science per se anymore, but combining scientific with local knowledge. Scientific interests cannot be priority number one alone in development work.

Hence, transdisciplinarity is of absolute importance in R4D. Only with knowledge and skills contribution of all stakeholders, adoption of reasonable innovations for sustainable yield increase is feasible. Local conditions must be studied in-depth and in accordance with local farmers in the first place, but also extension workers and farmers organizations must be involved. Farmers need to address their problems in reality, scientists are then questioned to come up with possible solutions which must be again reviewed by locals. Applicability as well as adoption probability must be discussed with the key persons. Key persons for agricultural R4D are farmers, extension workers, development practitioners, public- and private decision makers and (local) politicians (Holtland, 2007) – next to dedicated researchers.

Public investments in the agricultural sector with regard to training and education of extension workers is the central point in agricultural development. Agricultural R4D must contribute to capacity building, also via knowledge transfer. Train-the-trainers, i.e. extension workshops included in R4D projects for disseminating the gained findings could be an adequate way. Extension workers and farmers organizations could act as multipliers for productivity growth. Trained farmers would such be prepared to spread the gained knowledge across village borders. For this purpose, the inclusion of village heads as respectable persons is of great advantage.

Not only locally between farmers, also across researchers, knowledge exchange is due. So many data have been collected in the course of research, but have been forgotten after the respective project was finalized. These data must be made available to the public through follow-up projects. Only this way, researchers, non-governmental organizations, but also governments will be capable to make adequate decisions. One example is adapted land use planning according to environmental conditions. Those data could be merged in a so-called webGIS as it was generated for Tanzania in the course of the Trans-SEC project (http://sua.terragis.net/transsec/Welcome.html). Open access geographic information system software, available data sets from the Africa Soil Information Service (Hengl et al., 2015), climate data from the National Oceanic and Atmospheric Administration (http://www.noaa.gov) and yield data from the Tanzanian government – next to many others - were used for this purpose. The land evaluation tool, included in the webGIS, uses data from Sys et al. (1992) for evaluating land suitability according to certain crops.

As could be shown in this thesis, also landscape position related to subsurface expansion of water reserves, run off from slopes or distances from homesteads contributes to plant performance. For improved interpretability of environmental data, the implementation of the SOil and TERrain digital database (SOTER) could act as helpful means, beyond the pure soil unit approach. It is an initiative of the International Soil Science Society (ISSS, now IUSS), the Food and Agriculture Organisation of the United Nations (FAO), the International Soil Reference and Information Centre (ISRIC) and the United Nations Environment Programme (UNEP), launched in 1986 (http://www.isric.org/projects/soil-and-terrain-soter-database-programme). Within SOTER, land is made up of SOTER units consisting of terrain and soil bodies combinations. Spatial delineations of the SOTER units are determined by landform morphology and parent material.

Figure 6-3 displays the SOTER division approach. Including the landscape division concept from the beginning with slight transformations, i.e. include the field

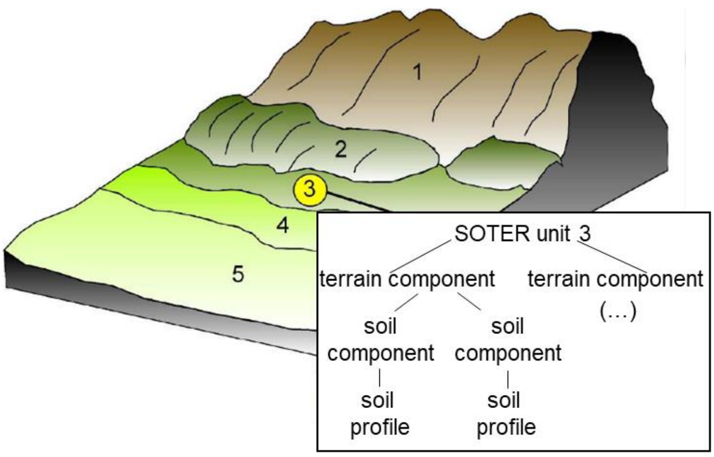


**Figure 6-3** Soil and landform division concept according to the SOTER approach (Dijkshoorn 2008)

distance from homesteads, would have led to more insightful results regarding plant performance on farmers' trials.
Implementation of drones for airborne gamma-ray surveys would be one way to even accelerate the used mapping approach. Besides, airborne surveys can display a broader and continuous picture of soil signatures in the area. An initial investigation with drones with a following ground-truthing survey for validation or clarification can save time with little extra-costs.

Detailed and sophisticated soil maps in developing countries, even of remote or hard to access terrain could be generated in the following way:

(1) Gain local knowledge about occurring soil types and its main properties via focus group discussions and high resolution satellite images, including cropping calendar for avoiding time conflicts for further participatory actions
(2) Use traditional soil science to assess the terrain via SOTER, classify the major soil types after e.g. the WRB (IUSS Working Group, 2015) together with gamma-ray signature measurements of reference soil profiles
(3) Apply drones with modern light gamma-ray detectors for soil type delineation
(4) Assess the produced tertiary images from $^{40}K$, $^{232}Th$ and $^{238}U$ signals in GIS software combined with digital elevation models for evaluation landscape position effects
(5) Ground-check anomalies or uncertainties, also for map validation
(6) Produce map with local denominations for farmers' use

Impact on crop performance is known to be the interaction of crop genotype, local environment and agricultural management (Vanlauwe et al., 2016). Research can, thus, further assist yield increase in harsh environments by breeding crop varieties that deliver stable yields with higher resistance to biotic and abiotic stresses in situ, e.g. drought or low phosphate availability, or stem borer infestation, instead of high yielding varieties. Researchers must not only connect to local knowledge and environmental conditions, also the advancement of local crop varieties is more promising than re-inventing the wheel.
With regard to possible yield increasing or land conservation measures, in order to stop degradation, traditional measures like terracing could help against loss of top

soil induced by water erosion. Farmers realized the misconception of land clearing for crops on slopes in the study area. They repeatedly requested tree planting to prevent erosion and to promote organic matter input to the soil. However, access to seedlings is bad. Besides, cattle due to feed scarcity will eat up the young trees. Corridors, where cattle invasion is prevented, must be established for regenerating natural vegetation. A traditional approach of the local population exactly covered this task (Holtland, 2007). The approach includes the grazing of cattle on crop residues on-farm directly after harvest. Subsequently, the cattle is enclosed in attended areas in valley bottoms called "luwindo", then moved to a corral ("milaga") near the cattle owner's field or house. Unfortunately, this system collapsed during colonial times in Tanzania and was never re-adopted.

Another approach for regeneration of natural vegetation is, instead of investing additional labor in planting, just let nature take back the land with indigenous and adapted plants, especially on slopes, where agricultural land cannot be established sustainably.

### 6.5. Concluding remarks

The combination of the participatory methods together with gamma ray spectrometry as a rapid and non-invasive modern opportunity served well for soil mapping in central Tanzania. The Trans-SEC approach with on-station, mother and baby trials, however, is disputable. Project internal and external aspects led to a non-satisfactory data set regarding repetition number for statistics and reliability. For transdisciplinary testing yield increasing innovations on-farm, it is, therefore, necessary to conduct multi-year interventions to deal with interferences to ensure the success in those treatments. Farmers will not participate without trust in the innovations. Only with positive visible outcomes, R4D can have an impact.

The overall target of agricultural R4D should be the improvement of local agricultural systems. For this purpose, multiple perspectives need to be considered to include the whole system contributing to agricultural sustainability and to achieve a long-term impact. Findings of agricultural R4D need to be disseminated to relevant stakeholders at all levels. Only interdisciplinary together with transdisciplinary collaboration can converge to global food security.

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## 7. Annex

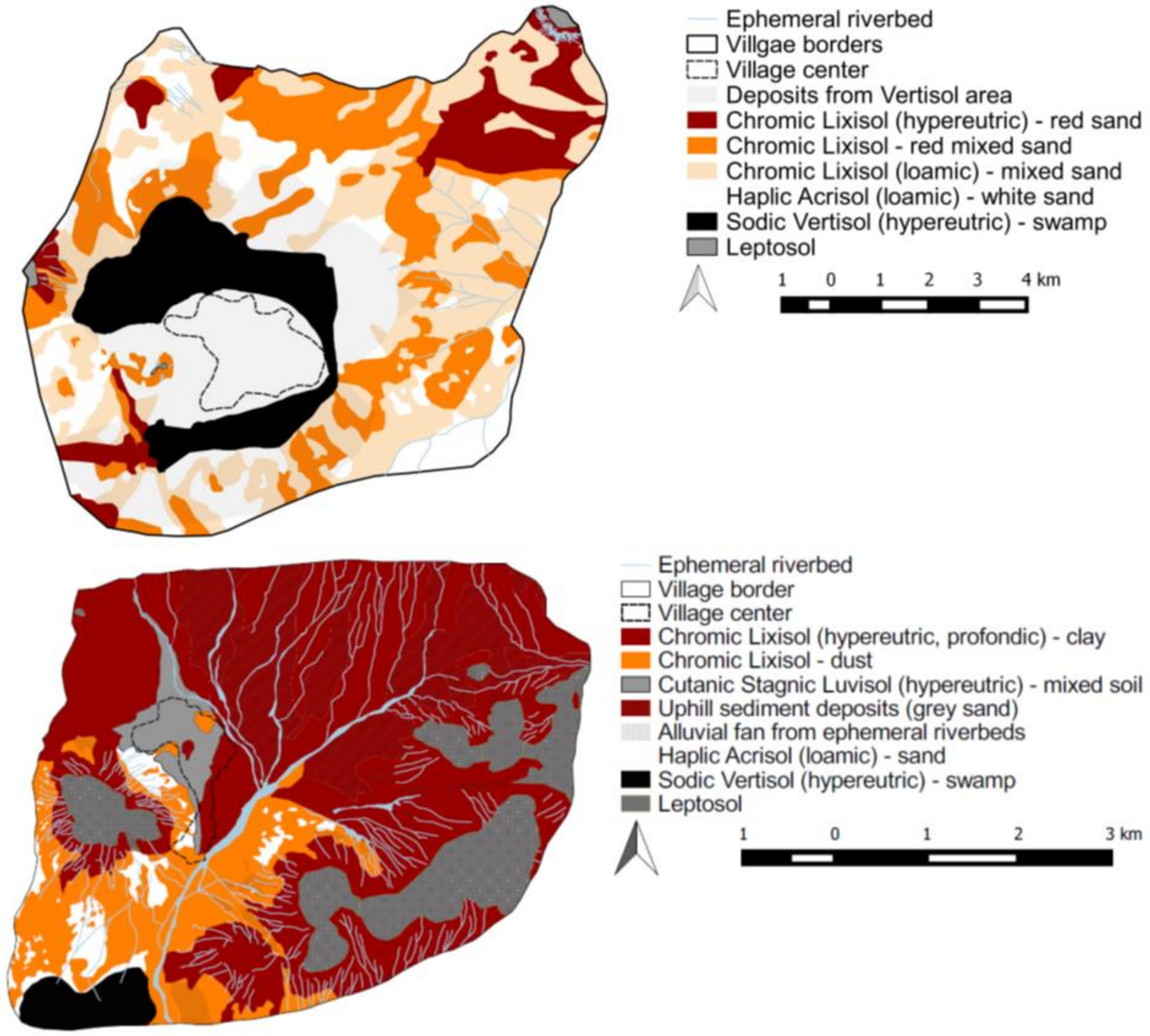


**Figure 7-1** Soil maps of Idifu (a) and Ilolo (b) in Dodoma region, Tanzania; names in the legend refer to the World Reference Base for soil resources (IUSS Working Group, 2015) and literally translated local soil names, used by farmers

**Table 7-1** Soil data (Ilolo, Chamwino district). BD: bulk density, $H_2O$: water content (gravimetric method), EC: electrical conductivity, P- and K-Bray: plant-available P and K. BS: base saturation. Number of measurements N = 2 except for BD (N=3)

| Soil | Horizon | BD [kg dm$^{-3}$] | Depth [dm] | Color | $H_2O$ [w%] | EC [µS cm$^{-1}$] | $pH_{H2O}$ - | P Bray [mg kg$^{-1}$] | K Bray [mg kg$^{-1}$] | BS [%] | Texture | Coordinates WGS84, EPSG 4326 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Haplic Acrisol (loamic)** | Ep | 1.40 | 1.7 | 2.5YR 4/6 | 1.02 | 65 | 5.6 | 7.7 | 189 | 69 | SL | 35.9005, -6.3520 |
| | Btw1 | 1.52 | 3.7 | 2.5YR 4/6-8 | 1.83 | 79 | 5.4 | 5.2 | 163 | 38 | SCL | |
| | Bw1 | 1.46 | 5.0 | 2.5YR 4/6-8 | 1.59 | 84 | 5.2 | 3.0 | 124 | 31 | SCL | |
| | Btw2 | 1.40 | 6.5 | 5YR 5/8 | 2.50 | 73 | 4.9 | 2.6 | 107 | 19 | SC | |
| | Bgw | 1.44 | >6.5 | 5YR 5/6 | 2.35 | 60 | 5.1 | 2.6 | 121 | SL | SC | |
| **Cutanic Stagnic Luvisol (hypereutric)** | Ep | 1.36 | 1.9 | 7.5YR 4/3 | 2.92 | 154 | 9.0 | 12.2 | 330 | 95 | SCL | 35.8975, -6.3368 |
| | Bt | 1.55 | 3.6 | 10YR 6/3 | 3.89 | 166 | 7.8 | 10.8 | 221 | 70 | SCL | |
| | Bgw | 1.46 | 5.6 | 10YR 6/4 | 5.50 | 144 | 8.0 | 11.0 | 270 | 93 | CL | |
| | BC | 1.34 | >5.6 | 7.5 YR 5/3 | 8.20 | 265 | 8.8 | 7.5 | 336 | 102 | CL | |
| **Sodic Vertisol (hypereutric)** | Ah | 0.97 | 1.0 | 5YR 4/1 | 10.9 | 413 | 8.4 | 0.8 | 267 | 73 | C | 35.8916, -6.3631 |
| | Bin | 1.21 | 5.6 | 5YR 5/1 | 12.6 | 2045 | 8.9 | 0.0 | 175 | 83 | C | |
| | Biw | 1.30 | 9.0 | 2.5YR 4/1 | 13.2 | 402 | 8.4 | 1.9 | 178 | 91 | C | |
| | Bw | 1.27 | >9.0 | 5YR 5/1 | 13.9 | 430 | 8.5 | 1.9 | 133 | 90 | C | |
| **Chromic Lixisol (hypereutric profondic)** | E | 1.42 | 0.9 | 10r 3/6 | 1.72 | 93 | 5.1 | 0.4 | 189 | 71 | SCL | 35.9014, -6.3454 |
| | Bt | 1.45 | 2.9 | 10r 3/6 | 3.55 | 91 | 4.3 | 0.3 | 84 | 73 | SC | |
| | Bw1 | 1.33 | 5.8 | 10r 3/6 | 2.57 | 87 | 6.4 | 0.0 | 36.4 | 80 | SC | |
| | Bw2 | 1.37 | 7.6 | 10r 3/6 | 1.48 | 88 | 6.9 | 0.9 | 26.4 | 69 | SC | |
| | Cw | 1.44 | >7.6 | 10r 4/6 | 1.17 | 123 | 6.3 | 0.3 | 37.4 | 98 | SCL | |
| **Chromic Lixisol** | Ap | 1.28 | 1.1 | 5YR 4/8 | 1.23 | 90 | 5.0 | 5.1 | 211.1 | 59 | SCL | 35.9036, -6.3550 |
| | E | 1.30 | 3.0 | 5YR 4/8 | 2.09 | 81 | 5.0 | 5.4 | 241.5 | 56 | SCL | |
| | Bt | 1.32 | 5.0 | 5YR 5/8 | 1.47 | 68 | 4.9 | 2.2 | 180.7 | 50 | SC | |
| | Bw1 | 1.38 | 7.5 | 5YR 5/8 | 1.65 | 82 | 4.9 | 2.3 | 94.1 | 52 | SC | |
| | Bw2 | 1.43 | >7.5 | 5YR 5/8 | 1.71 | 51 | 5.3 | 0.5 | 91.9 | 57 | SC | |

**Table 7-2** Soil data (Ilolo, Chamwino district). $C_t$: total C, $C_c$: carbonate C (after Scheibler), $C_{org}$: organic C, $N_t$: total N, $CEC_{pot}$: potential cation exchange capacity, $CEC_{clay}$: cation exchange capacity of clay. N = 2

| Soil | Horizon | $C_t$ [%] | $C_C$ [%] | $C_{org}$ [%] | $N_t$ [%] | $CEC_{pot}$ [mmolc+ kg$^{-1}$] | $CEC_{clay}$ [cmolc+ kg$^{-1}$] | Exchangeable cations $Na^+$ [mmolc+ kg$^{-1}$] | $K^+$ [mmolc+ kg$^{-1}$] | $Ca^{2+}$ [mmolc+ kg$^{-1}$] | $Mg^{2+}$ [mmolc+ kg$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Haplic Acrisol (loamic)** | Ep | 0.39 | * | 0.39 | 0.06 | 46.3 | 2.6 | 0.4 | 9.2 | 14.8 | 7.5 |
| | Btw1 | 0.33 | * | 0.33 | 0.05 | 62 | 15.2 | 1.0 | 8.5 | 8.8 | 5.0 |
| | Bw1 | 0.45 | * | 0.45 | 0.06 | 68 | 14.0 | 1.6 | 6.6 | 8.2 | 4.6 |
| | Btw2 | 0.31 | * | 0.31 | 0.05 | 83 | 15.6 | 1.5 | 2.6 | 6.8 | 4.6 |
| | Bgw | 0.26 | * | 0.26 | 0.05 | 97 | 18.6 | 4.3 | 2.6 | 9.9 | 6.2 |
| **Cutanic Stagnic Luvisol (hypereutric)** | Ep | 0.39 | * | 0.39 | 0.06 | 137 | 43.3 | 4.1 | 24.8 | 68 | 32.5 |
| | Bt | 0.32 | * | 0.32 | 0.05 | 215 | 53 | 5.3 | 19.6 | 94 | 30.8 |
| | Bgw | 0.26 | * | 0.26 | 0.04 | 302 | 66 | 12.2 | 20.0 | 167 | 81 |
| | BC | 0.40 | 0.25 | 0.15 | 0.04 | 226 | 46 | 21.7 | 21.3 | 92 | 96 |
| **Sodic Vertisol (hypereutric)** | Ah | 1.05 | 0.21 | 0.84 | 0.08 | 624 | 84 | 11.7 | 9.7 | 307 | 126 |
| | Bin | 0.90 | 0.37 | 0.53 | 0.07 | 667 | 80 | 115 | 7.0 | 280 | 150 |
| | Biw | 0.79 | 0.39 | 0.40 | 0.05 | 561 | 75 | 62 | 12.2 | 286 | 151 |
| | Bw | 0.62 | 0.40 | 0.22 | 0.06 | 559 | 71 | 97 | 12.7 | 260 | 133 |
| **Chromic Lixisol (hypereutric profondic)** | E | 0.34 | * | 0.34 | 0.05 | 72 | 17.5 | 0.6 | 9.6 | 29.2 | 11.7 |
| | Bt | 0.36 | * | 0.36 | 0.06 | 78 | 15.3 | 0.8 | 3.8 | 37.9 | 14.0 |
| | Bw1 | 0.31 | * | 0.31 | 0.06 | 77 | 15.3 | 1.3 | 2.0 | 43.4 | 15.0 |
| | Bw2 | 0.28 | * | 0.28 | 0.05 | 85 | 17.5 | 1.2 | 0.8 | 43.8 | 12.5 |
| | Cw | 0.30 | * | 0.30 | 0.05 | 87 | 19.7 | 2.6 | 1.4 | 66 | 15.4 |
| **Chromic Lixisol** | Ap | 0.38 | * | 0.38 | 0.06 | 43.9 | 8.0 | 0.3 | 10.6 | 9.5 | 5.4 |
| | E | 0.31 | * | 0.31 | 0.05 | 56 | 13.1 | 0.2 | 12.4 | 12.2 | 6.6 |
| | Bt | 0.29 | * | 0.29 | 0.05 | 60 | 10.4 | 0.4 | 5.0 | 15.2 | 8.6 |
| | Bw1 | 0.32 | * | 0.32 | 0.05 | 57 | 9.7 | 1.5 | 2.3 | 14.2 | 11.7 |
| | Bw2 | 0.31 | * | 0.31 | 0.05 | 60 | 11.0 | 2.8 | 2.3 | 16.8 | 12.4 |

*below detection limit

**Table 7-3** Soil data (Idifu, Chamwino district). BD: bulk density, $H_2O$: water content (gravimetric method), EC: electrical conductivity, P- and K-Bray: plant-available P and K. BS: base saturation. N = 2 except for BD (N=3)

| Soil | Horizon | BD [kg dm$^{-3}$] | Depth [dm] | Color | $H_2O$ [w%] | EC [µS cm$^{-1}$] | $pH_{H2O}$ - | P Bray [mg kg$^{-1}$] | K Bray [mg kg$^{-1}$] | BS [%] | Texture | Coordinates WGS84, EPSG 4326 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chromic Lixisol (loamic)** | Ep | 1.51 | 1.1 | 5YR 3/4 | 0.78 | 141 | 6.3 | 2.3 | 108 | 49 | SL | 35.9969, -6.4526 |
| | Bt | 1.58 | 4.6 | 5YR 4/4 | 1.22 | 127 | 6.3 | 4.0 | 114 | 55 | SCL | |
| | Bw | 1.48 | 1.7 | 5YR 4/6 | 2.88 | 121 | 6.6 | 2.1 | 41.2 | 55 | CL | |
| **Chromic Lixisol (hypereutric)** | Ep | 1.53 | 0.6 | 10R 3/4 | 1.00 | 161 | 7.1 | 1.9 | 111 | 69 | SL | 35.9539, -6.4548 |
| | Bt | 1.64 | 1.4 | 10R 3/4 | 1.69 | 177 | 7.2 | 1.5 | 94 | 74 | SCL | |
| | Bwk | 1.70 | 4.5 | 10R 3/4 | 2.12 | 177 | 7.0 | 2.9 | 56 | 77 | SCL | |
| | BC | | >2.5 | 10R 3/4 | 2.29 | 83 | 7.9 | 1.2 | 20.8 | 100 | L | |
| **Chromic Lixisol** | Ep | 1.38 | 0.5 | 2.5YR 3/4 | 0.78 | 149 | 6.4 | 0.6 | 112 | 52 | SL | 35.9947, -6.4408 |
| | Bt | 1.55 | 2 | 2.5YR 3/6 | 1.58 | 129 | 5.8 | 0.2 | 121 | 48 | SC | |
| | Bw1 | 1.46 | 3.6 | 2.5YR 3/6 | 1.48 | 143 | 6.3 | 0.2 | 125 | 56 | CL | |
| | Bw2 | 1.36 | 3.9 | 2.5YR 3/6 | 1.88 | 168 | 7.0 | 1.4 | 46.7 | 63 | SCL | |
| | Bwg | 1.37 | >1 | 2.5YR 3/6 | 2.28 | 225 | 8.1 | 0.9 | 29.2 | 85 | SL | |
| **Haplic Acrisol (loamic)** | Ap1 | 1.62 | 0.4 | 10YR 3/3 | 0.40 | 51 | 5.9 | 24.9 | 63 | 48 | LS | 35.9862, -6.4408 |
| | Ap2 | 1.65 | 2.0 | 10YR 4/3 | 0.31 | 61 | 5.6 | 0.3 | 73 | 41 | LS | |
| | Bt | 1.59 | 4.2 | 10YR 5/6 | 1.01 | 38 | 5.0 | 0.2 | 27.6 | 15 | SCL | |
| | Bg | 1.62 | >3.5 | 10YR 5/6 | 1.02 | 39 | 4.8 | 0.7 | 23.5 | 24 | SCL | |
| **Sodic Vertisol (hypereutric)** | Ap1 | 0.97 | 0.3 | 2.5YR 4/2 | 5.09 | 223 | 6.5 | 5.1 | 372 | 73 | C | 35.9628, -6.4520 |
| | Ap2 | 1.51 | 1.4 | 2.5YR 3/2 | 6.51 | 210 | 6.7 | 2.8 | 420 | 70 | C | |
| | Biw1 | 1.42 | 3.6 | 5Y 4/1 | 5.48 | 161 | 6.8 | 3.9 | 265 | 85 | C | |
| | Biw2 | 1.30 | 1.8 | 5Y 5/2 | 9.49 | 340 | 8.5 | 2.6 | 217 | 89 | C | |
| | Bwg | 1.27 | >3 | 2.5Y 5/2 | 8.00 | 607 | 9.8 | 1.2 | 205 | 100 | C | |

**Table 7-4** Soil data (Idifu, Chamwino district). $C_t$: total C, $C_c$: carbonate C (after Scheibler), $C_{org}$: organic C, $N_t$: total N, $CEC_{pot}$: potential cation exchange capacity, $CEC_{clay}$: cation exchange capacity of clay. N = 2

| Soil | Horizon | $C_t$ [%] | $C_C$ [%] | $C_{org}$ [%] | $N_t$ [%] | $CEC_{pot}$ [mmolc+ kg$^{-1}$] | $CEC_{clay}$ [cmolc+ kg$^{-1}$] | Exchangeable cations $Na^+$ [mmolc+ kg$^{-1}$] | $K^+$ [mmolc+ kg$^{-1}$] | $Ca^{2+}$ [mmolc+ kg$^{-1}$] | $Mg^{2+}$ [mmolc+ kg$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chromic Lixisol (loamic)** | Ep | 0.39 | * | 0.39 | 0.04 | 64 | 29.6 | 2.6 | 8.6 | 16.8 | 3.7 |
| | Bt | 0.37 | * | 0.37 | 0.04 | 81 | 23.9 | 2.5 | 10.7 | 25.2 | 5.9 |
| | Bw | 0.33 | * | 0.33 | 0.04 | 140 | 35.7 | 4.0 | 4.7 | 63 | 5.1 |
| **Chromic Lixisol (hypereutric)** | Ep | 0.48 | * | 0.48 | 0.05 | 78 | 27.1 | 4.8 | 8.5 | 35.2 | 5.1 |
| | Bt | 0.53 | * | 0.53 | 0.06 | 95 | 20.4 | 3.7 | 7.7 | 54 | 6.1 |
| | Bwk | 0.50 | * | 0.50 | 0.06 | 109 | 24.2 | 2.5 | 5.2 | 70 | 5.8 |
| | BC | 0.40 | 0.09 | 0.31 | 0.04 | 131 | 42.4 | 1.6 | 2.6 | 123 | 4.2 |
| **Chromic Lixisol** | Ep | 0.43 | * | 0.43 | 0.04 | 68 | 28.2 | 4.5 | 9.8 | 15.3 | 6.2 |
| | Bt | 0.32 | * | 0.32 | 0.04 | 86 | 18.4 | 3.4 | 11.6 | 20.1 | 6.5 |
| | Bw1 | 0.24 | * | 0.24 | 0.04 | 85 | 21.8 | 5.8 | 11.8 | 20.9 | 9.4 |
| | Bw2 | 0.23 | * | 0.23 | 0.04 | 106 | 35.2 | 6.8 | 4.3 | 45.2 | 10.6 |
| | Bwg | 0.21 | * | 0.21 | 0.02 | 100 | 43.6 | 7.6 | 3.5 | 73 | 1.3 |
| **Haplic Acrisol (loamic)** | Ap1 | 0.40 | * | 0.40 | 0.03 | 22.9 | 14.2 | 0.4 | 3.8 | 5.7 | 1.1 |
| | Ap2 | 0.31 | * | 0.31 | 0.03 | 24.8 | 25.8 | 0.9 | 4.2 | 4.3 | 0.8 |
| | Bt | 0.20 | * | 0.20 | 0.02 | 56 | 21.9 | 1.2 | 2.8 | 3.5 | 0.9 |
| | Bg | 0.19 | * | 0.19 | 0.02 | 59 | 20.6 | 1.2 | 2.8 | 5.6 | 4.3 |
| **Sodic Vertisol (hypereutric)** | Ap1 | 1.36 | * | 1.36 | 0.12 | 269 | 40.3 | 5.6 | 45.9 | 88 | 57 |
| | Ap2 | 1.49 | * | 1.49 | 0.14 | 270 | 39.4 | 5.4 | 52 | 94 | 38.5 |
| | Biw1 | 0.47 | * | 0.47 | 0.04 | 201 | 38.1 | 7.9 | 30.5 | 66 | 68 |
| | Biw2 | 0.36 | 0.09 | 0.27 | 0.03 | 294 | 40.0 | 33.2 | 29.9 | 119 | 80 |
| | Bwg | 0.60 | 0.34 | 0.26 | 0.03 | 301 | 40.8 | 84 | 33.8 | 143 | 40 |

*below detection limit

**Table 7-5** Gamma ray spectrometric data (K, eTh, eU) from reference profiles in Ilolo, Chamwino district. N = 5

| Ilolo | K [%] | SD | eTh [ppm] | SD | eU [ppm] | SD |
|---|---|---|---|---|---|---|
| **Haplic Acrisol (loamic)** | 0.83 | 0.01 | 2.43 | 0.15 | 0.38 | 0.10 |
| **Cutanic Stagnic Luvisol (hypereutric)** | 0.87 | 0.06 | 6.55 | 0.17 | 0.78 | 0.10 |
| **Sodic Vertisol (hypereutric)** | 0.70 | 0.06 | 8.0 | 0.60 | 1.10 | 0.14 |
| **Chromic Lixisol (hypereutric profondic)** | 1.83 | 0.03 | 6.75 | 0.33 | 0.33 | 0.17 |
| **Chromic Lixisol** | 0.37 | 0.02 | 4.20 | 0.23 | 0.35 | 0.13 |

**Table 7-6** Gamma ray spectrometric data (K, eTh, eU) from reference profiles in Idifu, Chamwino district. N = 5

| Idifu | K [%] | SD | eTh [ppm] | SD | eU [ppm] | SD |
|---|---|---|---|---|---|---|
| **Chromic Lixisol (loamic)** | 1.0 | 0.01 | 9.20 | 0.45 | 0.80 | 0.14 |
| **Chromic Lixisol (hypereutric)** | 0.29 | 0.04 | 4.70 | 0.62 | 0.55 | 0.22 |
| **Chromic Lixisol** | 0.48 | 0.02 | 5.73 | 0.22 | 0.83 | 0.06 |
| **Haplic Acrisol (loamic)** | 0.44 | 0.02 | 2.90 | 0.24 | 0.40 | 0.14 |
| **Sodic Vertisol (hypereutric)** | 0.94 | 0.01 | 5.10 | 0.53 | 0.40 | 0.09 |

**Table 7-7** (part 1) Transect soil data (weighted average for the top 30 cm) in Ilolo, Chamwino district. Lat: latitude, Long: longitude (WGS84), EC: electrical conductivity, P- and K-Bray: plant-available P and K, $C_t$: total C, $N_t$: total N; K, eTh, eU: gamma ray data of K, Th, U, CLAYR: clayrich. Texture was determined following Jahn et al. (2008). Soils were classified following WRB, IUSS working group, 2015). N = 2, except for gamma ray data (N = 5)

| Plot | Lat | Long | Elevation | Color | Texture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Denomination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 11 | -6.3489 | 35.9148 | 1085 | 2.5YR 3/6 | SCL | 190.6 | 6.8 | 2.8 | 218 | 0.04 | 0.33 | 0.97 | 3.03 | 0.49 | Chromic Lixisol |
| 12 | -6.3487 | 35.9145 | 1083 | 2.5YR 4/6 | SCL | 38.0 | 6.0 | 1.9 | 156 | 0.04 | 0.25 | 1.01 | 2.81 | 0.38 | Chromic Lixisol |
| 13 | -6.3483 | 35.9141 | 1087 | 2.5YR 4/8 | SCL | 43.1 | 5.4 | 1.1 | 122 | 0.03 | 0.25 | 0.91 | 2.78 | 0.40 | Chromic Lixisol |
| 14 | -6.3480 | 35.9138 | 1086 | 2.5YR 4/6 | SL CLAYR | 40.9 | 6.5 | 3.7 | 242 | 0.03 | 0.28 | 0.88 | 3.54 | 0.46 | Chromic Lixisol |
| 15 | -6.3474 | 35.9135 | 1085 | 2.5YR 4/6 | SCL | 49.5 | 5.9 | 3.3 | 242 | 0.04 | 0.54 | 1.01 | 2.11 | 0.35 | Chromic Lixisol |
| 16 | -6.3469 | 35.9132 | 1070 | 7.5YR 4/4 | SL | 27.2 | 6.1 | 4.9 | 268 | 0.03 | 0.30 | 1.03 | 2.86 | 0.36 | Chromic Lixisol |
| 17 | -6.3464 | 35.9127 | 1068 | 7.5YR 3/4 | SL CLAYR | 41.4 | 5.9 | 8.0 | 286 | 0.03 | 0.36 | 0.89 | 3.28 | 0.29 | Chromic Lixisol |
| 18 | -6.3457 | 35.9122 | 1068 | 5YR 4/8 | US | 9.2 | 6.1 | 2.4 | 65 | 0.03 | 0.29 | 1.07 | 1.89 | 0.43 | Chromic Lixisol (hypereutric, profondic) |
| 19 | -6.3449 | 35.9114 | 1074 | 5YR 3/6 | L | 37.2 | 6.3 | 2.2 | 159 | 0.02 | 0.23 | 1.02 | 1.84 | 0.34 | Chromic Lixisol (hypereutric, profondic) |
| 110 | -6.3436 | 35.9104 | 1075 | 10R 3/6 | LS | 14.3 | 6.8 | 0.9 | 88 | 0.01 | 0.16 | 1.37 | 7.04 | 0.73 | Chromic Lixisol (hypereutric, profondic) |
| 111 | -6.3433 | 35.9102 | 1076 | 10R 3/6 | SL | 19.1 | 6.9 | 2.5 | 92 | 0.01 | 0.24 | 1.22 | 10.59 | 0.93 | Chromic Lixisol (hypereutric, profondic) |
| 112 | -6.3428 | 35.9097 | 1078 | 5YR 4/8 | SL CLAYR | 19.6 | 6.4 | 2.8 | 156 | 0.01 | 0.26 | 1.28 | 11.27 | 0.84 | Chromic Lixisol (hypereutric, profondic) |
| 21 | -6.3386 | 35.9041 | 1079 | 2.5YR 3/4 | L | 99 | 7.3 | 12.0 | 476 | 0.04 | 0.41 | 0.60 | 17.30 | 1.43 | Chromic Lixisol |
| 22 | -6.3389 | 35.9037 | 1082 | 2.5YR 3/3 | L | 189 | 7.0 | 1.6 | 719 | 0.10 | 1.19 | 0.73 | 15.92 | 1.74 | Chromic Lixisol |
| 23 | -6.3390 | 35.9033 | 1072 | 7.5YR 3/4 | LS | 33.4 | 6.7 | 11.0 | 232 | 0.02 | 0.27 | 0.70 | 19.46 | 1.56 | Chromic Lixisol |
| 24 | -6.3392 | 35.9030 | 1071 | 5YR 4/4 | SL C | 40.2 | 6.5 | 4.9 | 261 | 0.12 | 1.38 | 0.63 | 21.17 | 1.30 | Chromic Lixisol |

**Table 7-7** (part 2)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS $cm^{-1}$] | - | [mg $kg^{-1}$] | [mg $kg^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 25 | -6.3394 | 35.9026 | 1070 | 7.5YR 3/3 | SL | 86 | 8.3 | 0.0 | 448 | 0.15 | 1.00 | 0.68 | 30.81 | 1.71 | Chromic Lixisol |
| 26 | -6.3399 | 35.9020 | 1075 | 5YR 3/3 | SL | 20.4 | 6.6 | 15.3 | 191 | 0.07 | 0.42 | 0.64 | 29.00 | 1.21 | Chromic Lixisol |
| 27 | -6.3404 | 35.9011 | 1065 | 7.5YR 4/6 | SL | 37.1 | 5.2 | 2.5 | 68 | 0.03 | 0.34 | 0.95 | 3.74 | 0.52 | Haplic Acrisol (loamic) |
| 28 | -6.3405 | 35.9008 | 1078 | 7.5YR 3/4 | SL | 22.8 | 6.5 | 6.7 | 161 | 0.03 | 0.25 | 0.91 | 5.06 | 0.53 | Haplic Acrisol (loamic) |
| 29 | -6.3410 | 35.9002 | 1079 | 5YR 4/6 | SL | 25.9 | 5.2 | 4.0 | 108 | 0.01 | 0.23 | 0.95 | 3.77 | 0.43 | Haplic Acrisol (loamic) |
| 210 | -6.3412 | 35.8998 | 1076 | 7.5YR 3/4 | SL | 40.7 | 5.2 | 3.9 | 161 | 0.03 | 0.31 | 0.84 | 3.90 | 0.40 | Haplic Acrisol (loamic) |
| 211 | -6.3416 | 35.8991 | 1086 | 5YR 4/6 | SL CLAYR | 61 | 5.3 | 1.3 | 144 | 0.02 | 0.32 | 0.87 | 3.48 | 0.45 | Haplic Acrisol (loamic) |
| 31 | -6.3194 | 35.9114 | 1126 | 2.5YR 3/6 | SL CLAYR | 26.9 | 6.0 | 0.9 | 99 | 0.07 | 0.41 | 1.23 | 9.93 | 0.64 | Chromic Lixisol (hypereutric, profondic) |
| 32 | -6.3198 | 35.9109 | 1122 | 2.5YR 2.5/4 | SL | 54 | 7.0 | 1.4 | 150 | 0.12 | 0.70 | 1.28 | 10.54 | 0.78 | Chromic Lixisol (hypereutric, profondic) |
| 33 | -6.3200 | 35.9106 | 1119 | 2.5YR 3/6 | LS | 34.3 | 6.2 | 1.0 | 142 | 0.07 | 0.36 | 1.30 | 12.90 | 0.76 | Chromic Lixisol (hypereutric, profondic) |
| 34 | -6.3206 | 35.9101 | 1117 | 2.5YR 3/6 | LS | 55 | 5.7 | 1.6 | 94 | 0.06 | 0.31 | 1.34 | 8.61 | 0.77 | Chromic Lixisol (hypereutric, profondic) |
| 35 | -6.3214 | 35.9094 | 1114 | 2.5YR 3/6 | LS | 31.5 | 5.7 | 2.5 | 77 | 0.02 | 0.16 | 1.37 | 7.04 | 0.47 | Chromic Lixisol (hypereutric, profondic) |
| 36 | -6.3223 | 35.9082 | 1112 | 2.5YR 3/4 | LS | 23.7 | 6.5 | 2.5 | 68 | 0.02 | 0.20 | 1.17 | 15.50 | 0.89 | Chromic Lixisol (hypereutric, profondic) |
| 37 | -6.3239 | 35.9070 | 1111 | 2.5YR 3/6 | LS | 25.7 | 6.7 | 0.3 | 28 | 0.02 | 0.22 | 1.21 | 9.86 | 0.84 | Chromic Lixisol (hypereutric, profondic) |
| 38 | -6.3248 | 35.9064 | 1110 | 5YR 3/4 | LS | 45.3 | 6.3 | 5.2 | 120 | 0.02 | 0.30 | 1.18 | 10.75 | 0.86 | Chromic Lixisol (hypereutric, profondic) |
| 39 | -6.3266 | 35.9052 | 1107 | 5YR 3/4 | LS | 35.9 | 6.1 | 3.1 | 96 | 0.01 | 0.22 | 1.24 | 9.41 | 0.81 | Chromic Lixisol (hypereutric, profondic) |
| 310 | -6.3270 | 35.9049 | 1106 | 2.5YR 3/4 | SL | 19.9 | 5.8 | 1.0 | 97 | 0.02 | 0.20 | 1.14 | 9.51 | 0.79 | Chromic Lixisol (hypereutric, profondic) |

**Table 7-7** (part 3)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 311 | -6.3277 | 35.9041 | 1105 | 2.5YR 3/4 | LS | 30.7 | 6.4 | 2.9 | 184 | 0.03 | 0.32 | 1.17 | 8.53 | 0.74 | Chromic Lixisol (hypereutric, profondic) |
| 312 | -6.3284 | 35.9033 | 1104 | 2.5YR 4/4 | LS | 28.9 | 6.3 | 1.3 | 217 | 0.12 | 0.86 | 1.04 | 11.47 | 0.96 | Gradient |
| 313 | -6.3292 | 35.9026 | 1100 | 5YR 3/4 | LS | 133 | 8.0 | 2.6 | 46.6 | 0.08 | 0.30 | 1.26 | 23.89 | 1.55 | Chromic Lixisol (hypereutric, profondic) |
| 314 | -6.3299 | 35.9019 | 1099 | 10YR 4/3 | SCL | 151 | 8.6 | 1.4 | 107 | 0.09 | 0.61 | 0.76 | 9.98 | 1.14 | Cutanic Stagnic Luvisol |
| 41 | -6.3635 | 35.8999 | 1060 | 10YR 4/1 | CL | 481 | 9.4 | 2.0 | 137 | 0.04 | 0.71 | 0.41 | 5.99 | 0.61 | Sodic Vertisol (hypereutric) |
| 42 | -6.3633 | 35.9002 | 1056 | 7.5YR 3/2 | CL | 133 | 8.6 | 2.5 | 159 | 0.05 | 0.73 | 0.46 | 6.47 | 0.77 | Sodic Vertisol (hypereutric) |
| 43 | -6.3632 | 35.9005 | 1057 | 7.5YR4/4 | CL | 582 | 2.9 | 6.0 | 155 | 0.04 | 0.67 | 0.83 | 12.19 | 0.89 | Vertisol with red overburden |
| 44 | -6.3630 | 35.9009 | 1056 | 7.5YR 4/4 | CL | 148 | 7.9 | 3.1 | 187 | 0.06 | 0.80 | 0.80 | 9.82 | 0.85 | Vertisol with red overburden |
| 45 | -6.3628 | 35.9012 | 1053 | 5YR 4/4 | L | 132 | 6.8 | 5.1 | 120 | 0.03 | 0.34 | 1.08 | 9.81 | 0.77 | Vertisol with red overburden |
| 46 | -6.3637 | 35.9014 | 1061 | 5YR 3/4 | SCL | 61 | 6.5 | 2.8 | 290 | 0.05 | 0.49 | 1.19 | 13.46 | 1.18 | Vertisol with red overburden |
| 47 | ** | ** | ** | 5YR 6/8 | SL | 16.7 | 6.3 | 1.0 | 25.1 | 0.01 | 0.04 | 1.52 | 4.71 | 0.42 | Chromic Lixisol |
| 48 | -6.3633 | 35.9023 | 1059 | 7.5YR 4/4 | L | 147 | 6.3 | 6.3 | 304 | 0.02 | 0.02 | 0.58 | 6.82 | 0.47 | Chromic Lixisol |
| 49 | -6.3628 | 35.9033 | 1061 | 7.5YR 3/4 | L | 147 | 6.3 | 6.3 | 304 | 0.02 | 0.02 | 0.28 | 4.80 | 0.47 | Chromic Lixisol |
| 410 | -6.3626 | 35.9036 | 1062 | 7.5YR 3/3 | SL CLAYR | 50 | 5.7 | 7.8 | 298 | 0.03 | 0.32 | 0.35 | 4.07 | 0.32 | Chromic Lixisol |
| 411 | -6.3623 | 35.9043 | 1067 | 5YR 4/6 | SL | 57 | 6.7 | 19.1 | 409 | 0.02 | 0.35 | 0.47 | 4.24 | 0.31 | Chromic Lixisol |
| 412 | -6.3620 | 35.9049 | 1071 | 2.5YR 3/4 | LS | 32.9 | 5.2 | 6.0 | 150 | 0.02 | 0.30 | 0.60 | 4.10 | 0.56 | Chromic Lixisol |
| 51 | -6.3418 | 35.8935 | 1109 | 5YR 3/4 | SL | 55 | 6.4 | 1.4 | 143 | 0.06 | 0.75 | 0.88 | 2.17 | 0.27 | Leptosol |
| 52 | -6.3414 | 35.8935 | 1106 | 5YR 4/4 | SL CLAYR | 41.4 | 6.5 | 4.3 | 267 | 0.05 | 0.47 | 0.64 | 2.55 | 0.30 | Leptosol |
| 53 | -6.3411 | 35.8935 | 1104 | 2.5YR 3/4 | SL | 24.6 | 6.7 | 2.8 | 204 | 0.04 | 0.45 | 0.73 | 3.18 | 0.31 | Leptosol |
| 54 | -6.3405 | 35.8935 | 1100 | 5YR 4/4 | SL CLAYR | 56 | 6.7 | 1.7 | 104 | 0.04 | 0.45 | 0.70 | 2.60 | 0.37 | Leptosol |

**missing

**Table 7-7** (part 4)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS $cm^{-1}$] | - | [mg $kg^{-1}$] | [mg $kg^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 55 | -6.3401 | 35.8935 | 1097 | 7.5YR 4/4 | L | 43.5 | 7.3 | 2.6 | 124 | 0.06 | 0.58 | 0.59 | 2.24 | 0.25 | Chromic Lixisol |
| 56 | -6.3396 | 35.8935 | 1093 | 5YR 4/4 | L | 33.2 | 5.7 | 1.4 | 149 | 0.02 | 0.27 | 0.52 | 3.28 | 0.38 | Chromic Lixisol |
| 57 | -6.3392 | 35.8935 | 1092 | 5YR 3/6 | L | 26.0 | 5.4 | 3.0 | 114 | 0.02 | 0.28 | 0.57 | 2.84 | 0.37 | Chromic Lixisol |
| 58 | -6.3388 | 35.8935 | 1091 | 5YR 4/4 | L | 31.3 | 6.9 | 16.9 | 198 | 0.02 | 0.27 | 0.65 | 2.85 | 0.49 | Chromic Lixisol |
| 59 | -6.3384 | 35.8935 | 1095 | 5YR 4/6 | LS | 29.4 | 5.8 | 4.2 | 90 | 0.02 | 0.23 | 0.71 | 2.74 | 0.36 | Chromic Lixisol |
| 510 | -6.3376 | 35.8934 | 1094 | 7.5YR 3/3 | L | 86 | 7.2 | 14.2 | 301 | 0.04 | 0.30 | 0.84 | 6.47 | 0.79 | buried Cutanic Stagnic Luvisol |
| 511 | -6.3372 | 35.8934 | 1097 | 7.5YR 3/4 | SL CLAYR | 25.6 | 6.1 | 2.4 | 211 | 0.03 | 0.29 | 1.26 | 7.36 | 0.73 | Chromic Lixisol (hypereutric, profondic) |
| 512 | -6.3369 | 35.8934 | 1099 | 7.5YR 3/4 | SL | 55 | 6.1 | 8.7 | 211 | 0.02 | 0.27 | 1.38 | 8.24 | 0.73 | Chromic Lixisol (hypereutric, profondic) |
| 61 | -6.3510 | 35.8925 | 1023 | 2.5YR 3/4 | SL | 29.7 | 6.3 | 3.7 | 155 | 0.04 | 0.48 | 0.55 | 4.56 | 0.41 | Chromic Lixisol |
| 62 | -6.3514 | 35.8924 | 1077 | 2.5YR 3/6 | SL | 886 | 7.9 | 0.0 | 264 | 0.04 | 0.49 | 0.54 | 4.56 | 0.40 | Chromic Lixisol |
| 63 | -6.3522 | 35.8923 | 1074 | 2.5YR 3/4 | SL CLAYR | 152 | 5.9 | 4.7 | 158 | 0.04 | 0.45 | 0.70 | 5.06 | 0.51 | Chromic Lixisol |
| 64 | -6.3526 | 35.8922 | 1073 | 2.5YR 3/6 | SL CLAYR | 43.5 | 5.8 | 1.7 | 201 | 0.03 | 0.30 | 0.67 | 5.33 | 0.42 | Chromic Lixisol |
| 65 | -6.3534 | 35.8921 | 1070 | 2.5YR 3/4 | SCL | 17.6 | 6.3 | 1.6 | 226 | 0.03 | 0.31 | 0.68 | 3.77 | 0.38 | Haplic Acrisol (loamic) |
| 66 | -6.3538 | 35.8920 | 1070 | 7.5YR 4/4 | SL | 22.0 | 6.1 | 1.8 | 137 | 0.03 | 0.36 | 0.72 | 3.64 | 0.42 | Haplic Acrisol (loamic) |
| 67 | -6.3545 | 35.8918 | 1067 | 7.5YR 4/6 | LS | 23.3 | 6.5 | 5.1 | 113 | 0.02 | 0.20 | 0.81 | 2.13 | 0.36 | Haplic Acrisol (loamic) |
| 68 | -6.3552 | 35.8917 | 1067 | 7.5YR 4/4 | LS | 20.1 | 5.8 | 4.4 | 138 | 0.02 | 0.26 | 0.75 | 4.50 | 0.50 | Haplic Acrisol (loamic) |
| 69 | -6.3556 | 35.8916 | 1068 | 7.5YR 4/4 | LS | 28.8 | 5.5 | 2.3 | 100 | 0.02 | 0.25 | 0.72 | 3.30 | 0.29 | Haplic Acrisol (loamic) |
| 610 | -6.3564 | 35.8916 | 1068 | 5YR 3/3 | SL CLAYR | 43.0 | 6.3 | 4.5 | 202 | 0.05 | 0.73 | 0.74 | 2.94 | 0.33 | Haplic Acrisol (loamic) |
| 611 | -6.3575 | 35.8913 | 1066 | 5YR 3/4 | SL CLAYR | 42.4 | 5.9 | 2.7 | 208 | 0.16 | 1.51 | 0.69 | 2.35 | 0.30 | Haplic Acrisol (loamic) |

**Table 7-7** (part 5)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 612 | -6.3587 | 35.8912 | 1065 | 7.5YR 3/3 | SL CLAYR | 55 | 5.8 | 2.0 | 208 | 0.07 | 0.42 | 0.66 | 2.81 | 0.37 | Haplic Acrisol (loamic) |
| 613 | -6.3592 | 35.8912 | 1064 | 7.5YR 4/4 | LS | 43.2 | 5.8 | 3.2 | 139 | 0.09 | 0.58 | 0.71 | 2.07 | 0.28 | Haplic Acrisol (loamic) |
| 614 | -6.3597 | 35.8913 | 1065 | 7.5YR 4/6 | LS | 28.1 | 6.2 | 8.8 | 269 | 0.13 | 1.30 | 0.69 | 1.67 | 0.25 | Haplic Acrisol (loamic) |
| 615 | -6.3603 | 35.8912 | 1060 | 7.5YR 4/4 | LS | 355 | 8.0 | 11.2 | 308 | 0.18 | 1.62 | 0.53 | 2.97 | 0.42 | Haplic Acrisol (loamic) |
| 616 | -6.3612 | 35.8911 | 1062 | 10YR 3/1 | CL | 237 | 8.5 | 2.0 | 156 | 0.14 | 2.87 | 0.31 | 4.52 | 0.70 | Sodic Vertisol (hypereutric) |

**Table 7-8** (part 1) Transect soil data (weighted average for the top 30 cm) in Idifu. Lat: latitude, Long: longitude (WGS84), EC: electrical conductivity, P- and K-Bray: plant-available P and K, $C_t$: total C, $N_t$: total N; K, eTh, eU: gamma ray data of K, Th, U, CLAYR: clayrich. Texture was determined following Jahn et al. (2008). Soils were classified following WRB, IUSS working group, 2015).
N = 2, except for gamma ray data (N = 5)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 11 | -6.4409 | 35.9887 | 997 | 2.5YR 3/3 | C | 672 | 7.9 | 31.5 | 881 | 0.24 | 2.84 | 0.80 | 4.49 | 0.86 | Sodic Vertisol (hypereutric) |
| 12 | -6.4407 | 35.9895 | 998 | 10YR 2/2 | SC | 226 | 6.9 | 18.1 | 558 | 0.14 | 1.35 | 0.66 | 4.87 | 0.75 | Sodic Vertisol (hypereutric) |
| 13 | -6.4407 | 35.9903 | 1001 | 10YR 3/3 | CL | 150 | 7.219 | 1.6 | 481 | 0.09 | 0.93 | 0.5325 | 4.4375 | 0.6375 | Sodic Vertisol (hypereutric) |
| 14 | -6.4405 | 35.9910 | 1002 | 10YR 3/4 | LS | 29.7 | 6.4 | 39.0 | 145 | 0.03 | 0.21 | 0.48 | 4.85 | 0.53 | Chromic Lixisol |
| 15 | -6.4405 | 35.9918 | 1005 | 7.5YR 4/4 | LS | 48.2 | 6.7 | 30.3 | 177 | 0.06 | 0.45 | 0.45 | 4.48 | 0.50 | Chromic Lixisol |
| 16 | -6.4406 | 35.9925 | 1004 | 5YR3/6 | LS | 25.6 | 6.5 | 12.4 | 214 | 0.05 | 0.34 | 0.47 | 5.36 | 0.53 | Chromic Lixisol |
| 17 | -6.4406 | 35.9934 | 1004 | 7.5YR 4/6 | LS | 23.5 | 6.0 | 12.0 | 181 | 0.06 | 0.30 | 0.49 | 5.84 | 0.66 | Chromic Lixisol |
| 18 | -6.4405 | 35.9950 | 1003 | 7.5YR 4/4 | SL | 22.2 | 5.9 | 7.0 | 222 | 0.06 | 0.36 | 0.45 | 5.38 | 0.55 | Chromic Lixisol |
| 19 | -6.4405 | 35.9966 | 1008 | 2.5YR 3/6 | SL | 37.5 | 6.6 | 2.1 | 281 | 0.07 | 0.36 | 0.45 | 6.30 | 0.39 | Chromic Lixisol |
| 110 | -6.4404 | 35.9982 | 1010 | 2.5YR 4/6 | LS | 35.9 | 6.3 | 4.7 | 225 | 0.06 | 0.43 | 0.42 | 6.12 | 0.52 | Chromic Lixisol |
| 111 | -6.4404 | 35.9989 | 1013 | 2.5YR 4/6 | SL | 35.5 | 5.8 | 5.8 | 228 | 0.06 | 0.37 | 0.40 | 5.82 | 0.78 | Chromic Lixisol |
| 112 | -6.4403 | 36.0004 | 1010 | 10YR 3/6 | SL | 41.5 | 5.9 | 5.1 | 251 | 0.07 | 0.49 | 0.43 | 6.81 | 0.67 | Chromic Lixisol |
| 113 | -6.4402 | 36.0027 | 1023 | 5YR 3/6 | SL | 34.3 | 5.7 | 1.8 | 373 | 0.09 | 0.63 | 0.48 | 6.41 | 0.69 | Chromic Lixisol |
| 114 | -6.4401 | 36.0038 | 1014 | 5YR 4/6 | LS | 33.4 | 5.6 | 12.8 | 368 | 0.07 | 0.44 | 0.73 | 6.21 | 0.55 | Chromic Lixisol |
| 115 | -6.4402 | 36.0034 | 1007 | 5YR 3/6 | LS | 98.3 | 6.6 | 28.4 | 351 | 0.05 | 0.41 | 0.66 | 8.09 | 0.73 | Chromic Lixisol |
| 21 | -6.4139 | 35.9705 | 1005 | 5YR 3/3 | CL | ** | ** | ** | ** | ** | ** | 0.53 | 5.53 | 0.83 | Sodic Vertisol (hypereutric) |
| 22 | -6.4125 | 35.9698 | 1004 | 5YR 3/2 | CL | 223 | 5.5 | 31.4 | 516 | 0.17 | 2.10 | 0.59 | 6.98 | 0.65 | Sodic Vertisol (hypereutric) |

**missing

**Table 7-8** (part 2)

| Plot No. | Lat [°] | Long [°] | Eleva-tion [m] | Color [w%] | Tex-ture | EC [µS cm$^{-1}$] | $pH_{H2O}$ - | P Bray [mg kg$^{-1}$] | K Bray [mg kg$^{-1}$] | $N_t$ [%] | $C_t$ [%] | K [%] | eTh [ppm] | eU [ppm] | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | -6.4118 | 35.9694 | 1005 | 5YR 3/3 | CL | 77.3 | 6.7 | 31.6 | 226 | 0.11 | 1.28 | 0.55 | 4.61 | 0.47 | Sodic Vertisol (hypereutric) |
| 24 | -6.4115 | 35.9692 | 1003 | 5YR 3/3 | LS | 36.9 | 6.7 | 8.6 | 266 | 0.06 | 0.84 | 0.54 | 3.87 | 0.46 | Haplic Acrisol (loamic) |
| 25 | -6.4111 | 35.9690 | 1000 | 5YR 4/4 | LS | 49.3 | 5.7 | 9.0 | 162 | 0.04 | 0.59 | 0.52 | 3.76 | 0.42 | Haplic Acrisol (loamic) |
| 26 | -6.4104 | 35.9687 | 1001 | 7.5YR 3/4 | LS | 56.6 | 6.0 | 2.5 | 197 | 0.04 | 0.45 | 0.63 | 5.36 | 0.53 | Chromic Lixisol (loamic) |
| 27 | -6.4096 | 35.9683 | 1003 | 5YR 3/4 | SL | 92.3 | 6.4 | 8.6 | 260 | 0.05 | 0.54 | 0.68 | 6.80 | 0.53 | Chromic Lixisol (loamic) |
| 28 | -6.4090 | 35.9679 | 999 | 5YR 2/4 | LS | 59.1 | 6.6 | 11.6 | 198 | 0.06 | 0.35 | 0.70 | 6.10 | 0.55 | Chromic Lixisol (loamic) |
| 29 | -6.4083 | 35.9676 | 999 | 5YR 2/3 | LS | 115 | 8.1 | 8.1 | 519 | 0.06 | 0.72 | 0.77 | 5.86 | 0.63 | Chromic Lixisol (loamic) |
| 210 | -6.4077 | 35.9672 | 1000 | 2,5YR 2/4 | LS | 195 | 6.5 | 8.3 | 389 | 0.05 | 0.50 | 0.76 | 6.79 | 0.58 | Chromic Lixisol (loamic) |
| 211 | -6.4070 | 35.9669 | 1000 | 2.5YR 3/4 | SL | 51.8 | 6.5 | 13.9 | 259 | 0.05 | 0.57 | 0.72 | 8.16 | 0.55 | Chromic Lixisol (loamic) |
| 212 | -6.4057 | 35.9662 | 1003 | 2.5YR 3/4 | LS | 38.1 | 6.6 | 5.1 | 202 | 0.05 | 0.67 | 0.72 | 6.59 | 0.66 | Chromic Lixisol (loamic) |
| 213 | -6.4050 | 35.9659 | 1007 | 10R 3/3 | SL | 41.0 | 6.3 | 5.2 | 271 | 0.07 | 0.47 | 0.59 | 5.25 | 0.52 | Chromic Lixisol |
| 214 | -6.4043 | 35.9655 | 1011 | 10R 4/6 | SL CLAYR | 104 | 6.2 | 3.6 | 376 | 0.05 | 0.45 | 0.57 | 5.43 | 0.53 | Chromic Lixisol |
| 215 | -6.4035 | 35.9652 | 1014 | 2,5YR 3/4 | SL | 51.5 | 6.1 | 3.6 | 283 | 0.04 | 0.55 | 0.56 | 5.93 | 0.55 | Chromic Lixisol |
| 216 | -6.4021 | 35.9643 | 1021 | 2.5YR 3/4 | SL | 44.8 | 6.2 | 4.3 | 292 | 0.04 | 0.57 | 0.52 | 5.34 | 0.60 | Chromic Lixisol |
| 217 | -6.4014 | 35.9639 | 1023 | 2.5YR 3/4 | SL | 46.4 | 6.3 | 5.7 | 259 | 0.04 | 0.60 | 0.49 | 5.56 | 0.44 | Chromic Lixisol |
| 218 | -6.4007 | 35.9635 | 1016 | 2.5YR 3/4 | LS | 57.8 | 5.6 | 11.0 | 195 | 0.04 | 0.44 | 0.49 | 5.50 | 0.51 | Chromic Lixisol |
| 31 | -6.3930 | 36.0031 | 999 | 5YR 3/6 | LS | 47.4 | 6.2 | 5.4 | 244 | 0.03 | 0.46 | 0.62 | 14.02 | 0.79 | Chromic Lixisol |

**Table 7-8** (part 3)

| Plot<br>No. | Lat<br>[°] | Long<br>[°] | Elevation<br>[m] | Color<br>[w%] | Texture | EC<br>[µS cm$^{-1}$] | $pH_{H2O}$<br>- | P Bray<br>[mg kg$^{-1}$] | K Bray<br>[mg kg$^{-1}$] | $N_t$<br>[%] | $C_t$<br>[%] | K<br>[%] | eTh<br>[ppm] | eU<br>[ppm] | Denomination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | -6.3937 | 36.0033 | 995 | 2.5YR 4/6 | SL CLAYR | 42.6 | 5.9 | 3.9 | 241 | 0.03 | 0.34 | 0.67 | 10.62 | 0.56 | Chromic Lixisol |
| 33 | -6.3945 | 36.0036 | 997 | 2.5YR 3/6 | L | 41.5 | 6.0 | 8.2 | 242 | 0.03 | 0.37 | 0.68 | 11.58 | 0.54 | Chromic Lixisol |
| 34 | -6.3952 | 36.0038 | 995 | 2.5YR 4/6 | SL | 29.7 | 6.4 | 7.1 | 298 | 0.05 | 0.48 | 0.73 | 12.10 | 0.71 | Chromic Lixisol |
| 35 | -6.3956 | 36.0039 | 994 | 7.5YR 3/6 | SCL | 62.9 | 6.0 | 6.2 | 441 | 0.04 | 0.41 | 0.82 | 13.86 | 0.60 | Chromic Lixisol (loamic) |
| 36 | -6.3959 | 36.0041 | 997 | 7.5YR 4/6 | LS | 58.1 | 7.2 | 10.2 | 328 | 0.04 | 0.34 | 0.87 | 12.19 | 0.53 | Chromic Lixisol (loamic) |
| 37 | -6.3963 | 36.0042 | 996 | 7.5YR 4/4 | LS | 32.0 | 6.7 | 18.8 | 291 | 0.04 | 0.35 | 1.05 | 14.84 | 0.45 | Chromic Lixisol (loamic) |
| 38 | -6.3967 | 36.0043 | 1000 | 7.5YR 4/3 | LS | 20.2 | 5.9 | 8.6 | 228 | 0.02 | 0.25 | 1.02 | 12.48 | 0.65 | Chromic Lixisol (loamic) |
| 39 | -6.3971 | 36.0045 | 995 | 2.5YR 4/6 | L | 53.6 | 5.6 | 0.4 | 136 | 0.03 | 0.39 | 0.72 | 12.10 | 0.81 | Chromic Lixisol |
| 310 | -6.3977 | 36.0047 | 998 | 10R 3/6 | L | 37.3 | 5.7 | 5.5 | 287 | 0.04 | 0.40 | 0.61 | 10.83 | 0.60 | Chromic Lixisol |
| 311 | -6.3984 | 36.0049 | 999 | 10R 3/6 | SL | 0.0 | 0.0 | 5.3 | 323 | 0.06 | 0.79 | 0.57 | 10.06 | 0.36 | Chromic Lixisol |
| 312 | -6.3991 | 36.0052 | 999 | 2.5YR 3/6 | SL CLAYR | 138 | 5.8 | 4.8 | 362 | 0.04 | 0.36 | 0.55 | 10.83 | 0.60 | Chromic Lixisol |
| 313 | -6.4001 | 36.0054 | 1000 | 2.5YR 3/4 | L | 88.2 | 6.6 | 5.7 | 427 | 0.05 | 0.47 | 0.36 | 8.91 | 0.69 | Chromic Lixisol |
| 314 | -6.4006 | 36.0055 | 997 | 2.5YR 3/4 | L | 31.9 | 6.3 | 8.3 | 363 | 0.05 | 0.45 | 0.36 | 10.81 | 0.51 | Chromic Lixisol |
| 41 | -6.4332 | 36.0004 | 1012 | 5YR3/4 | SL CLAYR | 64.8 | 6.4 | 5.5 | 398 | 0.05 | 0.53 | 1.04 | 9.62 | 0.74 | Chromic Lixisol (loamic) |
| 42 | -6.4335 | 36.0007 | 1012 | 5YR3/4 | SCL | 36.3 | 4.5 | 5.3 | 187 | 0.03 | 0.27 | 1.08 | 10.86 | 0.68 | Chromic Lixisol (loamic) |
| 43 | -6.4338 | 36.0010 | 1010 | 5YR3/6 | SCL | 32.7 | 6.4 | 3.6 | 296 | 0.06 | 0.52 | 1.00 | 11.35 | 0.98 | Chromic Lixisol (loamic) |
| 44 | -6.4341 | 36.0013 | 1008 | 2.5YR3/6 | SL | 26.2 | 5.7 | 2.8 | 243 | 0.04 | 0.43 | 0.93 | 13.61 | 0.79 | Chromic Lixisol (loamic) |
| 45 | -6.4347 | 36.0018 | 1007 | 5YR 7/6 | S | 33.8 | 6.76 | 3.39 | 307 | 0.04 | 0.41 | 0.67 | 13.51 | 0.77 | Street |

**Table 7-8** (part 4)

| Plot No. | Lat [°] | Long [°] | Eleva-tion [m] | Color [w%] | Tex-ture | EC [µS cm$^{-1}$] | $pH_{H2O}$ - | P Bray [mg kg$^{-1}$] | K Bray [mg kg$^{-1}$] | $N_t$ [%] | $C_t$ [%] | K [%] | eTh [ppm] | eU [ppm] | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 46 | -6.4347 | 36.0018 | 1008 | 7.5YR4/4 | LS | 18.6 | 6.1 | 4.3 | 192 | 0.05 | 0.54 | 1.12 | 12.58 | 0.85 | Chromic Lixisol (loamic) |
| 47 | -6.4357 | 36.0028 | 1009 | 2.5YR3/4 | L | 144 | 6.7 | 1.1 | 170 | 0.03 | 0.24 | 0.85 | 15.88 | 0.95 | Chromic Lixisol (loamic) |
| 48 | -6.4362 | 36.0033 | 1004 | 5YR3/4 | LS | 34.6 | 5.6 | 5.2 | 200 | 0.04 | 0.49 | 1.42 | 11.75 | 0.71 | Chromic Lixisol (loamic) |
| 49 | -6.4365 | 36.0036 | 1005 | 5YR3/4 | LS | 32.2 | 5.8 | 4.4 | 127 | 0.03 | 0.34 | 1.10 | 10.87 | 0.64 | Chromic Lixisol (loamic) |
| 410 | -6.4371 | 36.0042 | 1008 | 5YR3/6 | SL CLAYR | 75.5 | 5.9 | 3.1 | 238 | 0.05 | 0.45 | 0.74 | 8.14 | 0.62 | Chromic Lixisol (loamic) |
| 411 | -6.4375 | 36.0045 | 999 | 5YR4/8 | CL | 245 | 6.1 | 2.5 | 465 | 0.06 | 0.42 | 0.63 | 9.26 | 0.74 | Chromic Lixisol |
| 412 | -6.4377 | 36.0048 | 1001 | 5YR4/8 | LS | 37.3 | 5.9 | 2.4 | 200 | 0.04 | 0.41 | 0.76 | 8.09 | 0.70 | Chromic Lixisol (loamic) |
| 413 | -6.4383 | 36.0053 | 1005 | 2.5YR4/6 | L | 33.0 | 6.5 | 4.5 | 328 | 0.04 | 0.48 | 0.76 | 8.53 | 0.67 | Chromic Lixisol (loamic) |
| 51 | -6.4346 | 35.9479 | 979 | 5YR 4/6 | L | 42.1 | 5.8 | 8.7 | 250 | 0.04 | 0.45 | 0.47 | 3.86 | 0.39 | Haplic Acrisol (loamic) |
| 52 | -6.4348 | 35.9476 | 971 | 5YR 4/6 | SL | 47.8 | 6.2 | 4.6 | 228 | 0.02 | 0.30 | 0.36 | 3.39 | 0.39 | Haplic Acrisol (loamic) |
| 53 | -6.4352 | 35.9470 | 972 | 7.5YR 5/6 | SL | 56.0 | 5.2 | 5.2 | 273 | 0.03 | 0.36 | 0.36 | 6.38 | 0.50 | Haplic Acrisol (loamic) |
| 54 | -6.4355 | 35.9466 | 993 | 7.5YR 4/6 | SL | 127 | 5.5 | 3.8 | 288 | 0.04 | 0.48 | 0.35 | 6.33 | 0.44 | Haplic Acrisol (loamic) |
| 55 | -6.4358 | 35.9463 | 1015 | 7.5YR 6/4 | SL | 106 | 8.3 | 5.4 | 285 | 0.04 | 0.51 | 0.41 | 6.82 | 0.45 | Chromic Lixisol |
| 56 | -6.4364 | 35.9456 | 1021 | 7.5YR 6/4 | L | 41.2 | 6.2 | 8.4 | 200 | 0.05 | 0.53 | 0.42 | 5.86 | 0.40 | Chromic Lixisol |
| 57 | -6.4367 | 35.9452 | 1022 | 7.5YR 6/4 | L | 137 | 4.9 | 6.3 | 133 | 0.04 | 0.36 | 0.46 | 5.94 | 0.49 | Chromic Lixisol |
| 58 | -6.4370 | 35.9449 | 1022 | 7.5YR 6/4 | SL | 40.6 | 5.0 | 5.6 | 87 | 0.04 | 0.40 | 0.45 | 7.65 | 0.64 | Chromic Lixisol |
| 59 | -6.4372 | 35.9447 | 1022 | 7.5YR 6/4 | SL | 64.5 | 6.7 | 2.1 | 119 | 0.04 | 0.40 | 0.62 | 8.46 | 0.64 | Chromic Lixisol |

**Table 7-8** (part 5)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $N_t$ | $C_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 510 | -6.4376 | 36.9442 | 1025 | 10YR 5/4 | SL CLAYR | 23.6 | 6.3 | 6.2 | 155 | 0.01 | 0.15 | 0.91 | 9.15 | 0.56 | Chromic Lixisol (loamic) |
| 511 | -6.4381 | 35.9435 | 1025 | 10YR 5/4 | LS | 17.3 | 5.6 | 5.6 | 100 | 0.07 | 0.45 | 0.81 | 7.41 | 0.27 | Chromic Lixisol (loamic) |
| 512 | -6.4389 | 35.9428 | 1025 | 5YR 5/6 | LS | 27.5 | 6.3 | 29.4 | 143 | 0.07 | 0.48 | 0.83 | 6.71 | 0.41 | Chromic Lixisol (loamic) |
| 61 | -6.4378 | 35.9582 | 931 | 7.5YR 4/3 | LS | 31.5 | 6.7 | 3.9 | 80 | 0.10 | 0.72 | 0.41 | 3.10 | 0.36 | Leptosol |
| 62 | -6.4375 | 35.9581 | 943 | 7.5YR 4/4 | SL CLAYR | 39.1 | 6.1 | 2.7 | 64 | 0.02 | 0.27 | 0.52 | 3.71 | 0.38 | Leptosol |
| 63 | -6.4371 | 35.9579 | 941 | 5YR 3/6 | SL CLAYR | 27.6 | 6.0 | 7.1 | 138 | 0.02 | 0.27 | 0.31 | 4.29 | 0.53 | Chromic Lixisol |
| 64 | -6.4366 | 35.9579 | 938 | 10R 3/6 | SL CLAYR | 80.3 | 5.5 | 7.3 | 216 | 0.03 | 0.30 | 0.28 | 4.15 | 0.38 | Chromic Lixisol |
| 65 | -6.4363 | 35.9578 | 935 | 5YR 4/2 | CL | 31.1 | 5.5 | 23.0 | 114 | 0.03 | 0.33 | 0.29 | 4.18 | 0.49 | Chromic Lixisol |
| 66 | -6.4360 | 35.9578 | 951 | 2.5YR 4/6 | SCL | 24.7 | 5.4 | 3.1 | 136 | 0.02 | 0.20 | 0.32 | 4.21 | 0.33 | Chromic Lixisol |
| 67 | -6.4356 | 35.9577 | 955 | 7.5YR 4/4 | SL | 35.6 | 6.5 | 3.2 | 293 | 0.04 | 0.30 | 0.35 | 4.04 | 0.38 | Haplic Acrisol (loamic) |
| 68 | -6.4352 | 35.9577 | 952 | 7.5YR 4/4 | SL CLAYR | 53.8 | 6.3 | 2.9 | 362 | 0.04 | 0.34 | 0.29 | 3.34 | 0.33 | Haplic Acrisol (loamic) |
| 69 | -6.4345 | 35.9576 | 949 | 7.5YR 4/4 | L | 20.4 | 5.4 | 1.1 | 150 | 0.02 | 0.24 | 0.32 | 5.29 | 0.51 | Chromic Lixisol |
| 610 | -6.4337 | 35.9574 | 951 | 7.5YR 4/6 | SL CLAYR | 19.0 | 5.7 | 3.1 | 205 | 0.12 | 1.11 | 0.33 | 4.14 | 0.55 | Chromic Lixisol |
| 611 | -6.4329 | 35.9572 | 954 | 7.5YR 4/4 | SL CLAYR | 42.5 | 5.0 | 2.8 | 171 | 0.09 | 0.65 | 0.30 | 2.78 | 0.41 | Haplic Acrisol (loamic) |
| 612 | -6.4322 | 35.9571 | 954 | 7.5YR 4/6 | SL | 35.2 | 5.2 | 3.7 | 140 | 0.09 | 0.73 | 0.29 | 3.32 | 0.52 | Haplic Acrisol (loamic) |
| 613 | -6.4314 | 35.9570 | 957 | 7.5YR 5/4 | SL CLAYR | 311 | 5.0 | 7.8 | 272 | 0.06 | 0.55 | 0.21 | 2.61 | 0.41 | Haplic Acrisol (loamic) |

**Table 7-9** (part 1) Baby plot soil data (weighted average for the top 30 cm) in Ilolo, Chamwino district. Lat: latitude, Long: longitude (WGS84), EC: electrical conductivity, P- and K-Bray: plant-available P and K, $C_t$: total C, $N_t$: total N; K, eTh, eU: gamma ray data of K, Th, U, CLAYR: clayrich. Texture was determined following Jahn et al. (2008). Soils were classified following WRB, IUSS working group, 2015). N = 2, except for gamma ray data (N = 5)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 1 | -6.3258 | 35.9010 | 1130 | 2.5YR 3/4 | L | 266 | 7.7 | 22.6 | 791 | 0.28 | 0.04 | 1.20 | 12.13 | 1.04 | Chromic Lixisol (hypereutric, profondic) |
| 2 | -6.3121 | 35.9026 | 1168 | 2.5YR 3/4 | LS | 39.7 | 6.7 | 4.1 | 135 | 0.28 | 0.02 | 1.19 | 13.12 | 0.81 | Chromic Lixisol (hypereutric, profondic) |
| 3 | -6.3438 | 35.8892 | 1114 | 5YR 4/6 | SL | 14.1 | 5.5 | 2.8 | 71 | 0.23 | 0.03 | 0.94 | 2.89 | 0.32 | Haplic Acrisol (loamic) |
| 4 | -6.3426 | 35.8908 | 1097 | 2.5YR 4/6 | SCL | 32.4 | 5.8 | 4.3 | 212 | 0.31 | 0.03 | 0.95 | 2.95 | 0.46 | Chromic Lixisol |
| 5 | -6.3352 | 35.8930 | 1119 | 2.5YR 3/4 | SL CLAYR | 31.4 | 5.9 | 2.1 | 192 | 0.37 | 0.04 | 1.34 | 9.26 | 1.02 | Chromic Lixisol (hypereutric, profondic) |
| 6 | -6.3495 | 35.9109 | 1080 | 2.5YR 4/6 | SL | 25.0 | 5.6 | 2.8 | 122 | 0.31 | 0.03 | 1.16 | 1.83 | 0.40 | Haplic Acrisol (loamic) |
| 7 | -6.3486 | 35.9239 | 1104 | 2.5YR 3/4 | SL CLAYR | 55.2 | 6.1 | 1.4 | 112 | 0.31 | 0.04 | 0.88 | 2.58 | 0.28 | Chromic Lixisol (hypereutric, profondic)/ shallow, gully |
| 8 | -6.3475 | 35.9114 | 1076 | 2.5YR 4/4 | SL | 26.0 | 6.0 | 4.9 | 176 | 0.29 | 0.02 | 1.05 | 1.73 | 0.37 | Haplic Acrisol (loamic) |
| 9 | -6.3488 | 35.9086 | 1086 | 2.5YR 3/4 | SCL | 26.1 | 6.2 | 3.0 | 211 | 0.44 | 0.05 | 0.99 | 1.54 | 0.33 | Haplic Acrisol loamic |
| 10 | -6.3462 | 35.9180 | 1096 | 2.5YR 2/2 | LS | 20.9 | 5.7 | 2.3 | 69 | 0.18 | 0.01 | 1.06 | 1.71 | 0.24 | Haplic Acrisol (loamic) |
| 11 | -6.3397 | 35.9170 | 1093 | 5YR 4/4 | SL CLAYR | 36.0 | 5.6 | 3.7 | 171 | 0.29 | 0.02 | 1.37 | 14.18 | 0.64 | Chromic Lixisol (hypereutric, profondic) with sand overburden |
| 12 | -6.3574 | 35.9008 | 1070 | 5YR 3/4 | SL CLAYR | 50.6 | 6.5 | 4.8 | 214 | 0.46 | 0.05 | 0.65 | 9.82 | 0.64 | Chromic Lixisol |

**Table 7-9** (part 2)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS $cm^{-1}$] | - | [mg $kg^{-1}$] | [mg $kg^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 13 | -6.3556 | 35.8963 | 1076 | 7.5YR 4/3 | L | 85.8 | 7.4 | 13.3 | 402 | 0.36 | 0.04 | 0.54 | 3.28 | 0.39 | Gradient Chromic Lixisol to Haplic Acrisol (loamic) |
| 14 | -6.3333 | 35.8921 | 1099 | 10YR 4/4 | L | 41.3 | 6.4 | 4.3 | 167 | 0.35 | 0.04 | 0.58 | 4.22 | 0.48 | Chromic Lixisol |
| 15 | -6.3510 | 35.8965 | 1082 | 5YR 4/6 | L | 55.5 | 6.3 | 2.2 | 148 | 0.33 | 0.04 | 0.66 | 6.82 | 0.53 | Chromic Lixisol gradient to (hypereutric, profondic) |
| 16 | -6.3495 | 35.8951 | 1090 | 2.5YR 3/6 | SL CLAYR | 27.0 | 6.2 | 2.4 | 105 | 0.36 | 0.04 | 0.77 | 3.34 | 0.17 | Chromic Lixisol (hypereutric, profondic)/ shallow, gully |
| 17 | -6.3518 | 35.9000 | 1073 | 5YR 4/6 | SL | 22.6 | 5.7 | 2.0 | 113 | 0.23 | 0.01 | 0.96 | 2.74 | 0.31 | Haplic Acrisol (loamic) |
| 18 | -6.3495 | 35.9026 | 1024 | 2.5YR 3/6 | SL CLAYR | 28.5 | 5.5 | 6.3 | 171 | 0.34 | 0.03 | 0.55 | 4.15 | 0.32 | Chromic Lixisol |
| 19 | -6.3462 | 35.9040 | 1084 | 5YR 4/4 | SL CLAYR | 46.6 | 5.8 | 9.6 | 249 | 0.38 | 0.03 | 0.72 | 3.72 | 0.33 | Chromic Lixisol |
| 20 | -6.3438 | 35.8892 | 1114 | 2.5YR 3/4 | SL CLAYR | 98.6 | 7.7 | 6.4 | 311 | 0.52 | 0.05 | 1.24 | 13.95 | 1.04 | Chromic Lixisol (hypereutric, profondic) with sand overburden |
| 21 | -6.3393 | 35.9240 | 1112 | 7.5YR 4/4 | LS | 16.4 | 6.0 | 16.2 | 68 | 0.18 | 0.01 | 1.82 | 15.53 | 0.38 | Chromic Lixisol (hypereutric, profondic) with sand overburden |
| 22 | -6.3400 | 35.9243 | 1113 | 2.5YR 2/2 | SL CLAYR | 44.6 | 6.2 | 10.6 | 210 | 0.30 | 0.02 | 1.68 | 11.18 | 0.43 | Chromic Lixisol (hypereutric, profondic) |
| 23 | -6.3358 | 35.9198 | 1106 | 2.5YR 4/4 | LS | 39.4 | 5.7 | 3.9 | 203 | 0.32 | 0.03 | 1.28 | 12.49 | 0.77 | Chromic Lixisol (hypereutric, profondic) |

**Table 7-9** (part 3)

| Plot | Lat | Long | Elevation | Color | Texture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Denomination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 24 | -6.3487 | 35.8959 | 1083 | 2.5YR 3/4 | SCL | 28.7 | 5.4 | 1.3 | 154 | 0.31 | 0.04 | 1.19 | 16.65 | 0.73 | Chromic Lixisol (hypereutric, profondic) |
| 25 | -6.3238 | 35.9226 | 1076 | 2.5YR 3/4 | SL CLAYR | 35.1 | 5.8 | 0.7 | 158 | 0.27 | 0.03 | 1.16 | 10.50 | 0.64 | Chromic Lixisol (hypereutric, profondic) |
| 26 | -6.3282 | 35.9222 | 1070 | 2.5YR 3/4 | SL CLAYR | 29.2 | 6.2 | 1.7 | 197 | 0.32 | 0.04 | 1.36 | 10.71 | 0.74 | Chromic Lixisol (hypereutric, profondic) |
| 27 | -6.3287 | 35.9219 | 1066 | 2.5YR 3/6 | SL | 31.6 | 5.9 | 1.6 | 189 | 0.27 | 0.03 | 1.27 | 8.10 | 0.48 | Chromic Lixisol (hypereutric, profondic) |
| 28 | -6.3331 | 35.9199 | 1041 | 2.5YR 3/4 | SL | 31.4 | 6.1 | 1.8 | 169 | 0.57 | 0.05 | 1.27 | 18.67 | 0.79 | Chromic Lixisol (hypereutric, profondic) |
| 29 | -6.3356 | 35.9060 | 1104 | 2.5YR 4/4 | L | 33.4 | 5.7 | 2.9 | 181 | 0.38 | 0.03 | 1.11 | 5.35 | 0.52 | Chromic Lixisol (hypereutric, profondic) im Dorf |
| 30 | -6.3258 | 35.9034 | 1124 | 2.5YR 4/4 | SL | 46.8 | 7.3 | 9.6 | 239 | 0.37 | 0.03 | 1.28 | 10.96 | 0.64 | Chromic Lixisol (hypereutric, profondic) |
| 31 | -6.3399 | 35.9092 | 1090 | 2.5YR 3/4 | SL CLAYR | 26.4 | 6.5 | 4.2 | 187 | 0.30 | 0.02 | 1.25 | 15.37 | 0.99 | Chromic Lixisol (hypereutric, profondic) |
| 32 | -6.3631 | 35.8921 | 1058 | 10YR 4/2 | CL | 1196 | 7.9 | 4.1 | 282 | 1.10 | 0.07 | 1.28 | 12.45 | 0.70 | Sodic Vertisol (hypereutric) |

**Table 7-10** (part 1) Baby plot soil data (weighted average for the top 30 cm) in Idifu, Chamwino district. Lat: latitude, Long: longitude (WGS84), EC: electrical conductivity, P- and K-Bray: plant-available P and K, $C_t$: total C, $N_t$: total N; K, eTh, eU: gamma ray data of K, Th, U, CLAYR: clayrich. Texture was determined following Jahn et al. (2008). Soils were classified following WRB, IUSS working group, 2015). N = 2, except for gamma ray data (N = 5)

| Plot | Lat | Long | Elevation | Color | Texture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Denomination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 1 | -6.4458 | 35.9959 | 1002 | 2.5YR 3/4 | L | 25.0 | 6.2 | 2.2 | 181.7 | 0.04 | 0.39 | 0.53 | 9.00 | 0.89 | Chromic Lixisol (loamic) |
| 2 | -6.4492 | 36.0006 | 1011 | 5YR 3/4 | SL | 32.6 | 6.6 | 61.0 | 234.3 | 0.02 | 0.38 | 1.36 | 9.14 | 0.87 | Chromic Lixisol (loamic) - rock outcrops |
| 3 | -6.4452 | 35.9981 | 1000 | 2.5YR 3/4 | SL CLAYR | 30.9 | 6.2 | 6.9 | 297.1 | 0.04 | 0.43 | 0.98 | 8.77 | 0.78 | Chromic Lixisol (loamic) - rock outcrops |
| 4 | -6.4401 | 36.0035 | 993 | 5YR 3/4 | SL CLAYR | 41.4 | 6.1 | 7.6 | 352.8 | 0.05 | 0.49 | 0.68 | 8.44 | 0.75 | Gradient Chromic Lixisol to Chromic Lixisol (loamic) - rock outcrops |
| 5 | -6.4403 | 35.9976 | 1001 | 2.5YR 3/4 | L | 35.4 | 5.8 | 3.9 | 227.1 | 0.04 | 0.46 | 0.41 | 5.31 | 0.58 | Chromic Lixisol |
| 6 | -6.4458 | 35.9959 | 1001 | 2.5YR 3/4 | SL CLAYR | 28.9 | 5.4 | 4.2 | 249.8 | 0.04 | 0.44 | 0.70 | 6.73 | 0.77 | Chromic Lixisol |
| 7 | -6.4461 | 35.9912 | 998 | 5YR 4/6 | SL | 43.2 | 5.7 | 4.6 | 256.9 | 0.03 | 0.28 | 0.44 | 5.73 | 0.60 | Chromic Lixisol |
| 8 | -6.4376 | 35.9861 | 995 | 10YR 4/3 | SL | 22.8 | 6.4 | 2.9 | 154.4 | 0.03 | 0.28 | 0.45 | 5.75 | 0.64 | Haplic Acrisol (loamic) - vertisol sediment on top |
| 9 | -6.4477 | 35.9871 | 999 | 10YR 4/4 | SL | 26.9 | 6.0 | 12.5 | 203.3 | 0.03 | 0.37 | 0.72 | 8.73 | 0.63 | Chromic Lixisol (loamic) |
| 10 | -6.4398 | 35.9799 | 1006 | 10YR 4/3 | SL | 26.1 | 5.2 | 16.7 | 89.6 | 0.02 | 0.37 | 0.33 | 2.53 | 0.36 | Haplic Acrisol (loamic) |
| 11 | -6.4427 | 35.9808 | 1000 | 7.5YR 4/4 | SCL | 29.1 | 5.2 | 14.2 | 175.6 | 0.03 | 0.40 | 0.11 | 3.15 | 0.32 | Haplic Acrisol (loamic) |

**Table 7-10** (part 2)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 12 | -6.4447 | 36.0079 | 1013 | 5YR 3/4 | SL | 25.3 | 5.9 | 2.3 | 182.2 | 0.03 | 0.35 | 0.72 | 8.76 | 0.67 | Chromic Lixisol (loamic) |
| 13 | -6.4357 | 35.9788 | 1005 | 10YR 4/4 | LS | 26.0 | 6.4 | 7.4 | 115.5 | 0.02 | 0.24 | 1.15 | 3.22 | 0.37 | Haplic Acrisol (loamic) |
| 14 | -6.4342 | 35.9768 | 1009 | 10YR 4/3 | LS | 27.9 | 6.2 | 15.3 | 85.4 | 0.02 | 0.31 | 1.17 | 2.33 | 0.35 | Haplic Acrisol (loamic) |
| 15 | -6.4276 | 35.9778 | 1003 | 10YR 3/4 | SL CLAYR | 46.7 | 5.4 | 10.8 | 181.0 | 0.03 | 0.34 | 0.17 | 3.41 | 0.39 | Haplic Acrisol (loamic) - vertisol sediment on top |
| 16 | -6.4254 | 35.9754 | 1001 | 10YR 3/2 | SL | 67.1 | 6.7 | 17.3 | 235.1 | 0.04 | 0.49 | 0.21 | 3.37 | 0.37 | Haplic Acrisol (loamic) |
| 17 | -6.4411 | 35.9776 | 1015 | 10YR 4/2 | SL | 17.6 | 5.9 | 27.1 | 111.3 | 0.03 | 0.43 | 0.49 | 2.36 | 0.31 | Haplic Acrisol (loamic) |
| 18 | -6.4446 | 35.9754 | 1016 | 7.5YR 4/4 | SL CLAYR | 26.0 | 5.2 | 4.9 | 103.5 | 0.02 | 0.32 | 0.13 | 3.04 | 0.35 | Haplic Acrisol (loamic) |
| 19 | -6.4455 | 35.9636 | 1025 | 10YR 4/4 | L | 32.8 | 5.3 | 4.2 | 156.5 | 0.05 | 0.40 | 0.43 | 4.85 | 0.52 | Haplic Acrisol (loamic) |
| 20 | -6.4449 | 35.9628 | 1026 | 10YR 4/4 | SL | 46.1 | 5.8 | 10.3 | 117.6 | 0.03 | 0.39 | 0.48 | 2.03 | 0.23 | Haplic Acrisol (loamic) |
| 21 | -6.4477 | 35.9602 | 1028 | 7.5YR 4/4 | SL CLAYR | 27.9 | 5.3 | 3.8 | 169.0 | 0.04 | 0.39 | 0.23 | 3.27 | 0.39 | Haplic Acrisol (loamic) |
| 22 | -6.4595 | 35.9672 | 1043 | 2.5YR 3/6 | L | 43.6 | 5.7 | 3.1 | 189.7 | 0.04 | 0.34 | 0.44 | 8.42 | 0.80 | Chromic Lixisol (loamic) |
| 23 | -6.4560 | 35.9666 | 1033 | 5YR 4/4 | SL CLAYR | 21.9 | 5.9 | 3.2 | 150.3 | 0.03 | 0.34 | 0.37 | 5.14 | 0.45 | Chromic Lixisol |
| 24 | -6.4382 | 35.9706 | 1041 | 10YR 4/4 | LS | 30.2 | 5.6 | 14.5 | 80.0 | 0.02 | 0.27 | 0.16 | 2.46 | 0.17 | Haplic Acrisol (loamic) |
| 25 | -6.4362 | 35.9728 | 1045 | 10YR 4/2 | SL | 25.0 | 6.2 | 18.9 | 98.2 | 0.02 | 0.29 | 0.17 | 1.76 | 0.20 | Haplic Acrisol (loamic) |
| 26 | -6.4339 | 35.9705 | 1044 | 10YR 4/6 | SL | 15.0 | 5.5 | 6.3 | 63.2 | 0.09 | 0.63 | 0.16 | 1.93 | 0.22 | Haplic Acrisol (loamic) |

**Table 7-10** (part 3)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [$\mu S\ cm^{-1}$] | - | [$mg\ kg^{-1}$] | [$mg\ kg^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 27 | -6.4254 | 35.9659 | 1038 | 10YR 3/3 | SL CLAYR | 105.9 | 5.8 | 24.7 | 299.1 | 0.04 | 0.47 | 0.13 | 2.54 | 0.41 | Haplic Acrisol (loamic) |
| 28 | -6.4289 | 35.9614 | 1004 | 10YR 4/4 | SL | 21.6 | 5.4 | 11.9 | 94.2 | 0.02 | 0.27 | 0.22 | 3.39 | 0.18 | Haplic Acrisol (loamic) |
| 29 | -6.4294 | 35.9897 | 943 | 10YR 4/4 | L | 27.1 | 6.1 | 8.7 | 205.6 | 0.04 | 0.40 | 0.33 | 6.60 | 0.64 | Haplic Acrisol (loamic) |
| 30 | -6.4270 | 35.9955 | 952 | 7.5YR 4/4 | L | 43.1 | 5.8 | 8.7 | 275.1 | 0.05 | 0.45 | 0.44 | 8.41 | 0.84 | Haplic Acrisol (loamic) |
| 31 | -6.4213 | 35.9931 | 941 | 10YR 4/3 | SL | 26.8 | 5.7 | 14.5 | 179.7 | 0.04 | 0.43 | 0.36 | 7.26 | 0.51 | Haplic Acrisol (loamic) |
| 32 | -6.4177 | 35.9951 | 945 | 10YR 3/6 | SL CLAYR | 169.1 | 5.9 | 6.7 | 219.6 | 0.04 | 0.45 | 0.34 | 7.92 | 0.65 | Haplic Acrisol (loamic) |
| 33 | -6.4169 | 35.9985 | 943 | 5YR 3/4 | L | 33.1 | 6.1 | 7.3 | 307.0 | 0.05 | 0.50 | 0.54 | 7.65 | 0.46 | Chromic Lixisol (loamic) |
| 34 | -6.4327 | 35.9976 | 949 | 5YR 4/4 | SL | 52.9 | 5.7 | 14.6 | 326.6 | 0.05 | 0.45 | 1.21 | 11.32 | 0.98 | Chromic Lixisol (loamic) |
| 35 | -6.4142 | 35.9512 | 993 | 5YR 4/3 | SL CLAYR | 58.3 | 6.2 | 14.3 | 307.7 | 0.05 | 0.56 | 0.23 | 3.51 | 0.55 | Haplic Acrisol (loamic) |
| 36 | -6.4104 | 35.9460 | 999 | 5YR 3/4 | SL CLAYR | 42.5 | *7.0* | 6.5 | 169.3 | 0.03 | 0.36 | 0.88 | 2.37 | 0.31 | Chromic Lixisol |
| 37 | -6.4213 | 35.9404 | 997 | 2.5YR 3/6 | SL CLAYR | 51.2 | 5.6 | 4.3 | 200.2 | 0.03 | 0.36 | 0.50 | 2.91 | 0.43 | Chromic Lixisol |
| 38 | -6.4222 | 35.9403 | 997 | 2.5YR 3/4 | SCL | 38.3 | 5.7 | 4.0 | 182.3 | 0.03 | 0.34 | 0.56 | 3.10 | 0.51 | Chromic Lixisol |
| 39 | -6.4227 | 35.9402 | 996 | 5YR 3/4 | SL | 42.6 | 6.4 | 5.8 | 207.7 | 0.03 | 0.31 | 0.75 | 3.72 | 0.44 | Chromic Lixisol |
| 40 | -6.4234 | 35.9403 | 996 | 5YR 4/6 | SL | 28.8 | 5.9 | 2.5 | 131.0 | 0.03 | 0.31 | 1.00 | 11.90 | 0.43 | Chromic Lixisol (loamic) |
| 41 | -6.4093 | 35.9536 | 940 | 10YR 3/4 | SL | 215.2 | 6.3 | 14.0 | 282.6 | 0.04 | 0.37 | 0.33 | 6.33 | 0.68 | Haplic Acrisol (loamic) |
| 42 | -6.4014 | 35.9603 | 996 | 7.5YR 4/4 | SL | 35.1 | 5.9 | 8.8 | 244.2 | 0.05 | 0.50 | 0.50 | 4.72 | 0.40 | Haplic Acrisol (loamic) |

**Table 7-10** (part 4)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS $cm^{-1}$] | - | [mg $kg^{-1}$] | [mg $kg^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 43 | -6.3971 | 35.9685 | 975 | 10YR 3/6 | SCL | 261.4 | 6.8 | 21.2 | 714.6 | 0.04 | 0.37 | 0.50 | 6.29 | 0.42 | Haplic Acrisol (loamic) - beyond: Chromic Lixisol |
| 44 | -6.4010 | 35.9785 | 965 | 7.5YR 4/4 | SL CLAYR | 31.1 | 5.6 | 6.8 | 248.1 | 0.04 | 0.40 | 0.41 | 9.45 | 0.58 | Haplic Acrisol (loamic) |
| 45 | -6.4113 | 35.9861 | 949 | 10YR 3/4 | SL CLAYR | 126.1 | 6.8 | 30.0 | 405.7 | 0.05 | 0.54 | 0.53 | 10.32 | 0.86 | Chromic Lixisol (loamic) - Acrisol sediments on top |
| 46 | -6.4139 | 35.9834 | 949 | 7.5YR 3/4 | SL CLAYR | 373.1 | 6.7 | 28.0 | 536.7 | 0.03 | 0.36 | 0.34 | 8.80 | 0.82 | Haplic Acrisol (loamic) |
| 47 | -6.4119 | 35.9774 | 946 | 7.5YR 4/4 | SL CLAYR | 34.0 | 5.6 | 10.8 | 218.2 | 0.03 | 0.33 | 0.18 | 6.61 | 0.70 | Haplic Acrisol (loamic) |
| 48 | -6.4362 | 35.9497 | 934 | 10YR 4/4 | LS | 22.4 | 5.5 | 9.8 | 103.8 | 0.03 | 0.40 | 0.45 | 3.59 | 0.35 | Haplic Acrisol (loamic) |
| 49 | -6.4396 | 35.9541 | 985 | 2.5YR 4/6 | L | 36.0 | 6.1 | 4.9 | 131.2 | 0.03 | 0.36 | 0.29 | 4.15 | 0.45 | Haplic Acrisol (loamic) |
| 50 | -6.4363 | 35.9508 | 935 | 7.5YR 6/4 | LS | 24.1 | 5.4 | 6.4 | 82.9 | 0.03 | 0.32 | 0.65 | 4.46 | 0.41 | Haplic Acrisol (loamic) |
| 51 | -6.4428 | 35.9562 | 973 | 7.5YR 4/4 | SL CLAYR | 33.9 | 5.5 | 6.2 | 190.9 | 0.03 | 0.41 | 0.30 | 4.41 | 0.43 | Haplic Acrisol (loamic) |
| 52 | -6.4372 | 35.9644 | 958 | 10YR 3/3 | SL CLAYR | 57.9 | 6.9 | 69.4 | 422.3 | 0.04 | 0.43 | 0.23 | 6.00 | 0.51 | Haplic Acrisol (loamic) |
| 53 | -6.4367 | 35.9649 | 960 | 10YR 4/4 | SL | 41.4 | 5.7 | 22.2 | 169.1 | 0.02 | 0.40 | 0.16 | 3.71 | 0.26 | Haplic Acrisol (loamic) |
| 54 | -6.4336 | 35.9669 | 970 | 10YR 4/3 | CL | 118.4 | 5.7 | 6.3 | 250.1 | 0.04 | 0.47 | 0.30 | 4.61 | 0.54 | Haplic Acrisol (loamic) |
| 55 | -6.4319 | 35.9572 | 950 | 7.5YR 4/4 | SL CLAYR | 42.8 | 5.2 | 8.2 | 155.7 | 0.02 | 0.30 | 0.21 | 2.82 | 0.34 | Haplic Acrisol (loamic) |

**Table 7-10** (part 5)

| Plot | Lat | Long | Eleva-tion | Color | Tex-ture | EC | $pH_{H2O}$ | P Bray | K Bray | $C_t$ | $N_t$ | K | eTh | eU | Deno-mination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | [°] | [°] | [m] | [w%] | | [µS cm$^{-1}$] | - | [mg kg$^{-1}$] | [mg kg$^{-1}$] | [%] | [%] | [%] | [ppm] | [ppm] | |
| 56 | -6.4357 | 35.9855 | 995 | 10YR 4/3 | SL CLAYR | 54.8 | 6.4 | 14.5 | 241.5 | 0.04 | 0.45 | 0.39 | 6.28 | 0.59 | Haplic Acrisol (loamic) |
| 57 | -6.4345 | 35.9713 | 1004 | 10YR 4/4 | SL | 23.1 | 5.0 | 11.5 | 65.0 | 0.02 | 0.31 | 0.30 | 2.39 | 0.33 | Haplic Acrisol (loamic) |
| 58 | -6.4411 | 35.9509 | 1016 | 7.5YR 4/4 | SL CLAYR | 23.1 | 5.9 | 4.7 | 188.7 | 0.03 | 0.38 | 0.40 | 5.72 | 0.49 | Haplic Acrisol (loamic) |

**Table 7-11** Pearl millet yields of on-station experiments in year 2015 and 2016. WH: Water harvesting intervention, FT: flat ties, TR: tied ridging; FI: full irrigation; fertilizer was uniformly applied prior to seeding

| Field | Year | Block | WH | Grain yield [kg ha$^{-1}$] |
|---|---|---|---|---|
| A | 2015 | 3 | FT | 5 |
| A | 2015 | 4 | FT | 11 |
| A | 2015 | 1 | FT | 28 |
| A | 2015 | 2 | FT | 56 |
| A | 2015 | 2 | TR | 92 |
| A | 2015 | 4 | TR | 270 |
| A | 2015 | 3 | TR | 321 |
| A | 2015 | 1 | TR | 955 |
| B | 2015 | 4 | FI | 3418 |
| B | 2015 | 1 | FI | 3753 |
| B | 2015 | 2 | FI | 4292 |
| B | 2015 | 3 | FI | 4065 |
| B | 2015 | 2 | FT | 3 |
| B | 2015 | 3 | FT | 17 |
| B | 2015 | 1 | FT | 32 |
| B | 2015 | 4 | FT | 112 |
| B | 2015 | 4 | TR | 122 |
| B | 2015 | 3 | TR | 503 |
| B | 2015 | 2 | TR | 698 |
| B | 2015 | 1 | TR | 1271 |
| A | 2016 | 2 | FT | 135 |
| A | 2016 | 4 | FT | 3362 |
| A | 2016 | 3 | FT | 3385 |
| A | 2016 | 1 | FT | 4145 |
| A | 2016 | 2 | TR | 155 |
| A | 2016 | 4 | TR | 2610 |
| A | 2016 | 1 | TR | 3003 |
| A | 2016 | 2 | TR | 3339 |
| B | 2016 | 2 | FI | 2015 |
| B | 2016 | 1 | FI | 3172 |
| B | 2016 | 3 | FI | 3817 |
| B | 2016 | 4 | FI | 4066 |
| B | 2016 | 1 | FT | 1093 |
| B | 2016 | 4 | FT | 1382 |
| B | 2016 | 2 | FT | 1471 |
| B | 2016 | 3 | FT | 1530 |
| B | 2016 | 3 | TR | 2020 |
| B | 2016 | 1 | TR | 2044 |
| B | 2016 | 2 | TR | 2148 |
| B | 2016 | 4 | TR | 2546 |

**Table 7-12** Pearl millet yields on the respective mother plot in year 2015 and 2016. WH: Water harvesting intervention, FT: flat ties, TR: tied ridging; Fertilization: F0: no fertilizer, PF: placed fertilizer, Ilolo 2015: no yield

| Field | Year | Block | WH | Fertilization | Crop yield [kg $ha^{-1}$] |
|---|---|---|---|---|---|
| 2015 | Idifu | 1 | FT | FO | 273 |
| 2015 | Idifu | 1 | FT | PF | 540 |
| 2015 | Idifu | 1 | TR | FO | 288 |
| 2015 | Idifu | 1 | TR | PF | 1246 |
| 2015 | Idifu | 2 | FT | FO | 261 |
| 2015 | Idifu | 2 | FT | PF | 455 |
| 2015 | Idifu | 2 | TR | FO | 297 |
| 2015 | Idifu | 2 | TR | PF | 1395 |
| 2015 | Idifu | 3 | FT | FO | 238 |
| 2015 | Idifu | 3 | FT | PF | 264 |
| 2015 | Idifu | 3 | TR | FO | 175 |
| 2015 | Idifu | 3 | TR | PF | 912 |
| 2015 | Idifu | 4 | FT | FO | 250 |
| 2015 | Idifu | 4 | FT | PF | 553 |
| 2015 | Idifu | 4 | TR | FO | 386 |
| 2015 | Idifu | 4 | TR | PF | 1428 |
| 2015 | Idifu | 5 | FT | FO | 135 |
| 2015 | Idifu | 5 | FT | PF | 637 |
| 2015 | Idifu | 5 | TR | FO | 344 |
| 2015 | Idifu | 5 | TR | PF | 1521 |
| 2016 | Idifu | 1 | FT | FO | 334 |
| 2016 | Idifu | 1 | FT | PF | 628 |
| 2016 | Idifu | 1 | TR | FO | 389 |
| 2016 | Idifu | 1 | TR | PF | 1286 |
| 2016 | Idifu | 2 | FT | FO | 298 |
| 2016 | Idifu | 2 | FT | PF | 769 |
| 2016 | Idifu | 2 | TR | FO | 438 |
| 2016 | Idifu | 2 | TR | PF | 1688 |
| 2016 | Idifu | 3 | FT | FO | 389 |
| 2016 | Idifu | 3 | FT | PF | 871 |
| 2016 | Idifu | 3 | TR | FO | 391 |
| 2016 | Idifu | 3 | TR | PF | 924 |
| 2016 | Ilolo | 1 | FT | FO | 437 |
| 2016 | Ilolo | 1 | FT | PF | 942 |
| 2016 | Ilolo | 1 | TR | FO | 727 |
| 2016 | Ilolo | 1 | TR | PF | 1336 |
| 2016 | Ilolo | 2 | FT | FO | 371 |
| 2016 | Ilolo | 2 | FT | PF | 986 |
| 2016 | Ilolo | 2 | TR | FO | 736 |
| 2016 | Ilolo | 2 | TR | PF | 1196 |
| 2016 | Ilolo | 3 | FT | FO | 436 |
| 2016 | Ilolo | 3 | FT | PF | 809 |
| 2016 | Ilolo | 3 | TR | FO | 637 |
| 2016 | Ilolo | 3 | TR | PF | 1189 |

**Table 7-13** Pearl millet yields in proximation of 100 m (same soil unit) of the respective baby plot in Ilolo in year 2015 and 2016. Lat: latitude, Long: longitude (WGS84), WH: Water harvesting intervention, FT: flat ties, TR: tied ridging; Fertilizer: fertilization intervention, F0: no fertilizer, PF: placed fertilizer

| Plot | Year | Lat | Long | Elevation | WH | Fertilizer | Crop yield |
|---|---|---|---|---|---|---|---|
| No. | | [°] | [°] | [m] | | | [kg $ha^{-1}$] |
| 1 | 2015 | -6.3256 | 35.9010 | 1107 | TR | PF | 958 |
| 11 | 2015 | -6.3399 | 35.9171 | 1088 | TR | PF | 942 |
| 16 | 2015 | -6.3495 | 35.8949 | 1087 | PT | PF | 954 |
| 19 | 2015 | -6.3462 | 35.9040 | 1078 | FT | F0 | 389 |
| 29 | 2015 | -6.3356 | 35.9061 | 1108 | FT | F0 | 286 |
| 29 | 2015 | -6.3356 | 35.9061 | 1108 | TR | PF | 567 |
| 30 | 2015 | -6.3258 | 35.9035 | 1124 | FT | F0 | 397 |
| 30 | 2015 | -6.3258 | 35.9035 | 1124 | TR | PF | 822 |
| 31 | 2015 | -6.3400 | 35.9088 | 1085 | TR | PF | 1247 |
| 1 | 2016 | -6.3256 | 35.9010 | 1107 | FT | F0 | 363 |
| 1 | 2016 | -6.3256 | 35.9010 | 1107 | TR | F0 | 588 |
| 1 | 2016 | -6.3256 | 35.9010 | 1107 | TR | PF | 1304 |
| 6 | 2016 | -6.3498 | 35.9114 | 1079 | FT | F0 | 418 |
| 6 | 2016 | -6.3496 | 35.9108 | 1076 | FT | F0 | 235 |
| 6 | 2016 | -6.3496 | 35.9108 | 1076 | TR | F0 | 679 |
| 6 | 2016 | -6.3498 | 35.9114 | 1079 | TR | PF | 639 |
| 6 | 2016 | -6.3496 | 35.9108 | 1076 | TR | PF | 1004 |
| 15 | 2016 | -6.3510 | 35.8966 | 1080 | FT | F0 | 355 |
| 15 | 2016 | -6.3510 | 35.8966 | 1080 | TR | F0 | 506 |
| 15 | 2016 | -6.3510 | 35.8966 | 1080 | TR | PF | 804 |
| 16 | 2016 | -6.3495 | 35.8949 | 1087 | FT | F0 | 277 |
| 16 | 2016 | -6.3495 | 35.8949 | 1087 | TR | PF | 689 |
| 31 | 2016 | -6.3310 | 35.9088 | 1085 | FT | F0 | 303 |
| 31 | 2016 | -6.3310 | 35.9088 | 1085 | TR | PF | 1008 |

**Table 7-14** (part 1) Pearl millet yields in 100 m proximation (same soil unit) of the respective baby plot in Idifu, Chamwino district, in 2015 and 2016. Lat: latitude, Long: longitude (WGS84), WH: Water harvesting intervention, FT: flat ties, TR: tied ridging; Fertilizer: fertilization intervention, F0: no fertilizer, PF: placed fertilizer

| Plot No. | Year | Lat [°] | Long [°] | Elevation [m] | WH | Fertilizer | Crop yield [kg ha$^{-1}$] |
|---|---|---|---|---|---|---|---|
| 3 | 2015 | -6.4453 | 35.9980 | 1014 | TR | PF | 624 |
| 4 | 2015 | -6.4402 | 36.0035 | 995 | TR | PF | 1305 |
| 13 | 2015 | -6.4359 | 35.9789 | 1005 | TR | PF | 1231 |
| 14 | 2015 | -6.4341 | 35.9769 | 1010 | TR | F0 | 757 |
| 14 | 2015 | -6.4341 | 35.9769 | 1010 | TR | F0 | 509 |
| 16 | 2015 | -6.4254 | 35.9750 | 997 | TR | F0 | 665 |
| 19 | 2015 | -6.4454 | 35.9638 | 1004 | TR | PF | 1069 |
| 24 | 2015 | -6.4381 | 35.9707 | 1005 | TR | PF | 1099 |
| 38 | 2015 | -6.4219 | 35.9403 | 1006 | FT | PF | 518 |
| 38 | 2015 | -6.4219 | 35.9403 | 1006 | FT | PF | 373 |
| 46 | 2015 | -6.4133 | 35.9836 | 1002 | TR | PF | 1071 |
| 47 | 2015 | -6.4119 | 35.9773 | 1003 | FT | PF | 1231 |
| 53 | 2015 | -6.4365 | 35.9648 | 1001 | TR | PF | 975 |
| 53 | 2015 | -6.4365 | 35.9648 | 1001 | TR | PF | 827 |
| 58 | 2015 | -6.4409 | 35.9509 | 1007 | TR | F0 | 561 |
| 58 | 2015 | -6.4409 | 35.9509 | 1007 | TR | F0 | 491 |
| 3 | 2016 | -6.4453 | 35.9980 | 1014 | FT | F0 | 883 |
| 3 | 2016 | -6.4453 | 35.9980 | 1014 | FT | PF | 548 |
| 3 | 2016 | -6.4453 | 35.9980 | 1014 | TR | PF | 1483 |
| 4 | 2016 | -6.4402 | 36.0035 | 995 | FT | F0 | 634 |
| 4 | 2016 | -6.4402 | 36.0035 | 995 | TR | PF | 888 |
| 5 | 2016 | -6.4403 | 35.9976 | 1004 | FT | F0 | 770 |
| 5 | 2016 | -6.4403 | 35.9976 | 1004 | TR | F0 | 203 |
| 5 | 2016 | -6.4403 | 35.9976 | 1004 | TR | PF | 397 |
| 10 | 2016 | -6.4389 | 35.9791 | 1005 | FT | F0 | 410 |
| 10 | 2016 | -6.4389 | 35.9791 | 1005 | TR | F0 | 586 |
| 10 | 2016 | -6.4389 | 35.9791 | 1005 | TR | PF | 770 |
| 13 | 2016 | -6.4359 | 35.9789 | 1005 | FT | F0 | 391 |
| 13 | 2016 | -6.4359 | 35.9789 | 1005 | TR | PF | 639 |
| 15 | 2016 | -6.4271 | 35.9784 | 999 | FT | F0 | 178 |
| 15 | 2016 | -6.4271 | 35.9784 | 999 | TR | PF | 324 |
| 16 | 2016 | -6.4254 | 35.9750 | 997 | FT | F0 | 472 |
| 16 | 2016 | -6.4254 | 35.9750 | 997 | TR | F0 | 628 |
| 16 | 2016 | -6.4254 | 35.9750 | 997 | TR | PF | 1256 |
| 17 | 2016 | -6.4408 | 35.9781 | 1008 | FT | F0 | 544 |
| 17 | 2016 | -6.4408 | 35.9781 | 1008 | TR | F0 | 771 |
| 17 | 2016 | -6.4408 | 35.9781 | 1008 | TR | PF | 1017 |
| 18 | 2016 | -6.4447 | 35.9753 | 999 | FT | F0 | 236 |
| 18 | 2016 | -6.4447 | 35.9753 | 999 | TR | F0 | 423 |
| 18 | 2016 | -6.4447 | 35.9753 | 999 | TR | PF | 544 |
| 19 | 2016 | -6.4454 | 35.9638 | 1004 | TR | F0 | 1504 |
| 19 | 2016 | -6.4454 | 35.9638 | 1004 | TR | PF | 1586 |
| 20 | 2016 | -6.4449 | 35.9628 | 1027 | FT | F0 | 809 |

**Table 7-14** (part 2)

| Plot No. | Year | Lat [°] | Long [°] | Elevation [m] | WH | Fertilizer | Crop yield [kg ha$^{-1}$] |
|---|---|---|---|---|---|---|---|
| 20 | 2016 | -6.4449 | 35.9628 | 1027 | TR | PF | 1352 |
| 24 | 2016 | -6.4381 | 35.9707 | 1005 | FT | F0 | 654 |
| 24 | 2016 | -6.4381 | 35.9707 | 1005 | TR | F0 | 995 |
| 24 | 2016 | -6.4381 | 35.9707 | 1005 | TR | PF | 1162 |
| 25 | 2016 | -6.4362 | 35.9732 | 1008 | FT | F0 | 203 |
| 25 | 2016 | -6.4362 | 35.9732 | 1008 | TR | F0 | 345 |
| 25 | 2016 | -6.4362 | 35.9732 | 1008 | TR | PF | 397 |
| 28 | 2016 | -6.4289 | 35.9615 | 1005 | FT | F0 | 412 |
| 28 | 2016 | -6.4289 | 35.9615 | 1005 | TR | F0 | 582 |
| 28 | 2016 | -6.4289 | 35.9615 | 1005 | TR | PF | 1022 |
| 29 | 2016 | -6.4298 | 35.9897 | 1004 | FT | F0 | 805 |
| 29 | 2016 | -6.4298 | 35.9897 | 1004 | TR | PF | 1557 |
| 30 | 2016 | -6.4271 | 35.9959 | 1005 | FT | F0 | 745 |
| 30 | 2016 | -6.4271 | 35.9959 | 1005 | TR | F0 | 818 |
| 30 | 2016 | -6.4271 | 35.9959 | 1005 | TR | PF | 1008 |
| 40 | 2016 | -6.4236 | 35.9403 | 1005 | FT | F0 | 397 |
| 40 | 2016 | -6.4236 | 35.9403 | 1005 | TR | PF | 577 |
| 41 | 2016 | -6.4095 | 35.9535 | 1007 | FT | F0 | 677 |
| 41 | 2016 | -6.4095 | 35.9535 | 1007 | TR | PF | 1054 |
| 44 | 2016 | -6.4009 | 35.9785 | 1011 | FT | F0 | 375 |
| 44 | 2016 | -6.4009 | 35.9785 | 1011 | TR | PF | 1432 |
| 45 | 2016 | -6.4116 | 35.9859 | 1003 | FT | F0 | 401 |
| 45 | 2016 | -6.4116 | 35.9859 | 1003 | TR | PF | 1022 |
| 46 | 2016 | -6.4133 | 35.9836 | 1002 | FT | F0 | 768 |
| 46 | 2016 | -6.4133 | 35.9836 | 1002 | TR | PF | 1521 |
| 47 | 2016 | -6.4119 | 35.9773 | 1003 | FT | F0 | 800 |
| 47 | 2016 | -6.4119 | 35.9773 | 1003 | TR | PF | 1163 |
| 48 | 2016 | -6.4363 | 35.9502 | 1003 | FT | F0 | 1918 |
| 48 | 2016 | -6.4363 | 35.9502 | 1003 | TR | PF | 948 |
| 50 | 2016 | -6.4363 | 35.9511 | 1006 | FT | F0 | 534 |
| 50 | 2016 | -6.4363 | 35.9511 | 1006 | TR | PF | 1584 |
| 53 | 2016 | -6.4365 | 35.9648 | 1001 | FT | F0 | 676 |
| 53 | 2016 | -6.4365 | 35.9648 | 1001 | TR | F0 | 770 |
| 53 | 2016 | -6.4365 | 35.9648 | 1001 | TR | PF | 1281 |
| 55 | 2016 | -6.4318 | 35.9574 | 998 | FT | F0 | 260 |
| 55 | 2016 | -6.4318 | 35.9574 | 998 | TR | PF | 387 |
| 56 | 2016 | -6.4358 | 35.9850 | 1004 | FT | F0 | 1239 |
| 56 | 2016 | -6.4358 | 35.9850 | 1004 | TR | PF | 2010 |
| 58 | 2016 | -6.4409 | 35.9509 | 1007 | FT | F0 | 863 |
| 58 | 2016 | -6.4409 | 35.9509 | 1007 | TR | PF | 1391 |

## 7.1. References

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