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NUTRIENT MANAGEMENT AND SPATIAL VARIABILITY OF SOILS ACROSS SCALES AND SETTLEMENT SCHEMES IN ZIMBABWE

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Dedicated to the memory of my beloved father

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

1stDer : First Derivative
Al : Aluminum
ANOVA : ANalysis Of VAriance
AREX : Department of Agricultural Research and Extension (Zimbabwe)
C : Carbon
Ca : Calcium
CEC : Cation Exchange Capacity
CERES : Crop Environment REsource Synthesis (model)
CIAT : International Center for Tropical Agriculture
COE : Constant Offset Elimination
CSO : Central Statistical Office (Zimbabwe)
CV : Coefficient of Variation
DAPP : Development Aid from People to People
DRIFT : Diffuse Reflectance Infrared Fourier Transform (spectroscopy)
DYNBAL : DYnamic simulation of Nutrient BALances (model)
ESRI : Environmental Systems Research Institute
FAO : Food and Agriculture Organization (of the United Nations)
GIS : Geographic Information Systems
GPS : Global Positioning System
ILWIS : Integrated Land and Water Information System
ISRIC : International Soil Reference and Information Centre
ISSS : International Society of Soil Science
IN : Inflows
IRS : InfraRed Spectroscopy
K : Potassium
LAPSUS : LandscApe ProcessS modeling at mUltidimensions and Scales
MAS : Multi Agent Systems
Mg : Magnesium
MIR-PAS : Mid-InfraRed PhotoAcustic Spectroscopy
MIRS : Mid-InfraRed Spectroscopy
MSC : Multiplicative Scatter Correction
N : Nitrogen

NIRS : Near-InfraRed Spectroscopy
NGOs : Non-Governmental Organizations
NUANCES : Nutrient Use in Animal and Cropping Systems: Efficiencies and Scales
NUTMON : NUTrient MONitoring (model)
OUT : Outflows
P : Phosphorus
P_{av} : Available phosphorus
PC : Principal Component
PLS : Partial Least Square regression
RPD : Residual Prediction Deviation
RMSEE : Root Mean Square Error of Estimation
RMSEP : Root Mean Square Error of the Prediction
S : Sulphur
SAS : Statistical Analysis Software
SLS : Straight Line Subtraction
SOM : Soil Organic Matter
SSA : Sub Saharan Africa
TSBF : Tropical Soil Biology and Fertility institute
USDA : United States Department of Agriculture
USLE : Universal Soil Loss Equation
VN : Vector Normalization
VNIRS : Visible to Near Infrared Spectroscopy

CHAPTER 1

GENERAL INTRODUCTION

1. GENERAL INTRODUCTION

1.1. Background

Decline in soil fertility in Africa is one of the most limiting biophysical factors to agricultural productivity, as nutrient mining and low productivity are strongly related (Bayu et al., 2005; Hartemink, 2006a). Soil nutrient mining can be revealed by tools like nutrient balances, which account for all nutrients going in (e.g. fertilizers) and out (e.g. yields) of a system (Bindraban et al., 2000). Due to low investments in soil fertility in many places in Africa, results from nutrient balances, e.g. Nitrogen (N), are usually negative on this continent, clearly contrasting with results from countries like USA or China, where N inputs exceed by far respective outputs (Vitousek et al., 2009). A high heterogeneity in management, together with different biophysical, socio-economical and even political conditions across each agro-ecosystem, makes blanket recommendations to overcome soil fertility problems in Africa difficult, if not impossible (Snapp et al., 2003). Thus, acknowledging heterogeneity, and moreover quantifying it at different spatial scales, is the first step in making suitable recommendations to the different stakeholders, such as farmers, extension officers and policy makers (Huang et al., 2006; Yemefack et al., 2005). This thesis deals with the development of new methodological approaches for better understanding nutrient management and spatial variability of soils across different spatial scales in African agro-ecosystems, taking various small-holder settlement schemes in Zimbabwe as a case study.

1.2. Zimbabwe

Zimbabwe is located in Southern Africa, between 15°30’ - 22°30’ S and between 25° - 33°10’ E, comprising a total area of 390,757 km^2 (CSO, 2001). The national population is about 12 million, average household size is 4 people and literacy is 97% (CSO, 2004b). The country is divided in 10 provinces, which are further subdivided in several districts. Figure 1.1 shows Zimbabwe in continental Africa and the location of the three villages selected within the districts of Bindura and Shamva for the studies presented in Chapters 3 and 4.

1.2.1. Natural regions, vegetation and soils

Zimbabwe has been divided in five natural regions, based on the close relationship among climate, vegetation and soils (FAO, 2006). Region I is located in the east of the country and comprehends about 2% of total land area, with a mean annual rainfall > 1000 mm; hence it is

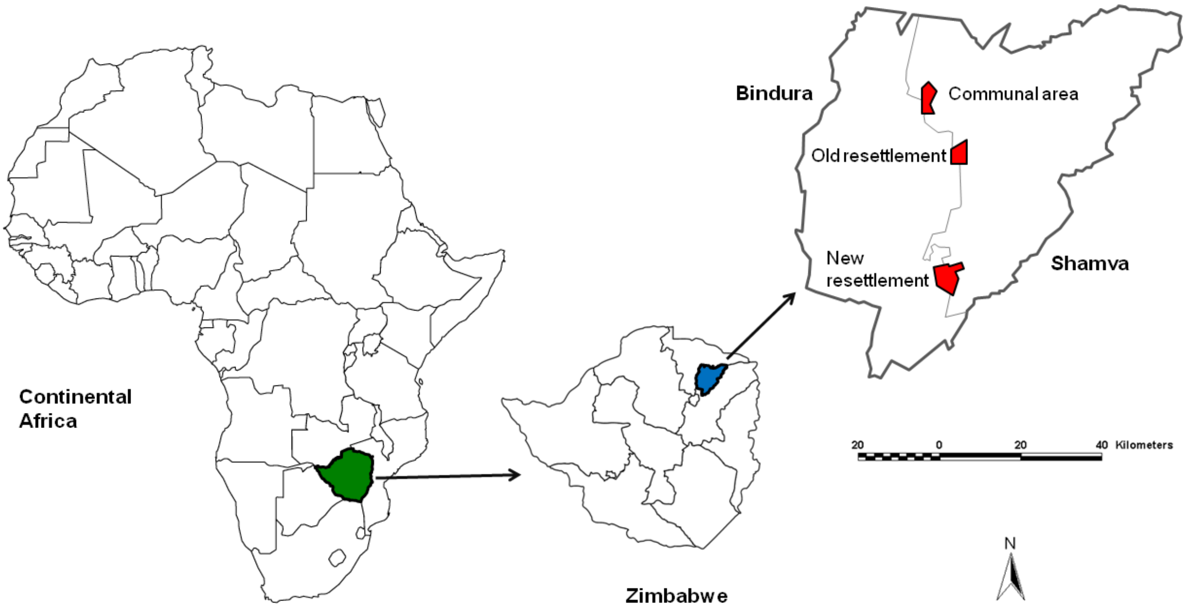

Figure 1.1. Location of Zimbabwe in continental Africa and the selected villages within the Bindura and Shamva districts (Mashonaland Central province), NE Zimbabwe. Villages' size was increased 50% for a better visualization. For detailed information of study sites please refer to section 3.4.1.

recommended for intensive diversified agriculture, dairy farming and timber production. Region II lies in the middle to north east, and comprises about 19% of total area, with a rainfall of 750-1000 mm; therefore it is suitable for intensive crop farming and livestock production. Region III can be found in the mid-altitudinal areas, covering about 17% of total area, with rainfall of 500-800 mm and recommended for semi- intensive mixed farming and drought tolerant crops. Region IV and V occupy the rest of the territory, presenting very low (<650 mm yr^{-1}) and erratic rainfall, and therefore is recommended for semi-extensive to extensive farming (FAO, 2006). The study sites of Chapters 3 and 4 are located in region II.

Regarding natural vegetation, a great part of the national territory is covered by savanna grasslands, with some dispersed bushes or trees, most of which are Miombo woodlands; while truly natural vegetation has almost disappeared due to anthropogenic impacts on environment (Nyamapfene, 1991). In fact, from 39 million of hectares that Zimbabwe encompasses, 41% is occupied by woodlands; from which close to a quarter consist of Miombo woodlands (Sukume and Guveya, 2003). Miombo woodlands are preferentially dominated by tree species of the Caesalpinoidae subfamily (Leguminosea), with an underlying layer of grass, and where *Brachystegia*, *Julbernardia* and *Isoberlinia* are the prevailing tree species (Kowero, 2003; Sukume and Guveya, 2003).

In terms of soils, Zimbabwe presents predominantly granite-derived (sandy) soils with low inherent fertility, and their management is usually deficient, which increases their susceptibility to degradation upon cultivation (Burt et al., 2001). These soils present mainly deficiencies in N, phosphorus (P) and sulphur (S), low cation exchange capacity (CEC) and low water retention capacities, due to low soil organic matter (SOM) and clay contents (Chuma et al., 1997; Nzuma and Murwira, 2000). In fact, opportunities for building-up SOM and fertility levels in sandy soils are generally limited as a result of high SOM decomposition, due to low protective effects of organic materials against microbial attack, and high potential leaching losses in these well-drained soils (Mtambanengwe et al., 2004). Derived-granite sandy soils occupy roughly two-third of Zimbabwe and can be found mainly in upland areas with 500-800 mm rainfall (Nyamapfene, 1991). However, the so-called red soils can also be found in the country, which are more productive, and typically located within former commercial lands (Twomlow and Bruneau, 2000). Red soils are derived from mafic rock formations and mainly occur on the central plateau in zones where rainfall ranges from 700-950 mm. These soils are inherent fertile due to high clay content, presenting also good hydrodynamic properties and physical stability (Nyamapfene, 1991). Sandy and red soils belong to the Fersiallitic group in the Zimbabwean soil classification, which roughly correspond to Alfisols in the USDA classification (*ibid.*). Research sites in Chapters 3 and 4 include both, sandy and red soils.

1.2.2. Land reform and the emergence of settlement schemes

When in 1980 Zimbabwean independence began, the disparity on land ownership and access to natural resources between a minority of white commercial farmers and a great majority of indigenous black small-holder farmers was the seed for the starting of the land reform (Moyo, 2005). In colonial times, almost half of the country's agricultural lands on the best soils were typically occupied by 6,000-7,000 white commercial farmers' families, leaving the other half of the land, on the less productive soils, to 700,000-800,000 black farmers' households in the so called 'communal areas' (Deininger et al., 2004; Elliott et al., 2006). Thus, after independence, previously white owned-land started to be redistributed to the black population in a willing-buyer, willing-seller basis (Deininger et al., 2004). However, during the first 20 years of the program the land situation hardly changed, and in 2000 a major land redistribution initiated by the government took place (i.e. fast track land reform) with the aim to size the rest of the territory on white farmers' hands (Moyo, 2005). This process altered significantly the ownership for the land in Zimbabwe, and by the end of 2003 most of the former white farmers' commercial land (i.e. more than 9 million ha or about 78% of their territory) were transferred to the black majority (Masiiwa, 2005). Although the land was initially planned to be redistributed in four model types (model A for individual farming, model B for cooperative organizations, model C centered on core estates, and model D for extensive cattle ranching), model A was the most widespread (Deininger et al., 2004; Elliott et al., 2006). Model A can be further subdivided in A1 (small-scale farmers) and A2 (small commercial farmers), being the first one the most popular. Small-holder farmers in communal and A1 resettlement areas accounts nowadays for 98% of all farms in the country, occupying near to 73% of the total land (Moyo, 2005). The land reform has resulted in evident agro-ecological and socio-economic changes in Zimbabwe (Elliott et al., 2006; Masiiwa, 2005), with discernible effects in other Southern African countries as well (Derman, 2006).

1.2.3. Small-scale farming systems

Substantial economic growth of a country, in which the agricultural sector is the key activity, is impossible without sustainable development of agriculture (Sanchez and Leakey, 1997). This is the case for the majority of African countries, like Zimbabwe, where near to 85% of the national territory is classified as agricultural (Sukume et al., 2000) and where about 65% of population live in rural areas and depend on agricultural activities for their livelihoods (CSO, 2004b). Smallholder farming in Zimbabwe, as in many other places in Africa, is based mainly on maize (*Zea mays* L.) which is planted by near 90% of farmers (CSO, 2004b; CSO, 2005). Sorghum and millets (*Sorghum bicolor / Pennisetum* spp.) are generally planted as substitute of maize in the drier zones of the country, but their demand and use is still limited (Sukume et al., 2000). Sunflower (*Helianthus annuus* L.) and groundnuts (*Arachis hypogaea* L.) are very popular by smallholder farmers as well, due to their low inputs needs and drought tolerance (Sukume et al., 2000). Cotton (*Gossypium* spp.) and soybeans (*Glycine max* L. Merr.) are also commonly cultivated (CSO, 2004b; CSO, 2005). Livestock production is a very important component of the agricultural sector as well, as more than 70% of Zimbabwe is pastoral-suitable (Frost and Mandondo, 1999). In fact, cattle is fundamental in small-holder farming systems because it provides transport, tillage power, meat, milk, manure and even cash (Bayu et al., 2005). However, it is typically restricted to wealthy families, involving only about half of the small-scale farmers in the country (Mapfumo and Giller, 2001). The use of communal rangelands is also a very important component of rural livelihoods, as small-scale farmers directly or indirectly depend on these areas for their sustenance (Chitiga and Nemarundwe, 2003; Frost and Mandondo, 1999). Communal rangelands are used to obtain fuel-wood and construction materials for the homestead, for grazing livestock, collecting litter as soil conditioners, picking up medicines, among others (Chitiga and Nemarundwe, 2003; Mapfumo and Giller, 2001).

1.2.4. Soil fertility management strategies

Although investments in soil fertility management by small-scale farmers in Southern Africa are minimal (Snapp et al., 1998; Snapp et al., 2003), several management practices have been carried out by small-holder farmers in Zimbabwe as a measure of supplying nutrients for keeping up crop yield levels. Use of mineral fertilizers, for instance, is one of the direct ways to replenish mined soil nutrients due to agricultural activities (Chuma et al., 1997). However, due to the removal of subsides in 1991 and the devaluation of local currency, mineral fertilizers have become unafordable for most small-holder farmers in Zimbabwe (Mutiro and Murwira, 2004). Animal manure is considered a good alternative to mineral fertilization as it improves soil physical-chemical conditions with time, being undoubtedly the most important nutrient source in the country (Ahmed et al., 1997; Chuma et al., 1997; Nhamo et al., 2004; Nyamangara and Bergström, 2004). Access to manure is, however, usually limited to wealthy farmers who own cattle and have enough available resources (Mapfumo and Giller, 2001; Nzuma and Murwira, 2000; Scoones, 1997). Moreover, manure quality (i.e. N content) is generally low due to impurities and losses during their storage and handling (Chuma et al., 1997; Nhamo et al., 2004; Nzuma and Murwira, 2000). Hence, it is needed in large amounts to improve significantly soil fertility; but big amounts of manure are usually difficult to obtain by smallholder farmers in Zimbabwe (Mapfumo and Giller, 2001).

Collection of leaf litter from rangelands for its application to the fields is another option small-scale farmers have to supply nutrients to their crops. This practice, however, is apparently more utilized for cattle owners, as cattle facilitate the collection and transport of litter to their fields (Mapfumo and Giller, 2001). In fact, large amounts of litter must be gathered for supplying enough nutrients to crops due to the typical low quality of these organic materials (Palm et al., 2001). But as this implies a high demand of labor, the practice is not widely used. Low amounts and low nutrient quality is also a usual characteristic of crop residues left in the field, with which its contribution on soil fertility is limited (Giller, 2002). Use of compost is a way to solve the problems of low quality of litter and crop residues, as it allows manipulating the quality of these nutrient sources. However, this technology also requires high labor efforts and therefore not many farmers use it (Mapfumo and Giller, 2001).

Inclusion of legumes into the systems has been also carried out to increase soil fertility, due to their capacity to fix N from the atmosphere (Giller et al., 2006). For example, maize-groundnut is the most common association on smallholder farms in sub-humid Zimbabwe (Waddington and Karigwindi, 2001). However, crop rotations are usually performed more often for exploiting residual soil nutrients in the short term, than for increasing soil quality in the long term (Ahmed et al., 1997; Mapfumo and Giller, 2001). Fallowing, on the other hand, is generally realized when there is no possibility to cultivate more land, due to lack of inputs, such as labor and fertilizers (Nzuma and Murwira, 2000). Hence, usually fallowing is also not consciously carried out as a measure for improving soil conditions (Mapfumo et al., 2005). In fact, all these activities are mainly chosen by farmers opportunistically, depending on the availability of their farm resources (biomass, labor, cash, etc.), and not as a systematic and intentional way to increase soil fertility levels (Mapfumo and Giller, 2001). Therefore, nutrient sources are generally used inefficiently and/or in lower levels than needed, and thereby nutrient balances are generally negative (*ibid.*).

1.3. Soil spatial variability at different scales

Soil variability is manifested at different spatial scales (Garten Jr. et al., 2007). At regional scale, for example, a country like Zimbabwe presents a wide variety of agricultural niches, due to their different agroecological zones (e.g. CSO, 2004a). Similarly, there is a wide variety of conditions at watershed scale, due to the different landforms across the landscape, from uplands to river banks (Nyamapfene, 1991). At lower scales (i.e. farm and plot level), variability also exists due to micro-relieve, different soil types, etc.; and these differences are generally well perceived by farmers, whom usually try to make an opportune use of them (Mapfumo and Giller, 2001). In fact, farmers' management is another important driving factor of soil spatial variability. For example, at farm level, African farmers usually allocate preferentially their resources (organic matter, nutrients, water, and/or labor) near to their homesteads, as this proximity assures easy management and vigilance (Giller et al., 2006). In this way, it can create what has been called soil fertility gradients, even in farms smaller than 0.45 ha (Tittonell et al., 2005). A main characteristic of these fertility gradients is that they are determined by farmers' wealth status, as wealthier farmers usually own livestock; and manure (as explained previously) is one of the main nutrient sources in small-holder farming systems (Giller et al., 2006). At village level, on the other hand, additionally to cropping fields, open access lands (i.e. grasslands and woodlands) are typically also used by farmers for livestock grazing, fuel-wood collection, obtaining litter as soil amendments, etc. (Kowero, 2003). However, wealthy farmers are who usually can get the most from these resources, due to the higher availability of assets they own (e.g. cattle, carts) which allows them to make significant transfer of nutrients from these lands to their farms (Giller et al., 2006)

Preceding sections clearly illustrate that biophysical, socio-economical and even political conditions, plus management, are thus important factors regulating soil spatial variability at different scales. In fact, driving factors affecting environmental processes usually operate across the whole spatial hierarchy (Heuvelink, 1998), although their effect typically differ at each scale (e.g. Veldkamp et al., 2001). In any case, soil spatial variability, if known, is not negative because a wider range of soil conditions involve a wider spectrum of opportunities for farmers to diversify their production systems. More important, this knowledge can be further used for specifically targeting technologies at contrasting sites for improving system management and performance (Tittonell et al., 2007). In fact, recognizing spatial patterns in soils is important in practice for predicting soil properties at unsampled locations (e.g. Liu et al., 2004; Liu et al., 2009; Wei et al., 2008), for a better understanding of complex relations among soil quality, topography and/or environmental factors (e.g. Emmerling and Udelhoven, 2002; Rüth and Lennartz, 2008; Wei et al., 2008), for recovering measures in problematic areas and/or enhancing use of resources (e.g. Borůvka et al., 2007; Liu et al., 2004; Wang et al., 2009), for improving crop yields (e.g. Dercon et al., 2003; Huang et al., 2006; Ndiaye and Yost, 1989; Taylor et al., 2003), and/or even for policy recommendations (e.g. Liu et al., 2009). In theory, knowledge about spatial variation is required for improving sampling designs in future agro-ecological studies (e.g. Rossi et al., 2009; Yan and Cai, 2008), to improve the accuracy of nutrient transfer models (e.g. Wang et al., 2009), and to enhance scaling-up soil assessments from low (e.g. plots) to higher (e.g. national) levels in the spatial hierarchy (e.g. Garten Jr. et al., 2007). Unknown soil spatial variability however, can be considered adverse, as in this case underlying patterns are not fully understood, and therefore actors cannot take adequate measures to control or make use of this variability.

1.4. Techniques used in this study

In this study, emphasis was placed in the use of mixed-methods, involving tools like nutrient balances and participatory approaches, and vanguard techniques like mid-infrared spectroscopy and geostatistics. The following sections introduce briefly each of these tools and justify their use within the context of this work.

1.4.1. Nutrient balances

By agricultural activities, like cropping, nutrients can be added to the systems (via fertilization), nutrients are exported from them (via harvesting yields or collecting crop residues), and other nutrients are either added by environmental processes (e.g. atmospheric deposition, nitrogen fixation) or lost (e.g. nutrients in eroded soil particles, leaching). Hence, by calculating the net difference between the amount of nutrients that are entering a system (i.e. inputs) and the nutrients that are removed (i.e. outputs) a nutrient balance (i.e. Σ inputs – Σ outputs) can be obtained (Smaling and Dixon, 2006). The method usually starts by predefining concrete spatial-temporal borders for limiting the dimension where calculations will take place, which is followed by the estimation of the nutrient flows of interest. In general, flows can be estimated by direct measurements, calculated by pedo-transfer functions or obtained from surveys, databases and/or literature (Oenema and Heinen, 1999). Negative nutrient balances indicate that the system is under nutrient deprivation and will degrade with time if the same trend continues; although the time to degradation will depend on inherent soil fertility (i.e. soil nutrient stocks) (Bindraban et al., 2000). Positive nutrient balances, on the other hand, indicate that nutrients in the system are accumulating, and even leading to pollution risks if accumulation is excessive (Vitousek et al., 2009). Nutrient balances are therefore useful for understanding soil fertility decline, recovery or pollution, and for planning new strategies dealing with soil management (FAO, 2003); but they are also very helpful for facilitating discussions with farmers about soil fertility issues and for policy recommendations (De Jager, 2005; Grote et al., 2005; Scoones and Toulmin, 1998). Alternative approaches for assessing nutrient depletion are also available though. This would be the case of expert knowledge systems (e.g. the Global Assessment of Human-induced Soil Degradation, GLASOD) and the monitoring of soil properties over time at the same site (i.e. data type I or chronosequential sampling) or under different land use systems at the same time (i.e. data type II or biosequential sampling) (Hartemink, 2006a). Each method presents its own advantages and disadvantages (see Table 1.1), although in general nutrient balances (also called nutrient budgets) has been the most used and cost-efficient technique dealing with soil fertility decline (*ibid.*). Detailed information about the nutrient balance approach in the African context is presented in Chapter 2; while in Chapter 3 the methodology was applied on three different Zimbabwean settlement schemes to assess potential nutrient mining by farmers in each study area.

Table 1.1. Main advantages and disadvantages of several approaches to assess soil fertility decline. Modified from Hartemink (2006a).

Approach	Description	Main advantages	Main disadvantages
Nutrient balances (nutrient budgets)	Net difference between inputs and outputs	Fairly rapid, use of existing data, indicative	Difficulties in measuring all flows, inclusion of lateral flows and setting of spatial-temporal boundaries, hard to follow changes over time
Expert knowledge systems	Qualitative knowledge about soil resources	Complementary information is provided	Data is not quantitative, may be (politically) biased
Data type I (Chronosequential sampling)	Comparing soil properties over time	Accurate, using existing data	Need same sampling sites, contamination of monitoring sites, critical soil sample storage, consistent laboratory procedures required, costly
Data type II (biosequential sampling)	Comparing soil properties under different land uses	Easy to obtain, rapid	Soils at sampling sites may differ, unknown land-use history of sites

1.4.2. Participatory approaches

Participatory approaches are a group of methods and/or tools utilized for facilitating the involvement of a targeted group (e.g. farmers) in the research process (Sutherland, 1998). They were conceived once participation of stakeholders in research was recognized as critical in the generation and adoption of new technologies (Johnson et al., 2004). Participatory research creates a favorable environment for the interaction farmers-researchers, allow to better understand farmers' needs, criteria and perceptions, and therefore it is very useful for improving the results of the research. Moreover, it may also conduce to farmers' empowerment, if the methods are appropriately carried out and the time of interaction is long enough (Hellin et al., 2008). For achieving these goals, many participatory tools and methods are available (e.g. semi-structured interviews, focused group discussions, preference and wealth rankings, flow diagrams, institutional charts, seasonal calendars, and participatory maps, among many others), which are usually chosen depending on the objectives of the assessment and the target group (White and Pettit, 2004). In fact, participatory methods can be applied to different groups in a community or region for being able to obtain divergences in needs, opinions and experiences in each category. This would be especially important, for example, when working with poor farmers, as they usually do not have the required organization skills and influence to represent themselves in mixed groups (Sutherland, 1998). Working with participatory methods, however, have some limitations. According to Bentley

(1994) establishing an unbiased and clear mean of communication between scientists and farmers is very difficult to achieve (although not impossible) mainly due to their socio-economical distance and different interests. Hence, participatory methods must be carried out by properly motivated and trained personnel, who know how to shorten those differences (*ibid.*); and by having clear objectives in mind, as *where to work*, *who to work with* and *how to work with them* are critical decisions that strongly affect the results (Bellon, 2001). Participatory research is also considered as a 'slow' process, since all meetings must be planned in advance to match schedules of all member of the target groups, and by giving enough time for each activity in the program, which not always fit scientists' agenda (Branney et al., 2000). Participatory approaches were used during fieldwork leading to studies presented in Chapters 3 and 4, to identify local knowledge, preferences, perceptions and priorities of farmers in each village regarding their production systems (and their communities in general), as well as for facilitating a proper feedback to farmers.

1.4.3. Infrared spectroscopy

Since the first infrared spectrum was obtained in 1905, infrared spectroscopy (IRS) has been an important analytical tool in research and in technical fields (Gremlich, 2000). However, their use only became routine in the last decades with the new developments in statistics, computers and software, and after the instruments got accessible to the public at reasonable prices (Shepherd and Walsh, 2004). IRS uses the spectral signatures in the infrared region (electromagnetic spectrum between 0.7 and 1000 µm) of molecular components of the sample to identify and quantify them (Gremlich, 2000). The spectra is a function of the reflected or absorbed infrared light directed to the sample, which in turn is a function of the electronic transitions and vibrational status of the atoms that form the molecules of the sample constituents (Du and Zhou, 2009). For example, most soil components have fundamentals tones on the mid infrared region (MIRS, 2.5–25 µm) but their overtones generally fall in the near infra-red region (NIRS, 0.7–2.5 µm) (Brown et al., 2005). The bands that conform the spectra are characteristics of certain sub-molecular groups, so using pattern recognition techniques functional properties of the sample can be obtained (Gremlich, 2000). However, because the direct analysis of the spectra is difficult to interpret in complex samples, like soils, multivariate statistical tools are commonly applied, e.g. multiple regression analyses, radial basis function networks, principal components regression, multivariate adaptive regression splines and partial least squares regression, among others (Shepherd and Walsh, 2002; Viscarra-Rossel et al., 2006). Among the advantages of IRS over conventional laboratory analyses are the lower price for scanned sample, the large amount of samples that can be scanned per day, measurements are non-destructive, and the integrated nature of the spectra in which several soil properties can be assessed simultaneously (Brown et al., 2005; Du and Zhou, 2009; Shepherd and Walsh, 2002; Shepherd and Walsh, 2004). In fact, both NIRS and MIRS can be successfully used for the prediction of many soil characteristics like textural fractions, total and organic carbon and nitrogen, pH, exchangeable bases, cation exchange capacity, carbonates, electric conductivity, microbial biomass, among others (Viscarra-Rossel et al., 2006). IRS could be also used as an integrative measure of soil quality and employed as a screening tool of soil condition; hence its application to soil variability assessment and monitoring at broad scale is a promising approach (Cécillon et al., 2009; Shepherd and Walsh, 2007). However, although MIR spectrometers are more expensive, complex and typically less portable than NIR instruments (Janik et al., 1998; Viscarra-Rossel et al., 2006), MIRS information is richer and predictions are generally more accurate than those obtained by NIRS, since NIRS peaks often overlap giving few and broad absorption features (Shepherd and Walsh, 2007). Among the disadvantages of MIRS are the need for local calibrations and sample preparation (e.g. grinding or ball-milling) for high sample throughput, and that soil properties not related to the chemistry of the soil matrix (e.g. available phosphorus) and in very low concentration or involved in transitory phases (e.g. nitrate or ammonia) are difficult to predict (Janik et al., 1998). MIRS techniques were used in Chapter 4 for assessing spatial variability of soils at landscape scale.

1.4.4. Geostatistics

Geostatistics is possibly the most utilized and powerful technique among the several existing methods for assessing and characterizing spatial variability, e.g. Mantel tests, Moran’s I, Geary’s C, dispersion indices, fractal analyses, among others (Goovaerts, 1999; Liebhold and Gurevitch, 2002; Sauer et al., 2006). According to Wagner and Fortin (2005) “goestatistical methods focus on the estimation of spatial covariance structure of a spatially structured variable (e.g. variogram modeling)”. Therefore, a variogram (or semivariogram, as it will be called further on for matching terminology in the international literature), is one of the main tools on which geostatistics is based. However, the creation of stable semivariograms usually requires extensive geo-referenced datasets, which is perhaps its main limitation (Davidson and Csillag, 2003). The semivariogram “measures the average dissimilarity between data separated by a [distance] vector…” and “it is computed as half the averaged square difference between the components of [all possible] data pairs” at a certain lag distance and direction (Goovaerts, 1999). If there is spatial dependence, typically the semivariance increases with distance up to a certain point where it reaches a maximum and stabilizes, indicating that spatial correlation among samples is not present anymore (Liu et al., 2004). Figure 1.2 shows a representation of a typical experimental semivariogram (and its respective fitted model, i.e. theoretical semivariogram) showing spatial dependence. The semivariogram is characterized by several parameters: the range indicates up to which scale (distance) there is spatial dependence; the sill shows the maximum amount of spatial variability that is present; and the nugget denotes the amount of variability that cannot be explained or that is present at lower distance than the minimum sampling interval (Rüth and Lennartz, 2008). Once a semivariogram is constructed, the information it contains can be further used for interpolation (i.e. prediction of values at unsampled locations based on the original data points) by using, e.g., Kriging (Wagner and Fortin, 2005). Kriging is just a “generic name adopted by geostatisticians for a family of generalized least-squares regression algorithms” (Goovaerts, 1999), which incorporates the spatial autocorrelation of the data as specified by the semivariogram (Largueche, 2006). Geostatistics (i.e. variography analysis) was used in Chapter 4 for analyzing the spatial variability of soils and to derive recommendations for future sampling designs.

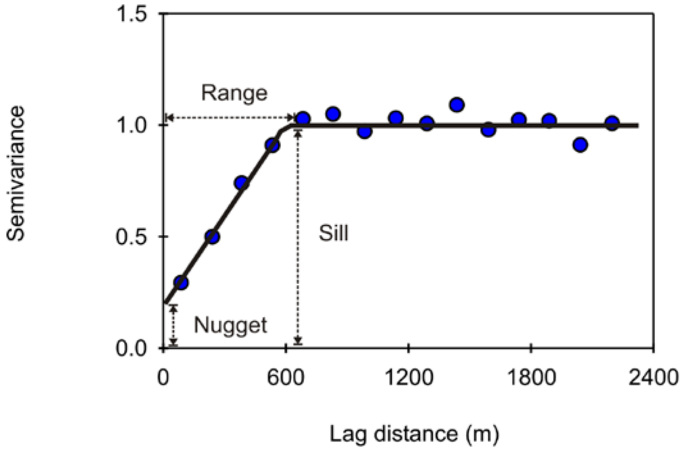

Figure 1.2. Experimental semivariogram (dots) and theoretical fitted model (line) for a hypothetical variable showing spatial autocorrelation. The three parameters (nugget, sill and range), from which the semivariogram is characterized, are indicated. For more information please refer to the text.

1.5. Justification

In Zimbabwe, as in many places in Africa, the unsustainable nature of the agricultural practices has led to deforestation and soil degradation (Chenje et al., 1998; Kamusoko and

Aniya, 2006). Approximately 70,000 hectares of forestland per year are lost in this country due to the accelerated expansion of cultivated area into the reserved rangelands (Shumba, 2001). Moreover, inherent poor soil conditions, scarcity of nutrient resources, lack of governmental support and political instability have affected overall land productivity (Moyo, 2005). All these factors have further increased soil nutrient depletion, soil erosion and overall environmental degradation (FAO, 2006). Therefore, there is an urgent need to develop and apply suitable and reliable indicators of soil nutrient mining and land degradation at different scales (Hartemink, 2006a; Schlecht and Hiernaux, 2004). Furthermore, it is essential to determine spatial variability of soil resources for managing more efficiently small-scale farming systems, which are typically heterogeneous. Unfortunately, research on soil fertility management strategies has usually neglected variability of small-scale farming systems in Africa (Zingore, 2006), as well as the need for multi-scale analyses of agro-ecosystems since driving factors, processes and actors typically differ with the spatial scale (e.g. Veldkamp et al., 2001). Moreover, despite some studies addressing the socio-economic impacts of almost three decades of land reform in Zimbabwe on agriculture and natural resources management (e.g. Barr, 2004; Chimhowu and Hulme, 2006; Deininger et al., 2004; Kinsey, 2004; Moyo, 2005; Waeterloos and Rutherford, 2004), few studies have quantified these impacts from a biophysical perspective (Elliott et al., 2006). With this gap in scientific knowledge, this work is scientifically relevant as it addresses not only the divergences on soil nutrient management strategies by African small-scale farmers and in different settlement schemes in Zimbabwe, but also the challenges of spatial variability and spatial scale.

1.6. Hypotheses

The main hypotheses addressed in this thesis are:

a) African land use systems are threatened by soil nutrient mining,

b) Issues of scale and spatial variability strongly affect nutrient balances' estimations,

c) Investments in soil fertility by small-scale African farmers decrease across typologies (from rich to poorer farmers) and plot types (by increasing the distance from homestead),

d) Small-scale farmers in the fertile resettlement areas of Zimbabwe heavily rely on soil nutrient stocks and have higher crop yields compared to farmers in communal areas with lower crop production,

e) Linking MIRS to geostatistical analyses is a suitable and cost-effective approach for assessing soil spatial variability at landscape level.

1.7. Goal and objectives

The goal of this study was to develop new methodological approaches for better monitoring nutrient management and spatial variability of soils across different spatial scales in African agro-ecosystems, having various settlement schemes in Zimbabwe as a case study. The specific objectives were:

1) To evaluate the results of nutrient balances in different African land use systems, and to review some of the narrative on the topic (Chapter 2)
2) To determine the reliability of the nutrient balance approach as indicator of soil nutrient mining in Africa, with special emphasis on issues of scale and spatial variability (Chapter 2 and 3)
3) To investigate the effects of plot type (i.e. distance to homestead) and farmers' typologies (i.e. wealth class) on nutrient mining of African small-holder systems (Chapter 2 and 3)
4) To assess the impact of small-scale farmers' management on soil nutrient mining and land productivity across different settlement schemes (communal areas, and old and new resettlements) in Zimbabwe (Chapter 3)
5) To determine the feasibility of linking MIRS to spatial analysis (i.e. geostatistics) in the assessment of soil spatial variability at landscape level (Chapter 4).

1.8. Outline of the study

This study is based on two published papers (Chapters 2 and 3) and one paper in press (Chapter 4). Chapter 1 contextualizes this thesis, introduces the study sites and briefly describes the techniques used. Chapter 2 includes a literature review on nutrient balances in Africa to show main trends, illustrate methodological complexities related to the calculation of balances and issues of scale, and develop recommendations for future studies. Chapter 3 and 4 include original data collected at the study sites in Zimbabwe, during the 2006-7 cropping season. Chapter 3 contains a plot and farm level study on cropping strategies, soil fertility investment and land management practices by smallholder farmers in three settlement schemes. Chapter 4 presents a study at village level in which soils from the same three areas were sampled to determine the feasibility of integrating MIRS and geostatistics for the assessment of soil spatial variability at landscape level. The manuscript continues with a general discussion (Chapter 5) and a section of references (Chapter 6). Summaries (in English, German and Spanish) and appendixes (i.e. abstracts of additional articles published during the doctoral time frame, M.Sc. and B.Sc. thesis co-supervised and courses followed) finalize the manuscript.

CHAPTER 2

NUTRIENT BALANCES IN AFRICAN LAND USE SYSTEMS ACROSS DIFFERENT SPATIAL SCALES: A REVIEW OF APPROACHES, CHALLENGES AND PROGRESS

2. NUTRIENT BALANCES IN AFRICAN LAND USE SYSTEMS ACROSS DIFFERENT SPATIAL SCALES: A REVIEW OF APPROACHES, CHALLENGES AND PROGRESS[i]

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2.1. Abstract

Nutrient balances are useful tools as indicators of potential land degradation and for optimizing nutrient use, and are thus highly relevant in the African context. A comprehensive literature review on nutrient balances in Africa was carried out to illustrate the main approaches, challenges, and progress, with emphasis on issues of scale. The review showed nutrient balances being widely used across the continent. The collected dataset from 57 peer-reviewed studies indicated, however, that most of the balances were calculated at plot and farm scale, and generated in East Africa. Data confirmed the expected trend of negative balances in the continent for nitrogen and potassium, where >75% of selected studies had mean values below zero. For phosphorus only 56% of studies showed negative mean balances. Several cases with positive nutrient balances indicated that soil nutrient mining cannot be generalized across the continent. Land use systems of wealthier farmers mostly presented higher nitrogen and phosphorus balances than systems of poorer farmers ($p<0.001$). Plots located close to homesteads also usually presented higher balances than plots located relatively farther away ($p<0.05$). Partial nutrient balances were significantly higher ($p<0.001$)

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[i] **This chapter has been reprinted from:**
Cobo JG, Dercon G, Cadisch G (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agriculture, Ecosystem and Environment,* 136 (1-2): 1-15 (DOI:10.1016/j.agee.2009.11.006), with permission from Elsevier (Copyright © 2010). The original publication is available at http://www.sciencedirect.com/science/journal/01678809.

than full balances calculated for the same systems, but the later carried more uncertainties. The change in magnitude of nutrient balances from plot to continental level did not show any noticeable trend, which challenges prevailing assumptions that an increasingly negative trend exists. However, methodological differences made a proper inter-scale comparison of results difficult. Actually, the review illustrated the high diversity of methods used to calculate nutrient balances and highlighted the main pitfalls, especially when nutrient flows and balances were scaled-up. Major generic problems were the arbitrary inclusion/exclusion of flows from the calculations, short evaluation periods, and difficulties on setting of spatial-temporal boundaries, inclusion of lateral flows, and linking the balances to soil nutrient stocks. The need for properly describing the methods used and reporting the estimates (i.e. appropriate units and measure of variability and error) were also highlighted. Main challenges during scaling-up were related to the type of aggregation and internalization of nutrient flows, as well as issues of non-linearity, and spatial variability, resolution and extent, which have not been properly addressed yet. In fact, gathered information showed that despite some few initiatives, scaling-up methods are still incipient. Lastly, promising technologies and recommendations to deal with these challenges were presented to assist in future research on nutrient balances at different spatial scales in Africa and worldwide.

2.2. Key words

Aggregation; internalization; methodological differences; nutrient budgets; nutrient flows; nitrogen; phosphorus; potassium; spatial scales; scaling-up.

2.3. Introduction

Decline in soil fertility is one of the main constraints of agricultural productivity in Africa (Sanchez and Leakey, 1997; Stoorvogel and Smaling, 1998), since food production in the tropics and sub-tropics usually relies on available soil nutrient stocks (Sheldrick et al., 2002). Despite major efforts from research centers, NGOs, governments, farmers and their organizations, effective soil fertility management remains a major challenge in the continent (Onduru et al., 2007). Therefore, there is an increasing need of using reliable indicators of soil nutrient mining and related land degradation (Sheldrick and Lingard, 2004). According to Hartemink (2006a) soil fertility decline can be assessed via expert knowledge systems, the monitoring of soil chemical properties over time (chronosequences) or at different sites (biosequences), and the calculation of nutrient balances, with the last one being the most used and cost-efficient technique. Nutrient balances (also known as nutrient budgets) are computed by the difference between nutrient inputs and outputs of a system with predefined spatial-temporal boundaries (Bindraban et al., 2000). Thus, they are generally expressed in amount of nutrient(s) per unit of area and time (e.g. kg ha^{-1} yr^{-1}). Negative nutrient balances indicate that a system is losing nutrients; on the contrary, nutrients are apparently accumulating (and maybe leading to extended losses if strongly in excess). The main assumption with regards to the nutrient balance approach is that a system in severe or continuous disequilibria is not sustainable in the long term (Harris, 1998; Hartemink, 2006a; Smaling, 1993).

Nutrient balances have been used extensively for improving natural resource management and/or for policy recommendations over the last decades (De Jager, 2005; Defoer et al., 1998; Grote et al., 2005; Smaling and Braun, 1996; Smaling and Toulmin, 2000). However, caution must be taken due to the often uncritical interpretation of the results, as several methodological complexities and uncertainties exist with this approach (Bationo et al., 1998; Færge and Magid, 2004; Hartemink, 2006a; Scoones and Toulmin, 1998). For example, it has been pointed out that scaling-up[ii] nutrient balances in the spatial hierarchy can introduce bias and major errors in the results if flows are not properly extrapolated (Oenema and Heinen, 1999; Schlecht and Hiernaux, 2004). This is partially due to the fact that detailed data needed for the calculations (e.g. erosion losses, N_2-fixation, etc.) are generally based on small-scale experiments or observations at plot level (Sheldrick and Lingard, 2004).

The nutrient balance approach in Africa became relevant since the pioneering study of Stoorvogel and Smaling (1990), and the research is still on the agenda (e.g. Vitousek et al., 2009). However, regardless that the knowledge base on the topic has been increasing and some challenges have been recognized, information is fragmented and varies widely (Grote et al., 2005). Although some attempts have been made to integrate the information of nutrient balances in Africa (e.g. Bationo et al., 1998; Nandwa and Bekunda, 1998; Schlecht and Hiernaux, 2004; Smaling and Braun, 1996), these initiatives included just few case studies, and their assessments were usually restricted to particular regions (e.g. West Africa; East and Southern Africa). Moreover, despite early reports on highly negative nutrient balances across the continent heading to an environmental disaster (e.g. Smaling et al., 1993; Smaling et al., 1997; Stoorvogel and Smaling, 1990), more recent evidence has shown that nutrient balance calculations have been often inaccurate and respective results have been misinterpreted (e.g.

[ii] In this work, scaling-up is referred to space, not time

Færge and Magid, 2004; Muchena et al., 2005). As alternate solutions are still lacking, the original approach of Stoorvogel and Smaling (1990) is still currently being widely used (Lesschen et al., 2007). Therefore, improvements in the calculation and a proper interpretation and reporting of nutrient balances for its use as indicator of land degradation at different spatial scales are required. This paper intends to contribute to this goal by: a) integrating peer-reviewed information on nutrient balances in Africa, b) describing the state of the art on the topic based on this comprehensive literature review, c) determining main trends in the results on nutrient balances in Africa for corroborating or demystifying some of the narrative on the topic, d) identifying main methodological differences and limitations between studies, e) identifying pit-falls on scaling-up nutrient balances by using the compiled information, and f) deriving some recommendations for guiding future studies on nutrient balances at different scales. Although the spotlight is on Africa, principles and methodologies discussed here are not restrictive to this continent, and results are thus generically applicable.

2.4. Data retrieval criteria and analyses

Data on nutrient balances in African land use systems from studies published in peer-reviewed journals were selected as the population of interest for an objective analysis and comparison among results. The selection was based on a search in the Scopus database (www.scopus.com), which firstly, used as key words “soil” AND different synonyms (singular and plural forms) of "nutrient balances" or “nutrient flows”. Use of the word “soil” narrowed the search to studies assessing land use systems, as nutrient balances are also used in other disciplines (e.g. marine sciences, hydrology, molecular biology, etc.). Subsequently, “Africa” was added as a keyword. Next, “Africa” was sequentially replaced for each of the 53 African countries. Finally, results of previous phases were merged. This final exercise came up with 144 hits. However, after an initial revision 49 studies were excluded as they dealt with subjects beyond the scope of this study. From the remaining 95 studies, 57 reported original data on nutrient balances. Therefore, information regarding their objectives, study sites, methodological approaches, and experimental classificatory variables were tabulated for their characterization. Additionally, reported data on nutrient balances were extracted from the text, tables or figures, and classified by the scale(s) of evaluation and the type of study, as well as by the type of balances (partial or full balances), depending on the flows considered. Partial nutrient balances are the difference between the inflows to a system from mineral and organic fertilizers, and its respective outflows from harvested products and crop residues removed (see Chapter 3); while full nutrient balances include additionally environmental flows (i.e. inputs from wet/atmospheric deposition, nitrogen fixation and sedimentation; and outputs from leaching, gaseous losses, and soil erosion) (Haileslassie et al., 2005). Double data entry was avoided and the units for expressing nutrient balances were standardized when possible (i.e. kg ha^{-1} season^{-1} when only seasonal assessments were done; kg ha^{-1} yr^{-1} when the evaluation was carried out for one or more entire years). Once all data were organized, box-and-whisker plots were constructed for each study as well as for the main spatial scales of evaluation. This helped to understand the distribution of the data in each study and to visualize whether a trend on the magnitude of balances existed across the spatial hierarchy. Box-and-whisker plots displayed the interquartile range (box), the 90th and 10th percentiles (whiskers), outliers (circles) and the mean and median (thick and thin horizontal line inside the box, respectively). To determine differences within farmers' typologies (rich *versus* poor farmers) and within field types (classified according to the distance to homestead) corresponding data pairs per study, for the same system under evaluation (for making them comparable), were plotted against each other by using scatter plots. Thus, only the extreme levels in the categories (i.e. poor vs. rich farmers; closest fields vs. furthest ones) were included in the comparisons; while intermediate levels (e.g. medium wealth class; middle fields) were omitted. This assured a relative comparison between contrasting groups, since farmers' typologies and field types are known to be site and/or study-specific. Differences between the types of balances (partial versus full balances) were also illustrated in a similar way, but including only data from studies reporting both types of balances simultaneously for the same system under analysis. All comparisons were further tested for statistical significance by carrying out paired t-tests for related samples according to Cody and Smith (1997). Box-and-whiskers plots and the t-tests were performed in SAS version 8 (SAS Institute Inc., 1999). Additionally to the peer-reviewed studies selected in Scopus, any other source of publication worldwide was used for the discussion of results.

2.5. Results and discussion

2.5.1. Nutrient balances in Africa

The present review confirms that nutrient balances have been widely used as indicators of soil nutrient mining in Africa. The overview presented in Table 2.1, however suggests that it has been in Kenya where most of the research on nutrient balances has been carried out (19 out of 57 studies), which is above two times more than in the succeeding countries, Ethiopia, Mali and Uganda. Most of the studies (42 out of 57) have been carried out for assessing the condition of different agroecosystems, but nutrient balances have been also calculated from experimental plots (13 studies) and after scenario simulations (8 studies). Nearly all studies (55 out of 57) assessed nitrogen (N) balances, while phosphorus (P) and potassium (K) balances received less attention (Table 2.1). Few studies (7) dealt with calcium and magnesium, and only four considered carbon (data not shown).

Table 2.1. Main methodological characteristics of selected nutrient balance studies in Africa (n=57). Data show the number and proportion of studies per each category.

Characteristic	Number of studies	% of studies
Country where balances were calculated[⊗]		
Kenya	19	33
Ethiopia	8	14
Mali	7	12
Uganda	6	11
Study type		
Agroecosystem assessment	42	74
Experiment	13	23
Scenario/simulation	8	14
Nutrients for which balances were calculated[⊗]		
N	55	96
P	47	82
K	36	63
Units in which balances were originally expressed[@]		
kg ha^{-1} yr^{-1}	30	53
kg ha^{-1}	24	42
kg ha^{-1} season^{-1}	3	5
Other (e.g. kg farm^{-1}, kg plot^{-1})	6	12
Type of balances reported[#]		
Full	39	68
Partial	31	54
Was variability of balances shown?		
No	45	79
Yes	12	21
Time frame of the study[⊗]		
1 year	23	40
1 season	11	19
2 years	8	14
Were balances linked to soil nutrient stocks?		
No	23	41
Yes	23	40
Not directly	11	19

[⊗] Although additional categories existed for these characteristics only the top options are shown

[@] In original tables or figures (before conversion)

[#] Even when few additional flows were included or excluded from the calculations, balances were still classified as partial or full by approximation.

Nutrient balances were mainly expressed in kg ha^{-1} yr^{-1} (53% of studies) or in kg ha^{-1} (42% of studies), but were also presented in kg ha^{-1} $season^{-1}$, in amount of nutrient per system (e.g. kg $farm^{-1}$) or nutrient per system per unit of time (e.g. kg $farm^{-1}$ yr^{-1}) (Table 2.1). This depended mainly on the spatial-temporal boundaries of the study and their specific objectives. For the purposes of this study, however, units of balances were uniformized where possible (e.g. kg ha^{-1} per year or season), as previously mentioned.

Nutrient balance results from all 57 selected studies, irrespective of the type of balances, spatial scale, and units (Figure 2.1), indicated that most systems had negative N and K balances (i.e. 85 and 76% of studies showed negative means, respectively). For P the trend was less noteworthy (i.e. only 56% of studies presented means below zero). These observations are broadly consistent with the general claim of nutrient mining across the continent (e.g. Hartemink, 2006a; Sanchez and Leakey, 1997; Smaling et al., 1996; Smaling et al., 1999a), at least for N and K. As input use in Africa is the lowest in the world (Bayu et al., 2005; Muchena et al., 2005; Nandwa and Bekunda, 1998; Place et al., 2003), soil nutrient balances are often negative (Bationo et al., 1998; De Jager, 2005; Scoones and Toulmin, 1998; Wortmann and Kaizzi, 1998). This situation can be critical in regions where land users are extensively mining soil resources for their livelihoods. For example, according to Nkonya et al. (2005) and Esilaba et al. (2005) between 95-100% of studied farmers in Eastern Uganda were soil miners. Based on nutrient balances results and associated socio-economical information De Jager et al. (1998b) and van der Pol and Traore (1993) calculated for Kenya and Mali, respectively, that 30-40% of farm income came from soil mining. De Jager et al. (2001) even argued that this proportion for subsistence-oriented farmers in Kenya is as high as 60-80%.

Despite the overall negative trend on nutrient balances in Africa, positive balances could also be found on the continent. This is evidenced in Figure 2.1, especially for P, and where mean values from 44, 24 and 15% of the studies (for P, N and K, respectively) were above zero; as well as in all positive observations from many of the studies. In fact, land use systems of wealthier farmers usually had higher nutrient balances than respective systems from poorer farmers (i.e. 52 cases out of 67 for N; 51 cases out of 52 for P) (Figure 2.2A). This is usually explained by the extended possibilities (in terms of cash, labor, livestock) of wealthier farmers for investing in soil fertility (Chapter 3), sometimes at the expense of poorer farmers (Zingore et al., 2007). In a similar way, fields near to the homestead (infields) usually

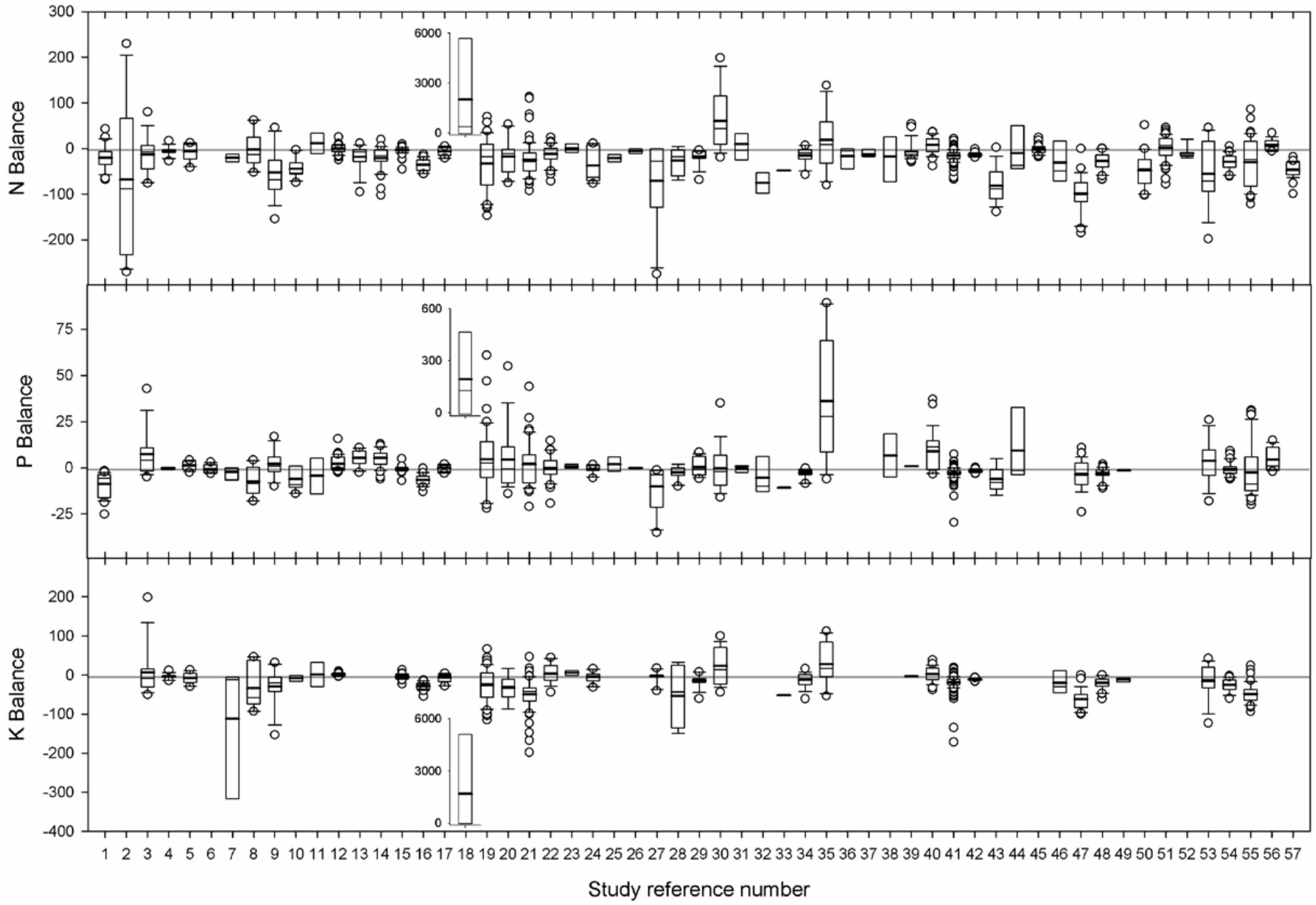

Figure 2.1. Box-and-whiskers plots of reported nutrient balances from 57 peer-reviewed studies in Africa, irrespective of the type of balances. Balances are expressed in kg ha^{-1} yr^{-1} with the exception of studies no. 23 and 25 (kg ha^{-1}), and 14, 15, 17, 28, 34, 35, 39, 40, 45, 50, 51 and 52 (kg ha^{-1} season^{-1}). Study no. 18 was out of the range and is presented with its own y-axis. See study reference numbers' description in next page.

Figure 2.1. Study reference numbers: 1: Adu-Gyamfi et al., 2007, 2: Akonde et al., 1997, 3: Baijukya and De Steenhuijsen, 1998, 4: Baijukya et al., 2005, 5: Bekunda and Manzi, 2003, 6: Bontkes and Van Keulen, 2003, 7: Brand and Pfund, 1998, 8: Carsky and Toukourou, 2005, 9: De Jager et al., 1998b, 10: De Jager et al., 2001, 11: Defoer et al., 1998, 12: Dougill et al., 2002, 13: Elias and Scoones, 1999, 14: Elias et al., 1998, 15: Esilaba et al., 2005, 16: Folmer et al., 1998, 17: Gachimbi et al., 2005, 18: Graefe et al., 2008, 19: Haileslassie et al., 2005, 20: Haileslassie et al., 2006, 21: Haileslassie et al., 2007, 22: Harris, 1998, 23: Harris, 1999, 24: Kanmegne et al., 2006, 25: Kanyama-Phiri et al., 1998, 26: Krogh, 1997, 27: Laclau et al., 2005, 28: Lehmann et al., 1999, 29: Lesschen et al., 2007, 30: Lupwayi and Haque, 1999, 31: Manlay et al., 2004b, 32: Mathuva et al., 1998, 33: Nkonya et al., 2005, 34: Onduru and Du Preez, 2007, 35: Onduru et al., 2007 (Napier data omitted), 36: Poss and Saragoni, 1992, 37: Powell et al., 1996, 38: Radersma et al., 2004, 39: Ramisch, 2005, 40: Saïdou et al., 2003, 41: Sheldrick and Lingard, 2004, 42: Sheldrick et al., 2002, 43: Shepherd et al., 1996, 44: Shepherd and Soule, 1998, 45: Singh et al., 2003, 46: Smaling and Fresco, 1993, 47: Smaling et al., 1993, 48: Stoorvogel et al., 1993, 49: Stoorvogel et al., 1997a, 50: Tittonell et al., 2005, 51: Tittonell et al., 2006, 52: Tittonell et al., 2007, 53: Van den Bosch et al., 1998, 54: van der Pol and Traore, 1993, 55: Wortmann and Kaizzi, 1998, 56: Zingore et al., 2007, 57: Zougmore et al., 2004.

had higher nutrient balances than plots of same farmers located relatively further away (outfields) (43 cases out of 48 for N, 11 cases out of 14 for P) (Figure 2.2B), as farmers frequently allocate their resources and effort to the closest fields (Tittonell et al., 2007). These situations, however, are not always the case (e.g. data pairs below the 1:1 line in Figure 2.2), as differences within wealth classes and within field types are usually dependent on the crop grown, field/farm size and the related particular soil management practices, among other factors (Elias and Scoones, 1999; Haileslassie et al., 2007; Ramisch, 2005). An extreme case of positive balances is reported by Graefe et al. (2008) for urban and peri-urban gardens in Niger, where the use of nutrient-loaded wastewater for irrigation increased N, P and K partial balances up to excessive levels of +7.3, +0.5 and +6.8 Mg ha^{-1} yr^{-1}, respectively, indicating high pollution risks. Cases showing positive nutrient balances are an indication that some farmers, in a conducing environment (as exemplified before), have managed to overcome soil degradation by adapting existing resources and technologies to challenging situations (De Jager, 2005). Moreover, these examples support the premise of other researchers (e.g. De Ridder et al., 2004; Mortimore and Harris, 2005; Muchena et al., 2005; Vanlauwe and Giller, 2006) that the simple narrative of African soil fertility being universally in danger is, in reality, more complex and therefore must be re-analyzed and treated with more caution.

2.5.2. Methodological approaches and limitations

Basically, most of the work done on nutrient balances in Africa has followed the approach of Stoorvogel and Smaling (1990), in which five major inputs (mineral fertilizers, organic fertilizers, wet and dry deposition, nitrogen fixation and sedimentation) and five major

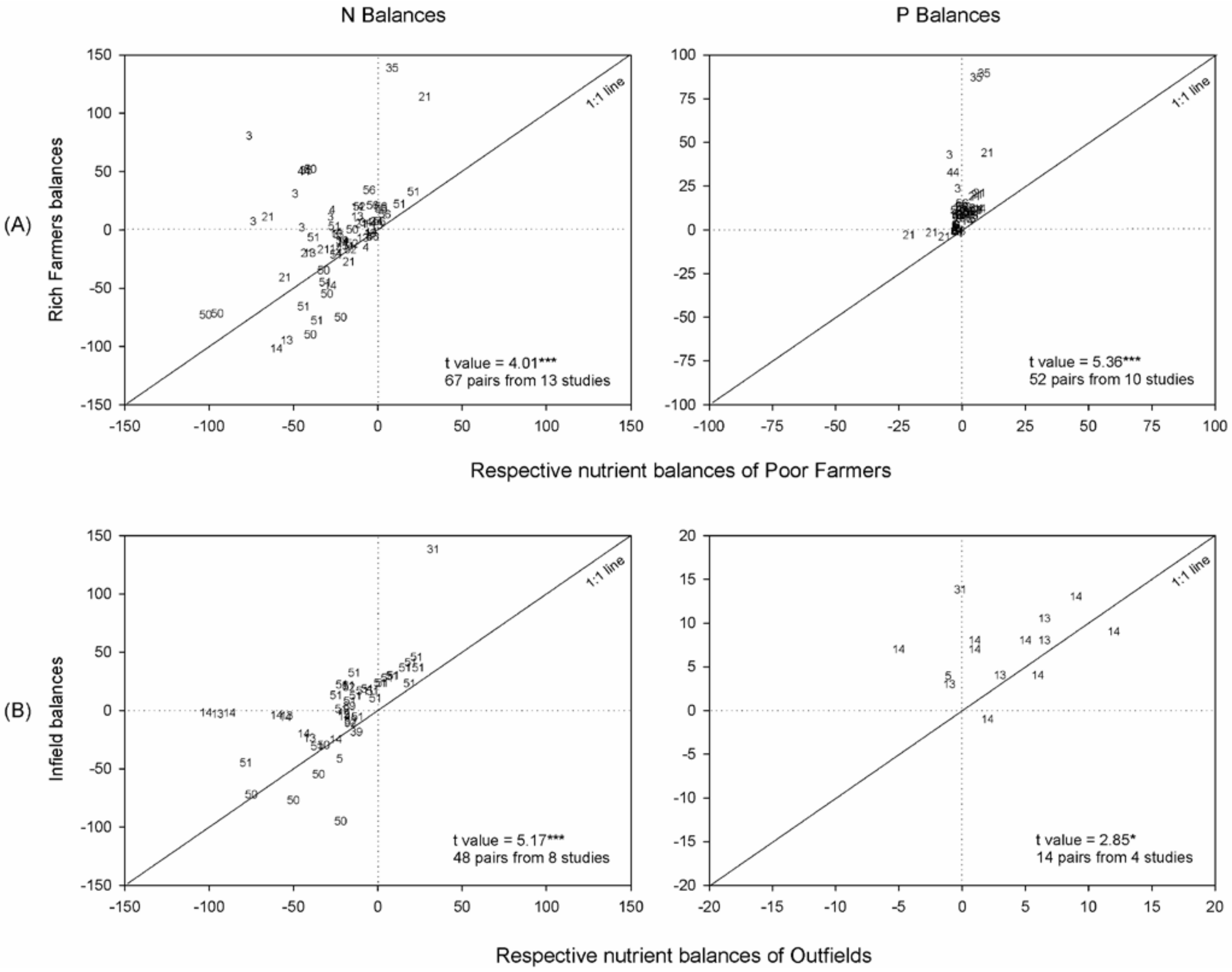

Figure 2.2. Comparisons within (A) farmers' resource endowment (rich *versus* poor farmers) and (B) within field types (infields *versus* outfields) for N and P balances (in kg ha^{-1} yr^{-1} or kg ha^{-1} season^{-1}) from different studies in Africa. For the comparisons to be valid, only data pairs per study, for the same system under evaluation, were plotted against each other. Results of the paired t-test for related samples are shown (*** : *p*<0.001, * : *p*<0.05). All data pairs are represented by its study's reference number according to Figure 2.1.

outputs (harvested crops, crop residues removed, leaching, gaseous losses and soil erosion) have been considered. As several of these fluxes are difficult to measure (e.g. leaching, erosion), transfer functions are commonly used (Bindraban et al., 2000; Lesschen et al., 2007; Smaling and Fresco, 1993; Stoorvogel, 1998). Transfer functions, however, are only approximations as site-specific conditions are not correctly applied in many cases and resulting estimates are rarely checked against field measurements (Færge and Magid, 2004; Hartemink, 2006a). In fact, from the 57 studies evaluated, 39 studies worked with full balances, while 31 studies estimated partial balances (Table 2.1). Partial balances only consider flows 'easy' to measure or estimate (FAO, 2004; Smaling and Toulmin, 2000), like inputs from mineral and organic fertilizers, and outputs from crop yields and residues. A partial balance approach permits to better discuss with farmers the potential implications of the results, as considered flows are 'visible' and 'easily managed' by farmers (Defoer et al., 1998). However, a shortcoming of partial balances is that excluded flows (e.g. N fixation, erosion) could have a high relative importance, especially in low external input agriculture (Janssen, 1999). Differences between partial and full nutrient balances were evident once both types of balances for the same land use systems were compared (Figure 2.3). This comparison showed that partial balance estimates were significantly higher than their respective full balances (t values: 4.1 to 9.3, $p<0.001$), especially for N and K (89 and 99% of the cases, respectively); while for P this was less remarkable (only 66% of the cases were higher). This is possibly due to the fact that P is less mobile in soils than N and K, making it less susceptible to losses (e.g. leaching). The difference between partial and full balances clearly suggests that both types of balances must be treated separately, as they are simply different indicators. Therefore, they must be discussed accordingly, but this basic distinction is sometimes not explicitly stated in the literature.

Even when a specific type of balances (full or partial) is chosen, some authors often decide arbitrary to include or exclude some flows, or estimate them differently. For example, both Nkonya et al. (2005) and Wortmann and Kaizzi (1998) calculated full balances for farming systems in eastern Uganda. However, while the first study considered all flows, the second study excluded sedimentation, despite it being a substantial process in the system. Additionally, Nkonya et al. (2005) estimated most flows by transfer functions, while Wortmann and Kaizzi (1998) estimated leaching, volatilization, and denitrification by the CERES-maize model. Flows rarely considered in the computation of nutrient balances are inputs by livestock urine (FAO, 2003), inputs from seeds (Hartemink, 1997) and nutrient

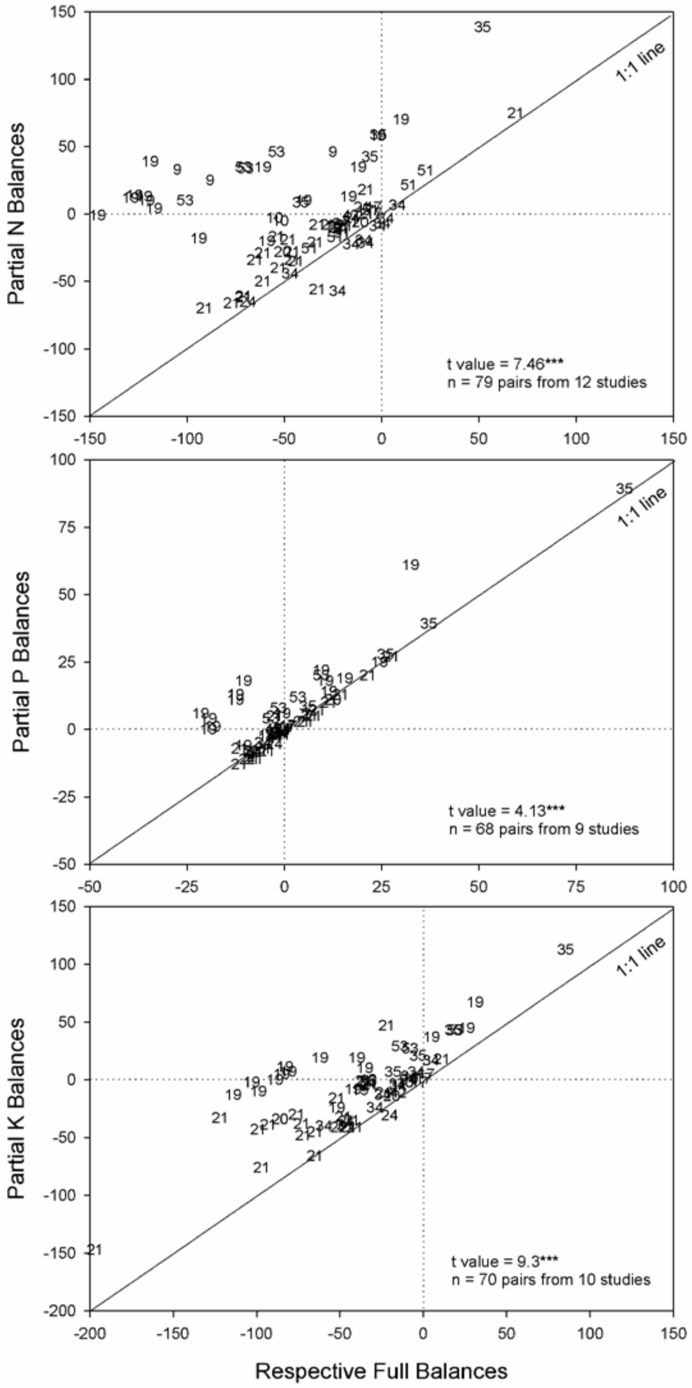

Figure 2.3. Comparison between partial and full balances (in kg ha^{-1} yr^{-1} or kg ha^{-1} $season^{-1}$) for studies in Africa reporting both types of balances simultaneously for the same system under evaluation. Results of the paired t-test for related samples are shown (*** : $p<0.001$). All data pairs are represented by its study's reference number according to Figure 2.1.

losses and deposition by wind erosion (Visser and Sterk, 2007; Visser et al., 2005), with the last one being a considerable scale-dependent flow in semi-arid areas (Stoorvogel et al., 1997b; Warren, 2007). At large spatial scales, processes like river-basin sediment transport and forest burning are rarely considered (FAO, 2003). Of prime importance is the inclusion of livestock-related nutrient flows, especially in integrated crop-livestock systems, as manure is an essential nutrient source in Africa (Harris, 1999; Harris, 2002; Sheldrick et al., 2003). However, the fact that in Africa most livestock graze not only in communal areas but also inside cropping lands after harvest, together with a varied management of the animals and manure, complicates the estimations (Oenema and Heinen, 1999; Schlecht and Hiernaux, 2004).

Significant variation between nutrient balances can also be the result of using different methods for field sampling, sample handling and storage, laboratory analysis, and/or interpretation of results (Hartemink, 2006a; Hartemink, 2006b; Oenema and Heinen, 1999). Thus, once all these errors are aggregated, nutrient balances may show a high variability. However, studies on nutrient balances seldom report the variations on the estimates (i.e. only 21% of selected studies included a measure of variability, Table 2.1), thus assessment of their accuracy is not feasible. This is undesirable, because a balance of, e.g., -12 ± 4 kg ha^{-1} yr^{-1} has a very different connotation that one of -12 ± 20 kg ha^{-1} yr^{-1}; and a value of just -12 kg ha^{-1} yr^{-1} simply lacks information. Uncertainty analysis would allow better determining the errors in the estimations due to the variability in input data (Oenema and Heinen, 1999). However, this type of analysis is “severely hampered by difficulties in the assessment of input and model error” (Heuvelink, 1998), which are difficult to properly address in practice (e.g. see Lesschen et al., 2007), but nevertheless needs more attention in future studies.

The time period chosen by the researcher can be considered a source of variation and error too, as once a time window is fixed, some biophysical and socio-economical processes can be excluded from the time boundary, even when they are substantial. This would be the case of residual effects of manures and crop rotations, long-term soil organic carbon cycling, and livestock reproduction cycles (Schlecht and Hiernaux, 2004). Considering all these factors, plus the effects of climate, migration, and availability of resources within the farm (i.e. cash and labor), variation among different years and even between cropping seasons is expected. For example, Esilaba et al. (2005) found significant differences among five cropping seasons, where N balances results from the long season were up to nearly two-fold more negative than those found during the short season. This is why ‘snap-shots’ assessing only one period of study are considered limited, especially when long-term dynamic processes require to be understood (Scoones and Toulmin, 1998; Sheldrick and Lingard, 2004). However, studies considering more than two years are few, being 1 year or 1 season the most frequent periods of evaluation (see Table 2.1). Moreover, dry season effects on balances are seldom included. Future nutrient balance studies should thus pay more attention to long-term assessments to be able to address the basic assumption of this approach regarding sustainability of systems.

Issues related to the spatial extent and heterogeneity of the system under evaluation, and the resolution of the assessment, are also aspects of relevance. Sometimes system boundaries can be easily delimited, like in the case of a plot or a farm, as they usually have very defined borders; but in others instances it is more difficult. This was illustrated by Manlay et al. (2004b) when realizing the area of their villages did not always match the area exploited by their residents. In some cases the system boundary can be used as the basic spatial unit where flows are quantified, like in the case of “farm gate” balances; while in other approaches the quantification of flows takes place on system compartments (i.e. plots, administrative units or grids) which can be aggregated afterwards (Oenema and Heinen, 1999). Spatial variability is also critical, as complete homogeneity is assumed inside spatial boundaries or units, which is often not the case in reality (Scoones and Toulmin, 1998; Smaling et al., 1997). Moreover, lateral flows between contiguous units could occur, inducing synergies or antagonisms to the system (interactions) which only by the sum of the individual units is not possible to detect (van Noordwijk, 1999). All these issues are of additional and crucial relevance when flows and balances need to be scaled-up, as will be discussed further below.

Even if measurements and calculations are correct, nutrient balances alone are not sufficient as indicators of land degradation. Negative balances, for example, do not directly imply an immediate decline in crop production as nutrient-rich soils (those with high soil nutrient stocks) can still support continued cultivation for several years (Stoorvogel and Smaling, 1998; Vanlauwe and Giller, 2006). Hence, the dynamics of soil fertility decline (i.e. nutrient mining) or recovery (i.e. nutrient accumulation) would be better estimated as a rate of change (proportion) of the total soil nutrient stocks (Bindraban et al., 2000). Unfortunately, the number of studies that link nutrient balances to soil nutrient stocks are limited (i.e. 23 studies out of 57, Table 2.1). In fact, not always do soil fertility studies include measurements of soil bulk density, which are necessary to express nutrient stocks in the same units that balances are calculated (Hartemink, 2006a); and when included usually different soil depths are considered for the calculations (Schlecht and Hiernaux, 2004). In any case, an accurate determination of soil nutrient pools is very difficult to achieve due to the dynamic and stochastic characteristics of soil system processes (Singh et al., 2001; van Noordwijk, 1999).

Table 2.2. Methodological issues related to the scale of the study and scaling-up from selected nutrient balance studies in Africa (n=57). Data show the number and proportion of studies per each category.

Characteristic	Number of studies	% of studies
Main spatial scales where balances have been calculated		
Plot	30	53
Farm	22	39
Village / Watershed	7	12
District / Regional	6	11
National	6	11
Continental	3	5
Were flows/balances scaled-up?		
Yes	36	63
No	21	37
Specification of scaling-up methods?[&]		
Yes	20	56
No or not clear	16	44

[&] From those studies that scaled-up flows and balances

2.5.3. Nutrient balances at different spatial scales

Nutrient balances for Africa, as well as worldwide, have been calculated at different spatial scales, ranging from plot to continental level. Most of the assessments, however, have been carried out at plot and farm level (i.e. 53 and 39% of studies, respectively); while only 12, 11, 11 and 5% of studies have been done at village/watershed, region/district, nation, and continental level, respectively (Table 2.2). Whereas the number of studies at plot and farm level was similar for partial and full balances, full balances studies dominated (two-to-five times) at higher scales (data not shown). In any case, nutrient balances are usually grouped (e.g. by crop type, wealth class) according to the specific objectives of each study (see Table 2.3). Differences in nutrient balances among systems, system components, sites and seasons can be attributed to a great diversity of factors, which typically depend on the spatial scale of the study. Based on the hierarchy theory in ecology (O'Neill et al., 1991), lower spatial scales are mainly dominated by natural processes acting at plant level, and climate and geomorphology usually dominate higher spatial scales (Veldkamp et al., 2001). Nevertheless, social, cultural, economical, and political conditions are also important drivers of variation in

Table 2.3. Examples of different spatial scales and sub-levels at which nutrient balances studies in Africa have been carried out.

Scale or sub-level*	Description of the scale or sub-level	Study used as example	Units of analyses
Plot (field)	Different plots in a farm	Harris, 1998	Field_1, field_2… field_n
Plot types	Grouping of plots according to a common feature	Tittonell et al., 2007	Infields vs. outfields
Crop (primary production unit, land use type)	A crop or crop activity consisting of one or more crops grown deliberately	Baijukya et al., 2005	Maize, potato, cassava
Production systems (activity level, farm-subsystems)	Grouping of units within farm according to production objectives or farming activities	Esilaba et al., 2005	Crop production system, animal production system, household
Farm (household)	Different farms in a village or region	Bekunda and Manzi, 2003	Farm_1, farm_2… farm_n
Farm typologies (wealth class, soil fertility managers)	Stratification of households by biophysical and/or socio-economical conditions	Zingore et al., 2007	Very rich, rich, poor, very poor farmers
Farm management system (farming system)	Grouping of farms or areas under same farming systems	Haileslassie et al., 2006	Enset system, teff system
Village (community)	One or several villages in a region	Manlay et al., 2004a	Sare Yorobana village (Senegal)
Watershed, Catchment	One or several watershed or catchment in a region	Kanyama-Phiri et al., 1998	Songani Watershed (Malawi)
Land cover	Different land covers in a district or region	Powell et al., 1996	Rangelands, Croplands
District, Region	One or several districts or regions in a nation	Smaling et al., 1993	Kisii District, Southwestern Kenya
Production system, Land use system	Stratification of areas by crop inside units of similar cropping systems and use intensity	Folmer et al., 1998	Maize in Small or large scale rain-fed or irrigated farming
Crop type (cropping systems)	Grouping of crops within farm according to a common feature	Haileslassie et al., 2005	Permanent crops, vegetables, pulses, oil crops, cereals
Land water class, Agro-ecological zone	Stratification of areas by units of similar production potential	Stoorvogel et al., 1993	(Rain-fed, flooded, irrigated land) x (high, medium, low soil fertility)
Nation (country)	One or several countries	Sheldrick and Lingard, 2004	All countries in Africa
Sub-continent	A specific area or region inside a continent	Stoorvogel et al., 1993	Sub-Saharan Africa
Continent	A continent as a whole	Sheldrick et al., 2002	Africa

* Some synonyms are included in brackets as terminology occasionally differs according to the source and is even used for different scales

nutrient flows and balances at different scales (e.g. De Jager, 2005). For example, differences in nutrient balances between plot and farm types are usually associated not only to landscape position and specific soil fertility management practices (Haileslassie et al., 2007), but also to farmers' wealth class and even land tenure (Chapter 3). However, these factors may have less influence at a regional scale where main soil types, access to markets and climate are usually more influential (Haileslassie et al., 2007). At large scales, policy is usually a dominant force (e.g. Urban, 2005). Policy, however, can influence a wide variety of other factors, from specific soil fertility management practices to markets and institutional conditions (De Jager, 2005), thereby having significant impact across the whole spatial hierarchy. In fact, most factors affecting environmental processes usually operate at several spatial scales (Heuvelink, 1998); but then, they usually act differently at each spatial level (Veldkamp et al., 2001).

Table 2.4. Potential objectives, users, resolution accuracy, and units of nutrient balance studies across main spatial scales. Modified from Bindraban et al. (2000) and Stoorvogel (1998).

Spatial scale	Objectives of the assessment	Main users	Level of accuracy*	Balances should be also expressed as&:
Plot	Testing new soil fertility management practices; improving nutrient use efficiencies	Farmers	High	Fertilizer equivalents
Farm	Developing more sustainable production systems; improving allocation of nutrient resources	Farmers	High	Fertilizer equivalents
Village	Discussions around sustainability of agricultural production systems and communal areas	Community, local organizations	Medium	Fertilizer equivalents and yield loss
Region	Identification of target areas for intervention (research and/or development); incentives	Local government and institutions	Low	Qualitative classes, but also in terms of yield loss and monetary values
Nation	Accounting exercises; national nutrient budgeting; scenario studies linked to policy and markets	National institutions and policy makers	Low	Qualitative classes, but also in terms of yield loss and monetary values
Continent	Creating awareness, global environmental assessments	International institutions and policy makers	Very low	Broad qualitative classes

*Under similar availability of resources and same time period.

&Balances at all spatial scales must be reported as kg ha^{-1} yr^{-1}, kg ha^{-1} season^{-1} or kg per system (e.g. farm, country) per year or season, depending of the objective of the study, together with their respective deviation or error.

Having different spatial scales of evaluation for nutrient balance studies actually allows scientist to achieve diverse objectives as well as to reach different users (Bindraban et al., 2000; Stoorvogel, 1998). For example, nutrient balances from plot to farm level can be carried out for improving soil fertility management and nutrient use, and targeted to farmers as it is at these levels that they operate (Table 2.4). Balances at national and continental levels, on the other hand, can be carried out for performing national and global budgeting to guide decision- and policy making on agricultural sustainability and environmental protection issues. Likewise, units on which nutrient balances are expressed can be used differentially across the spatial hierarchy to match knowledge and preferences of potential users. For instance, while most farmers would prefer nutrient balances expressed in terms of fertilizer equivalents than corresponding estimates expressed as, e.g., kg ha^{-1} yr^{-1}, policy makers would find them more influential in terms of yield loss and monetary values (Lesschen et al., 2007). All this means that it would be simply impossible to conceive a generic optimal spatial scale for nutrient balances studies (Haileslassie et al., 2007); although optimum spatial scales for different objectives and users could be proposed (e.g. Table 2.4).

Given the limited number of studies at scales higher than the farm (Table 2.2), and considering methodological differences, we refrained from a detailed comparison of results between scales, but plotted the data from only those studies that assessed full balances and which results could be expressed in kg ha^{-1} yr^{-1} to look for a noticeable trend (Figure 2.4). A similar exercise using partial balances could not be performed due to the limited number of observations per category at higher spatial levels. The data did not reveal a major trend in the magnitude of N, P and K balances by increasing the spatial scale from plot to continental level. This is in apparent contradiction to Haileslassie et al. (2007), Schlecht and Hiernaux (2004), and Onduru and Du Preez (2007) who claimed a trend of highly negative nutrient balances with increasing scale of observation; although their statements were based on a limited number of cases only. Even though our sample size is relatively larger and coherent in the type of balances and units, a limitation of results in Figure 2.4 is that the diversity of systems assessed and the inclusion of sub-levels within main scales could increase variability. Therefore, evidence seems inconclusive, and new studies aiming to validate the impacts of spatial scale on nutrient balance estimations are required. Possibly the only way to perform a rigid comparison would be if the same methodology is applied at each different scale and carried out under the same biophysical and socio-economical conditions. However, in practice this would be difficult as the input data for nutrient balances studies, as well as the data collection strategy, strongly depend on the scale of evaluation, available resources and the location, hence calculations of nutrient balances usually vary accordingly (Bindraban et al., 2000; FAO, 2003; FAO, 2004; Scoones and Toulmin, 1998).

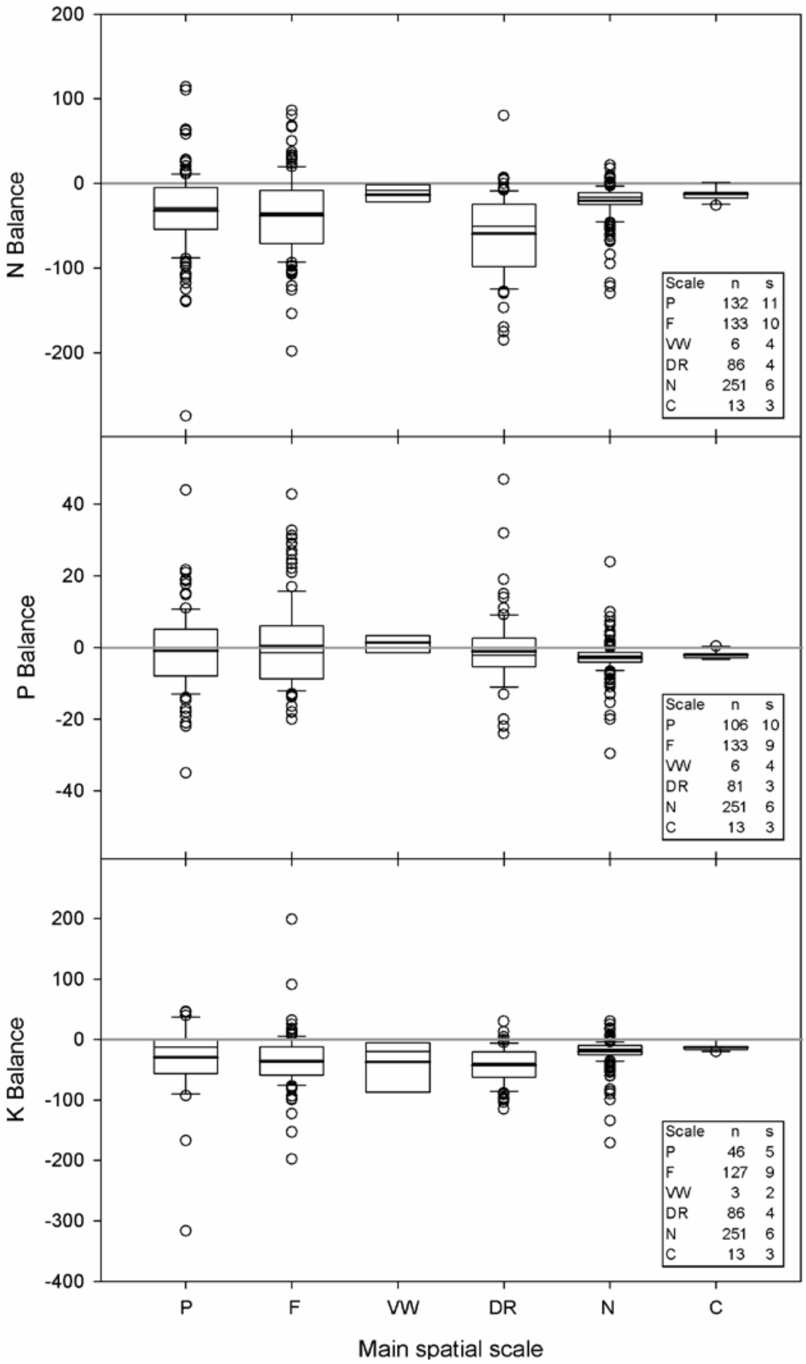

Figure 2.4. Nutrient balances at main spatial scales from different studies in Africa (P: plot, F: farm, VW: village & watershed, DR: district & region, N: nation, C: continent). Only data expressed as kg ha^{-1} yr^{-1} and derived from full nutrient balances studies were plotted for the comparison. Number of observations (n) and studies (s) per category are shown in the rectangles.

2.5.4. Scaling-up challenges

The issue of scale takes even greater relevance when nutrient flows and balances are scaled-up. A problem with scaling-up is that the bulk of understanding of biological processes and its dynamics usually resides at lower scales (Urban, 2005). In fact, soil nutrient balances at any scale usually depend on plot scale measurements, as this is the lowest level where most of the flows are based or determined (Stoorvogel and Smaling, 1998). Thus, great attention must be paid to the way flows are extrapolated, as different procedures can be used which may lead to loss of information and/or to bias in the results (Oenema and Heinen, 1999; Scoones and Toulmin, 1998).

Aggregation can be carried out as a linear function of the components or based on non-linear functions, depending on the interactions among system components, like in the case of substantial lateral fluxes, as explained previously (Dalgaard et al., 2003; van Noordwijk, 1999). The internalization of flows (which refers to their qualification as internal to a system at a specific spatial scale) is also a critical factor, as once a flow is internalized, it would be not considered or considered only partially in the nutrient balance calculation (Schlecht and Hiernaux, 2004; Smaling and Dixon, 2006). For example (Table 2.5), organic fertilizers are a net input to the plots; but if the organic inputs have been produced within the farm (e.g. by composting crop residues) these flows should be internalized in a farm gate level approach. A similar effect would happen for crop products. While all yields go out of the plot at plot scale, home consumption must be accounted for at the farm level, so this flow must be partially internalized. Therefore, the higher the scale where boundaries are established, the more likely a flow must be internalized (Table 2.5). Hence, different types of aggregation and internalization would produce different results, and this is usually a function of the degree of heterogeneity and resolution of the system under analysis and the process in consideration (Heuvelink, 1998; van Noordwijk, 1999). Unfortunately, but expected, aggregation and internalization of flows can mask important differences within the lower levels (Haileslassie et al., 2007), as up-scaling and loss of information are closely connected (FAO, 2003; van der Hoek and Bouwman, 1999). In fact, by decreasing the resolution of assessment and increasing its extent, the identification of key processes and factors usually turns more difficult (Kok and Veldkamp, 2001). Moreover, as system heterogeneity and complexity increase with scale, precision and accuracy of nutrient balances calculations usually decrease (FAO, 2003; Stoorvogel and Smaling, 1998).

Table 2.5. Internalization of main nutrient flows during their scaling-up by using the main scale as the system boundary. The type of internalization (N: none, P: partial, T: total) in some cases would depend on the specific characteristics of the system under study.

	Main spatial scale						
Flow description	Plot	Farm	Village	Region	Nation	Continent	Global
Mineral fertilizer	N	N	N	N	P	P/T	T
Organic fertilizer	N	N/P	N/P/T	P/T	T	T	T
Purchased food and feed	N	N	P/T	P/T	P/T	P/T	T
External grazing	N	N/P	P/T	P/T	T	T	T
Wet and dry deposition	N	N	N	N	N	N/P	T
N fixation	N	N	N	N	N	N	T
Sedimentation	N/P	P	P	P/T	P/T	P/T	T
Crop products	N	P	P	P/T	P/T	P/T	T
Animal products	N	P	P	P/T	P/T	P/T	T
Crop residues	N	P	P/T	T	T	T	T
Grazing	N	P/T	P/T	P/T	T	T	T
Leaching	N	N	N	N	N	N	T
Gaseous losses	N	N	N	N	N	N	T
Soil erosion	N/P	P	P	P/T	P/T	P/T	T

Then, how to properly extrapolate nutrient flows and balances across the spatial hierarchy? Unfortunately, the answer is not straightforward, as scaling-up is still a big challenge not only in nutrient balance studies, but also in many other disciplines as well (Dalgaard et al., 2003; Urban, 2005). Current approaches, challenges and progresses, however, could be identified by analyzing some contemporary case studies in the literature. Undesirably, not all studies properly report the methods used during the scaling-up process (Table 2.2), which clearly limit the analysis. It is also important to notice that no author has used the same input data type in a multi-scale study across the spatial hierarchy, which would be ideal for a proper analysis of results and factors during the scaling-up process. This issue is clearly demonstrated in van der Hoek and Bouwman (1999), Bekunda and Manzi (2003), FAO (2004) and Haileslassie et al. (2006; 2007; 2005). At smaller scales data are usually gathered through measurements, while at larger scales most data are typically obtained from information already aggregated, such as maps, agricultural statistics, and national and international databases (De Jager et al., 1998a; Heuvelink, 1998). Thus, information is usually found for scaling-up exercises comprising only few (1-2) levels. Scaling-up is evidently more difficult when several scales are included. Three main approaches, therefore, could be broadly distinguished according to the scaling-up procedures carried out in practice, as outlined as follows:

2.5.4.1. Scaling-up to the farm or village/watershed level

Scaling-up to the farm level has been carried out frequently in Africa (Table 2.2). For example, Zingore et al. (2007), estimated farm level balances by taking “the difference between total nutrient inputs and total outputs from all plots on a farm” and later dividing it by the total area, where “direct movements of nutrients between plots were considered as internal”. In fact, farm scale balances are mostly carried out by direct measurements or estimations of flows from the plots or administrative units from which the farm is composed, which is followed by a linear aggregation of data (internal flows excluded). Although the method is quite straightforward and typically used by most of the studies in Africa, a major problem is the existence of non-linear effects due to the high level of interacting flows among plots and other farm components (Stoorvogel and Smaling, 1998); which is usually more noteworthy on farms with several plots and which are highly diversified (Haileslassie et al., 2007). Choosing the basic spatial unit to be used in the study (plot or administrative unit) is also important, as this would affect the internal variability within units, as well as the amount of local interactions (van Noordwijk, 1999). Including non-linear effects in the calculations, however, would require detailed information of related fundamental processes within the farm (e.g. Dalgaard et al., 2003). Modeling and spatial statistics (see section 3.5) could help overcome this problem. In any case, a proper internalization of flows at this spatial level and the inclusion of home gardens, homestead, fallows, and hedgerows should be also considered.

Scaling-up to the village or communities, on the other hand, has been carried out to a lesser extent than at farm level (Table 2.2). Selecting the study of Ramisch (2005) as illustration, up-scaling to the community level was achieved by “the sum of all the balances for all the plots within the relevant sub-region or [household] class, averaged over the total area of those plots”. This approach seems also straightforward, although it suffers from issues of non-linearity among plots (as explained for the farm scale), but also among farms, which make it more complex. Another critical issue relates to whether calculations are based on an ‘average farm’ (e.g. Shepherd and Soule, 1998) instead of farm typologies, as this would influence until which extent diversity between farms is accounted for. If a farm typology is selected, emphasis should be placed on how well it is capturing the differences among farms (e.g. resource endowments), and this would depend further on the indicators (criteria) chosen for the classification. Selecting an ‘average’ farm for extrapolation would only be acceptable when no significant differences among farming systems in the area under observation occur, which is exceptionally rare in Africa. Manlay et al. (2004a), on the other hand, calculated balances at village level in an apparently similar way, but included in the calculations not just cropping fields but also fallow areas, woodlands, grasslands, and livestock-mediated flows. This is important, as rangelands and fallows at village scale (and higher levels) are generally excluded from the assessments despite their importance as sources of nutrients for agricultural land (Harris, 1999; Smaling and Toulmin, 2000), as well as sinks or traps for nutrients from erosion (Warren, 2007). Therefore, a cautious interpretation of results must be carried out, as negative balances from agricultural land do not necessarily mean that nutrients leave the area completely, as they can be deposited on adjacent ecosystems (Haileslassie et al., 2006). In fact, scaling-up nutrient flows and balances are especially critical when substantial lateral flows (e.g. soil, nutrients, water) are involved (van Noordwijk, 1999; van Noordwijk et al., 2004). As lateral flows are scale-dependent, and this scale-dependency is very difficult to quantify, they are generally ignored in the calculations, which usually results in overestimations of the final budget (De Ridder et al., 2004). For example, flows due to soil erosion and deposition are an example of lateral flows most affected by the scale (Schlecht and Hiernaux, 2004; Stoorvogel and Smaling, 1998) as actual losses by erosion at scales beyond the plot level are considerably smaller than those ones usually estimated at the plot scale due to re-deposition (De Ridder et al., 2004; Visser and Sterk, 2007). Unfortunately, few studies have been conducted to determine the proper contribution of soil erosion/deposition processes to nutrient balance studies at different scales (Visser et al., 2005). Moreover, methodologies for scaling-up data of run-off and erosion are still not available (De Ridder et al., 2004), despite the fact that scaling-up methods are even more relevant for erosion model building than the actual measurements (Hashim et al., 1998). In this regard, the use of LAPSUS (LandscApe ProcessS modeling at mUltidimensions and Scales) is apparently a better alternative than USLE (the Universal Soil Loss Equation), as it includes a feedback between erosion and sedimentation (FAO, 2003; Haileslassie et al., 2005; Lesschen et al., 2007). Moving from farm to higher scales also implies that not one farmer but the community is responsible for natural resource management; therefore, common property land management and use become an issue as well. This would be especially important in the case of communities with restricted access to grazing and forested areas, as potential conflicts could arise which would affect nutrient flows into the system (Schlecht and Hiernaux, 2004). In section 2.5.5 some alternatives for dealing with this issue are presented.

2.5.4.2. Scaling-up to province, district, region, or agro-ecological zone

The levels of province, district, region, or agro-ecological zone are a suitable entry point for policy-making at sub-national level, as well as for private sector interventions (FAO, 2003). Here the main problem is that very few input data at the required resolution and quality actually exist (Bekunda and Manzi, 2003; FAO, 2004). Therefore, data must be scaled-up from plot, farm or village levels (by aggregation of data), and/or scaled down from higher scales (by disaggregation). The “mesolevel” study from FAO (2004) in Ghana, Kenya and Mali clearly showed this problem, especially in Ghana where less data were available. This study “involved establishing relations between land use and soils in order to compensate for the lack of spatial data”, and calculations were finally made in a tabular form. Thus, data from lower levels (e.g. surveys, weather stations) and higher scales (e.g. national statistics, international databases) were used to feed the multiple functions in the calculations. The problem with aggregating data from lower scales is that usually not the entire range of bio-physical and socio-economical conditions can be practically covered, and results would depend on the criteria used during extrapolation (van der Hoek and Bouwman, 1999). The issue with disaggregating data from macro-scale studies, on the other hand, is that in this process “variability should be added instead of being leveled out and this is generally considered a difficult problem” (Heuvelink, 1998). Therefore, uncertainties may be propagating from both the micro and macro -scales, and thus several of the problems identified earlier in point 2.5.4.1 and in the next point would also apply.

2.5.4.3. Scaling-up to national, supra-national or continental level

National, supra-national and continental assessments of nutrient balances in Africa strongly depend on the collection of national or international studies and databases, which are already aggregated (De Jager et al., 1998a). For example, Lesschen et al. (2007) calculated spatially-explicit nutrient balances at national level for Burkina Faso. They based their methodology on a land use map, produced via qualitative land evaluation (a FAO methodology), which used diverse biophysical databases and statistical data for the allocation of crops over the generated map units at 1-km resolution. Nutrient balances were later calculated for each grid unit and results aggregated (by simple averaging) to 20-km grid cells for final presentation. From a spatial point of view, the approach was roughly similar to the macro-scale study of FAO (2004) in Kenya, Ghana and Mali; and essentially differed from earlier approaches (spatially-explicit, e.g. Folmer et al., 1998; and non-spatially-explicit, e.g. Stoorvogel et al., 1993), where grid cells were used as the basic spatial units for the estimation of balances, instead of using coarser land use classes. Although the approach included several innovations (e.g. improvement of some pedotransfer functions, estimation of uncertainties), due to the higher scale of evaluation complexities were inevitable. For example, macro-scale assessments are typically limited by the availability of data to be used in the calculations, as these vary per country (Bindraban et al., 2000; Stoorvogel, 1998). This is why Lesschen et al. (2007) had to use fertilizer input data from Mali and Senegal, as there was none available for Burkina Faso. Moreover, due to data limitations, a great variety of datasets, maps and information from different times, sources, qualities and resolutions are typically utilized. Use of GIS is assumed to solve the problem of convergence among different data. However, for the calculations to being accurate, biophysical and socio-economical information must be collected at the same spatial units, sampling designs and times (Schreier and Brown, 2001), which has been hardly ever carried out. Additionally, most applications in GIS assume data to be proportional to the area they occupy for extrapolation (van Noordwijk, 1999) which, as it has been discussed previously, is usually not the case. In Lesschen et al. (2007), erosion-deposition process were included by using the LAPSUS model. However, this model was developed at watershed level making its results at higher scales uncertain. Another important issue refers to the internalization of the flows, which at these levels is rarely considered (Schlecht and Hiernaux, 2004). Balances calculated from national to continental levels also traditionally refer to arable land (excluding fallows and rangelands), thus redistribution of nutrients out of the boundaries (as discussed previously) is seldom recognized (Haileslassie et al., 2007). In any case, the wide diversity of agricultural systems in Africa makes it very difficult to obtain a general meaningful value at these scales. These estimates should be better expressed as broad qualitative classes due to their typically low accuracy and uncertainty (Table 2.4).

The previous study cases and the associated discussion clearly showed that, despite new initiatives on scaling-up nutrient flows and balances, major challenges still remain. The proper use of rapidly growing computer power and associated advances in mathematics, (geo)statistics, chemometrics, and remote sensing, among others, should be crucial for dealing with these challenges in the near future.

2.5.5. Vanguard techniques for nutrient balance studies

Although the traditional nutrient balance methodology offers the possibility to explore the impact of different management practices on land quality under different scenarios

(Bindraban et al., 2000), it has the disadvantage of only providing a static view of a system (Scoones and Toulmin, 1998). This is why modeling approaches have being called for the calculation of nutrient budgets (Schlecht and Hiernaux, 2004), as “models are the principle vehicle for scaling and extrapolation” (Urban, 2005). In this regard, the NUTrient MONitoring model (NUTMON), though it is non-dynamic, has been the most extensive model used until recently for calculating nutrient balances in Africa. The model has been applied mainly in Kenya, although it has been used in other African countries as well (see www.nutmon.org/project.php3). NUTMON tackles biophysical and socio-economical dimensions of soil fertility at both plot and farm scale. Input data are obtained by direct measurements, estimated by pedo-transfer functions or assumed from literature and ‘common sense’ (Smaling and Fresco, 1993). However, the main limitations of this approach are the high demand of data (FAO, 2003; Smaling and Fresco, 1993), as well as that transfer functions on which calculations are based tend to exaggerate losses, producing lower nutrient balances than would be expected (Færge and Magid, 2004). Sheldrick et al. (2002) and Sheldrick and Lingard (2004), on the other hand, employed a dynamic mass balance model, which used nutrient efficiencies coupled to FAO databases for the calculation of nutrient balances at national and continental level for several years. According to them, this facilitated the calculations as detailed evaluation of nutrient losses is difficult, and helped to incorporate residual effects across seasons. However, the main assumption of the model (i.e. nutrient efficiencies are a direct function of nutrient inputs) does not reflect reality, thus its reliability has been questioned (FAO, 2003). Bontkes and van Keulen (2003) used a dynamic modeling approach at farm and regional scales in Mali, where decision-making by farmers was modeled via decision rules to determine impacts on soil fertility and socio-economic indicators. Nevertheless, the limited diversity of farm and soil types on which simulations were based, together with the hypothetical nature of the decision rules involved were its main limitation. The model of Shepherd et al. (1996) was a static approach for calculating nutrient balances for a standard Kenyan farm. Although the model was useful for exploring the impact of different agroforestry technologies, the approach was considered too simplified. Thus, Shepherd and Soule (1998) developed a dynamic model also at the farm scale in Kenya, in which both biophysical and socioeconomic realities were integrated at a yearly time step, and several soil productivity indicators were generated to be linked to the nutrient balance data. Some limitations of this approach were that the spatial-temporal variability of input data was not accounted for and that total farm production was underestimated. Tittonell et al. (2007; 2006) employed a dynamic model (DYNBAL-N, DYnamic simulation of Nutrient BALances) which was applied at field scale also in Kenya. The model used daily time steps and was less data-demanding than NUTMON, but used some of its pedotransfer functions. Although results were limited to N and the model was recommended just to 'explore and discuss' soil fertility management options, it was embedded within a broad modeling-based framework called AfricaNUANCES. NUANCES (Nutrient Use in Animal and Cropping Systems: Efficiencies and Scales) is a "series of databases and an analytical modeling framework… that combines spatial and temporal dimensions of African smallholder farming systems" (see: http://www.africanuances.nl). It seems, then, that despite the wide variety of models available, none is flawless. Moreover, they are mostly scale-specific, which clearly limit any multi-scale analysis. Hence, users must consider each option to choose the model that better fit their objectives and the type of data they are dealing with.

Due to the increasing need for understanding the spatial variation of soil processes and phenomena, coupling models with GIS for a spatially-explicit quantification of nutrient balances across different scales seems even more promising (Hartemink, 2006a; Schlecht and Hiernaux, 2004). In fact, recent advances in remote sensing and the accessibility to new geographical databases (on climate, soils, etc.) and software make all these tasks nowadays easier than before. The macro-scale studies cited in section 2.5.4.3 are a good example of this. A decision support system approach has also been proposed by Singh et al. (2001), which integrates nutrient balance calculations, crop simulation models, bio-economic databases, and GIS. A similar approach but linking dynamic nutrient balance models to land use change models is even envisaged in the near future to be able to explore the different effects of land use and land cover dynamics in nutrient flows and balances with time, which would be highly relevant in agroecological research (Lesschen et al., 2007). In any case, (spatially-explicit) models and decision support systems should further allow soon the integration of off-site effects at different scales, as well as the actions of different stakeholders into the systems. In the first case, the use of fractal approaches for incorporation of lateral flows has been proposed by van Noordwijk et al. (2004), in which a fractal dimension (with self-similar properties at different scales) is identified and applied across different scales where its rules operate. This approach, however, has not been apparently applied yet in nutrient balances studies in Africa. Multi Agent Systems (MAS), on the other hand, would have the potential of incorporating management decisions of actors or groups of actors in the agroecosystems, which would be especially important when dealing with communal resource management (e.g. grazing areas, forests) at the scale of village and beyond (Schlecht and Hiernaux, 2004). The experiences from Schreinemachers et al. (2007) in Uganda with this kind of approach are encouraging.

Infrared spectroscopy and geostatistics can be also of great utility for the quantification of nutrient balance studies. Infrared spectroscopy (in the near or mid region) can be used as an alternative to conventional laboratory analyses as the measurement of soil or plant samples take just few seconds and several constituents can be analyzed simultaneously with only one spectra (Shepherd and Walsh, 2007). Geostatistics, on the other hand, can be successfully used in spatially-explicit studies for interpolation and up-scaling of data via Kriging and related procedures (Sauer et al., 2006). Therefore, both approaches would be relevant for facilitating the access to the required input data for landscape assessments (Chapter 4). Moreover, recent advances from the GlobalSoilMap.net project in the development of a digital soil map of the world (Sanchez et al., 2009b) would increase possibilities even more. In any case, it must be clear that complex methodologies not necessarily produce better outputs than simpler ones. This is especially true if a high level of complexity is translated into a high demand of data that cannot be properly obtained in practice; or when efforts to produce accurate estimates of flows at the basic spatial units are later eclipsed at the final (higher) scale by using inadequate scaling-up methods.

2.6. Conclusions and further recommendations

Nutrient balance studies have been extensively carried out in Africa. Most assessments, however, have been conducted in East Africa and at lower spatial levels (e.g. plot, farm). From these studies balances were usually negative, suggesting potential problems of soil mining, especially for N and K; while for P the trend was less remarkable. Positive balances could be also found across the continent (e.g. in gardens, infields, wealthier farmers' plots), which counter the myth that all soils in Africa are already degraded or under degradation. In fact, the large diversity of land use systems in the continent is reflected in the high variability of nutrient balance estimations. However, methodological differences also partially explain the divergent results. A main difference refers to the type of balances used (full or partial), as partial balances are usually significantly higher than full balances. Thus, both types of balances must be treated as separate indicators, interpreted accordingly, and this important distinction explicitly stated in the literature. Other problems identified were the arbitrary selection of flows for the calculations, the short evaluation periods of the studies, and difficulties during setting spatial-temporal boundaries, in the inclusion of lateral flows and by linking balances to soil nutrient stocks. Therefore, a simultaneous and independent check of nutrient balance results would be very useful. An example of this could be the soil carbon stocks involved (e.g. Manlay et al., 2004a), as they usually follow the trends of nutrient mining or accumulation (Shepherd and Soule, 1998).

Data of nutrient balances showed no trends by increasing the scale of observation, which is in disagreement with the presumed assumption by some researches that a trend exists. However, this is possibly due to methodological differences during nutrient balances calculations, which make an accurate comparison among studies difficult, even within the same agroecosystem (Janssen, 1999). Thus, more research is still required to accurately determine the effects of spatial scale on nutrient balance results. This information also highlighted the need for more studies at higher spatial scales, especially by using partial balances, as these data are relatively scarce.

An extremely relevant issue for multi-scale research on nutrient balances is the scaling-up. This review basically showed that despite some improvements for more accurately estimating nutrient flows at the primary spatial units, and the use of more sophisticated techniques, we are still facing the same challenges as in earlier studies. It is time that nutrient balance studies deviate from oversimplifications during scaling-up exercises and strongly address issues of non-linearity and spatial heterogeneity, resolution and extent, which are critical in multi-scale ecological research (e.g. Kok and Veldkamp, 2001; Urban, 2005), but largely neglected in nutrient balance studies. When to internalize or not a nutrient flow and the type of aggregation used were also identified as critical issues during the scaling-up process. All this further suggests that current scaling-up methods may generate larger errors in the results than those ones produced by the original estimations of flows at the primary spatial units, and clearly advocates for more research in this area. Inter-disciplinary collaboration and the opportune use of new available techniques in the fields of ecology, mathematics, (geo)statistics, chemometrics, modeling and GIS, appear to be crucial in this quest.

Despite methodological limitations and uncertainties, nutrient balances have been proven to be useful tools for natural resource management assessments in Africa. Nutrient balances clearly illustrate the impact of human intervention on soil fertility (FAO, 2003) and allow the identification of problematic land use systems and flows where corrective land-use strategies should be properly adopted (e.g. Bindraban et al., 2000; Haileslassie et al., 2007). In fact, at lower spatial scales, nutrient balance exercises seem more appropriate for comparing how different systems and technologies potentially impact nutrient mining or recovery, and which and where prospective measures for tackling imbalances are most likely to be successful. At larger spatial scales, the assessment should focus more on creating awareness for policy recommendations on food security and land degradation. The challenge for Africa still resides in providing more external agricultural inputs (nutrients) while building-up systems' soil organic matter, inside a policy framework that facilitate these interventions, and even supports monitoring pathways of change across time (Vitousek et al., 2009). Editors and reviewers also have an important role, as recurring errors in soil nutrient balance studies are still present in the recent literature (see Table 2.6 for a list of usual errors on nutrient balances studies and recommended solutions), which could head to misleading information for the different target groups. Hence, if the scientific community wants to encourage African farmers to adopt more sustainable soil management practices and/or to convince African policy makers to enhance governmental strategies to reduce soil mining, the calculations, interpretation, and presentation of nutrient balances as indicators of land degradation at different spatial scales must be improved.

Table 2.6. Typical errors found in studies reporting nutrient balances at different scales in Africa and recommendations for its rectification

Error	Solution
Errors during estimations of flows and/or calculations of nutrient balances:	
- Transfer functions are used under different conditions from where they were developed	- Estimates of parameters must be checked against field measurements or data from (at least) similar sites. Transfer functions without validation should be avoided.
- Some flows are excluded from the calculations, despite its acknowledged importance	- If full balances need to be calculated, the excluded flows need to be included. On the contrary, uncertainties must be acknowledged or partial balances must be used
- Partial N balances are used on N_2-fixing ecosystems	- Input from N_2-fixation must be accounted for
- Flows are not properly internalized when up-scaled	- Total or partial internalization of flows must be carried out accordingly
- Direct extrapolation of erosion measurements from plot to higher spatial levels are carried out	- Soil re-deposition across spatial scales must be accounted for; thus particular scaling-up procedures for erosion versus soil deposition processes must be properly reported
- Nutrient balances are not linked to soil nutrient stocks	- Samples for bulk density must be taken together with soil fertility determinations for being able to link them accordingly
Errors in reporting the methods used:	
- No clear definition of land use systems studied	- As nutrient balances studies can assess only cropping fields or include additionally rangelands and/or fallows, this must be properly mentioned in the methodology
- Time frame of the study is not mentioned	- The time frame as well as the year or season of study must be clearly stated
- Units of balances are not mentioned or used erroneously	- Balances should be presented in kg per units of space and time, unless they are needed to calculate necessary inputs to a system (e.g. kg farm^{-1} or country^{-1} per year or season)
- No proper explanation of how flows are estimated	- An explicit methodology explaining the specific procedures done must be stated
- No clear distinction of type of balances used	- Partial or full balances must be clearly defined and interpreted accordingly
- Resolution of the assessment is not clear	- The basic unit where the calculation of balances took place (plot, field, administrative unit, cell, etc.) must be clearly stated
- Scale of evaluation of nutrient balances is not mentioned	- The scale, as well as the sub-levels used for the assessment, must be clearly mentioned in the methodology
- Methods used during scaling-up flows and balances are not properly explained	- The specific way how flows are extrapolated, aggregated and internalized must be clearly mentioned in the methodology
- Variability of estimates are not shown	- A measure of dispersion or uncertainty must accompany the reported results

CHAPTER 3

CROPPING STRATEGIES, SOIL FERTILITY INVESTMENT AND LAND MANAGEMENT PRACTICES BY SMALLHOLDER FARMERS IN COMMUNAL AND RESETTLEMENT AREAS IN ZIMBABWE

3. CROPPING STRATEGIES, SOIL FERTILITY INVESTMENT AND LAND MANAGEMENT PRACTICES BY SMALLHOLDER FARMERS IN COMMUNAL AND RESETTLEMENT AREAS IN ZIMBABWE[iii]

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3.1. Abstract

Three smallholder villages located in typical communal (from 1948), old (1987) and new (2002) resettlement areas, on loamy sand, sandy loam and clay soils, respectively, were selected to explore differences on natural resource management and land productivity. Focus group discussions and surveys were carried out with farmers. Additionally, farmers in three wealth classes per village were chosen for a detailed assessment of their main production systems. Maize grain yields (Mg ha^{-1}) in the communal (1.5-4.0) and new resettlement areas (1.9-4.3) were similar but significantly higher than in the old resettlement area (0.9-2.7), despite lower soil quality in the communal area. Nutrient input use was the main factor controlling maize productivity in the three areas (R^2=59-83%), while soil quality accounted for up to 12%. Partial N balances (kg ha^{-1} yr^{-1}) were significantly lower in the new resettlement (-9.1 to +14.3) and old resettlement (+7.4 to +9.6) than in the communal area (+2.1 to +59.6) due to lower nutrient applications. Averaged P balances were usually negative. Consistently, maize yields, nutrient applications and partial N balances were higher in the high wealth class than in poorer classes. This study found, that most farmers in the new resettlement area were exploiting the inherent soil nutrient stocks more than farmers in the other two areas. We argue that effective policies supporting an efficient fertilizer distribution and improved soil

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management practices, with clearer rights to land, are necessary to avoid future land degradation and to improve food security in Zimbabwe, particularly in the resettlement areas.

3.2. Key words

Conservation practices; Fertilizer use; Land reform; Maize productivity; Nutrient balances; Natural Resource Management.

3.3. Introduction

In Zimbabwe about 65% of the population lives in rural areas and depends on agricultural activities for their livelihoods (CSO, 2004b) . Smallholder farming is based mainly on maize (*Zea mays* L.) (Sukume et al., 2000) as it is the staple food and grown by nearly 90% of farmers (CSO, 2005). As in other regions in sub-Saharan Africa, agricultural production in Zimbabwe is affected by biophysical and socio-economic factors, with low soil fertility being one of the most limiting (Mapfumo and Giller, 2001; Nyamangara et al., 2000). Soils of Zimbabwe are predominantly granite-derived with low inherent soil fertility, presenting mainly deficiencies in N and P (Nyamangara et al., 2000; Nyamapfene, 1991), low CEC (Chuma et al., 1997) and low water retention capacities due to low SOM (Mapfumo and Giller, 2001). Sandy soils occupy roughly two thirds of the country, especially where communal areas are located (Chuma et al., 1997; Mapfumo and Giller, 2001; Nzuma and Murwira, 2000). However, highly productive soils are also found in the country: the so-called red soils, more associated with former commercial farming areas (Twomlow and Bruneau, 2000).

To overcome inherent low soil quality small-scale farmers use a wide range of nutrient sources in their farms, such as chemical fertilizers, manure, compost, wood-ash, leaf litter, termitaria, green manures and fallowing (Nzuma and Murwira, 2000; Place et al., 2003). However, the choice of the source is mainly based on the availability of the resources (labor and cash) at the farm rather than a systematic and intentional way to increase soil fertility (Mapfumo and Giller, 2001). In fact, inorganic fertilizers are nowadays unavailable for the majority of smallholders (FAO, 2006) and production of manure and other organic sources of nutrients are generally limited and restricted to those who have access to cattle, cash and labor (Mapfumo and Giller, 2001; Nzuma and Murwira, 2000; Zingore et al., 2007).

Further aggravating low soil quality and poor productive capacity of the farmland, are Zimbabwe´s changes in land use and tenure reforms over the last 30 years. Identity in Africa is often linked to land, and some countries (i.e. Zimbabwe, South Africa and Namibia) have proceeded with land reform programs for tackling historical injustices on land access during colonialism (Derman, 2006). In fact, during the colonial period in Zimbabwe, nearly 700,000 small-scale indigenous farmers were placed in communal zones with typically inherent poor sandy soils and erratic rainfall (Deininger et al., 2004). These communal areas represented about half of all farming land in Zimbabwe and were generally overpopulated and highly exploited (Moyo, 2005). Meanwhile, nearly 7,000 commercial white farmers were mostly positioned on better farmlands with fertile soils and consistent rainfall, representing the rest of the country's agricultural land (Deininger et al., 2004). Due to this inequitable land distribution, immediately after independence in 1980, the government started to acquire commercial white-owned land for redistribution; thus the first resettlement areas were established (Masiiwa, 2005). In the following 15 years, a total of 3.5 million hectares of land were seized and around 70,000 families were transferred to former white-owned farms (Moyo, 2005). However, land that was redistributed in this period was usually located in marginal areas of the country (Masiiwa, 2004). Subsequently, in 2000 a new phase of land reform officially started (Fast Track program) and most of the fertile commercial farm lands were seized and redistributed to small-scale black farmers, war veterans and landless people (Moyo, 2005). According to Moyo (2005) by the end of 2002 the Fast Track program had acquired around 10 million of ha of land, from which near to 90% had previously belonged to commercial white farmers. The land reform is still in progress and has resulted in evident agro-ecological and socio-economic changes in Zimbabwe (Elliott et al., 2006; Masiiwa, 2005; Moyo, 2005) affecting even the Southern African region (Derman, 2006). Beneficiaries of the land reform are authorized to reside in the old and new resettlements, but these rights can be withdrawn at any time (Deininger et al., 2004).

Nowadays smallholder farmers in communal areas (peasants) and resettled smallholder farmers (A1 farmers) account for 98% of total farms in Zimbabwe, occupying near to 73% of total land (Moyo, 2005). However, in spite of the continued crop cultivation of the resettlement areas in small parcels by the new occupants, it has been seen that crop yields have dropped significantly in the past decade (Derman, 2006; Masiiwa, 2005; Moyo, 2005). To date there is a lack of empirical quantitative biophysical information about how natural resource management and land productivity, in both communal and resettlement areas, have been affected by the land reform process (Derman, 2006). In fact, most of the available literature refers to socio-economic impacts and is usually out of date. The current study contributes to closing this knowledge gap, from a biophysical point of view, combining participatory approaches, surveys and detailed crop and soil sampling procedures. The specific objectives of this work were: a) to determine differences in cropping systems strategies, soil fertility investments and land management practices among farmers stratified into three wealth classes in three villages as typical cases of three smallholder settlement schemes (i.e. communal, old and new resettlement areas), b) to determine differences in crop productivity and partial nutrient balances among these factors, and c) to identify the main drivers controlling crop productivity (i.e. maize) in each zone.

3.4. Materials and methods

3.4.1. Selection and description of research sites

Communal areas are typically characterized by poor sandy soils, while most of the fertile commercial farm lands were distributed by the land reform program after 2000 (Moyo, 2005). Therefore, in the district of Bindura and Shamva (north-east Zimbabwe) a village from a communal area on a typical poor sandy soil; a village from an old resettlement area (from 1987) on a sandy loam soil of low fertility; and another village from a new resettlement area (from 2002) on a typical fertile clay soil, were selected as case studies. The selection criteria of villages was mainly based on their particular time of settlement and characteristic soil quality (e.g. Moyo, 2005), whilst sharing similar farmers' production objectives, climate, land tenure type and access to markets (Table 3.1). In fact, the villages are located within natural region II of Zimbabwe. This region, which encompasses a zone with altitudes of 1000 to 1800 m.a.s.l. and annual unimodal rainfall of 750-1000 mm, is suitable for semi-intensive crop and livestock production, and accounts for 75-80% of the area planted to crops in the country (FAO, 2006). The cropping season 2006-2007, in which the assessment was carried out, was slightly drier (620 mm) as compared to the historical mean (785 mm) for this particular zone during the last 25 years (data source: Meteorological Services Department, Zimbabwe). Soils in the three areas correspond to the Kaolinitic order, Fersiallitic group, under the Zimbabwean soil classification, which is the most extensive soil type in Zimbabwe, ranging from sandy to clay soils (Nyamapfene, 1991). Soils in the communal and old resettlement areas have been classified as mainly coarse grained sandy to sandy loam soils formed on granitic rocks (Agritex, 1995), corresponding most closely to Luvisols in the FAO classification (ISSS-ISRIC-FAO, 1998). The dominant soil type in the new resettlement area has been classified as mainly silty clay loam to clay formed on mafic sediments (Agritex, 1995), corresponding most closely to Ferrasols in the FAO classification. The three areas present a medium to high erosion risk according to the erosion hazard map of Zimbabwe (SADCC, n.d.).

Table 3.1. Main characteristics of the three smallholder settlement areas under study.

	Village		
Characteristic	Kanyera (Madziwa)	Chomutomora	Hereford Farm
Settlement type	Communal area	Old resettlement	New resettlement
Settlement time (approx.)	1948	1987	2002
Location (District, Ward)	Shamva, 6	Shamva, 15	Bindura, 8
Dominant soil type[&]	Chromic Luvisols	Chromic Luvisols	Rhodic Ferrasols
- Textural class	Loamy sand	Sandy Loam	Clay
- pH	5.1 ± 0.7	5.5 ± 0.6	5.0 ± 0.3
- Total carbon (g kg^{-1})	7.0 ± 2	9.0 ± 2	20 ± 7
- Total nitrogen (g kg^{-1})	0.5 ± 0.2	0.7 ± 0.2	1.4 ± 0.5
- P available (mg kg^{-1})	24 ± 13	18 ± 14	3 ± 2
- CEC ($cmol_c$ kg^{-1})	2.3 ± 1.4	6.1 ± 3.7	21.1 ± 10.5
Main crop	Maize	Maize	Maize
Total no. of households	90	38	72
- High wealth class (%)	22	34	49
- Medium wealth class (%)	36	42	28
- Low wealth class (%)[@]	42	24	24
Village area (ha)	730	780	1360
Closest main city by road	Bindura, 30 km	Bindura, 27 km	Bindura, 20 km

[&] According to FAO soil classification. Physical-chemical characterization (means ± standard deviation) was obtained from 49 maize plots at 0-20 cm depth. [@] For definition criteria of wealth classes see Table 3.2

3.4.2. Community meetings, group activities and surveys

Once the aims and activities of the study were explained to farmers and expectations clarified, the communities were classified into three wealth categories with the assistance of key informants and extension workers. The number of cattle owned, yield reliability to sustain the family till next season and labor availability were the main variables used for wealth classification (i.e. high, medium, low); but off-farm income and machinery owned were also considered (Table 3.2). Livestock ownership was higher for resettlement areas, as resettled farmers own more cattle than communal farmers (Deininger et al., 2004). Focus group discussions with 10-15 farmers (male and female) per wealth class per village were subsequently carried out to assess natural resource management at village level. In follow-up community meetings, four groups of about 10 farmers were randomly selected in each village to obtain: (i) a village resource map, showing all biophysical village features, (ii) a village seasonal calendar, indicating the timing of all principal agricultural activities, and (iii) a historical profile, presenting the main events that took place since settlement. Final surveys were done by conducting open-ended interviews to headmen, extension agents and more than 40% of farmers per wealth class in each community. Headmen interviews (n=3) dealt mainly with management rules of communal resources; extension agents' interviews (n=5) dealt mainly with recommended agricultural practices; and interviews of farmers (n=87) referred mainly to soil fertility management, land conservation practices and farmers' perceptions on soil fertility and crop productivity.

Table 3.2. Criteria used for the stratification of farmers by wealth classes in the villages under study.

	Wealth class		
Criteria	High	Medium	Low
No. cattle per household[&]	>5 or >7	1-5 or 1-7	0
Crop yields and/or reserves	Abundant	Satisfactory	Not enough
Access to labor	Hire labor	Sometimes hire labor	Sell labor locally
Access to off-farm income	Occasionally	Occasionally	Seldom
Access to machinery	Own all implements	Own some	Own small implements

[&] Higher holdings were applied to resettlement areas.

3.4.3. Detailed assessment of stratified selected farmers

Based on the wealth classification of the communities, three farmers were randomly selected from each wealth class in each village (27 farmers in total) to assess in detail their cropping systems. Transect walks were carried out on their farms after which a detailed farm resource flow map was drawn by each selected farmer, where flows of main nutrient resources (e.g. fertilizers, manure, litter, fuel-wood, crop residues, etc.) from/to/within their farms were identified. Once resource flows were cross-checked, for instance by calibrating carrying tools such as scotch carts and wheelbarrows commonly used on farm, both inputs and cropping fields were sampled. Composite samples (6-10 sub-samples) were obtained from manure or compost heaps. Crop sampling focused on maize, as it is the staple food in the three areas.

As farmers generally own more than one maize plot, a total of 49 maize plots were selected across the three villages. Maize plots were measured and sampled at harvest time, where up to six geo-referenced sampling subplots were randomly selected. Subplots consisted of two maize rows of 5 m length, where plant density, height of the maize and number of cobs were recorded. All maize plants were cut at their base and plant parts (grain, cores, husk, stover) and weeds were weighed and sub-sampled for dry weight correction and chemical analyses.

A composite soil sample (4 points, 0-20 cm depth) was later taken on both in-row and out-rows within the subplot and thoroughly mixed for physical-chemical analyses. As farmers mentioned during the focus group discussions that maintenance of contour ridges (an obvious land characteristic in all Zimbabwe due to their compulsory introduction by the British government in the colonial era (Scoones, 1997)) was a frequent activity, condition of contour ridges on all selected farmers fields were measured for validation against local standards (Elwell, 1981). A minimum of three contour ridges per farm were systematically chosen, and 3-4 points per contour were selected to assess: width of the contour, height of the ridge, and the width and depth of the channel. Once sampling was carried out, an interview was conducted with each selected farmer to obtain additional information about crop management and input use on each of their maize plots, as well as about other cultivated crops.

3.4.4. Soil and plant analysis

Soil samples were air-dried for at least one week and sieved (<2 mm). Subsequently, sub-samples were taken for analysis of texture, pH, total carbon (C) and nitrogen (N), available P (P_{av}) and exchangeable cations (CEC). Soil texture was determined by Bouyucos (Anderson and Ingram, 1993), pH by $CaCl_2$ (Anderson and Ingram, 1993), C and N by combustion using an auto-analyzer (EL, Elementar Analysensysteme, Germany), P_{av} by molybdenum blue complex reaction method (Bray and Kurtz, 1945) and effective CEC by extraction with ammonium chloride (Schöning and Brümmer, 2008). Plant, manure and compost samples, on the other hand, were first air and then oven dried (<55°C) until constant weight, weighted for dry weight correction, ground to <2 mm and then analyzed for total C, N and P. Total C and N were determined by an auto-analyzer (VarioMax CN, Elementar Analysensysteme, Germany) while total P was determined by the method of Gericke and Kurmies (1952).

3.4.5. Calculations and statistical analyses

Maize yield was expressed as grain weight at 12.5% water content, while crop residues were expressed as oven-dry biomass. Calculations of nutrients were limited to N and P as these are the most limiting nutrients in Zimbabwean soils (Nyamapfene, 1991). Partial N and P balances were calculated at plot level (kg ha^{-1} yr^{-1}) for maize as indicator crop, using the generated information from the detailed assessment with selected farmers. Partial nutrient balances are the difference between the inflows to a system, i.e. mineral (IN1) and organic fertilization (IN2), and its respective outflows, i.e. harvested products (OUT1) and crop residues removed (OUT2) (Zingore et al., 2007) as indicated below:

Partial balance (kg ha^{-1} yr^{-1}) = (IN1 + IN2) – (OUT1+OUT2) (equation 3.1)

Treatments means of all variables were calculated by each factor, and reported with their standard deviations when results from statistical tests are not presented. For comparing contour ridges characteristics against the recommended standard values, a paired T-test for related samples was done (Cody and Smith, 1997). Analyses of variance were carried out using mixed models with ‘settlement area’ and ‘wealth class’ as fixed effects (Piepho et al., 2003). In the communal area, a comparison was done between infields (plots closer to the homestead) and outfields (plots farther away), as farmers allocated preferentially their resources (fertilizers and labor) in the nearby field parcels. This creates what has been called soil fertility gradients, even in farms smaller than 0.45 ha (Giller et al., 2006). In this case, ‘field type’ and ‘wealth class’ were assigned as fixed effects in the mixed model. Factors affecting maize productivity in the three areas were analyzed via stepwise multiple regression. Variables entered into the models included soil data, land characteristics and management-related factors, whereas categorical variables (i.e. some of the management factors) were transformed to dummy variables prior to analysis. To avoid multi-collinearity, N and P inputs were aggregated to only one variable (N+P), where different proportions of P (i.e. 1×P, 2×P… 6×P) were tested and the simplest aggregation (1×N + 1×P) was chosen as it explained the highest variance. All statistical analyses were performed in SAS (SAS Institute Inc., 1999).

3.5. Results

3.5.1. Cropping systems

Average farm size in the communal area, independent of wealth class, was 2.9 ha of which 54% and 15% was allocated to maize and groundnuts (*Arachis hypogaea* L.) in the 2006-7 season, respectively (Table 3.3). In the old and new resettlement areas, the average farm size was 5 ha, of which 42% and 47% was under maize, respectively; while 24% of the area in both villages was allocated to cotton (*Gossypium* spp.). Other crops (e.g. sunflower (*Helianthus annuus* L.), soybeans (*Glycine max* L. *Merr*), tobacco (*Nicotiana tabacum* L.)) were also planted but they occupied less than 3% of the area (data not shown). Cropping activities in the three villages were carried out during similar calendar periods. For example, for maize 94% of sampled plots were planted between mid-November and end of December 2006, with medium maturing hybrids of high yield potential and good drought tolerance (i.e. SC513 and SC627 from SeedCo® and PAN6243 from Pannar®). Thus, harvest started after

April 2007. Livestock also played an important role in the production system of the three areas, as a source of manure, tillage power and transport, although only high and medium wealth farmers owned cattle ($p<0.01$, Table 3.3). Goats were of relative lower importance, particularly in the old resettlement area. Cattle manure in the three areas had values ranging from 7-12 g N kg^{-1} soil, 1.2-1.4 g P kg^{-1} soil and 0.25-0.45 g ash g^{-1} soil ($p>0.1$, n=14).

Table 3.3. Main characteristics of farms from stratified surveyed farmers (n=87) by wealth class in the three areas under study.

Characteristics /	Communal area			Old resettlement			New resettlement		
wealth class	High	Medium	Low	High	Medium	Low	High	Medium	Low
Area (ha):									
of the farm	3.7	2.6	2.4	5.3	5.2	4.5	4.9	5.1	4.9
under maize	2.6	1.2	0.9	2.5	1.5	2.3	2.3	2.2	2.6
under cotton	0.1	0.0	0.0	1.6	1.1	1.0	1.4	1.5	0.7
under groundnut	0.6	0.4	0.3	0.5	0.4	0.2	0.2	0.1	0.1
No. cattle	9	3	0	10	4	0	11	4	0
No. goats	2	2	1	1	0	0	3	1	3

Characteristic	Settlement	Wealth class	S*WC
Area of the farm	***	(*)	ns
Area under maize	***	(*)	(*)
Area under cotton	***	(*)	ns
Area under groundnut	***	*	ns
No. cattle	ns	***	ns
No. goats	ns	ns	ns

*** : $p<0.001$, * : $p<0.05$, (*) : $p<0.1$ and ns : $p\geq0.1$ after ANOVA.

3.5.2. Maize performance

Averaged maize yields by wealth class from farmers' plots on communal (1.5-4 Mg ha^{-1}) and new resettlement areas (1.9-4.3 Mg ha^{-1}) were similar, but significantly differed ($p<0.05$) from yields in the old resettlement area (0.9-2.7 Mg ha^{-1}; Figure 3.1a). Maize residue production ranged from 0.8-8.7 Mg ha^{-1}, but did not differ significantly ($p>0.1$) among settlement areas. Averaged harvest indexes ranged from 0.31 to 0.46. Maize yields and residues consistently increased with increase in wealth class in each village ($p<0.05$). The analysis done in communal areas to compare infields (plots closer to the homestead) and outfields (plots farther away) (Figure 3.1b) showed that average maize yields by wealth class were significantly ($p<0.01$) higher in infields (2.2-4.7 Mg ha^{-1}) than in outfields (0.7-2.5 Mg ha^{-1}), and a similar trend was found for maize residues. The same analysis could not be done in old and new resettlement areas as most of the farmers had all their plots located away from homestead. In fact, resettled farmers mentioned during focus group discussions that ‘distance’ was usually not considered as a factor driving resource allocation.

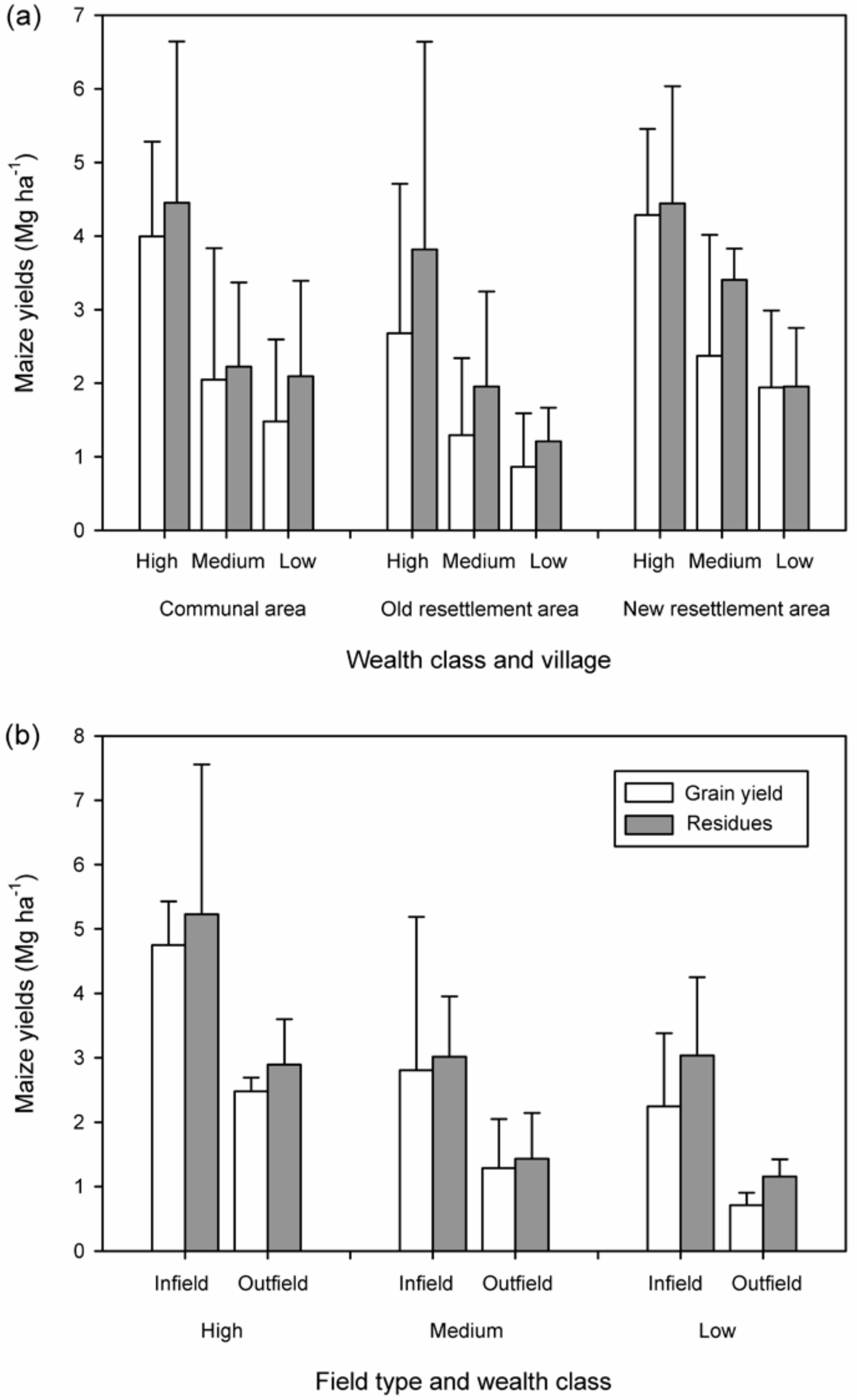

Figure 3.1. Maize grain yield and residues (means ± standard deviations, in Mg ha^{-1}) at plot level from: (a) selected farmers plots (n=49) stratified by wealth class and settlement area; and (b) different plot types (infields vs. outfields) in the communal area (n=18) stratified by wealth class.

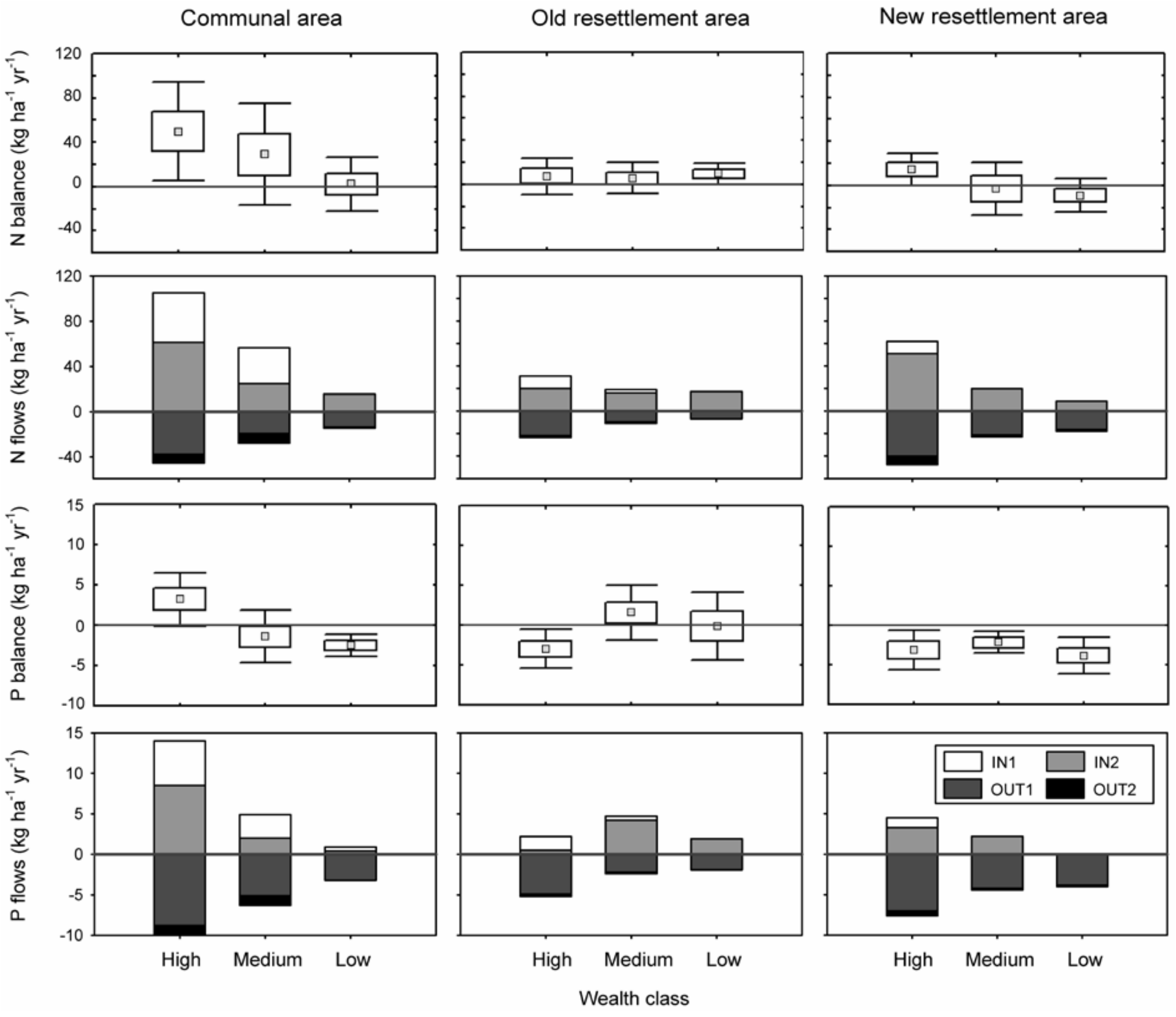

Figure 3.2. Partial N and P balances and associated nutrient flows (kg ha^{-1} yr^{-1}) at plot level as calculated from 49 maize plots from selected farmers stratified by wealth class and settlement area. Box and whisker plots in balances indicate mean ± standard error ± standard deviation. IN1 and IN2 are inflows from mineral and organic fertilization, respectively; while OUT1 and OUT2 are outflows from harvested products and crop residues removed, respectively.

3.5.3. Partial nutrient balances

Despite the variability found within each wealth class per village, as shown by the box and whisker plots in Figure 3.2, partial nutrient balances at plot level were found to be significantly different among villages ($p<0.05$). Averaged partial N balances by wealth class were significantly lower in the new resettlement (-9.1 to +14.3 kg ha^{-1} yr^{-1}) and old resettlement (+7.4 to +9.6 kg ha^{-1} yr^{-1}) than in the communal area (+2.1 to +59.6 kg ha^{-1} yr^{-1}); while corresponding partial P balances were -2.2 to -3.8, -2.0 to +2.3 and -2.5 to +3.9 kg ha^{-1} yr^{-1}, respectively. Nitrogen balances generally increased with the wealth class ($p<0.05$), although no significant differences in the old resettlement area were found. Differences among wealth classes for P balances were not significant ($p>0.1$). Figure 3.2 also indicates the nutrient flows from which balances were calculated. Using N as an example, it can be observed that in the communal area the high wealth class applied an average of >100 kg N ha^{-1} yr^{-1} to their plots, from which 58% were inorganic-derived (IN1); while 46 kg N ha^{-1} yr^{-1}were exported by harvest (OUT1) and collected crop residues (OUT2). This is in contrast to values obtained in the old and new resettlement areas where the high wealth class applied an average of 31 and 60 kg N ha^{-1} yr^{-1}, respectively (65 and 82% in the form of mineral fertilizers, IN1); but corresponding exports (OUT1 and OUT2) reached 24 and 48 kg N ha^{-1} yr^{-1}. With the particular exception of P in the old resettlement area, nutrient applications increased with the wealth class in each village ($p<0.05$); being significantly higher ($p<0.01$) in the communal area than in resettlement areas. In the communal area, nutrient applications were significantly ($p<0.01$) higher in infields (90 and 9 kg of N and P ha^{-1} yr^{-1}, respectively) than in outfields (23 and 4 kg of N and P ha^{-1} yr^{-1}, respectively) (data not shown).

Table 3.4. Main factors explaining maize yield variability in the areas under study after stepwise multiple regression analyses. n = 49, 18, 16 and 15 for all the three areas together, the communal, old and new resettlement areas, respectively. Only factors at $p<0.1$ are shown.

Model	Parameter estimate	Partial R^2	Cumulative Model R^2	F value	Pr > F
<u>All three areas together</u>					
(model Intercept)	-2.439			15.0	***
- N and P application (kg ha^{-1})	0.028	0.60	0.60	165.2	***
- Soil organic matter (g kg^{-1})	1.025	0.12	0.72	37.4	***
- Plant density (no. plants ha^{-1})	0.00005	0.07	0.80	18.3	***
- Stage of contour ridges[&]	0.023	0.02	0.81	4.3	*
<u>Communal area</u>					
(model Intercept)	2.600			16.7	***
- N and P application (kg ha^{-1})	0.021	0.82	0.82	66.6	***
- Total area of farm (ha)	-0.205	0.03	0.85	4.7	*
- Slope (%)	-0.255	0.03	0.89	4.1	(*)
<u>Old resettlement</u>					
(model Intercept)	-4.648			25.3	***
- N and P application (kg ha^{-1})	0.042	0.59	0.59	35.3	***
- Plant density (no. plants ha^{-1})	0.00005	0.17	0.76	6.4	*
- Soil organic matter (g kg^{-1})	2.462	0.07	0.83	12.1	**
- Stage of contour ridges[&]	0.061	0.07	0.90	7.3	*
<u>New resettlement</u>					
(model Intercept)	1.613			47.8	***
- N and P application (kg ha^{-1})	0.039	0.83	0.83	63.9	***

[&] As measured by the depth of the channel as a proxy
*** : $p<0.001$, ** : $p<0.01$, * : $p<0.05$, (*) : $p<0.1$ and ns : $p\geq0.1$.

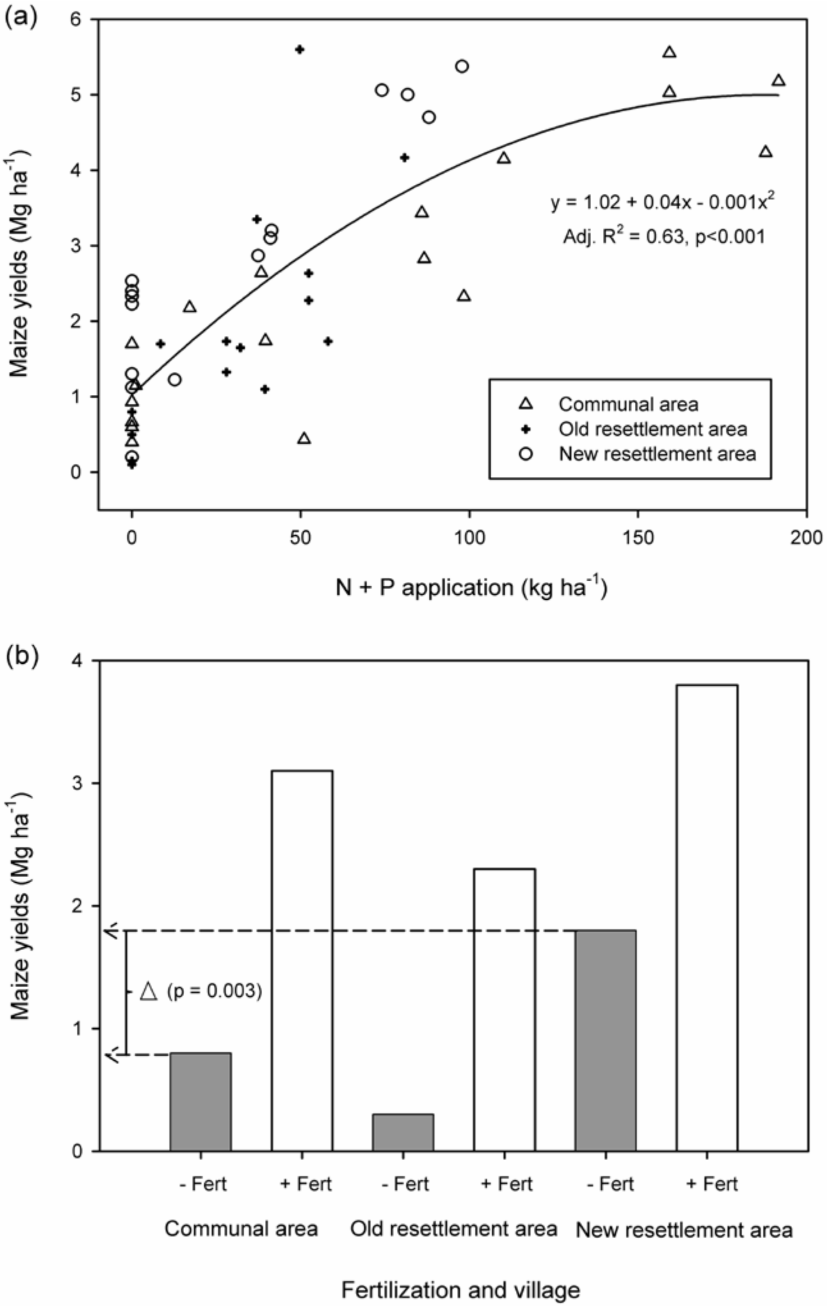

Figure 3.3. Effect of N+P fertilization on maize yields (Mg ha^{-1}) from 49 maize plots in the three areas under study: (a) scatter-plot and best fitted model showing the increase on maize yields with fertilization levels; (b) bar-chart comparing maize yields from non-fertilized plots (gray bars) and fertilized ones (white bars, independent of the level of fertilization). Δ denotes the difference between non-fertilized plots from the communal and new resettlement areas.

3.5.4. Factors affecting maize productivity

Nutrient (N+P) application was the main factor affecting maize productivity in all three areas, irrespective of whether the analysis was done by pooling the data or separately for each settlement area (R^2=59-83%, p<0.001) (Table 3.4). Moreover, 82-83% of the variation of maize yields could be explained by this factor in the communal and new resettlement areas, respectively. Soil organic matter, as a proxy for soil quality, accounted for 12% of the variation in maize yield in the overall analyses; but when analyses were done by village, it was only significant ($p<0.05$) in the old resettlement area and accounted just for 7%. Models for the entire dataset and the old resettlement area also included plant density (partial R^2= 0.07 and 0.17, respectively) and the condition of contour ridges (partial R^2= 0.02 and 0.07, respectively); while in the communal area farm size and slope were included (partial R^2= 0.03, for both factors). No additional factors to N+P application were selected for the new resettlement at $p<0.1$. When all significant factors ($p<0.1$) were considered, models could explain 81-90% of the total variation on maize productivity. Effect of fertilization on maize was non-linear, with a yield plateau at about 160 kg ha^{-1} (Figure 3.3a). Figure 3.3a also indicates that under zero application of nutrients some plots in the new resettlement area reached relatively higher yields than those obtained in the other two areas under no inputs. Therefore, a comparison was made for non-fertilized plots among villages (Figure 3.3b), which showed that maize yields under zero fertilization in the new resettlement (~1.8 Mg ha^{-1}) were significantly higher ($p<0.01$) than maize yields under no fertilization in the communal (0.8 Mg ha^{-1}) and the old resettlement area (0.3 Mg ha^{-1}).

3.5.5. Soil management practices

More than 57% of the farmers in the three villages under study used inorganic fertilizers in their maize plots, but frequency diminished consistently across the wealth classes, being typically lower in the new resettlement as compared to the other two areas (Figure 3.4). Animal manure application followed a similar trend although the frequency of farmers using this input was comparatively lower. Compost was only used in the communal area (13-29% of farmers) and litter was not used at all in the old resettlement. Crop rotation was practiced by 65-100% of the farmers in the three villages; while intercropping was practiced by 20-75% of farmers, being generally more frequent in the low wealth class. Between the seasons 2005-6 and 2006-7, the most frequent rotations found in the three areas were maize-groundnuts (mainly in the communal area) and maize-cotton (mainly in resettlement areas); while intercropping of maize was mainly done at low population densities with pumpkins, beans or sunflower (data not shown). Fallowing was also practiced, with periods usually lower than 2 years, being typically more common in the low wealth class in resettlement areas. Collection of crop residues from cropping fields after harvest (for taking them to the *kraal*) was more frequent in the communal area (29-88%) than in resettlement areas (14-50%), being typically less practiced in the low wealth class (Figure 3.4).

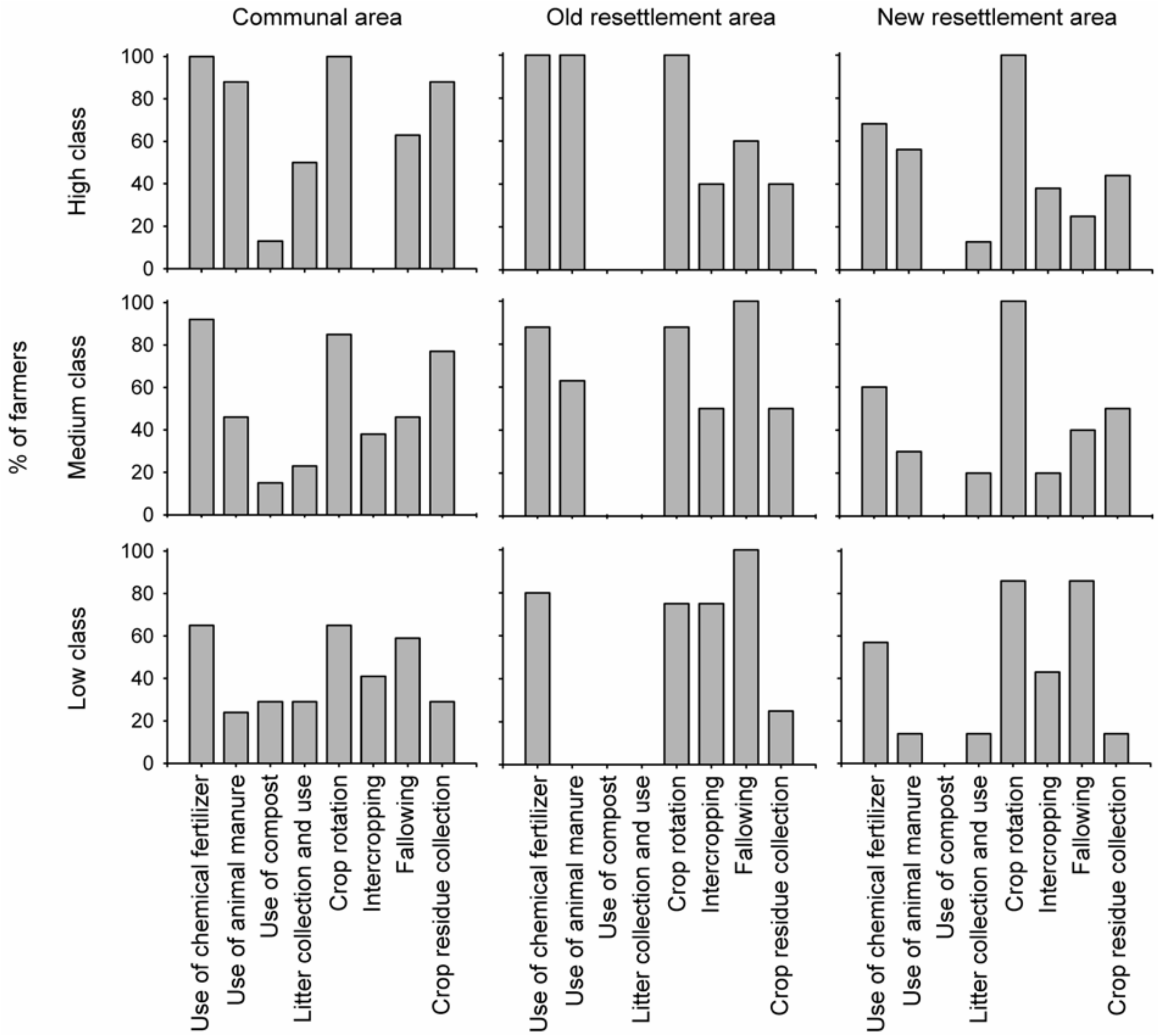

Figure 3.4. Proportion (%) of stratified surveyed farmers by wealth class in the three settlement areas under study using different soil fertility and land conservation practices in their maize plots. Only main practices are shown.

Maintenance of contour ridges was mentioned during focus group discussions as a frequent activity mainly done in the resettlement areas. Actual measurements in cropping fields (Table 3.5), however, revealed that the width of the contour, the height of the ridge and the width and depth of the channel were significantly ($p<0.05$) lower than recommended standards dimensions (Elwell, 1981) for most of the farmers in the three areas. This indicates that contour ridges have not been properly maintained. Conditions of the channel (width and depth) were significantly better ($p<0.001$) in the high wealth class as compared to the other wealth classes, and in the old resettlement area as compared to the other villages (Table 3.5).

Table 3.5. Condition of contour ridges as measured on selected farmers' fields in the three areas under study. Data in brackets indicate that the differences between actual measurements and standard values[&] for contour characteristics according to the paired T-test were not significant ($p > 0.05$).

Characteristics /	Communal area			Old resettlement			New resettlement		
wealth class	High	Medium	Low	High	Medium	Low	High	Medium	Low
Measurements									
No. contours measured	13	17	9	9	9	9	10	10	9
Total points measured	28	47	16	27	25	17	23	23	22
Fields' characteristics									
Field length (m)	176	166	203	241	222	261	269	196	183
Field slope (%)	4	4	8	5	6	6	5	5	6
Contour' characteristics[&]									
Width of contour (m)	(3.5)	2.5	1.9	(3.4)	2.9	2.7	3.1	(3.4)	(3.5)
Height of ridge (cm)	13	9	(16)	13	11	10	15	17	14
Width of channel (m)	0.6	0.3	0	(1.2)	0.6	0.6	0.2	0	0
Depth of channel (cm)	16	8	0	(24)	15	14	8	0.4	0

Characteristics	Settlement	Wealth class	S*WC
Field length (m)	ns	ns	ns
Field slope (%)	ns	ns	ns
Width of contour (m)	***	***	***
Height of ridge (cm)	(*)	ns	*
Width of channel (m)	***	***	(*)
Depth of channel (cm)	***	***	ns

[&] Standard values for contour ridges in Zimbabwe (Elwell, 1981) for comparison are: 3.4 m, 23 cm, 1.7 m and 23 cm for total width of the contour, height of the ridge, and width and depth of the channel, respectively.

*** : $p < 0.001$, * : $p < 0.05$, (*) : $p < 0.1$ and ns : $p \geq 0.1$ after ANOVA.

3.5.6. Farmers' perceptions of soil fertility and crop productivity changes with time

Perception of changes in crop yields over time by farmers, as captured by the survey (Table 3.6), was very variable in the communal area: 50% of respondents from the high wealth class believed that yields have increased over time, 62% of the medium class thought that yields have declined, while there was no clear consensus in the low wealth class. However, while over 67% of farmers in the old resettlement, independent of wealth class, perceived that crop yields have decreased over time, 57-80% farmers in the new resettlement believed yields have increased. When farmers where asked about their perception on soil fertility change over time, 50-80% of farmers in the communal and old resettlement areas (independent of wealth class) stated that soil fertility has decreased; while 44-70% of farmers in the new resettlement area believed that soil fertility has been steady (Table 3.6). Low crop growth rate was the main indicator of soil fertility decline by all farmers, while an unreliable access to fertilizers was the main cause of perceived changes in crop response and soil quality.

Table 3.6. Farmers' perceptions about changes on crop productivity and soil fertility with time. Data is the proportion of respondents per each wealth class per village.

	Communal area			Old resettlement			New resettlement		
Perceptions on:	High	Medium	Low	High	Medium	Low	High	Medium	Low
Crop yield changes									
- Declined (%)	13	62	38	80	75	67	19	0	14
- Steady (%)	38	23	38	0	13	0	19	20	29
- Increased (%)	50	15	25	20	13	33	63	80	57
Soil fertility changes									
- Declined (%)	63	77	76	80	63	50	50	20	29
- Steady (%)	25	23	24	20	25	50	44	70	57
- Increased (%)	13	0	0	0	0	0	0	10	0
- Don't know (%)	0	0	0	0	13	0	6	0	14

3.6. Discussion

3.6.1. Linking crop production, soil fertility investments and soil quality

Significant differences among settlement areas were found regarding maize productivity and how farmers dealt with inherent soil quality. Maize yields in the new resettlement were similar to yields obtained by farmers in communal areas, despite better soil quality of fields in the new resettlement. This was attributed mainly to the higher applications of nutrients in the communal area, compared to one in the other two areas. The role of inherent soil quality was indicated by multiple regression analyses on the overall dataset where soil organic matter, as a proxy, explained 12% of the variation in maize yields. Despite slightly lower than average rainfall during the 2006-7 season, maize productivity seems not to have been impeded, as shown by the high grain yields obtained by high wealth class farmers in the three villages and further corroborated during the interviews. Average maize grain yields and amounts of N applied as mineral and organic fertilizers in the communal area (1.5-4.0 Mg grain yield ha^{-1}; 17-105 kg N ha^{-1}) corresponded with average rates previously reported by Zingore et al. (2007) for communal farmers in Murewa, Zimbabwe (0.5-4.4 Mg grain yield ha^{-1}; 17-121 kg N ha^{-1}). Nutrient application rates in the three areas were relatively large when compared to the average fertilizer use in Africa, which in the late 1990s was around 9 kg ha^{-1} (Place et al., 2003). Nevertheless, with exception of the high wealth class in the communal area, rates of input use are still lower than fertilization recommendations for maize in Zimbabwe; i.e. 300 kg ha^{-1} of compound-D fertilizer (N:P:K 8:6:6) at planting (=24 and 18 kg N and P ha^{-1}) and 250 kg ha^{-1} of Ammonium Nitrate (34.5%N) at 3 and 6 weeks after emergence (=86 kg N ha^{-1}) (FAO, 2006). Use of uniform fertilization recommendations for all conditions (blanket formulations), however, does not enhance for efficient allocation of nutrient resources (Nyamangara et al., 2000), as differences in soil quality can be found among the different settlement schemes, and even among fields from the same farmer, as it was shown in the communal area for infields and outfields.

Average partial N balances by wealth class were found to be positive in communal and the old resettlement areas (+2.1 to +59.6 kg ha^{-1} yr^{-1}), in contrast to reported nutrient depletion trends in other countries in SSA and Africa in general (Hartemink, 2006a; Sheldrick and Lingard, 2004). However, average partial balances in the new resettlement (-9.1 to +14.3 kg ha^{-1} yr^{-1}) showed that medium and low wealth class farmers are mining the soils to a greater extent compared to farmers in the other two areas, as N and P balances were negative. The main assumption with regard to the nutrient balance method is that a system with continuous negative nutrient balances is not sustainable in the long term, although the time for soil to degrade is dependent on initial soil nutrient stocks (Hartemink, 2006a). Thus, if the current management continues (i.e. low investment in soil fertility) newly resettled farmers with negative nutrient balances would not perceive soil degradation in the short-term since soil quality in this area is relatively high.

3.6.2. Access to nutrient resources

Smallholder farmers have various ways to manage their soils, depending on their skills, labor and other socio-economic and biophysical factors (Scoones, 1997; Zingore et al., 2007). Use of mineral fertilizers for maize, for example, was more frequent in the communal than in the old and new resettlement areas; and a similar trend was found for the use of animal manure. Use of alternative nutrient sources (i.e. compost, litter, termitaria, ash, crop residues) was occasional but generally more diverse in the communal area. Efficient use of organic resources in cropping systems have been proposed as a key issue for addressing soil N depletion in Africa (Giller et al., 2006). Access to manure, however, is limited to wealthy farmers who own cattle (Mapfumo and Giller, 2001; Nzuma and Murwira, 2000) and have enough resources available (Scoones, 1997); while litter collection from woodlands for application to cropping fields is a high labor-demanding activity, as great amounts of litter must be collected to supply adequate nutrients to crops due to its typical low quality (Palm et al., 2001). Crop residues are generally collected by farmers for feeding the cattle in the kraal, used on-site by livestock or even burned, thus limiting its potentially positive impact on soil fertility (Giller, 2002). Incorporation of N_2-fixing plants into cropping systems has also been proposed to counteract soil fertility mining (Giller et al., 2006). However, for efficient N-transfer to soil and to subsequent crops, N_2-fixing plants must encounter favorable growth conditions; thus, in poor soils results are often unsatisfactory (Chikowo et al., 2004). Therefore, even when organic inputs are available in sufficient quantities for all farmers and N_2-fixing plants are incorporated into the systems, they need to be used in combination with inorganic fertilizers (Chikowo et al., 2004; Giller, 2002; Mapfumo et al., 2005; Place et al., 2003; Sheldrick and Lingard, 2004; Vanlauwe et al., 2001; Zingore et al., 2007). However, according to FAO (2006), national fertilizer consumption trends in Zimbabwe have declined since 2000 due to the disruptions caused by the land reform program. In fact, lack of access to fertilizers is the single most important external factor affecting investment in soil fertility, especially in resettlement areas, and failing fertilizer supply (amounts delivered and timing of delivery) was actually mentioned as a cause of low input use on cropping fields by the majority of farmers involved in the present study.

3.6.3. Linking investments in soil fertility and land conservation to farmers' perceptions

As stated before, nutrient application was the main factor affecting maize productivity in the three areas. However, when only plots without fertilization were compared, maize yields in the new resettlement area were significantly higher than yields obtained in the other two areas. This was due to a better inherent soil quality of the new resettlement area than in the other two villages. Having relatively good yields under no fertilization could explain why many farmers in the new resettlement did not perceive a decrease in crop yields and soil fertility with time, as opposed to what most farmers noticed in the communal and old resettlement areas. Moreover, it could explain further the significantly lower applications of inputs and the lower nutrient balances in the new resettlement area, when compared with the communal area. In other words, these data would suggest that most farmers in the new resettlement area did not see as imperative the need for investing in soil fertility as soil is still relatively fertile and productive even when no inputs were used; while for farmers in the communal area it was necessary to compensate for the low fertility of their soils with substantial amounts of inputs in order to obtain high yields. In the old resettlement area there was a combination of low soil quality and low inputs, which explained the poor performance of maize grain yields, and presumably the perceived decline in soil fertility and crop productivity by farmers. Moreover, other factors than nutrient applications were also found to be important in this area, such as plant density, contour ridges' condition and soil quality, which contributed to 31% of the variation on maize yields.

Land tenure is another external factor that could affect investment in soil fertility and land conservation. With the current tenure system, farmers in the resettlement areas do not really own the land; they are only allowed to use it and issued permits can be revoked any time (Deininger et al., 2004). Thus, resettled farmers presumably do not have a real incentive for investing in conservation measures. This was shown by Zikhali (2008) after working with communal and resettlement farmers in the north-east of the country. His study revealed how the land reform program created a highly significant and negative impact on the perception of land tenure security among its beneficiaries and negatively affected investments in soil conservation. In fact, according to Stocking (2003) the highest risk for soil degradation generally occurs under land tenure insecurity. Under such uncertain circumstances farmers may want to invest in soil conservation only in the short term (e.g. fertilizer application) and not in the long term (e.g. physical soil conservation measures). In addition re-settlement programs often bring along farmers with poor knowledge of the local farming conditions. Stocking (2003) also mentioned that farmers are willing to invest in soil conservation only when risk to their food security is minimal and economic and socio-cultural benefits are evident. This could be also the cause of the poor condition of contour ridges in the three areas, as these structures require high labor for their maintenance, which is in conflict with productive activities at the farm. Moreover, there is a certain reluctance on the part of farmers to establish field contours, as they were imposed in colonial times as a non modifiable package (Hagmann, 1996; Scoones, 1997). Although contours are potentially effective in avoiding land degradation (Elwell, 1981), erosion control by contour ridges as an isolated technology is apparently not sufficient, even when the contours are properly managed, due to other causes of erosion that can appear (i.e. water influx from roads and waterways) (Hagmann, 1996). Thus, contour ridges should be used together with other soil conservation practices, like conservation tillage, mulching and vegetative strips, among others.

3.6.4. Policy implications and future research needs

An inadequate investment in soil fertility endangers food security and leads to land degradation (FAO, 2006). Thus, investment in soil fertility in Africa is critical for poverty alleviation (Place et al., 2003; Sheldrick and Lingard, 2004). However, as Sanchez and Leakey (1997) and Place et al. (2003) suggest, besides tackling directly soil fertility depletion as a fundamental constraint to food security, there is also the need for enabling a supportive policy environment in Africa for rural development. In fact, only with the right governmental support (e.g. by facilitating credits, promoting better markets for agricultural inputs and the produce, deregulating price controls, improving extension services) the smallholder sector in Africa would be productive. This seems particularly critical for Zimbabwe (FAO, 2006), especially now when the relative importance of the smallholder sector is increasing (Derman, 2006), as it accounts now for 98% of all farms in the country occupying near to 73% of the total land (Moyo, 2005). Thus, more efforts from the government are required to reinforce the input distribution systems to small scale farmers, to encourage improved land conservation practices by proper support of extension services, and to guarantee more secure land rights to farmers, as this will limit land degradation while increasing food security.

Future research must be carried out considering different scales of evaluation (scaling-up from plot to landscape level), as well as to include a wider range of smallholder areas (scaling-out to other villages, even in different natural regions of the country), as each scale and each area has its own intrinsic condition and variability. This would show the multi-dimensional nature of the different driving factors and their impacts throughout national territory (Elliott et al., 2006). In fact, more than ever it is necessary to understand these changing areas as a result of different driving forces (biophysical, cultural, economic, political) as all this information will be required for taking correct decisions by policy makers in Zimbabwe, especially when land reform is ongoing, and in other African countries where the ‘land issue’ is still under debate.

3.7. Conclusions

Land reform in Zimbabwe, as in other countries of sub Saharan Africa, has triggered substantial socio-economic and environmental changes (Deininger et al., 2004; Elliott et al., 2006; Moyo, 2005). However, biophysical data are scarce regarding the nature and impact of these changes on the quality of natural resources and their management. The present study showed that a differential investment in soil fertility was the main cause of similar maize yields found in both communal and new resettlement areas, despite contrasting soil quality between these two areas. This differential investment in soil fertility was attributed mainly to how farmers perceived and responded to differences in inherent soil quality. In contrast to other African countries, the averaged partial N balances by wealth class were positive in the communal and old resettlement areas, and the productive capacity, in spite of the declining trend after land reform, was still relatively high. However, medium and low wealth categories in the fertile new resettlement area showing negative partial nutrient balances suggesting most farmers having a stronger dependency on inherent soil nutrient stocks than farmers in the other two areas. This would lead to soil fertility mining if the current management practices by these farmers continue in the future. Data also showed the importance of access to nutrient sources, especially to chemical fertilizers, as their use is absolutely necessary for an optimum crop production. In fact, direct and indirect evidence suggests that an inefficient fertilizer distribution system, as well as land tenure insecurity, appear to be important external factors affecting investment in soil fertility and land conservation, especially in resettlement areas. Therefore, effective policies supporting an efficient fertilizer distribution system and improved soil management practices by the re-enforcement of extension services, with more secure and clear land tenure rights, are imperative to avoid future land degradation and increasing food security in Zimbabwe. Experiences from the Millennium Villages project and countries like Malawi and Ethiopia leave little doubt that by implementing science-based policies, community mobilization and effective governance sub-Saharan African nations can greatly improve food security and reverse soil nutrient depletion and land degradation (Sanchez et al., 2009a).

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CHAPTER 4

INTEGRATION OF MID-INFRARED SPECTROSCOPY AND GEOSTATISTICS IN THE ASSESSMENT OF SOIL SPATIAL VARIABILITY AT LANDSCAPE LEVEL

4. INTEGRATION OF MID-INFRARED SPECTROSCOPY AND GEOSTATISTICS IN THE ASSESSMENT OF SOIL SPATIAL VARIABILITY AT LANDSCAPE LEVEL[iv]

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4.1. Abstract

Knowledge of soil spatial variability is important in natural resource management, interpolation and soil sampling design, but requires a considerable amount of geo-referenced data. In this study, mid-infrared spectroscopy (MIRS) in combination with spatial analyses tools is being proposed to facilitate landscape evaluation and monitoring. MIRS and geostatistics were integrated for evaluating soil spatial structures of three land settlement schemes in Zimbabwe (i.e. communal area, old resettlement and new resettlement; on loamy-sand, sandy-loam and clay soils, respectively). A nested non-aligned design with hierarchical grids of 750, 150 and 30 m resulted in 432 sampling points across all three villages (730-1360 ha). At each point, a composite topsoil sample was taken and analyzed by MIRS. Conventional laboratory analyses on 25-38% of the samples were used for the prediction of concentration values on the remaining samples through the application of MIRS - partial least

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squares regression models. These models were successful ($R^2 \geq 0.89$) for sand, clay, pH, total C and N, exchangeable Ca, Mg and effective CEC; but not for silt, available P, K and Al ($R^2 \leq 0.82$). Minimum sample sizes required to accurately estimate the mean of each soil property in each village were calculated. With regard to locations, fewer samples were needed in the new resettlement area than in the other two areas (e.g. 66 versus 133-473 samples for estimating soil C at 10% error, respectively); regarding parameters, less samples were needed for estimating pH and sand (i.e. 3-52 versus 27-504 samples for the remaining properties, at same error margin). Spatial analyses of soil properties in each village were assessed by constructing standardized isotropic semivariograms, which were usually well described by spherical models. Spatial autocorrelation of most variables was displayed over ranges of 250-695 m. Nugget-to-sill ratios showed that, in general, spatial dependence of soil properties was: new resettlement > old resettlement > communal area; which was attributed to both intrinsic (e.g. texture) and extrinsic (e.g. management) factors. As a new approach, geostatistical analysis was performed using MIRS data directly, after principal component analyses, where the first three components explained 70% of the overall variability. Semivariograms based on these components showed that spatial dependence per village was similar to overall dependence identified from individual soil properties in each area. In fact, the first component (explaining 49% of variation) related well with all soil properties of reference samples (absolute correlation values of 0.55-0.96). This demonstrated that MIRS data could be directly linked to geostatistics for a broad and quick evaluation of soil spatial variability. It is concluded that integrating MIRS with geostatistical analyses is a cost-effective promising approach, i.e. for soil fertility and carbon sequestration assessments, mapping and monitoring at landscape level.

4.2. Key words

Autocorrelation; chemometrics; DRIFT; sampling designs; spatial patterns; Zimbabwe.

4.3. Introduction

Soil properties are inherently variable in nature mainly due to pedogenetical factors (e.g. parental material, vegetation, climate), but heterogeneity can be also induced by farmers' management (Dercon et al., 2003; Giller et al., 2006; Samake et al., 2005; Wei et al., 2008; Yemefack et al., 2005). Soil spatial variability can occur over multiple spatial scales, ranging from micro-level (millimeters), to plot level (meters), up to the landscape (kilometers) (Garten Jr. et al., 2007). Thus, soil spatial variability is a function of different driving factors and spatial scale (in terms of size and resolution), but also of the specific soil property (or process) under evaluation and the spatial domain (location), among others factors (Lin et al., 2005). Recognizing spatial patterns in soils is important as this knowledge can be used for enhancing natural resource management (e.g. Borůvka et al., 2007; Liu et al., 2004; Wang et al., 2009), predicting soil properties at unsampled locations (e.g. Liu et al., 2009; Wei et al., 2008) and improving sampling designs in future agro-ecological studies (e.g. Rossi et al., 2009; Yan and Cai, 2008). In fact, the identification of spatial patterns is the first step to understand processes in natural and/or managed systems, which are usually characterized by spatial structures due to spatial autocorrelation: i.e. where closer observations are more likely to be similar than by random chance (Fortin et al., 2002). Conventional statistical analyses are not appropriate to identify spatial patterns, as these analyses require the assumption of independence among samples, which is violated when auto-correlated (spatially dependent) data are present (Fortin et al., 2002; Liebhold and Gurevitch, 2002). Thus, since 1950s, alternative methods, so-called spatial statistics, have been developed for dealing with spatial autocorrelation (Fortin et al., 2002). Nowadays several methods for spatial analyses exist (e.g. Geoestatistics, Mantel tests, Moran’s I, Fractal analyses), while the reasons of the different studies carried out to date on spatial assessments are also diverse (e.g. hypotheses testing, spatial estimation, uncertainty assessment, stochastic simulation, modeling) (Goovaerts, 1999; Liebhold and Gurevitch, 2002). However, a common characteristic is that all methods intent to capture and quantify in one way or another underlying spatial patterns of a specific spatial domain (Liebhold and Gurevitch, 2002; Olea, 2006).

Geostatistics is one of the most used and powerful approaches for evaluating spatial variability of natural resources such as soils (Sauer et al., 2006). However, construction of stable semivariograms (the main tool on which geostatistics is based) requires considerable amount of geo-referenced data (Davidson and Csillag, 2003). Infrared spectroscopy (IRS) has been suggested as a viable option to facilitate access to the extensive soil data required (Cécillon et al., 2009; Shepherd and Walsh, 2007). IRS is able to detect the different molecular vibrations due to the stretching and binding of the different compounds of a sample when illuminated by an infrared beam in the near, NIRS (0.7-2.5 μm), or mid, MIRS (2.5-25 μm) ranges. The result of the measurements is summarized in one spectrum (e.g. wavelength versus absorbance), which is further on related by multivariate calibration to known concentration values of the properties of interest (e.g. carbon content, texture) from reference samples. Thus, a mathematical model is created and used later for the prediction of concentration values of these properties in other samples from which IRS data is also available (Conzen, 2003). IRS measurements are, therefore, not destructive, take seconds, and one spectra can be related to multiple physical, chemical and biological soil properties (Janik et al., 1998; McBratney et al., 2006). Hence the technique is more rapid and cheaper than conventional laboratory analysis, especially when a large number of samples must be analyzed (Viscarra-Rossel et al., 2006). IRS has the additional advantage that spectral information could be used as an integrative measure of soil quality, and therefore employed as a screening tool of soil conditions (Shepherd and Walsh, 2007). The few existing initiatives in this regard are, however, limited to NIRS. For example, a visible-NIRS (VNIRS) soil fertility index based on ten common soil properties has been developed and applied in Madagascar (Vågen et al., 2006); ordinal logistic regression and classification trees were used to discriminate soil ecological conditions by using biogeochemical data and VNIRS in the USA (Cohen et al., 2006); and in Kenya, Awiti et al. (2008) developed an odds logistic model based on principal components from NIRS for soil fertility classification. Nevertheless, despite its multiple applications, IRS has not been widely used to date, especially for wide-scale purposes and in developing countries (Shepherd and Walsh, 2007).

African regions are usually characterized by food insecurity and poverty, which have been extensively attributed to low soil fertility and soil mining (Sanchez and Leakey, 1997; Vitousek et al., 2009). Therefore, to boost land productivity in the continent, there is an increasing need to develop and apply reliable indicators of land quality at different spatial scales (Chapter 2). In fact, Shepherd and Walsh (2007) proposed that the successful “combination of infrared spectroscopy and geographic positioning systems will provide one of the most powerful modern tools for agricultural and environmental monitoring and analysis” in the next decade. The present study aims to contribute to this goal, and follows up a study from Cobo et al. (Chapter 3), in which three villages as typical cases of three settlement schemes in north-east Zimbabwe (communal area, old resettlement and new resettlement) were evaluated to determine specific cropping strategies, soil fertility investments and land management practices at each site. The assessment, however, was done at plot and farm level, and did not take into account spatial structures of soil properties. Hence, the same three villages of Chapter 3 were systematically sampled, soils characterized by MIRS, and data subsequently analyzed using conventional statistics and geostatistics tools. The main objectives of this study were: i) to evaluate advantages and disadvantages of using MIRS and geostatistics in the assessment of spatial variability of soils, ii) to test if MIRS can be directly integrated with geostatistics for landscape analyses, and iii) to present recommendations for guiding future sampling designs.

4.4. Materials and methods

4.4.1 Description of study sites

The study sites consisted of three villages, selected as typical cases of three small-holder settlement schemes, in the districts of Bindura and Shamva, north-east Zimbabwe (Table 4.1). The first village, Kanyera, is located in a communal area, covers 730 ha, and is mainly characterized with loamy sand soils of low fertility. The second village, Chomutomora, is located in an old resettlement area (from 1987), covers 780 ha and mostly presents sandy loam soils of low quality. The third village, Hereford farm, is placed in a new resettlement area (from 2002), covers 1360 ha and is predominantly characterized by clay soils of relatively higher fertility. All villages are located in natural region II, which covers a region with altitudes of 1000 to 1800 m a.s.l. and unimodal rainfall (April to October) with 750–1000 mm per annum (FAO, 2006). Maize (*Zea maiz* L.) is the main crop planted in the three areas, and farmers have free access to communal grazing areas and woodlands. A full description of the sites' selection and characteristics is provided in Chapter 3.

Table 4.1. Main characteristics of the villages under study

Village name	Kanyera	Chomutomora	Hereford Farm
Settlement type	Communal area	Old resettlement	New resettlement
Settlement time (year)	1948	1987	2002
Location (District, Ward)	Shamva, 6	Shamva, 15	Bindura, 8
Dominant soil type[&]	Chromic Luvisols	Chromic Luvisols	Rhodic Ferrasols
Mean soil textural class	Loamy sand	Sandy Loam	Clay
Village area (ha)	730	780	1360

[&] According to FAO soil classification

4.4.2. Soil sampling design

A non-aligned block sampling design was used in the three villages to capture both small and large variation over large areas (Urban, 2002). It started with the delineation of the villages' boundaries by using a hand-held GPS. Coordinates were later overlaid in ArcView (www.esri.com) to a Landsat TM image of the zone acquired on 12 June 2006. A buffer of 30 m inside each village boundary was created and later a grid of 750 x 750 m was drawn for

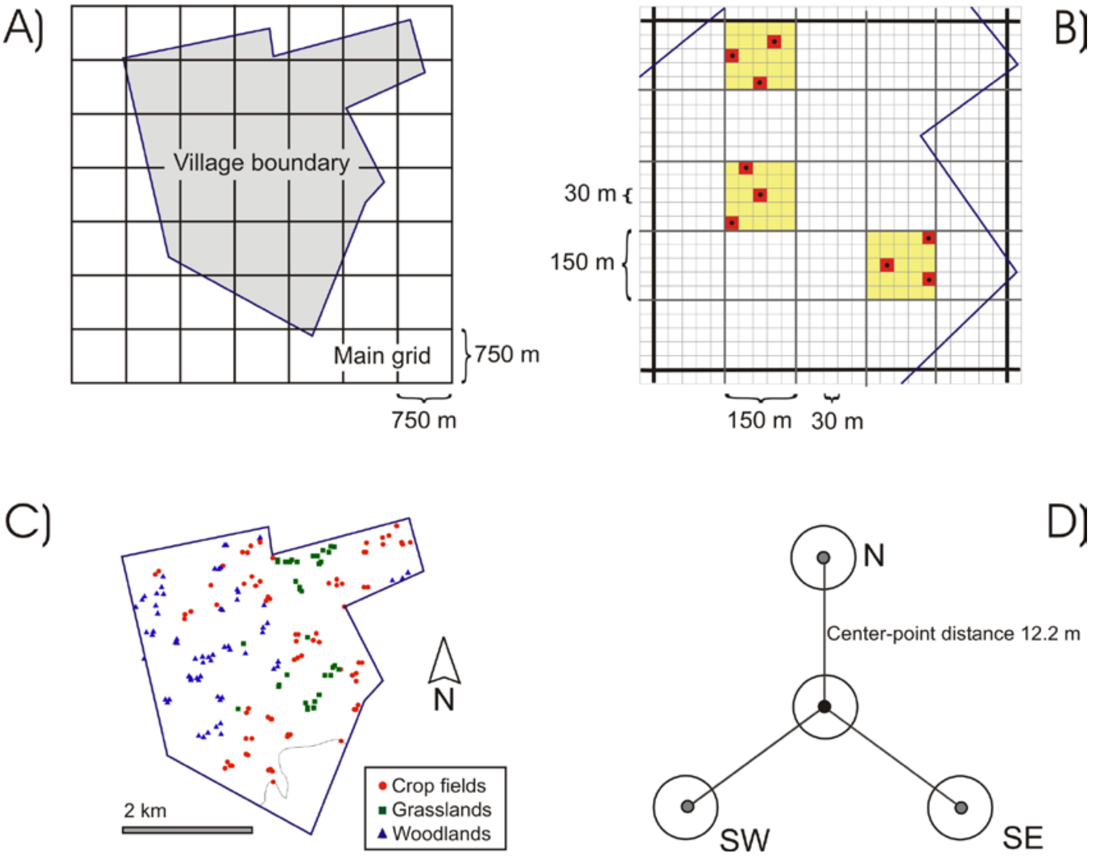

Figure 4.1. Soil sampling design. Hereford farm is used here as illustration: A) Representation of the overlay of a village boundary with main grid of 750 x 750 m; B) Zooming into a cell of 750 x 750 m where grids of 150 x 150 and 30 x 30 m, and selected sub-cells and micro-cells (with respective centroids), are shown; C) Final distribution of sampling points in the village; D) Schematic representation of the radial arm for each sampling point, where central circle indicates the centroid of each micro-cell (N: north, SW: south west; SE: south east).

each village in ILWIS (www.ilwis.org) (Figure 4.1a). Next, each main cell of 750 x 750 m was divided in 25 sub-cells of 150 x 150 m, which were subsequently divided once again in 25 micro-cells of 30 x 30 m. All grids were later transferred to ArcView, where 3 sub-cells from each main cell and 3 micro-cells from each sub-cell were randomly selected. This yielded a cluster of 9 micro-cells per main cell (Figure 4.1b). Finally, the centroids of each selected micro-cells were estimated and included into the GPS to locate these points in the field (Figure 4.1c). However, as some points were found in unsuitable places for sampling (e.g. road, water way, household) they were re-located (if possible) in alternate locations within cropping fields, grasslands or woodlands, mostly inside a radius of 30 m. In the same way, in cropping fields maize was preferentially chosen for future comparison purposes. At Hereford farm, a part of the woodlands in the southern border was considered to be sacred by the villagers, hence this sector was excluded. 432 points were successfully sampled in the three villages: 159 points in cropping fields (105 in maize, 32 in fallow and 22 in other crops), 163 in woodlands and 110 in grasslands. Maximum sampling distance between points was 5.2 (communal area), 3.8 (old resettlement) and 4.6 km (new resettlement); while minimum sampling distance was 30 m (for all three villages). Sample collection was carried out at the end of the 2006-7 cropping season.

Each sampling point consisted of a radial-arm containing four sampling plots: one central and other three located at 12.2 m in directions north, south-west and south-east (Figure 4.1d), which were designed to represent the internal characteristics and variations in each 30 x 30 m micro-cell (K. Shepherd & T. Vågen, personal communication, 2006). Once plots were established, they were fully characterized by using the FAO land cover classification system (FAO, 2005). Soils were sampled (0-20 cm depth) in each plot and all soil samples per point (4 plots) were thoroughly mixed to account for short-range (<30 m) spatial variability, and a composite sub-sample (~250 g) was taken from the field. Composite soil sub-samples were air-dried, sieved (<2 mm) and a sub-sub-sample sent to Germany for laboratory analyses.

4.4.3. Conventional and MIRS analyses of soil samples

Soil texture, pH, total carbon (C) and nitrogen (N), available phosphorus (P_{av}), exchangeable potassium (K), calcium (Ca), magnesium (Mg) and aluminum (Al), and effective cation exchange capacity (CEC) were analyzed on 25% (texture) to 38% (other soil properties) of all collected samples (referred in this study as “reference samples”) for the calibration and validation of the MIRS models. Soil texture was determined by Bouyucos (Anderson and Ingram, 1993), pH by $CaCl_2$ (Anderson and Ingram, 1993), total C and N by combustion using an auto-analyzer (EL, Elementar Analysensysteme, Germany), P_{av} by the molybdenum blue complex reaction method of Bray and Kurtz (1945) and exchangeable cations and effective CEC by extraction with ammonium chloride (Schöning and Brümmer, 2008).

All 432 soil samples were analyzed by Diffuse Reflectance Infrared Fourier Transform (DRIFT) -MIRS. Five grams of ball-milled soil samples were scanned in a TENSOR-27 FT-IR spectrometer (Bruker Optik GmbH, Germany) coupled to a DRIFT-Praying Mantis chamber (Harrick Scientific products Inc., New York, US). Spectra were obtained at least in triplicate, from 600 to 4,000 wavenumber cm^{-1}, with a resolution of 4 cm^{-1} and 16 scans/sample, and expressed in absorbance units [log(1/Reflectance)]. Pure potassium bromide (KBr) was always used as a background. All spectral replicates per sample were averaged and later subjected to multivariate calibration by using partial least square (PLS) regression, which relates the processed spectra (e.g. Figure 4.2) to the related concentration values from the reference samples. Half of the reference samples were used as calibration, while the other half left for validation. Chemometric models were constructed with the “Optimization” function of the OPUS-QUANT2 package (Bruker Optik GmbH, Germany). Calibration regions were set to exclude the background CO_2 region (2300-2400 cm^{-1}) and the edge of the detection limits of the spectrometer (<700 and >3900 cm^{-1}) to reduce noise. Prediction accuracy of selected MIRS models was evaluated by the residual prediction deviation (RPD) value, the coefficient of determination (R^2) and the root mean square error of the prediction (RMSEP). Once suitable chemometric models were selected, models were applied to every spectrum replicate of non reference samples for the prediction of unknown concentration values for each possible soil property; and results of all replicates per sample were finally averaged. All spectral manipulation and development of chemometric models were carried out in OPUS, version 6.5 (Bruker Optik GmbH, Germany).

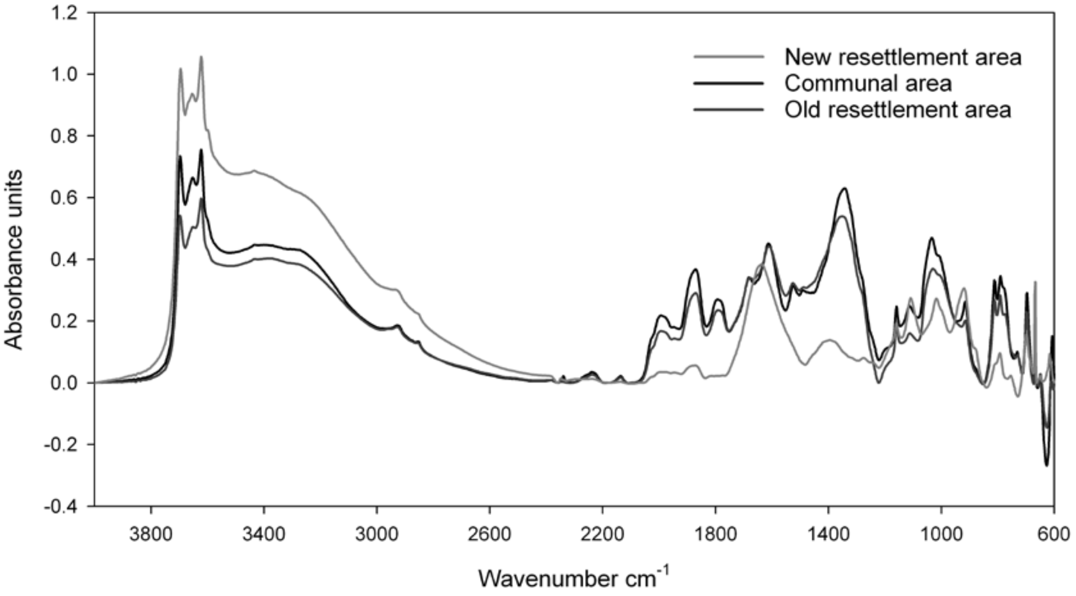

Figure 4.2. Examples of mid infrared spectra of soil samples from the three villages under study: i.e. the baseline-corrected spectrum of one sample per village having an average C content of 7, 11 and 29 g kg^{-1} for the communal area, and the old and new resettlement areas, respectively.

4.4.4. Conventional statistical analyses

Descriptive statistics were calculated to explore the distribution of each soil property under evaluation and as a critical step before geostatistical analyses (Olea, 2006). This comprised the calculation of univariate statistical moments (e.g. mean, median, range), construction of scatter plots, box plots, frequency tables and normality tests, as well as the identification of true outliers and their exclusion, if necessary, by following Makkawi (2004), as even few outliers can produce very unstable results. The coefficient of variation (CV) was calculated as an index for assessing overall variability (Gallardo and Paramá, 2007). The non-parametric tests of Kruskal-Wallis and Mann-Whitney (a Kruskall-Wallis version for only two levels) were chosen for testing the equality of medians among villages following the method of Bekele and Hudnall (2006). All classical statistical analyses were performed in SAS version 9.2 (SAS Institute Inc).

4.4.5. Minimum sample size estimations

The minimum number of samples required for estimating the mean of the different evaluated soil properties in each village, at different probabilities of its true value (error), with a 95% of confidence, was estimated by using equation 4.1:

$$n = [(t_\alpha * s)/d]^2 \qquad \text{(equation 4.1)}$$

where n is the sample size, t is the value of t Student (at α=0.05 and n-1 degrees of freedom, i.e. 1.96), s is the standard deviation, and d is the margin of error (Garten Jr. et al., 2007; Rossi et al., 2009; Yan and Cai, 2008).

4.4.6. Geo-statistical analyses of estimated soil properties

Spatial dependence of soil properties in each area was assessed by using geostatistical analyses, via the semivariogram, which measures the average dissimilarity of data as a function of distance (Goovaerts, 1999) as illustrated in equation 4.2:

$$\gamma(h) = 1/2N(h) \sum_i \sum_{i+h} [z(i)-z(i+h)]^2 \qquad \text{(equation 4.2)}$$

where γ is the semivariance for N data pairs separated by a distance lag h; and z the variable under consideration at positions i and $i+h$. As construction of semivariograms assumes a Gaussian distribution (Olea, 2006; Reimann and Filzmoser, 2000), most of the variables were transformed to approximate normality and to stabilize variance (Goovaerts, 1999). Data were also detrended by fitting low-order polynomials according to the exhibited trend (if existing) for accounting for any systematic variation (i.e. global trend) and, hence, fulfilling the assumption of stationarity (Bekele and Hudnall, 2006; Sauer et al., 2006). Thus, after detrending, respective residuals were used to construct standardized isotropic semivariograms for each soil property in each village. Hence, anisotropy (effect of direction in the intensity of spatial dependence) was not taken into account, as this analysis required higher number of samples for the construction of stable semivariograms in each direction. When number of samples is limited an ommnidirectional (isotropic) characterization of spatial dependence is more recommendable (Davidson and Csillag, 2003). The standardization was achieved by dividing the semivariance data by the sample variance, allowing a fair comparison among variables and sites (Pozdnyakova et al., 2005). The half of the maximum sampling distance in each village was chosen as the active lag distance for the construction of all semivariograms, and more than 100 pairs per each lag distance class interval were included in the calculations.

Once semivariograms were constructed, theoretical semivariogram models were fitted to the data. This was done by selecting the model with the lowest residual sum of squares and highest R^2 (e.g. Liu et al., 2009; Wang et al., 2009; Wei et al., 2008). As the spherical model characterized well most of the cases, this model was selected to fit all data (with the exception when a linear trend was found). Having the same model further facilitates comparisons among variables and villages (Cambardella et al., 1994; Davidson and Csillag, 2003; Gallardo and Paramá, 2007). The spherical model is defined in equation 4.3 (Liu et al., 2004; Pozdnyakova et al., 2005) as:

$$\begin{aligned} \gamma(h) &= \{ Co + C\,[\,1.5\,(h/a) - 0.5(h/a)^3\,] \quad 0 < h \leq a \qquad \text{(equation 4.3)} \\ &= \{ Co + C \quad h > a \end{aligned}$$

where γ is the semivariance, h the distance, Co is the nugget, $Co+C$ is the sill, and a is the range. These parameters were used to describe and compare spatial structures of soil properties in each village. ArcGIS version 9 (ESRI) and procedures Univariate, Means and Variogram of SAS version 9.2 were used for exploratory data and trend analyses; while Proc GLM of SAS was used for data detrending. Construction of semivariograms and model fitting were performed in GS^+ version 9 (Gamma Design Software, USA).

4.4.7. Geo-statistical analyses of MIRS data

To determine the feasibility of using MIRS data as direct input for the determination of spatial variation of soils, all spectra were baseline corrected and derived (1st derivative) in

OPUS. Data were later exported to SAS, where the CO_2 regions and the edges of the spectra were excluded, as explained for the multivariate calibration. Next, spectral data were reduced by re-sampling at 12 cm^{-1}, and selected wavenumbers (i.e. variables) subjected to Spearman correlation analyses among each other, where highly autocorrelated variables (i.e. $r > 0.99$) were manually excluded. Data were later standardized to zero mean and unit variance, and analyzed by principal component analyses (Borůvka et al., 2007; Yemefack et al., 2005). The three first components were retained, rotated (varimax option) and respective scores assigned to each soil sample. Score components were, thus, used as input variables for the constructions of semivariograms per each village, by following the same methodology previously explained for the conventional soil parameters. Spearman correlation analyses were finally performed between the principal components and chemical data from reference samples.

4.5. Results

4.5.1. MIRS models and prediction

A good representation across the different concentration ranges for most of the soil properties was obtained by the selection of the samples, as shown in Figure 4.3. Calibration and validation models also showed that predictability potential of MIRS varied with the specific soil property under evaluation and location, as indicated by the different model fit and performance indicators (Figure 4.3, Table 4.2). For example, in agricultural applications RPD values higher than 5 indicate that predictions models are excellent; RPD values greater than 3 are considered acceptable; while values less than 3 indicate poor prediction power (Pirie et al., 2005). Besides, R^2 values near 1 typically indicate good models (Conzen, 2003). Hence, excellent models ($5<\text{RPD}\leq6.8$, $0.96\leq R^2\leq0.98$) were obtained for sand, clay, C, N, Ca and CEC; acceptable models ($3<\text{RPD}<5$, $0.89<R^2<0.92$) were obtained for pH and Mg; while unsuitable models ($\text{RPD}<3$, $R^2\leq0.82$) were obtained for silt, P_{av}, K and Al. Poor validation for these last variables (especially P_{av}, K and Al) was the result of a deficient calibration, as indicated by their model fit (Figure 4.3) and parameters (Table 4.2). Thus, MIRS models for these variables were not used for prediction, and hence these data were dropped from any further analyses. Silt fraction, however, could be calculated from the other two fractions (silt = 100 – sand - clay). Therefore, by using the selected MIRS models shown in Table 4.2 for the prediction of soil parameters in non-reference samples, the entire dataset of sand, silt, clay, pH, C, N, Ca, Mg and CEC could be completed.

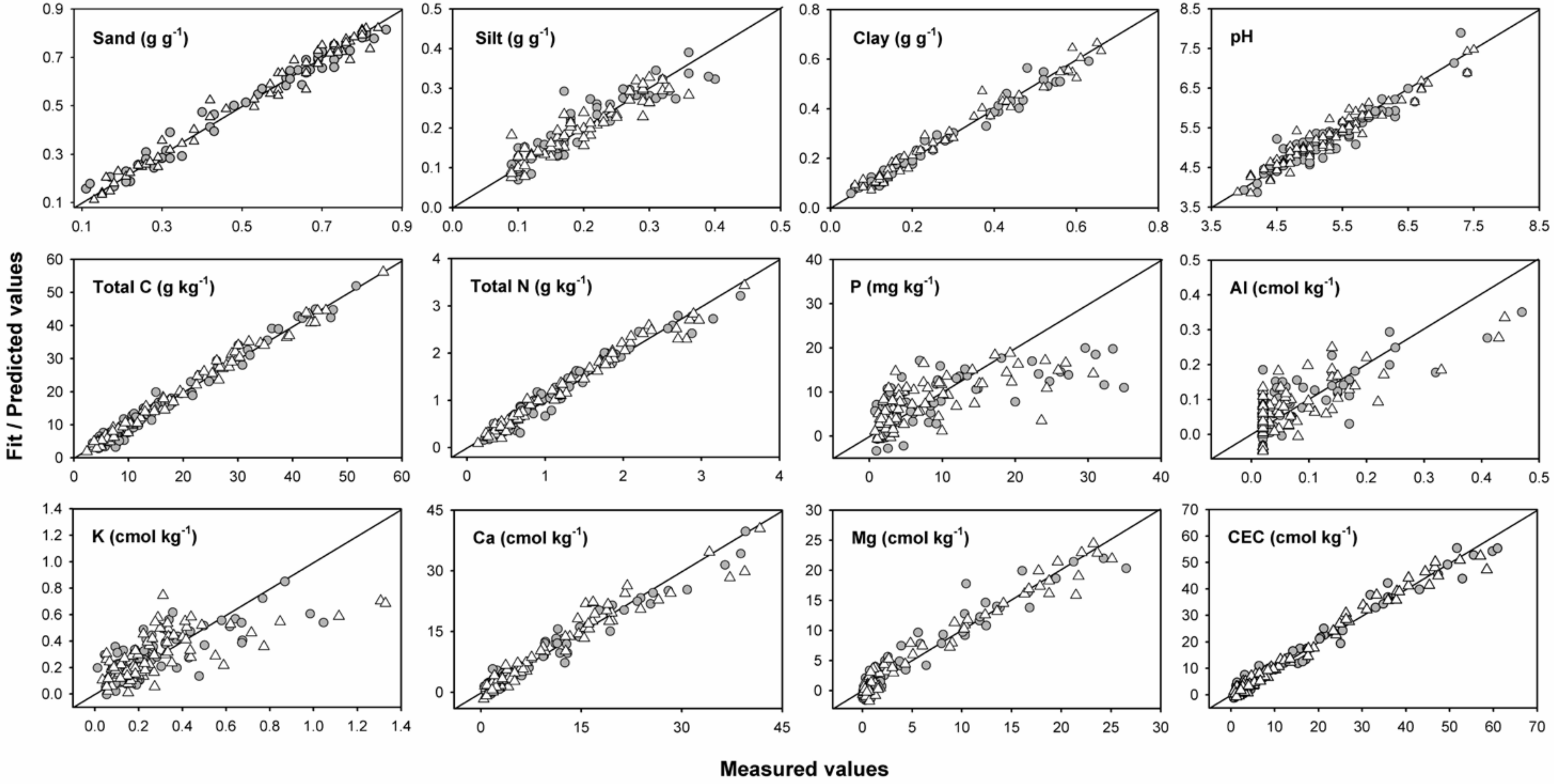

Figure 4.3. Calibration (triangles) and validation (circles) scatter plots of MIRS models from evaluated soil properties. For respective performance indicators refer to Table 4.2.

Table 4.2. Optimization parameters and performance indicators of best MIRS models for each soil property under evaluation.

Soil property	Preprocessing method[&]	Rank	Calibration R^2	Calibration RMSEE	Calibration RPD	Validation R^2	Validation RMSEP	Validation RPD	Prediction
Sand	1stDer+VN	7	0.98	3.7	6.7	0.98	3.3	6.8	Yes
Silt	1stDer+VN	6	0.85	3.1	2.6	0.82	3.6	2.4	No[#]
Clay	1stDer+SLS	3	0.97	3.0	6.1	0.97	2.6	6.2	Yes
pH	1stDer+SLS	9	0.93	0.20	3.8	0.89	0.24	3.1	Yes
C	1stDer+VN	14	0.99	0.14	10.1	0.98	0.19	6.4	Yes
N	1stDer+VN	9	0.98	0.01	6.6	0.96	0.02	5.2	Yes
P_{av}	SLS	6	0.47	5.5	1.4	0.49	6.2	1.4	No
K	None	5	0.48	1.9	1.4	0.56	1.4	1.5	No
Ca	COE	8	0.94	25.2	4.1	0.96	18.7	5.1	Yes
Mg	1stDer+MSC	8	0.96	14.8	5.2	0.92	18.0	3.4	Yes
Al	1stDer+SLS	12	0.69	0.70	1.8	0.66	0.61	1.8	No
CEC	1stDer+VN	9	0.98	22.8	7.6	0.98	24.4	6.6	Yes

[&] 1stDer: 1st derivative, COE: constant offset elimination, SLS: straight line subtraction, MSC: multiplicative scatter correction, VN: vector normalization. Considered spectral regions from the optimization process are not shown. Rank: Number of factors used in the PLS regression; RMSEE: Root Mean Square Error of Estimation, RMSEP: Root Mean Square Error of the Prediction, RPD: Residual Prediction Deviation.

[#] But could be calculated from the other two textural fraction

4.5.2. Exploratory data analysis and differences among villages

Exploratory data analyses in the entire dataset indicated that most soil properties presented skewed and kurtic distributions (data not shown). For example, texture fractions showed clearly a bimodal distribution, which suggested the presence of different populations, as it was in fact the case (i.e. different villages presenting different textural classes). Descriptive statistics and histograms were therefore also obtained by village. In this case, although texture fractions generally approximated normality, most of the other parameters still exhibited non-normal distributions (data not shown). Non-normality is usually the rule and not the exception when dealing with geostatistical and environmental data (Reimann and Filzmoser, 2000). This is why the median (instead of the mean) and non-parametric approaches were preferably used for classical statistical analyses, in spite of data transformation usually helped to approximate normality.

Overall variability of soil properties in each area was evaluated by its coefficient of variation. According to Wei et al. (2008), a CV less than 10% indicates that variability of a considered property is low; while a CV higher than 90% indicates high variation. Thus, calculated CVs in the entire dataset (Figure 4.4A) showed that Ca, Mg and CEC were the properties with the highest overall variability (>90%); while only pH presented a relative low variation (~10%). Other evaluated soil properties showed intermediate variability (CV=10-90%). When calculations were performed by village (Figure 4.4B-D), CVs of all soil properties reduced considerably, as expected. Data showed that Mg varied the most in the three villages, while pH (in all villages) and sand (in the communal and old resettlement area) presented the lowest variation. With the particular exception of sand and pH, variability of all soil properties in the new resettlement was lower than in the other two areas.

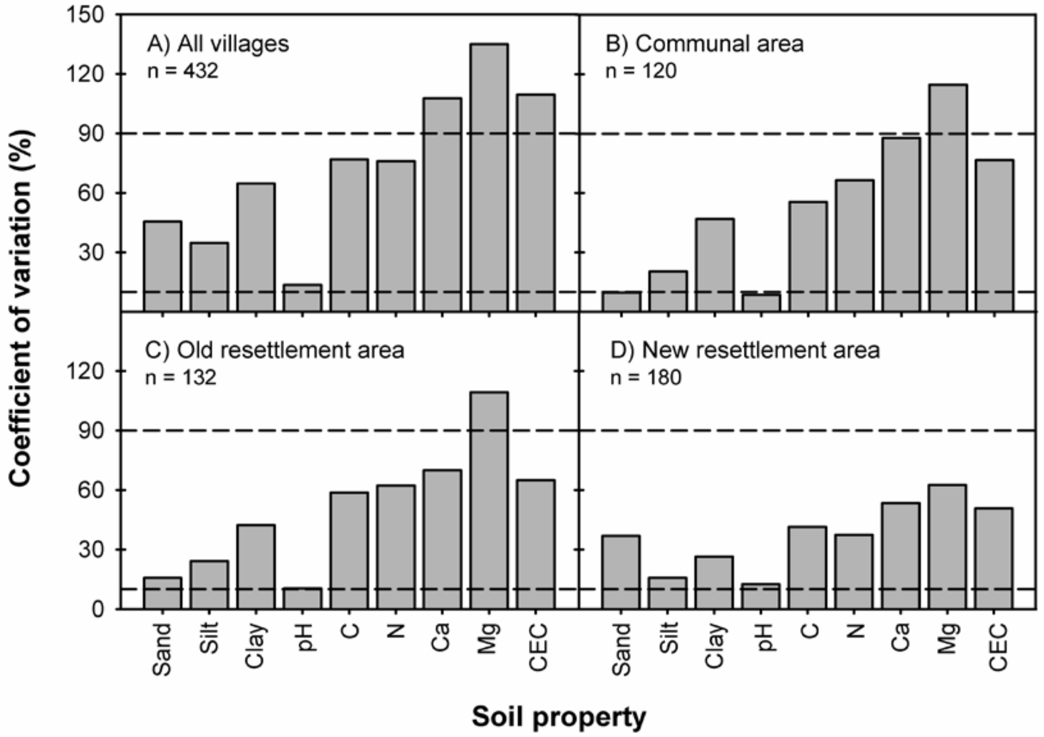

Figure 4.4. Coefficient of variation of soil properties in the entire dataset (A), and in each village under evaluation (B-D). Dashed lines indicate reference values of 10 and 90% for low and high variation, respectively.

Differences in medians among villages for all soil properties were significant at $p<0.001$ (Figure 4.5). Differences were especially evident when the communal and old resettlement areas were compared to the new resettlement area, mainly due to divergent soil textural types (Table 4.1). In fact, the new resettlement area presented the lowest values for sand and the highest for the remaining properties. This is why a Mann-Whitney test was also performed to compare only between the communal and old resettlement area. This analysis showed highly significant differences ($p<0.001$) in medians between these two villages for all evaluated soil properties (Figure 4.5).

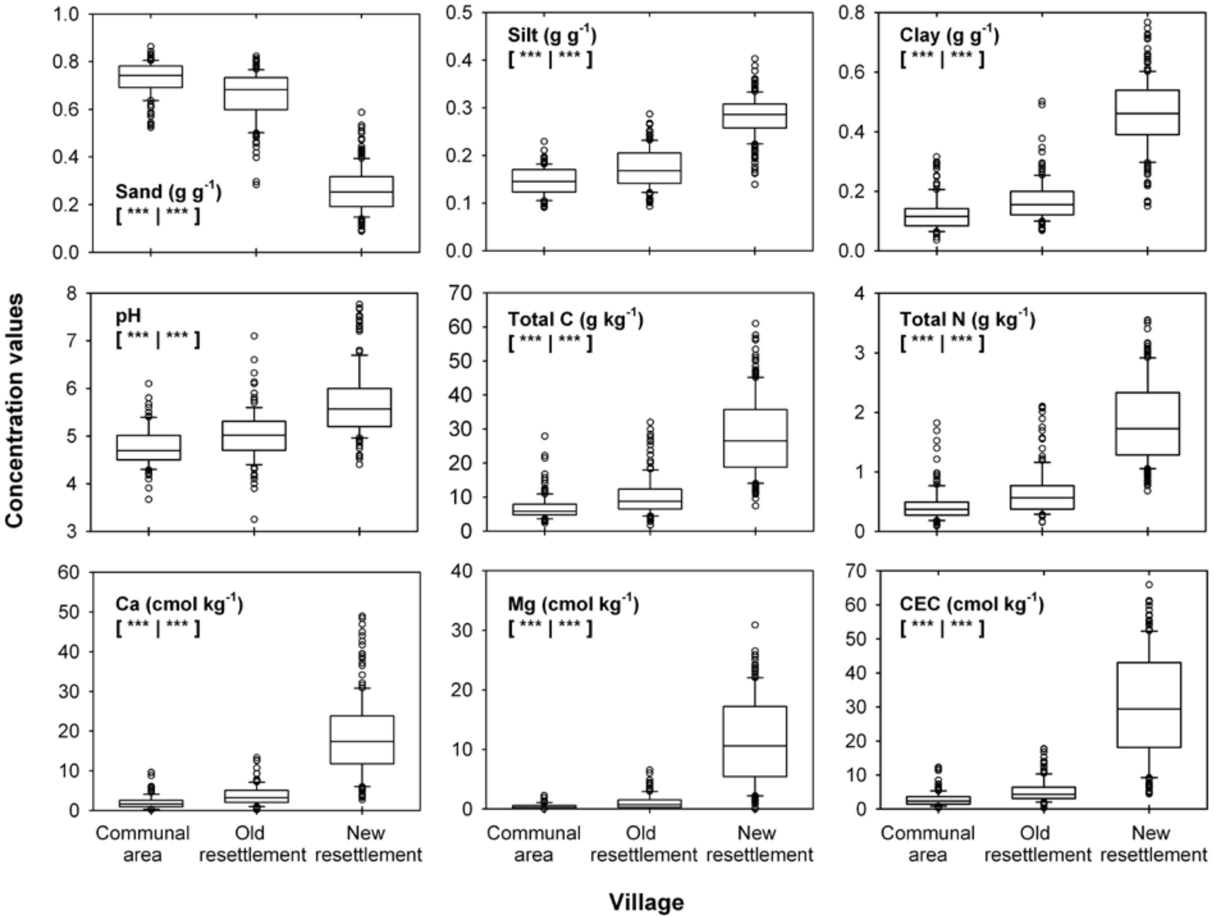

Figure 4.5. Box and whisker plots of soil properties in each village under evaluation, and associated statistical differences (*** : $p<0.001$) according to the [Kruskall-Wallis | Mann-Whitney] tests. Kruskall-Wallis compared medians (horizontal line inside boxes) of the three villages, while Mann-Whitney compared only the communal and old resettlement areas. Number of data as shown in Figure 4.4.

4.5.3. Minimum sample size requirements

Estimated minimum sample sizes, for all evaluated parameters, exhibited a negative exponential trend by increasing the margin of error (Figure 4.6). Taking soil C as an example, a minimum of 473 samples would be required in the communal area to estimate the mean at 5% of its true value; while a minimum of 118, 53, 30 and 19 samples would be necessary at margins errors of 10, 15, 20 and 25%, respectively. With the exception of sand and pH, the required number of samples was found to be lower in the new resettlement area than in the other villages. In general, a higher number of samples would be required for Mg, CEC and Ca, while relatively fewer samples would be necessary for pH, silt and sand.

4.5.4. Geostatistical analyses of generated soil data

Geostatistical analyses require data following Gaussian distribution. Thus, transformation of variables was carried out and this generally allowed to approximate normality. However, for

Mg in the communal and old resettlement areas any transformations used could shift the highly skewed distribution of this variable. This was attributed to the low concentrations measured (Figure 4.5), where a high proportion of samples had null values as they were below analytical detection limits. Approximations to normality in a situation like this is simply not possibly by any mean (Reimann and Filzmoser, 2000); therefore data for Mg must be interpreted with caution for these two areas.

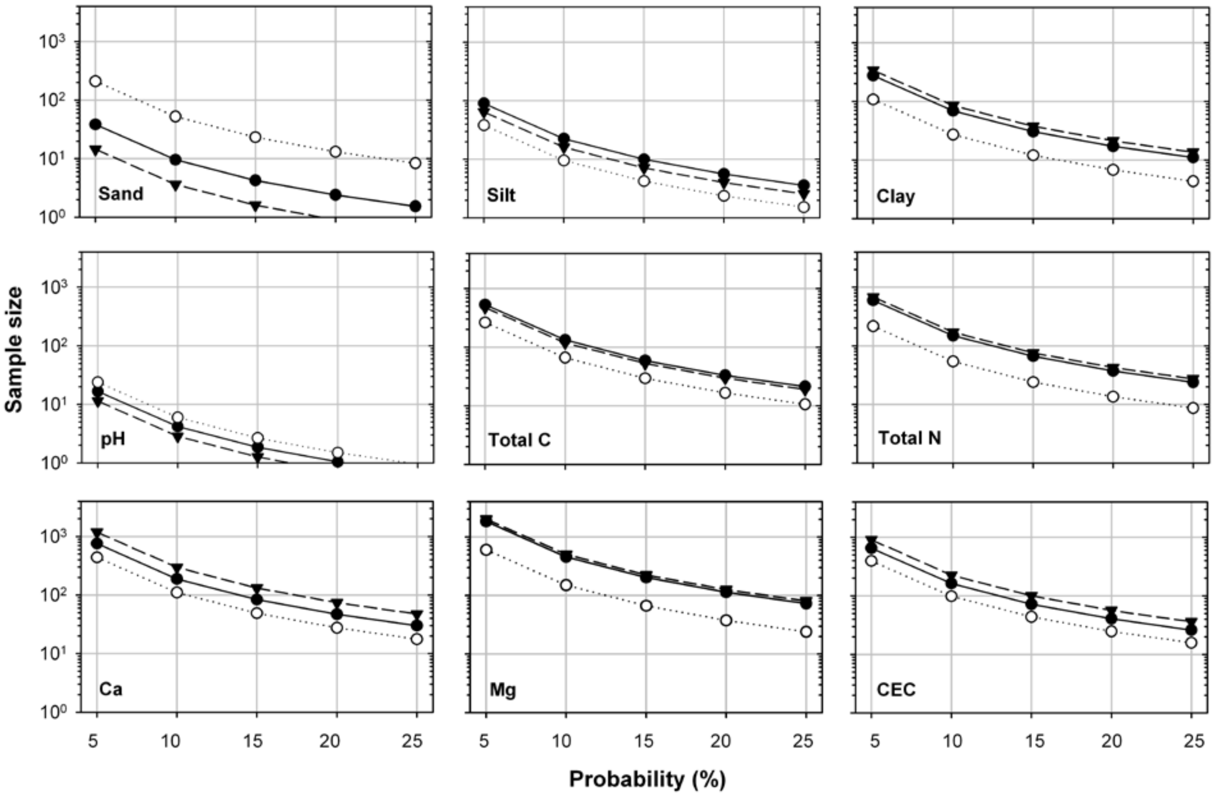

Figure 4.6. Estimated minimum sample sizes required for estimating the mean of different evaluated soil properties at different probabilities of its true value (margin of error), with a 95% of confidence in: communal area (closed triangles), old resettlement (closed circles) and new resettlement (open circles). Notice that Y-axes are in logarithmic scale. Number of data for calculations and units as shown in Figure 4.4.

To determine the grade of spatial dependence of each soil property, the nugget-to-sill ratio from all semivariograms was calculated. According to Cambardella et al. (1994), and since then further applied by many others (e.g. Huang et al., 2006; Rossi et al., 2009; Wang et al., 2009), if this ratio is lower than 25% the spatial dependence is considered strong; if the ratio is between 25-75% the dependence is considered moderate; and if this ratio is higher than 75% the dependence is considered weak. A similar approach was used here, but their moderate range of spatial dependence (25-75%), that in our opinion is quite wide, was subdivided, and the following classes of spatial dependency used: class I (very strong) <25%, class II (moderately strong) = 25-50%, class III (moderately weak) = 50-75%, class IIII (very weak) >75%, and class O (null) = 100%. Hence, spatial dependence of evaluated soil properties was mostly moderately strong to very strong in the new resettlement area; moderate weak to moderately strong in the old resettlement area; and null to moderately weak in the communal area (Figure 4.7, Table 4.3). In fact, in the communal area N and CEC

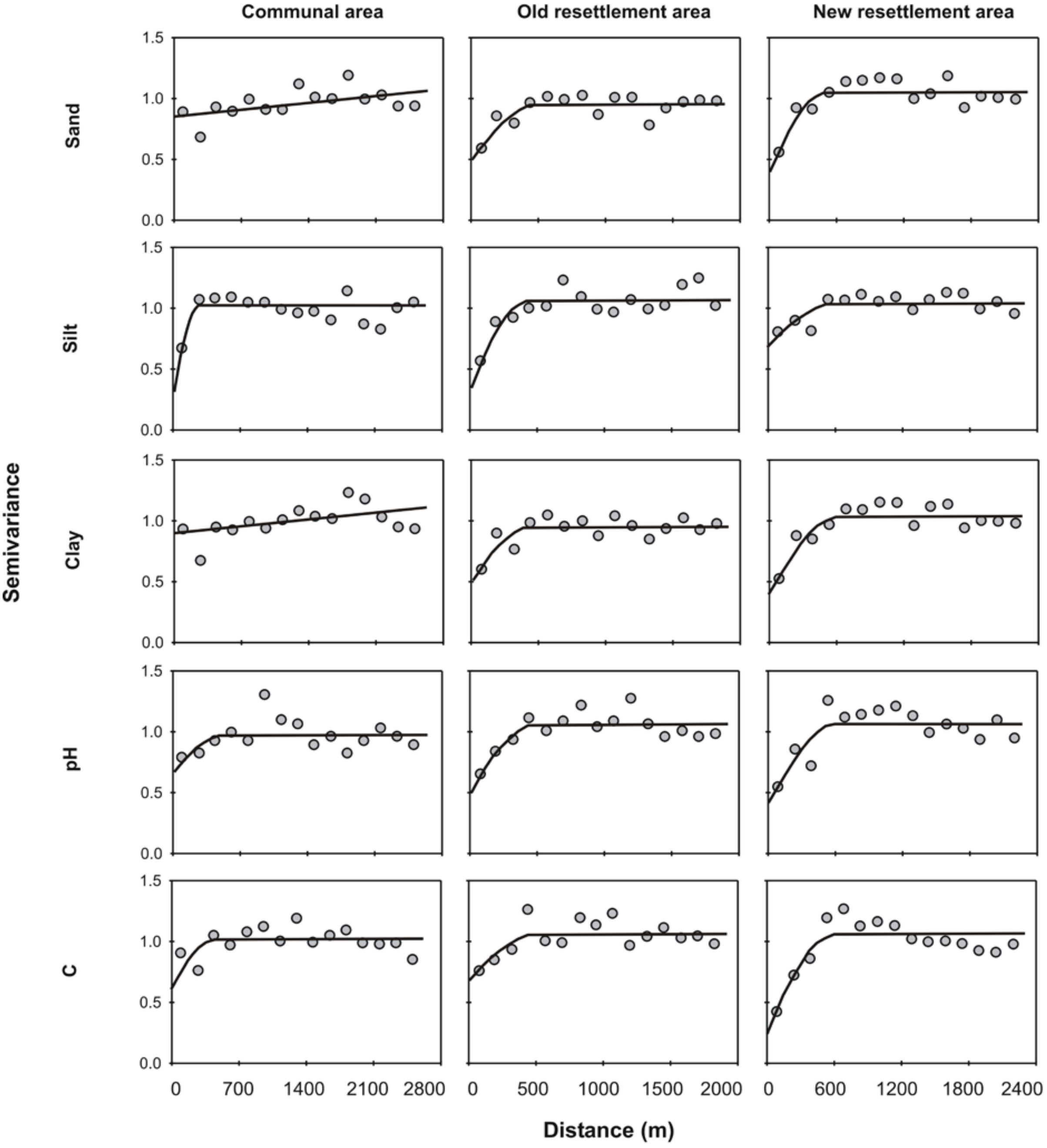

Figure 4.7. Standardized experimental (circles) and theoretical (line) semivariograms for evaluated soil properties in the three areas under study. For model parameters please refer to Table 4.3.

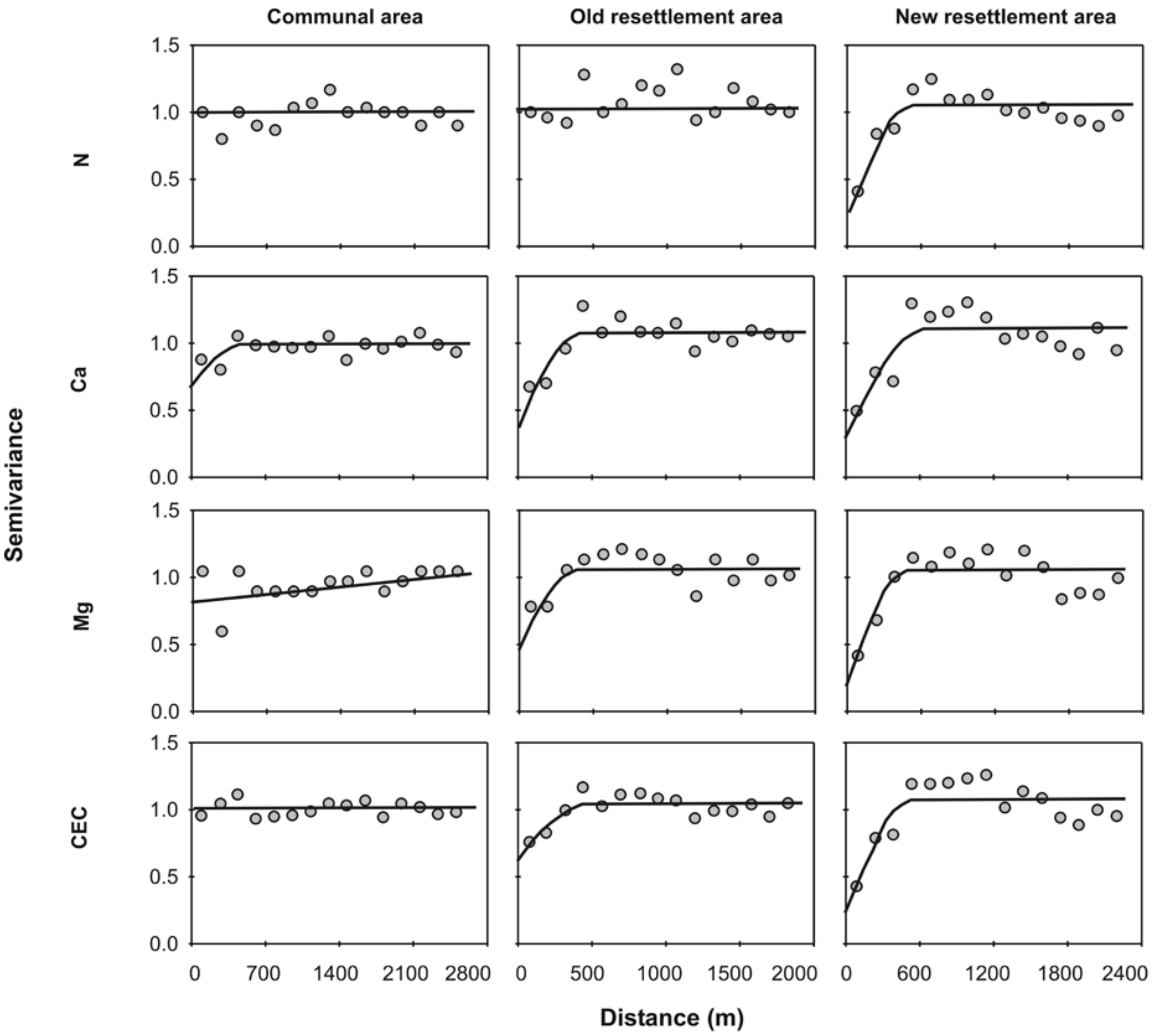

Figure 4.7. Continuation

showed null spatial dependency, while sand, clay and Mg exhibited a linear trend with an undefined spatial autocorrelation at the considered lag distance. From the other two areas only N in the old resettlement area exhibited lack of spatial dependence. All the rest of the cases could be very well represented by spherical models with variable parameters depending on the soil property and area under evaluation. For example, while the nugget-to-sill ratio for Ca was 74% in the communal area (moderately weak dependency), in the old and new resettlement areas this ratio reduced up to 42 and 28% (moderately strong dependency), respectively. This contrasted with silt, as the nugget-to-sill ratio increased from 30 and 34% in the communal and old resettlement area, respectively, up to 67% in the new resettlement area. Ranges of the semivariograms for all soil properties and sites ranged from 250 m (silt in the communal area) to 695 m (clay in the new resettlement). With the exception of Ca, estimated ranges were lowest in the communal area and highest in the new resettlement area.

Table 4.3. Model parameters of standardized theoretical semivariograms of evaluated soil properties in the three villages under study. See Figure 4.7 for a visualization of respective experimental and theoretical semivariograms.

Property	Type of Model	Nugget *Co*	Sill *Co+C*	Range *a* (in m)	*Co/(Co+C)*[#]	Class[&]
Communal area						
Sand	Linear	0.86	1.05	∞	82.1	IIII
Silt	Spherical	0.30	1.01	250	29.7	II
Clay	Linear	0.89	1.09	∞	81.1	IIII
pH	Spherical	0.62	0.97	451	63.6	III
C	Spherical	0.56	1.01	400	56.0	III
N	-	1.0	1.0	∞	100	O
Ca	Spherical	0.72	0.98	527	73.6	III
Mg	Linear	0.86	1.04	∞	82.8	IIII
CEC	-	1.0	1.0	∞	100	O
Old resettlement area						
Sand	Spherical	0.49	0.94	441	51.6	III
Silt	Spherical	0.36	1.06	426	34.2	II
Clay	Spherical	0.48	0.95	415	50.4	III
pH	Spherical	0.51	1.07	484	48.1	II
C	Spherical	0.69	1.06	532	65.2	III
N	-	1.0	1.0	∞	100	O
Ca	Spherical	0.45	1.08	483	41.6	II
Mg	Spherical	0.54	1.09	459	49.8	II
CEC	Spherical	0.61	1.02	386	60.0	III
New resettlement area						
Sand	Spherical	0.42	1.06	506	39.4	II
Silt	Spherical	0.69	1.03	671	67.3	III
Clay	Spherical	0.46	1.05	695	43.7	II
pH	Spherical	0.39	1.08	638	36.2	II
C	Spherical	0.23	1.05	577	21.4	I
N	Spherical	0.23	1.04	517	22.1	I
Ca	Spherical	0.31	1.10	649	28.1	II
Mg	Spherical	0.17	1.05	522	15.8	I
CEC	Spherical	0.25	1.08	604	23.3	I

[#]: Nugget-to-sill ratio (%), [&]: Spatial dependency class: I = very strong, II = moderately strong, III = moderately weak, IIII = very weak, O = null.

4.5.5. Principal components and geo-statistical analyses of MIRS data

Forty nine percent (49%) of overall variability of MIRS data could be explained by the first principal component (PC1), while 11, 10, 6, 4 and 4% could be explained by PC2, PC3, PC4, PC5 and PC6 respectively. Therefore, only the first three components (accounting for 70% of overall variability) were retained, and their scores correlated to concentration values on reference samples. In general, PC1 related very well to texture fractions, C, N, Ca and Mg (absolute Spearman coefficient values of 0.55-0.96, Figure 4.8); while relationships between PC2 or PC3 with analyzed soil properties were weaker (0.39-0.69) or mostly non significant (0.01-0.27), respectively (data not shown).

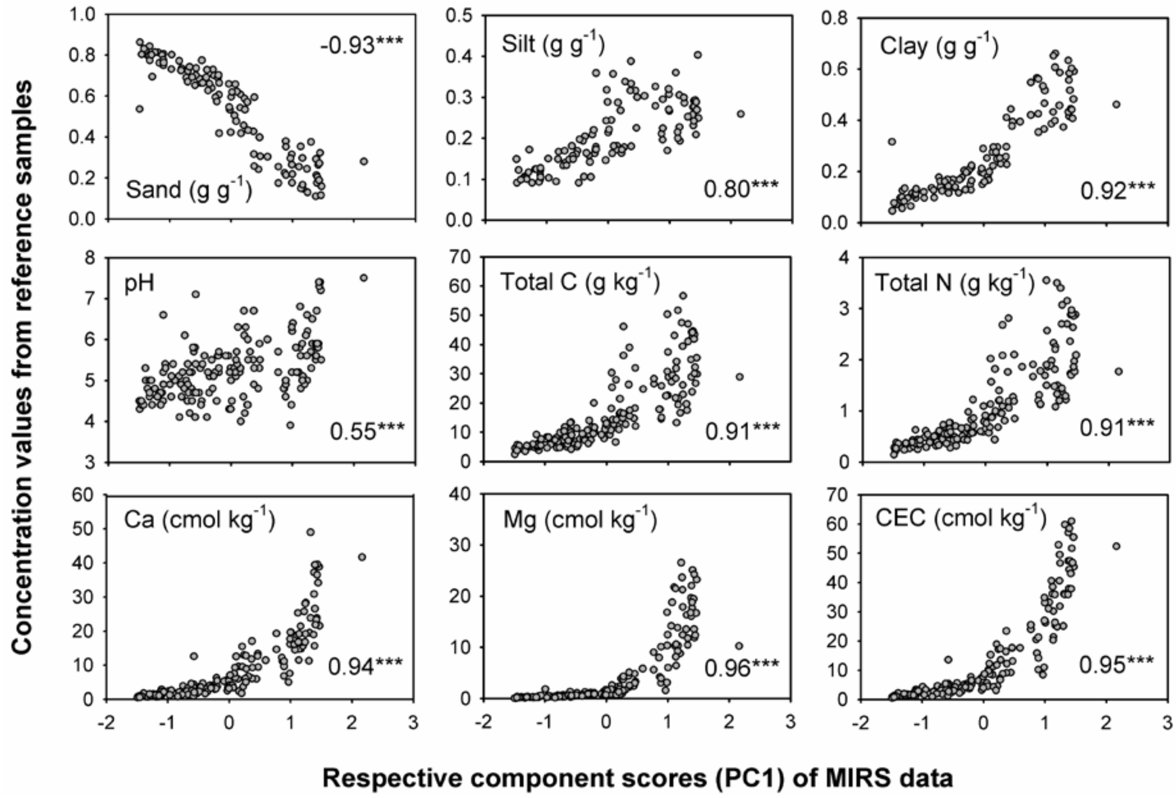

Figure 4.8. Scatter plots and Spearman correlation coefficients for the relationships between soil properties from reference samples (i.e. analyzed by conventional laboratory procedures) and respective component scores of the first principal component (PC1) based on MIRS data. ***: $p<0.001$.

Standardized semivariograms based on the principal components were usually represented very well by spherical models, with variable parameters according to the component and village. PC1, however, showed a linear trend in the communal area, indicating an undefined spatial dependence at the considered lag distance. In fact, semivariograms showed mainly that spatial dependence was usually moderately strong to very strong in the new resettlement area; moderate weak to moderately strong in the old resettlement area; and very weak to moderately weak in the communal area (Figure 4.9, Table 4.4). Ranges of these semivariograms were 399 m (in the communal area), 161-481 m in the old resettlement area, and 604-744 m in the new resettlement area.

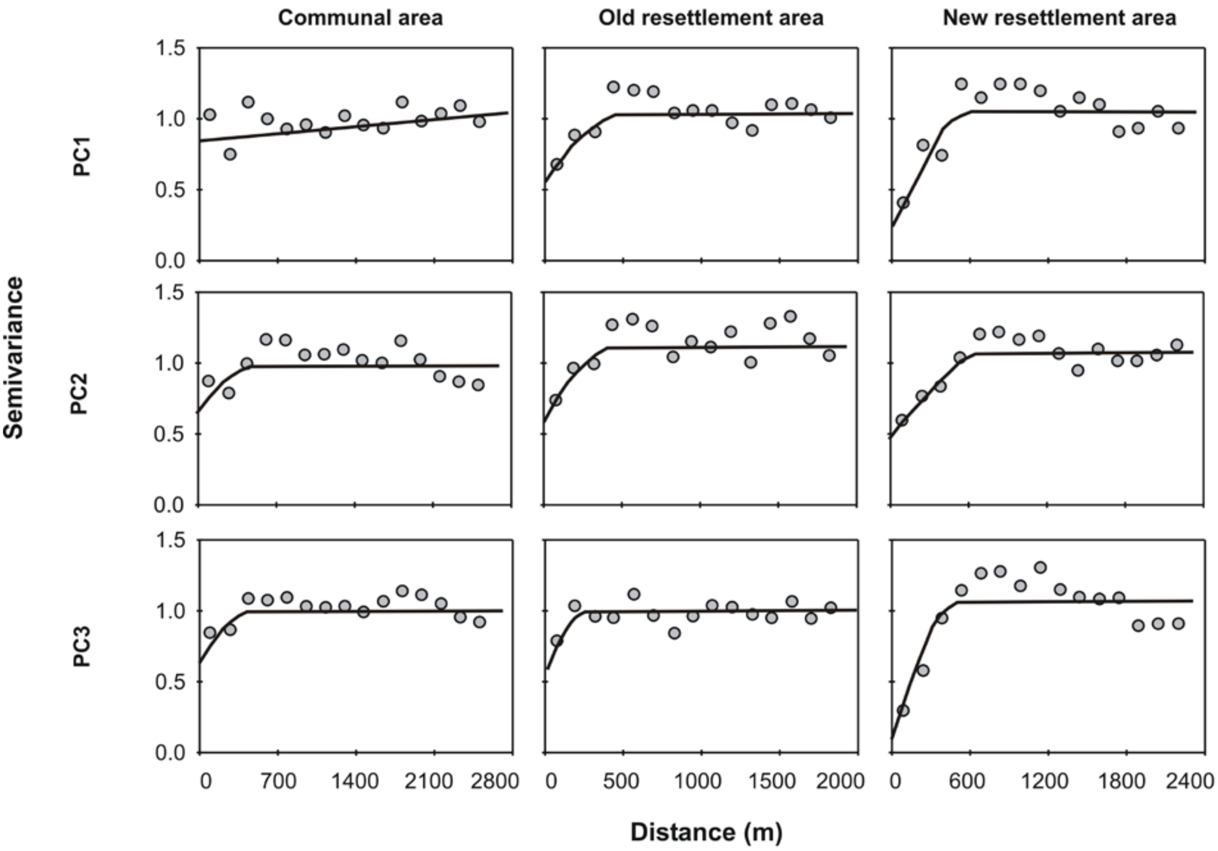

Figure 4.9. Standardized experimental (circles) and theoretical (line) semivariograms for the three first principal components based on MIRS data from all soil samples collected in the three areas under study. For model parameters please refer to Table 4.4.

4.6. Discussion

4.6.1. MIRS and Geostatistics: a viable combination?

This study clearly illustrated that MIRS can be successfully used for complementing large soil datasets required for spatial assessments at landscape level. Furthermore, it was demonstrated that spectral information from MIRS, after principal component analyses, could be directly integrated in geostatistical analyses without the need of a calibration/validation step. Effectively, MIRS proved its potential in predicting most of the soil properties under evaluation; although the technique was not sensible for all properties. This was evident for silt, P_{av}, K and Al which presented inadequate MIRS models. Therefore, predictions for these variables could not be carried out and semivariograms were not constructed due to limited number of data. Working with different soils in Vietnam, and by using the same MIRS methodology and equipment, Schmitter et al. (2010) found, conversely, acceptable models for silt and K; while their models for clay and CEC were inadequate (P. Schmitter, personal communication, 2009). Hence, applicability and efficacy of MIRS is dependent of the soil type and/or location, and illustrates why regional calibrations are still required for a successful prediction of soil properties (McBratney et al., 2006; Shepherd and Walsh, 2004). These issues limit a generic applicability of MIRS in the prediction of soil variables for agro-ecological assessments. Some advances in the development of global calibrations, however, have been achieved in the last few years (Brown et al., 2005; Cécillon et al., 2009), which should help to overcome this limitation in the near future. Alternative solutions could be the use of MIRS-based predictions models to estimate through pedotransfer functions those soil properties that cannot be predicted accurately by sole MIRS (McBratney et al., 2006), or the utilization of auxiliary predictors (i.e. simple and inexpensive conventional soil parameters, like pH and sand; or from complementary sensors, like NIRS) which can improve the prediction of other soil properties (Brown et al., 2005). Thus, all data could be later used in spatial analyses without restriction.

Table 4.4. Model parameters of standardized theoretical semivariograms of the three first principal components from MIRS data of the three areas under study. See Figure 4.8 for a visualization of respective experimental and theoretical semivariograms.

Property	Type of Model	Nugget *Co*	Sill *Co+C*	Range *a* (in m)	*Co/(Co+C)*[#]	Class[&]
Communal area						
PC1	Linear	0.94	1.03	∞	90.9	IIII
PC2	Spherical	0.59	1.01	399	58.7	III
PC3	Spherical	0.60	1.03	399	58.0	III
Old resettlement area						
PC1	Spherical	0.54	1.05	481	51.0	III
PC2	Spherical	0.59	1.15	479	51.1	II
PC3	Spherical	0.41	0.99	161	41.0	II
New resettlement area						
PC1	Spherical	0.20	1.10	606	18.3	I
PC2	Spherical	0.45	1.10	744	41.0	II
PC3	Spherical	0.05	1.11	604	4.6	I

[#]: Nugget-to-sill ratio (%), [&]: Spatial dependency class: I = very strong, II = moderately strong, III = moderately weak, IIII = very weak.

Semivariograms based on the soil dataset clearly showed that spatial autocorrelation of most soil properties in the villages followed the order: communal area < old resettlement < new resettlement. Variography analyses based on the principal components from MIRS data showed very similar spatial patterns. This implies important savings in terms of analytical costs and time, as it creates the possibility of a broad and quick assessment of soil spatial variability at landscape scale based only on MIRS, confirming previous suggestions by

Shepherd and Walsh (2007) and complementing studies based on NIRS (i.e. by Awiti et al., 2008; Cohen et al., 2006; Vågen et al., 2006). A related approach to our study, but at plot level and by using NIRS, was carried out by Odlare et al. (2005). However, they found out that spatial dependence from principal components (based on spectral information) was not related to the spatial dependence from considered soil properties (i.e. C, clay and pH). Hence, although spatial variation based on NIRS could be identified, the authors did not know what the variation represented. Thus, to properly understand the meaning of the spatial structures from the principal components it is necessary to link the component scores to soil parameters of reference samples. In our case, this was possible for the first principal component (PC1), which was well related to textural fractions, C, N, Ca, Mg and CEC. Therefore, PC1 was clearly associated to soil fertility, and consequently, derived spatial results could be used for distinguishing areas of different soil quality. However, for PC2 and PC3 simple relationships with measured variables were not evident. A reason for this may be related to the explained variance in each component, where PC1 accounted for 49% of the overall variability, while the other two components each explained a lower proportion (10-11%). The unexplained variance and lack of relationships for the other components suggests that MIRS captured additional characteristics of soils, which this study did not take into account (e.g. carbonates, lime requirements, dissolved organic C, phosphatase and urease activity, among others). In fact, MIRS can be related to a wide range of physical, chemical and biological soil characteristics (for further details please refer to Shepherd and Walsh, 2007; and Viscarra-Rossel et al., 2006). All this would further suggest that MIRS may present great potential as an integrative measurement of soil status and, hence, could be a valuable tool for characterizing spatial variation of soils.

4.6.2 Analyses of spatial patterns

Nearly all experimental semivariograms of soil properties were very well described by the spherical model, with a reachable sill, which clearly indicates the presence of spatial autocorrelation. However, some of the semivariograms in the communal area (for sand, clay, Mg and PC1), could only be described by a linear model with an undefined spatial dependence. If there is no reachable sill this could indicate that spatial dependence may exist beyond the considered lag distance (Huang et al., 2006). Semivariograms for N and CEC in the communal area, and N in the old resettlement showed instead pure nugget effect. Pure nugget effect can represent either extreme homogeneity (all points have similar values) or extreme heterogeneity (values are very different, in a random way). Nevertheless, pure nugget effect do not compulsory reveal spatial independence, as spatial structure may be present but at lower resolution than our minimum sample distance (that in our case was 30 m) (Davidson and Csillag, 2003). In any case, a high nugget effect would imply higher uncertainty when further interpolation is necessary (e.g. by using Kriging). In such circumstances, calculating the mean value from sampled locations would be enough for interpolation, as no spatial structure could be detected at the scale of observation. Finding no spatial dependence for some soil parameters is not an unusual result, as its magnitude (from strong to null dependency) can vary as a function of the soil property and location, among others factors (Garten Jr. et al., 2007).

As indicated before, spatial dependence (either based on soil properties or on MIRS data) was in general lowest in the communal area and highest in the new resettlement. Although the reasons for these differences are not completely understood, since our experimental design did not allow a proper separation of causal factors, direct and indirect evidence suggest some potential drivers that nevertheless need to be corroborated in future studies. For example, it is generally accepted (Cambardella et al., 1994; Liu et al., 2004; Liu et al., 2009; Rüth and Lennartz, 2008) that a strong spatial dependency of soil properties is controlled by intrinsic factors, like texture and mineralogy; while a weak dependence is attributed to extrinsic factors, like farmers' management (e.g. fertilizer applications). Thus, in terms of intrinsic factors, spatial dependence seems to follow the particular textural classes and inherent soil quality of each area. On the other hand, in Chapter 3 was shown that investments in soil fertility and land management in cropping fields was higher in the communal area than in the two resettlement areas, which would supports the idea of extrinsic factors also acting accordingly. Moreover, the communal area presents a higher population density than the other two areas and has been under exploitation since the late 40s; while the old and new resettlement areas were only redistributed to local people in the late 80s and early 2000, respectively. This would suggest a higher grade of disturbance of natural resources in the order: communal area > old resettlement > new resettlement, which would also affect correspondingly the spatial variability of soil properties. The coefficient of variation of evaluated soil properties seems to support this, as (with the exception of pH and sand) usually the highest CVs were obtained in the communal area, while the lowest values were found in the new resettlement. However, despite this global trend, no clear relationships were found between the CVs and their respective spatial variability parameters, which indicates once more that only part of the variation could be explained. Similar observations between CVs and spatial variability parameters have been reported by Gallardo and Paramá (2007).

4.6.3. Relevance of findings for future sampling designs

Knowledge of sample sizes for each soil property and village presented in this study could be used as a guide for better planning sampling designs at landscape scale in areas of similar conditions, as it helps to estimate approximate minimum number of samples that must be taken in each location for achieving a predetermined level of precision. These data, however, do not indicate how samples should be distributed in space. Derived ranges from variography analyses complement very well this information. They indicate the adequate sample distances among points for obtaining spatially-independent samples (i.e. that distance that exceeds the ranges of the semivariograms), as better results are obtained when samples are not autocorrelated (Rossi et al., 2009). However, if a high level of precision is required, collection of spatially-independent samples may be problematic, especially for those properties exhibiting high ranges, due to the potential difficulty of arranging a high number of samples at the required (i.e. long) separation distances. For example, for C assessments, if a 5% of error is selected, a minimum of 264 samples should be distributed at >577 m of separation among each other in the new resettlement, which is simply not possible if we consider the same spatial domain. Nevertheless, at 10% of error, only 66 samples are needed, thus their distribution in the same area is feasible. In the case of sand, clay, N, Mg and CEC for the communal area, and N for the old resettlement, samples could be placed at random instead, as these properties showed pure nugget effect. Data for pH, on the other hand, should be cautiously interpreted, as it is already in a logarithmic scale; hence, not surprisingly it showed the lowest CVs and minimum sample sizes. If the intention of the sampling is to characterize again the spatial variability within villages, results indicated that a sampling distance of 30 m is acceptable for the new resettlement; but lower distances may be necessary for the communal and old resettlement to be able to capture shorter-range variability which this study was not be able to detect. In any case, care is required if direct extrapolation of sampling sizes and ranges to other scales is carried out (e.g. at plot or national levels), as spatial dependence usually differ with the scale (Cambardella et al., 1994).

4.7. Conclusions

Results from this study clearly showed that required large soil datasets can be built by using MIRS for the prediction of several soil properties, and later successfully used in geostatistical analyses. However, it was also illustrated that not all soil properties exhibit a MIR spectral response, and those ones who were well predicted (i.e. sand, clay, pH, C, N, Ca, Mg and CEC) usually depend on the success of regional calibrations. As a new approach, it was demonstrated that MIRS data can be directly integrated, after principal component analyses, in geostatistic assessments without the necessity of calibration/validation steps. This approach is very useful when time and funds are limited, and when a coarse measure of soil spatial variability is required. However, principal components must be associated to soil functional characteristics to be able to explain the results, as it was demonstrated with the soil properties considered in this study. Understanding variability of soils and its spatial patterns in these three contrasting areas brought out also important recommendations for future sampling designs and mapping. By combining information about minimum sample sizes, with corresponding reported ranges from the semivariograms, a better efficiency (in terms of time, costs and accuracy) during sampling exercises could be obtained. Hence, it is concluded that MIRS and geostatistics can be successfully integrated for spatial landscape analyses and monitoring. A similar approach would be very valuable in regional and global soil fertility assessments and mapping (e.g. Sanchez et al., 2009b) and carbon sequestration campaigns (e.g. Goidts et al., 2009), where large soil sample sizes are required and uncertainty about sampling designs prevail.

CHAPTER 5

GENERAL DISCUSSION

5. GENERAL DISCUSSION

5.1. Are all African land use systems threatened by soil nutrient mining?

The review on nutrient balances in Africa (Chapter 2) clearly indicated that the majority of land use systems evaluated of the continent suffered from N and K mining, as balances for these nutrients were predominantly negative. Nevertheless, in the case of P, the situation was less noteworthy, as just around half of the studies had negative mean P balances. Nutrient mining, however, may not only be restricted to N, P and K. Other nutrients could also being mined (or not) by agriculture activities, like Ca, Mg and S, and even C, which could be currently limiting the productivity of several African agro-ecosystems (Bationo et al., 2004). For example, in Zimbabwe deficiencies of S in soils are frequent (Nyamapfene, 1991) and Mg has been shown to strongly limit maize productivity on continuously cropped sandy soils (Mapfumo and Mtambanengwe, 2004). Likewise, soil organic C in most African lands is inherently low (<30 mg kg^{-1}) and is declining due to continuous cultivation, which seriously threatens soil productivity (Bationo et al., 2006). Unfortunately, there is limited information available on the balances of these nutrients across Africa. This was actually indicated in Chapter 2, where only 7 studies (from 57) worked with Ca and Mg, 4 considered C, and just one considered S. This suggests, that more research on other nutrients is needed, as it would bring important complementary information about the extent of nutrient mining in the continent. The derived message from these findings is that the usual narrative of a generalized soil nutrient mining in Africa (e.g. Smaling et al., 1997) would broadly apply for N and K, but not necessarily for P and other nutrients. Effectively, the review also indicated the existence of several particular cases where nutrient balances were positive, especially for P (Figure 2.1). This clearly indicates that, despite the general trends, there are successful experiences of farmers overcoming soil nutrient mining in Africa, corroborating argument of other researchers (De Ridder et al., 2004; Mortimore and Harris, 2005; Muchena et al., 2005; Vanlauwe and Giller, 2006). One could analyze each case individually to try to reveal the reasons of this success. However, generalizations would be hampered by methodological differences among nutrient balances studies, as well as by the high variability of the farmers' systems involved (e.g. diverse biophysical conditions of each system and the heterogeneous nutrient management strategies of each farmer, even within the same farm). In spite of this, some typical examples of positive cases can be usually found in wealthy farmers' fields, plots near to homestead, gardens and intensive production systems where a relatively higher investment in soil fertility is usually carried out. It is important, however, to consider that not all positive nutrient balances are beneficial, since excessive nutrient accumulation could lead to pollution risks. This was evident in the study of Graefe et al. (2008), where the use of wastewater for the irrigation of urban and peri-urban gardens in Niger raised N, P and K partial balances up to +7.3, +0.5 and +6.8 Mg ha^{-1} yr^{-1}, respectively.

Excessive nutrient accumulation cases are not very common in Africa but in countries like China and in several European states, due to the excessive use of fertilizers in production systems, which has lead to the development of strict policies in these regions to restrict environmental pollution (Smaling et al., 1999b; Vitousek et al., 2009). Policies in Africa, in contrast, must support the use of more nutrients and management practices leading to increase soil organic matter, in a framework that also targets food security objectives, especially during early agriculture development stages (Vitousek et al., 2009). It is clear that nutrient mining in Africa will continue being critical if access to nutrients is not appropriately resolved in the next years. Therefore, tackling soil fertility depletion as a direct threat to food security, together with the facilitation of the political environment in the region and the diversification and intensification of land uses, are essential factors for a sustained development in the continent (Bationo et al., 2006; Sanchez and Leakey, 1997). Some options aiming these goals are the re-introduction of subsidies in fertilizers prices and transportation costs at the farm gate (Kinyanjui et al., 2000); the development of local fertilizer sectors and the promotion of farming practices leading to increase nutrient use efficiencies (Bationo et al., 2006); the higher use of high value crops and agro-forestry (Sanchez and Leakey, 1997); the facilitation of micro-credits to farmers for buying fertilizers and seeds (Smaling and Toulmin, 2000); and a better infrastructure on rural areas, the improvement on farmers’ land tenure, education and social capital building, as well as farmers’ access to competitive markets and efficient extension services (De Jager, 2005; Sanchez and Leakey, 1997). This clearly indicates that interventions for reversing soil fertility depletion must be multi-sectorial (Muchena et al., 2005); and also suggests that a proper implementation of these technologies and policies on the ground (De Jager, 2005; Kinyanjui et al., 2000) would determine the future sustainability of African agro-ecosystems. Future research should therefore consider soil nutrient mining not only within the farmers’ domains at plot, farm or village scales, but also from organizational, institutional and policy perspectives at regional, national and supranational levels; and in this context issues of scale make clear relevance.

5.2. How do issues of scale and spatial variability affect nutrient balance estimations?

Nutrient balances as indicators of land degradation have been used at different spatial scales, covering practically the whole spatial hierarchy (i.e. from plot to continental level). A bias, however, has been indicated in Chapter 2 (Table 2.2) regarding the scale at which balances have been predominantly calculated, i.e. at plot and farm level. This is understandable, due to the difficulties in scaling-up nutrient flows and balances (as it will be discussed further below), and due to the fact that at these levels resource management by farmers can be practically influenced (Defoer et al., 1998). Nevertheless, more information at different scales is necessary to be able to reach other users (e.g. policy makers and institutions), and this is one of the main reasons why scaling-up is necessary (Bindraban et al., 2000). In this case, scaling-up methods must be properly chosen for obtaining spatial-specific characteristics of the system being analyzed (Oenema and Heinen, 1999; Schlecht and Hiernaux, 2004). Because of the typical diversity and heterogeneity of African farming systems, an important effect to consider by scaling-up nutrient flows and balances is that zones of nutrient depletion and accumulation, as well as other potential important bio-physical and socio-economical conditions are masked, i.e. information is lost (FAO, 2003; Haileslassie et al., 2007). Then, resulting estimates could not be fully representative of essential attributes of the system being analyzed, and this may affect the results of potential interventions to be taken (Scoones and Toulmin, 1998). In fact, by increasing the scale of evaluation, complexity of systems rises and therefore accuracy and reliability of nutrient balances generally decreases (Figure 5.1).

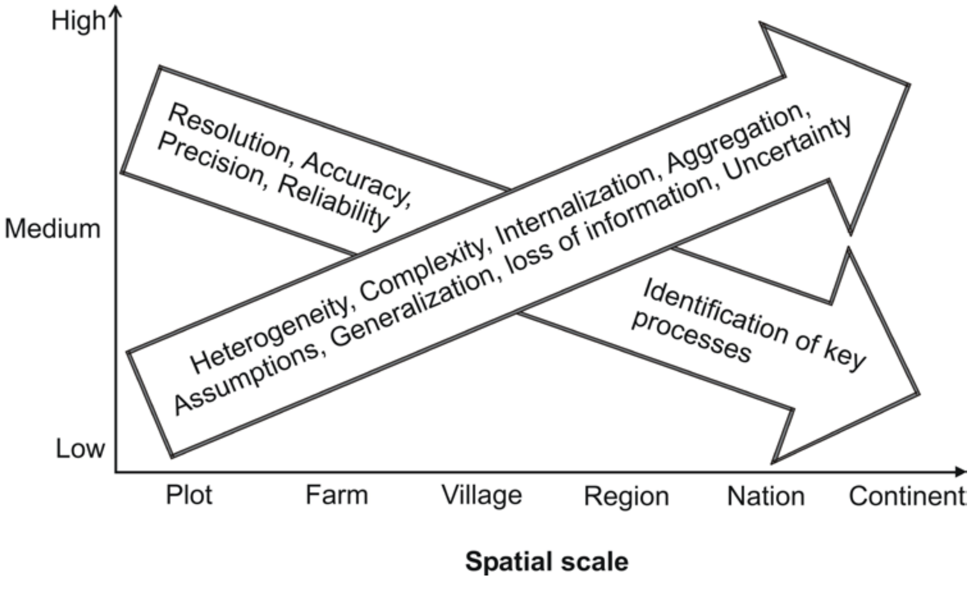

Figure 5.1. Schematic representation of how processes and system's characteristics are affected by the spatial scale when nutrient flows and balances are scaled-up from plot to continental level.

The analysis of selected studies and literature in Chapter 2 showed that scaling-up has been realized by using three broad approaches. Firstly, scaling-up is carried out from plot to farm or to village/watershed level. This approach uses the plot as the primary unit of analysis and further extrapolation, although the different plots or administrative units within the farm (or the farm per se) could be also used. Results are typically not made spatially-explicit. Secondly, scaling is done at the level of province, district, region or agro-ecological zone. This is done by scaling up data from the previous levels or by disaggregation of data from upper levels, as few data at the required resolution are available. Results are usually not made spatially-explicit. Finally, scaling-up is done to the national, supra-national or continental level. In this approach, land use classes or grids belonging to specific land uses are used as the primary spatial units over which calculated flows are later extrapolated to the respective scale. Results sometimes are made spatially-explicit. The problem with most of these approaches is that minimalistic methods are usually performed during the scaling-up process (e.g. Schlecht and Hiernaux, 2004). It is obvious that if data are extrapolated to another scale by using unsuitable scaling-up methods, results will be highly inaccurate and largely uncertain. For example, as explained in Chapter 2, aggregation of flows is usually carried out in a linear way and internalization of flows across scales is not always performed. It was also shown how spatial heterogeneity is typically neglected inside spatial boundaries, and that lateral flows are regularly excluded from calculations once spatial-temporal boundaries are established. There is also a big difference according to the type of primary spatial units used (plots, production units, grids), as heterogeneity and interaction of flows inside spatial boundaries change accordingly (e.g. van Noordwijk, 1999). Unfortunately these issues, though fundamental in multi-scale environmental research (e.g. Kok and Veldkamp, 2001; Urban, 2005), have not been appropriately addressed yet in nutrient balance studies. Studies on nutrient balances could learn from other disciplines such as ecology, physics or economy where some advances in scaling-up issues have been achieved in the past decades (Dalgaard et al., 2003). Issues of scale and spatial variability on nutrient balance estimations suggest that scaling-up procedures, as currently used in practice, may generate higher errors than those produced by the original estimations of flows at the primary spatial units, making the results at the final scale highly uncertain. This is worrying, as nutrient balance results have been used for policy formulation and interventions aiming soil fertility depletion at national and supranational levels in Africa (e.g. Kinyanjui et al., 2000; Scoones and Toulmin, 1998). Hence, if nutrient balances results from meso and macro-level studies have been inaccurate, formulation of policies and respective interventions based on these outcomes may also be flawed. In fact, former predictions of an imminent collapse of African farming systems (Smaling et al., 1997; Stoorvogel and Smaling, 1990) have been proven wrong in the last decade (e.g. Færge and Magid, 2004; Muchena et al., 2005; Vanlauwe and Giller, 2006). Thereby, there is an urgent need for basic research on scaling-up nutrient flows and balances (i.e. tackling the issues previously mentioned in this section and in Chapter 2), for being able to present accurate messages to all stakeholders, especially to those acting at high spatial scales (e.g. policy makers and institutions).

5.3. Is the nutrient balance approach a suitable indicator of soil mining in Africa?

The review presented in Chapter 2 clearly showed that the nutrient balance approach has been extensively used as an indicator of soil mining in the continent. However, the majority of studies came from West Africa, which would indicate that knowledge on the topic and derived perceptions may be geographically biased. In fact, most of the pedotransfer functions for calculating environmental flows (e.g. in NUTMON) have been developed in this region, but regardless of this, functions have been frequently applied to other African conditions without the correspondent validation (Færge and Magid, 2004). Gathered information also clearly indicated that the nutrient balance approach have made the evaluation of the condition of different land use systems in the continent possible and in a relatively easy way, especially if a partial balance approach is used (e.g. Chapter 3). Results from partial balances are usually less negative than corresponding results from full balances, as the later includes additionally environmental flows, which are more difficult to assess. Therefore full balances bring along a higher uncertainty (Zingore et al., 2007). In fact, the literature review and the analyses of selected studies in Chapter 2 suggest that several methodological complexities are still present, which are typically addressed differently by each researcher (e.g. nutrients considered, differences on setting of spatial-temporal boundaries, the arbitrary inclusion/exclusion of flows from the calculations, use of different pedotransfer functions for calculating flows, different scaling-up procedures, etc.). The different approaches usually vary according to the objectives of the study and the scale of the evaluation, as well as the availability of resources and data (FAO, 2004; Scoones and Toulmin, 1998).

An indicator is a “descriptor that represent a condition and convey information on changes or trends in that condition” (Dumanski et al., 1998). Therefore, an ideal indicator of soil fertility decline should be able to monitor the dynamic of soil status across different spatial scales and across time, while being relevant in relation to agricultural productivity (Bindraban et al., 2000; Smaling and Dixon, 2006). Previous discussion in Section 5.2 showed that, in fact, nutrient balances can be calculated at different scales, but it was also pointed out that scaling-up methods are still incipient to obtain accurate results at higher spatial levels. Hence, data at higher scales may be better presented as broad qualitative classes while suitable scaling-up methods are developed. The nutrient balance approach also allows performing assessments across different seasons or years, but may fail to show the dynamics of evaluated systems. The use of modeling in nutrient balance studies has been thereby proposed for assessing this dynamic (Schlecht and Hiernaux, 2004); although there is still a lot to achieve, especially in incorporating residual effects, lateral flows and the consequences of the different stakeholders in the system (see chapter 2). For being meaningful, results of nutrient balances must be also related to soil nutrient stocks, as fertile soils under negative nutrient balances can still support cultivation for several seasons; and usually farmers are aware of this opportunity and by ‘short-term’ thinking, they generally make use of it (e.g. farmers in the fertile new resettlement area, Chapter 3). Another important issue relates to the improper presentation of the results for nutrient balance studies. In several cases, the methodology for estimating the flows and their scaling-up are not properly described, which limit any replication of the research. Failing in reporting the units of balances can also be found. Units of nutrient balances, by definition, must circumscribe a spatial-temporal dimension; but in practice this is not always the case (Table 2.1). Moreover, usually a measure of dispersion or error does not accompany the nutrient balance results. In this situation, it is simply impossible to determine how variable the estimations were and to establish their uncertainty.

Methodological differences among studies and failing in interpretation and presentation of results do not invalidate the nutrient balance approach, especially when used for comparing different conditions or management strategies within the same study. In fact, nutrient balances “do reveal options to improve land quality and productivity” (Bindraban et al., 2000) and without them “it will be difficult to develop and sustain modern agricultural systems without incurring continuing human and environmental costs”, i.e., from nutrient mining or pollution (Vitousek et al., 2009). However, as diverse approaches are usually performed, comparisons among different studies and scales are difficult, even under the same agroecosystem (Janssen, 1999). Thereby, a standardization of the methodology is strongly recommended, and as stated in Chapter 2, a parallel check of the results from nutrient balances (e.g. with carbon stocks involved) is also suggested. Editors and reviewers in earth sciences and other disciplines (like environmental modeling, economy or policy) should also share responsibility with scientists on the proper report of nutrient balance estimations, as current literature still include several methodological errors and fails during interpretation and presentation of results.

5.4. How do nutrient management strategies of small-scale farmers change across plot types and farmers' typologies?

As was clearly demonstrated in Chapter 2, the magnitude of nutrient balances in plots nearer to farmers' homesteads (i.e. infields) are usually higher than balances from plots located relatively farther away (i.e. outfields). This is due to the fact that allocation of inputs and labor is facilitated in the closer fields (Tittonell, 2003). Hence, usually lower soil fertility with increasing distance from the homestead is found (i.e. soil fertility gradients), and crop production generally responds to this variability (Giller et al., 2006). In fact, data presented in Chapter 3, showed that farmers in the communal area allocated preferentially their nutrient resources (e.g. mineral fertilizers, animal manure) in plots closer to the homestead, while those plots farther away typically received less inputs. Thus, not surprisingly soil nutrient mining was lower and crop productivity was higher in infields than in respective outfields. Observations made by Tittonell et al. (2007) further indicated that even if no significant differences in nutrient inputs or soil nutrient contents between plot types were found, variations in crop management (e.g. planting time, plant density) and the preferential allocation of labor can determine a higher crop productivity of infields in comparison with outfields (i.e. management intensity gradients). Nevertheless, exceptions to these spatial patterns of resource use and nutrient mining can also be found (i.e. Figure 2.2), as depending on availability of nutrient inputs and labor, farmers may want occasionally to adjust this within-farm heterogeneity and therefore invest resources in the more distant fields (Tittonell et al., 2007). Although this practice may be seen as ineffective by outsiders, farmers typically have their own particular strategies as a response to challenging situations and usually act in a way that they can see a return from (Stocking, 2003). In the old and new resettlement areas evaluated in Chapter 3, on the other hand, the concept of infields and outfields is apparently inexistent as usually all cropping fields are located away from homestead. Therefore, 'distance from homestead' is usually not consider by farmers as a factor driving resource allocation in these areas (see next point for further details on this issue).

Nutrient balances of wealthy farmers, on the other hand, are usually higher than balances of poorer farmers, as was clearly shown in Chapter 3 for the communal and new resettlement areas, and also demonstrated at a broad scale in Chapter 2. Wealthy farmers by its typological definition (e.g. Table 3.2) own livestock, which is an important source of animal manure, transport and even cash. Therefore, a higher investment in soil fertility, due to a higher availability of nutrient resources, is usually carried out by wealthy farmers in comparison to poorer farmers. Wealthy farmers can also make better use of communal resources (e.g. grazing, fuelwood, litter collection) due to the better possibilities in terms of labor and assets they have (e.g. cattle, carts), which allow them to make significant transfer of nutrients from communal lands to their farms (Giller et al., 2006). Moreover, after harvest, cropping fields in the villages are usually 'transformed' to communal grazing lands, and livestock therefore can graze freely, even on fields from poor farmers who don't possess any livestock at all. In this case, transfer of nutrients to wealthy farmers also occurs, but at the expense of the less favored (Zingore et al., 2007). Hence, any measure taken to empower poor farmers (e.g. most options mentioned at the end of Section 5.1), have a great chance to conduce them to have better access to nutrient sources and would clearly facilitate a higher investment in soil fertility, reduce soil mining and ensure food security (Stocking, 2003).

5.5. How has land reform affected nutrient management strategies of small-scale farmers in Zimbabwe?

There is little doubt that after thirty years since the starting of the land reform the agriculture sector in Zimbabwe has not been affected. Skilled farmers were taken out of their fields, indigenous farmers came to new areas; infrastructure of farms was damaged; markets of inputs and products were disrupted; export revenues dropped; land use change accelerated; quality and extent of extension services diminished; rural unemployment intensified; etc. (Derman, 2006; Masiiwa, 2005; Moyo, 2005). Therefore, productivity of the agricultural sector has significantly declined (Masiiwa, 2005) and environmental degradation has evidently increased (FAO, 2006). In this scenario, small-scale indigenous farmers, which now occupy great part of the national territory (Moyo, 2005), had had to adapt to these new challenging circumstances, especially those farmers who migrated to a new land in the resettlement areas. In fact, an evident effect of the land reform for small scale resettled farmers relates to the 'unknown'. New occupants usually came from different regions in the country, and therefore had to adapt the knowledge they had (e.g. from communal areas) to a new environment (e.g. different soil type and climate, new neighbors, etc). Moreover, several of the migrants were not farmers, but war veterans, supporters of the government or landless people, some of which had no adequate farming experience (Deininger et al., 2004; Derman, 2006). Although one of the objectives of the land reform was to train farmers and facilitate the required inputs and markets in the resettlement areas, this was unfortunately never achieved in a proper way (Masiiwa, 2005). It is clear that with no proper knowledge and support, an efficient management of the land is a challenge (Stocking, 2003). Nevertheless, participatory activities and informal discussion with farmers during the field work, conducted for Chapters 3 and 4, suggested that social networks were created in each community, which have apparently helped inexperienced farmers to adapt to the new circumstances. This would support findings by Barr (2004) of the evolution of active civil societies in the resettlement areas. Evidence on soil nutrient mining and conservation practices (chapter 3) unfortunately demonstrated, however, that management of the land in the study sites was not satisfactory yet. Land tenure insecurity in resettlement areas (Deininger et al., 2004) may be preventing the new occupants of doing long-term investments in soil fertility and conservation. Although no direct evidence of this was obtained from farmers in Chapter 3, due to the political sensibility of the topic, experiences from other researchers in the same region corroborate this premise (e.g. Zikhali, 2008). In fact, soil nutrient mining usually occurs under land tenure insecurity (Stocking, 2003).

One of the most noticeable effects of the land reform relates to the accessibility of inputs. According to (FAO, 2006) “fertilizer consumption has fallen since 2000 owing to the disruption caused by the agrarian reform, physical unavailability, increased fertilizer prices and financial constraints”. Chapter 3 clearly showed this problem, as an improper distribution of fertilizers in the study sites was evident, which limited most farmers to make significant soil fertility investments in their fields. It was, however, also shown that farmers in each village responded differentially to this limitation. Farmers in the communal area already knew that if no substantial application of fertilizers is done to their fields, crop yields will be very low due to the poor inherent soil quality. Therefore, they actively mobilized themselves to find nutrient sources for applying them later to their plots. Farmers in the new resettlement, on more fertile soils, may not have seen this situation as critical, as even with no fertilization they were able to obtain reasonable yields (Figure 3.3), but at the expense of soil nutrient stocks (Figure 3.2). The differential soil type in each settlement scheme was also the apparent cause of different perceptions regarding crop productivity and soil degradation across time. This was evident, as many farmers in the communal and old resettlement area perceived a decrease in crop yields and soil fertility with time, while in the new resettlement (where soils can sustain crop productivity for longer time) the perceptions about a possible decline were not so obvious (Table 3.6). Time since settlement (which is typically different between villages, Table 3.1), however, could be a confusing factor, as communal farmers have been in the village longer than old and new resettled farmers.

Another important factor relates to the planning of the model A1 of resettlement, which applies to the old and new resettlement areas evaluated in Chapters 3 and 4. Here villages were planned as a 'nuclear' array, with homesteads located in a centralized area in which supposedly cultivation is not allowed, and cropping fields and grazing areas placed in the vicinity (Elliott et al., 2006). This arrangement clearly differs from the current layout in the communal area where usually farmers have cropping fields adjacent to homestead (infields) and other fields located farther away (outfields) (Figure 5.2). This divergence among schemes could explain why in the resettlement areas "distance from homestead" was not usually considered by farmers as a factor driving allocation of resources in their fields; while in the communal area the existence of soil fertility/management gradients was evident. Disparity on the layout of the fields could be also affecting other nutrient management strategies in these areas. For example, while a high proportion of farmers in the communal area used to collect crop residues from their plots for feeding their cattle in the *kraal*, in the other two villages (especially in the old resettlement area) the proportion of farmers performing this activity was lower (Chapter 3). According to several farmers in the resettlement areas long distances from their households to their fields prevented them to do this activity more frequently.

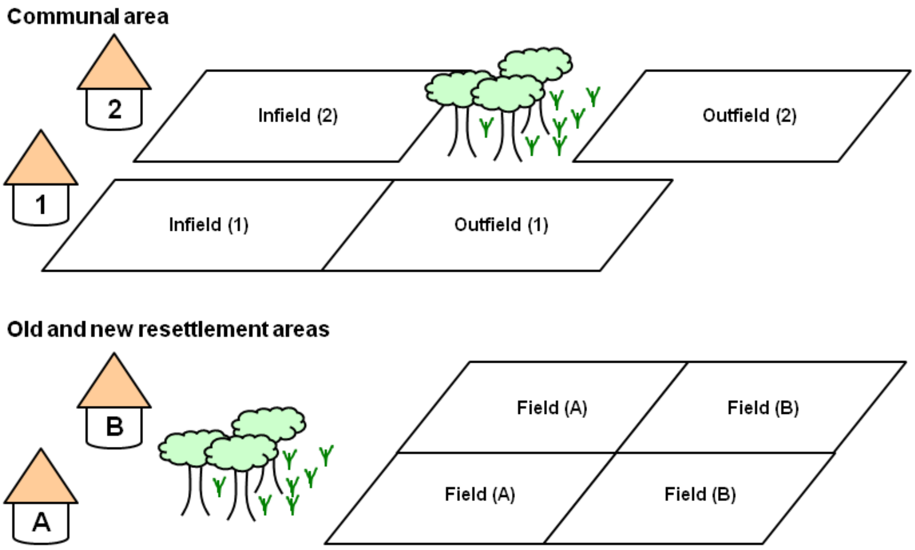

Figure 5.2. Layout of cropping fields in regard to homesteads in the communal and resettlement areas evaluated in NE Zimbabwe. This simplified representation shows two typical farms for settlement type, each one with two fields. For more explanation refer to the text.

Differences among communal and resettlement areas call the attention for new research on soil fertility management in Zimbabwe, where communal areas has been typically being the target (Derman, 2006). Moreover, it advocates researchers to determine, from a biophysical perspective, how land quality, crop productivity and nutrient management strategies by farmers have been affected by the land reform process, as most of the available literature on the topic refers to socio-economic impacts, and it is usually out of date.

5.6. Is MIRS linked to geostatistics a suitable approach for spatial landscape analysis?

It was clearly demonstrated in Chapter 4 that MIRS can be successfully coupled to geostatistical analyses for the assessment of spatial variability of agroecosystems; and this could be basically performed in two ways. Firstly, MIRS can be used to complement the extensive soil datasets required in spatial analyses through the development of prediction models for the soil parameters needed. Nevertheless, it must be noticed that MIRS models are not always able to make accurate predictions for all cases, which is usually a function of the soil property, soil type and/or location (McBratney et al., 2006; Shepherd and Walsh, 2004). This was the reason why not all variables of interest could be incorporated in the spatial analyses (Chapter 4), as MIRS predictions models for P_{av}, Al and K were deficient. In the case of P_{av}, this was really unfortunate as this is one of the most limiting soil nutrients in Zimbabwe (Nyamapfene, 1991). Prediction models for P_{av} are typically not adequate since this parameter is more related to its concentration in the soil solution than to the soil matrix, which makes it very difficult for the method to detect (Janik et al., 1998). Some options for overcoming limitations in the predictions by MIRS have been suggested though. For example, the development and use of global calibrations, for example, has attracted the attention of several researchers in the last few years as it would supposedly assure better calibrations independently of the soil type and/or location (Cécillon et al., 2009). According to Brown et al. (2005) improved results with this kind of approach can be achieved by utilizing auxiliary predictors (e.g. simple and inexpensive conventional soil parameters, like pH and sand; or from complementary sensors, like NIRS) and by supplementing the global model with local calibration samples. McBratney et al. (2006), instead, have proposed the use of soil inference systems for the estimation of those soil properties that MIRS cannot be accurately predicted through the use of pedotransfer functions. A variation of the technique, i.e. mid-infrared photoacustic spectroscopy (MIR-PAS), has been recently proposed as being even more effective than conventional MIRS or NIRS, since recorded spectra contains more information, it can be used to detect available nutrients (e.g. available N and P), and sample pre-treatment is not required (Du and Zhou, 2009; Du et al., 2009).

An alternative approach is to depart from the prediction of single parameters and to use instead integrative spectral indicators (covering a wider range of soil characteristics), which would allow to identify problems related to functional capacity of soils (Shepherd and Walsh, 2007). In fact, in Chapter 4, data from MIRS could be summarized by principal component analyses, and components scores used later as input variables for geostatistics. Hence, no predictions models were necessary. However, it was shown that it is necessary to relate the components scores to soil parameters for being able to adequately interpret the results (i.e. PC1 which was related to soil fertility, Figure 4.8). If this is not carried out, interesting spatial patterns could be found, but it would be simply impossible to know what they would represent (Odlare et al., 2005). Components scores could be even correlated to the wavelengths of the spectra, to be able to discern which spectral regions are more associated to each component. All these findings are relevant since very few initiatives currently exist (i.e. Awiti et al., 2008; Cohen et al., 2006; Odlare et al., 2005; Vågen et al., 2006) on the use of IRS information as a direct input for the evaluation of soil condition. Moreover, those existing studies have been based on NIRS rather than MIRS.

The integration of MIRS and geostatistics seems to be a very promising approach, especially where there is a high priority for assessing, monitoring and mapping land degradation and soil fertility at landscape scale (Shepherd and Walsh, 2007). This is particularly pertinent, for example, within the Africa Soil Information Service (AfSIS, http://www.africasoils.net), a part of the GlobalSoilMap.net initiative (GSM, Sanchez et al., 2009b), where the aim is "developing a practical, timely, and cost-effective soil health surveillance service [in Africa] to map soil conditions, set a baseline for monitoring changes, and provide options for improved soil and land management". In fact, the approach could be even be based on data from air and space-borne platforms, which would be ideal for the assessment of soil erosion and land degradation at regional, national and continental level, and/or for real-time assessments for precision agriculture and watershed management (Shepherd and Walsh, 2004; Shepherd and Walsh, 2007; Vågen et al., 2006). However, use of IRS from remote sensing has still several limitations that need to be solved for their routinely use, like difficulties for proper atmospheric and geometric corrections, low signal-to-noise ratios, spatial-temporal variability of soil surface conditions, vegetation and residue cover (for more information see Cécillon et al., 2009).

5.7. Concluding remarks and final recommendations

One of the challenges in soil science is “to capture diversity by developing appropriate cross-disciplinary analytical methods and measures” (Stocking, 2003). The use of mixed-methods in this thesis, i.e. nutrient balances and participatory tools (Chapter 3), and mid-infrared spectroscopy and geostatistics (Chapter 4), proved to be useful for understanding soil nutrient mining, assessing nutrient management strategies, and describing soil spatial variability across the different settlement schemes under evaluation. In Chapter 2, the nutrient balance approach was very valuable for indicating soil mining of different African land use systems at different spatial scales. Having results at different scales clearly facilitates tackling soil nutrient mining from diverse angles across the whole spatial hierarchy where stakeholders may have influence (e.g. from plot and farm levels with farmers, to regional, national and supra-national levels with policy makers). However, it is imperative to address several methodological complexities of the nutrient balance approach, especially issues of spatial variability, resolution and extent during scaling-up procedures, to be able to obtain accurate results at higher spatial levels. In any case, results from nutrient balances (Chapter 2 and 3), and associated information obtained from stakeholders (e.g. farmers’ perceptions and results from group discussions in Chapter 3) clearly indicated the need of facilitating to farmers the access to nutrient sources. So they can significantly invest in soil fertility for having greater opportunities to overcome soil mining while increasing land productivity. Data from Chapter 2 and 3 also highlighted the importance of distinguishing spatial variability of farming systems (e.g. soil fertility/management intensity gradients), as once this heterogeneity is recognized it could be used for targeting site-specific technologies aiming at soil restoration. Chapter 4 clearly demonstrated that the integration of MIRS and geostatistics is a very promising approach to be successfully utilized for soil fertility assessments at the landscape level. A similar approach could be also applied to address relevant issues related to conservation agriculture and soil carbon sequestration, which are currently considered priority by several development and research organizations (Giller et al., 2009; Govaerts et al., 2009). Possibilities will be even greater in the next few years due to continuous advances in basic sciences (e.g. mathematics, physics and chemistry), electronics and software, and the foreseen developments on multi-scale agroecological research (Chapter 2).

From the case studies in Zimbabwe (Chapter 3 and 4), results additionally showed that agroecological research in the country should consider the diversity of the various settlement schemes. In addition to being in communal areas, small-scale farmers are also present in previous former commercial white farmers' lands (resettlement areas), most of which are located in lands of high productive potential. This diversity was evident in Chapter 3, where small scale farmers in the three studied settlement schemes showed different cropping strategies, soil fertility investments and land management practices, which directly affected nutrient mining and crop productivity. Findings presented in Chapter 4 also clearly showed, that spatial variability of soil properties diverged across villages, which were presumably attributed to both intrinsic (e.g. soil quality) and extrinsic (e.g. farmers' management) factors acting distinctively in each area. Further research is nevertheless needed to corroborate the actual contribution of these potential factors to soil spatial variability in these areas, as our experimental design did not allow it. It is also important to mention that identical soil and crop management practices and spatial patterns may not necessarily occur in other communal and resettlement areas in the country, as each area may present its individual variability, since driving factors (e.g. biophysical and socio-economical) usually act zonally. Therefore, further research is also necessary for assessing nutrient management strategies and spatial variability of soil properties in other communal and resettlement areas of the country. Understanding the effects of land reform on the variability of natural resources (e.g. soils) would help not only farmers and extension agents to take better decisions about natural resource management, but also policy makers (Liu et al., 2009). In this regard, applied science and technology development will play crucial roles, and tools like participatory research, nutrient balances, MIRS and geostatistics will find a very relevant position. In fact, in the near future, and after the main limitations presented here in this manuscript are properly been solved, holistic approaches incorporating all these tools and remote sensing technologies will be key to cost-effectively analyze and monitor changes on fertility and spatial variability of soil across different scales in the diverse agroecosystems of Africa and other developing countries (e.g. Sanchez et al., 2009b; Shepherd and Walsh, 2007). This thesis is a small contribution to the achievement of these important goals.

CHAPTER 6

REFERENCES

6. REFERENCES

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SUMMARY

Decline in soil fertility in Africa is one of the most limiting biophysical factors to agricultural productivity, as nutrient mining and low yields are strongly related. However, the high heterogeneity in management together with different biophysical, socio-economical and political conditions across each African agro-ecosystem make blanket recommendations difficult. Thus, acknowledging heterogeneity, and moreover quantifying it at different spatial scales, are the first steps to make adequate recommendations for the different actors. The goal of this thesis was to develop new methodological approaches to better understand nutrient management and spatial variability of soils across different scales in African agro-ecosystems, having various small-holder settlement schemes in Zimbabwe as a case study.

Firstly, the thesis includes a literature review on nutrient balances in Africa, which was carried out to illustrate main approaches, challenges, and progress made, with emphasis on issues of scale. The review revealed that nutrient balances are widely used across the continent. The collected dataset from 57 peer-reviewed studies indicated, however, that most of the balances were calculated at plot and farm scale, and generated in East Africa. Data confirmed the expected trend of negative balances for N and K (>75% of studies had mean values below zero), while for P only 56% of studies showed negative mean balances. Several cases with positive nutrient balances indicated that soil nutrient mining cannot be generalized across the African continent. Land use systems of wealthier farmers and plots located close to homesteads mostly presented higher N and P balances than systems of poorer farmers ($p<0.001$) and plots located relatively farther away ($p<0.05$). Partial nutrient balances were significantly higher ($p<0.001$) than full balances calculated for the same systems, but the latter carried more uncertainties. The change in magnitude of nutrient balances from plot to continental level did not show any noticeable trend, which challenges prevailing assumptions that a trend exists. However, methodological differences made a proper inter-scale comparison of results difficult. Actually, the review illustrated the high diversity of methods used to calculate nutrient balances and highlighted the main pitfalls, especially when nutrient flows and balances were scaled-up. In fact, gathered information showed that despite some few initiatives, appropriate scaling-up methods are still incipient.

In the next chapter, the nutrient balance approach was applied in NE Zimbabwe. Three smallholder villages located in a typical communal area (colonial settlement from 1948), and

in old (1987) and new (2002) resettlement areas (post- land reform settlements), on loamy sand, sandy loam and clay soils, respectively, were selected to explore differences in natural resource management and land productivity. Focus group discussions and surveys were carried out with farmers. Additionally, farmers in three wealth classes per village were chosen for a detailed assessment of their main production systems. Maize grain yields (Mg ha^{-1}) in the communal (1.5-4.0) and new resettlement areas (1.9-4.3) were similar but significantly higher than in the old resettlement area (0.9-2.7), despite lower soil quality in the communal area. Nutrient input use was the main factor controlling maize productivity in the three areas (R^2=59-83%), while inherent soil fertility accounted for up to 12%. Partial N balances (kg ha^{-1} yr^{-1}) were significantly lower in the new resettlement (-9.1 to +14.3) and old resettlement (+7.4 to +9.6) than in the communal area (+2.1 to +59.6) due to lower nutrient applications. P balances were usually negative. Consistently, maize yields, nutrient applications and partial N balances were higher for the high wealth class than in poorer classes. It is argued that effective policies supporting an efficient fertilizer distribution and improved soil management practices, with clearer rights to land, are necessary to avoid future land degradation and to improve food security in Zimbabwe, particularly in the resettlement areas.

In the last chapter, the same three villages in NE Zimbabwe were sampled to determine the feasibility of integrating mid-infrared spectroscopy (MIRS) and geostatistics, as a way of facilitating landscape analysis and monitoring. A nested non-aligned design with hierarchical grids of 750, 150 and 30 m resulted in 432 sampling points across all villages. At each point, a composite topsoil sample was taken and analyzed by MIRS. Conventional laboratory analyses on 25-38% of the samples were used for the prediction of concentration values on the remaining samples through the application of MIRS - partial least squares regression models. Models were successful ($R^2 \geq 0.89$) for sand, clay, pH, total C and N, exchangeable Ca, Mg and effective CEC; but not for silt, available P, and exchangeable K and Al ($R^2 \leq 0.82$). Minimum sample sizes required to accurately estimate the mean of each soil property in each village were calculated. With regard to locations, fewer samples were needed in the new resettlement area than in the other two areas; regarding parameters, least samples were needed for estimating pH and sand. Spatial analyses of soil properties in each village were undertaken by constructing standardized isotropic semivariograms, which were usually well described by spherical models. Spatial autocorrelation of most variables was displayed over ranges of 250-695 m. The nugget-to-sill ratios showed that overall spatial dependence of soil properties was: new resettlement > old resettlement > communal area; which was attributed to both intrinsic (e.g. texture) and extrinsic (e.g. management) factors. As a new approach, geostatistical analysis was performed directly using MIRS data, after principal component analyses, where the first three components explained 70% of the overall variability. Semivariograms based on these components showed that spatial dependence per village was similar to overall dependence identified from individual soil properties in each area. The first component (explaining 49% of variation) related well with all soil properties of reference samples (absolute correlation values of 0.55-0.96). This demonstrated that MIRS data could be directly linked to geostatistics for a broad and quick evaluation of soil spatial variability. Integrating MIRS with geostatistical analyses is a cost-effective promising approach, i.e. for soil fertility and carbon sequestration assessments, mapping and monitoring at landscape level.

In conclusion, nutrient balances showed the urgent need to facilitate access to nutrients to African farmers as a measure of counteracting soil mining and increasing crop yields. The work in Zimbabwe clearly demonstrated that the effect of the land reform and the existence of different settlement schemes should be considered as critical driving factors of nutrient management and spatial variability in small-holder farming systems in the country. It can be finally concluded that the use of mixed methods (e.g. nutrient balances and participatory tools, and mid-infrared spectroscopy and geostatistics), proved to be very useful for assessing nutrient management strategies, understanding soil nutrient mining and describing spatial variability across the different settlement schemes under evaluation.

ZUSAMMENFASSUNG

In Afrika gehört der Rückgang von Bodenfruchtbarkeit zu den am stärksten limitierenden Faktoren landwirtschaftlicher Produktion. Übernutzung von Böden und niedrige Erträge sind weit verbreitete Folgen dieses Zustands. Allerdings können allgemeine landwirtschaftliche Empfehlungen angesichts sehr unterschiedlicher physikalischer, biologischer, sozioökonomischer und politischer Voraussetzungen in afrikanischen Agrarökosystemen nicht gegeben werden. Somit ist die Untersuchung der zugrundeliegenden Heterogenität, besonders über unterschiedliche räumliche Skalen hinweg, ein erster notwendiger Schritt, um Anbauempfehlungen für lokale Akteure geben zu können. Ziel der vorliegenden Arbeit war es daher auf Basis einer Fallstudie in mehreren kleinbäuerlichen Siedlungen in Simbabwe ein besseres Verständnis der räumlichen Variabilität von Böden über Skalen hinweg und über Nährstoffmanagement in afrikanischen Agrarökosystemen zu erlangen.

Die Studie beinhaltet eine Literaturrecherche zu Nährstoffbilanzen in Afrika, welche die grundsätzlichen Ansätze, Herausforderungen und Fortschritte der Forschung unter besonderer Berücksichtigung räumlicher Maßstäbe untersuchte. Die Recherche zeigte, dass die Erstellung und Verwendung von Nährstoffbilanzen auf dem gesamten Kontinent weit verbreitet ist. Die kompilierten Daten aus 57 wissenschaftlichen Fachpublikationen zeigten jedoch auch, dass sich die meisten dieser Bilanzen auf die Schlag- bzw. Betriebsebene bezogen und auf Ostafrika begrenzt waren. Die Datensätze bestätigten die erwartete Tendenz negativer N- und K-Bilanzen (in über 75% der Studien mit Mittelwerten unter 0), während für P nur 56% der Fallstudien negative Mittelwerte ergaben. Positive Bilanzen in einigen Fällen zeigten, dass verallgemeinernd von Bodenübernutzung in Afrika nicht ausgegangen werden kann. Dabei schnitten besonders N- und P-Bilanzen von Feldern wohlhabenderer Bauern und in der Nähe von Ansiedlungen besser ab als solche ärmerer Bauern ($p<0.001$) oder in größerer Entfernung von Siedlungen ($p<0.05$). Partielle Nährstoffbilanzen ergaben deutlich ($p<0.001$) höhere Werte als Gesamtbilanzen der selben Flächen, welche allerdings statistisch mit höheren Unsicherheiten behaftet waren. Im Gegensatz zu verbreiteten Annahmen war ein Trend der Größenordnungen von Nährstoffbilanzen über Skalen – von Feld- bis zur Kontinentebene – nicht zu erkennen. Dabei muss jedoch angemerkt warden, dass methodische Unterschiede auf unterschiedlichen räumlichen Ebenen einen direkten Vergleich der Ergebnisse verschiedener Studien erschwerten. Zusätzlich zeigte die Recherche die große Anzahl verschiedener methodischer Ansätze auf, verbunden mit Schwierigkeiten, die besonders beim Hochskalieren von Nähstofflüssen und –bilanzen auftreten können. Dabei wurde vor allem deutlich, dass mit

wenigen Ausnahmen zur Zeit kaum geeignete Methoden zur Übertragung von Ergebnissen auf höhere räumliche Skalen existieren.

Im darauffolgenden Kapitel wird der methodische Ansatz einer Nährstoffbilanz auf ein Fallbeispiel in NO-Simbabwe angewandt. Drei kleinbäuerliche Dörfer in repräsentativen sogenannten kommunalen (seit 1948, noch zu Kolonialzeiten, bestehenden), alten (seit 1987) und neuen (seit der Landreform 2002) Umsiedlungsgebieten auf lehmigem Sand, sandigem Lehm und Tonböden wurden ausgewählt, um Unterschiede in Bewirtschaftungsweise und landwirtschaftlicher Produktivität zu untersuchen. Dazu wurden zunächst Gruppendiskussionen und Feldbegehungen mit Landwirten durchgeführt. Ausserdem wurden die wichtigsten Produktionszweige von Betrieben dreier unterschiedlicher Wohlstandsniveaus näher betrachtet. Dabei lagen die Kornerträge für Mais (in Mg ha^{-1}) in den kommunalen (1.5-4.0) und neueren Siedlungen (1.9-4.3) trotz geringerer Bodenfruchtbarkeit der kommunalen Gebiete klar über denen der älteren Ansiedlungen (0.9-2.7). Den wichtigsten ertragsbestimmenden Faktor für Mais stellten in allen drei Siedlungsgebieten externe Nährstoffinputs dar (R^2=59-83%), während die natürliche Bodenfruchtbarkeit nur 12% des Ertragsniveaus statistisch erklärte. Partielle Stickstoffbilanzen (kg ha^{-1} a^{-1}) in den neueren (-9.1 bis +14.3) und älteren (+7.4 bis +9.6) Siedlungen lagen aufgrund niedrigerer Düngergaben deutlich unter jenen der kommunalen Gebiete (+2.1 bis +59.6). P-Bilanzen waren im allgemeinen negativ. Folglich lagen sowohl Maiserträge als auch Nährstoffgaben und partielle Stickstoffbilanzen auf Feldern wohlhabenderer über denen ärmerer Betriebe. Dies legt den Schluss nahe, dass effektive Maßnahmen, besonders effiziente Düngemittelzuteilung und verbesserte Bodenbewirtschaftung sowie Rechtssicherheit beim Zugang zu Ackerland, unabdingbar zur Vermeidung von Bodendegradierung und zur Verbesserung der Ernährungssicherung in Simbabwe sind. Dies betrifft besonders die Umsiedlungsgebiete.

Das letzte Kapitel beschreibt am Beispiel der erwähnten drei Siedlungsgebiete Ansätze zur Integration von MIRS (mid-infrared spectroscopy) und geostatistischen Methoden mit der Zielsetzung, Analyse und Monitoring landschaftsbezogener Daten zu vereinfachen. Eine “nested non-aligned“ Versuchsanlage mit hierarchischer Rasterung von 750, 150 and 30m ergab 432 Messpunkte in allen drei Gebieten. An jedem dieser Punkte wurde eine Mischprobe Oberboden entnommen und per MIRS analysiert. 25-38% der Proben wurden zusätzlich mittels klassischer Labormethoden analysiert. Auf Basis dieser Wertepaare wurden dann die entsprechenden Parameter der restlichen Punkte mittels MIRS und partial least squares Methode modelliert. Die Modelle schnitten für die Parameter Sand, Ton, pH, Gesamt-C und –

N, austauschbares Ca^{2+} und Mg^{2+} sowie effektive Kationenaustauschkapazität gut ab ($R^2 \geq 0.89$). Für Schluff, verfügbare P-, K- und Al-Gehalte wurden dagegen nur Bestimmtheiten von $R^2 \leq 0.82$ erreicht. Die statistisch notwendige Mindestzahl an Proben lag in den neueren Siedlungen unter derjenigen der anderen Gebiete. Bezüglich Bodenparametern wurden die wenigsten Proben für pH und Sand benötigt. Die räumliche Verteilung von Bodeneigenschaften in jedem der Dörfer wurde mittels standardisierter isotroper Variogramme untersucht, die in aller Regel durch sphärische Modelle hinreichend beschrieben werden konnten. Die räumliche Autokorrelation der meisten Variablen wurde über Bandbreiten von 250-695m abgedeckt. Die Größenverhältnisse zwischen nugget und sill in den Semivariogrammen zeigten, dass die räumliche Variabilität der Bodeneigenschaften in den neueren Siedlungen höher lag als in den älteren und wiederum den kommunalen. Dies wurde sowohl auf intrinsische (z.B. Textur) als auch externe (z.B. Bewirtschaftung) Faktoren zurückgeführt. In einem innovativen Ansatz wurden MIRS-Werte nach einer Hauptkomponentenanalyse direkt geostatistisch ausgewertet. Dabei erklärten die drei wichtigsten Komponenten 70% der Gesamtvariabilität. Die Semivariogramme zeigten, dass der räumliche Einfluss der Hauptkomponenten sowie der individuellen Bodenparameter in den jeweiligen Siedlungsgebieten ähnlich groß war. Die erste Hauptkomponente, die 49% der Variabilität erklärte, korrelierte mit Werten zwischen 0.55 und 0.96 klar zu den Bodeneigenschaften der Referenzproben. Dies zeigt, dass eine direkte Kombination aus MIRS und geostatistischen Methoden zur umfassenden und zeitsparenden Bewertung räumlicher Variabilität von Bodenparametern geeignet ist. Zudem bietet die Integration von MIRS und Geostatistik eine kostengünstige Alternative für Kartierung, Monitoring und Bewertung von Parametern wie Bodenfruchtbarkeit oder Kohlenstoffsequestrierung auf Landschaftsebene.

Zusammenfassend zeigten die Nährstoffbilanzen die dringende Notwendigkeit eines verbesserten Zugangs afrikanische Landwirte zu Nährstoffinputs, um Verarmung von Böden zu verhindern und Erträge zu erhöhen. Am Fallbeispiel Simbabwes konnte deutlich gezeigt werden, dass Auswirkungen der Landreform und die Existenz unterschiedlicher Siedlungstypen maßgeblichen Einfluss auf Nährstoffhaushalt und räumliche Variabilität von Bodenparametern in kleinbäuerlichen Betrieben hatten. Die Anwendung kombinierter methodischer Ansätze (z.B. Nährstoffbilanzen und partizipative Methoden, MIRS und Geostatistik) erwies sich als aussagekräftig zur Bewertung von Nährstoffmanagementstrategien, zum besseren Verständnis von Mustern der Nährstoffverarmung in Böden und zur Beschreibung räumlicher Variabilität verschiedener Siedlungstypen.

RESUMEN

La reducción en la fertilidad de los suelos en Africa es una de las principales limitaciones a la producción agrícola, ya que la excesiva extracción de nutrientes y los bajos rendimientos de los cultivos están estrechamente relacionados. Sin embargo, la alta heterogeneidad en el manejo agrícola, en conjunto con las diferentes condiciones biofísicas, socio-económicas y políticas en los agroecosistemas Africanos, hacen difícil la aplicación de recomendaciones generalizadas. De esta manera, admitir que la heterogeneidad existe, y más aún, cuantificarla a diferentes escalas espaciales, es el primer paso para formular recomendaciones apropiadas para los diferentes actores. El propósito de esta tesis fue el de desarrollar nuevos enfoques metodológicos para entender mejor el manejo de los suelos y su variación espacial a diferentes escalas en agroecosistemas Africanos, teniendo varios esquemas de asentamiento de la tierra en sistemas agrícolas de pequeña escala en Zimbabue como estudio de caso.

En primera instancia, la tesis incluye una revisión de literatura sobre el balance de nutrientes en África, lo cual fue realizado para ilustrar los principales enfoques, desafíos y progresos en el tema, con un énfasis en asuntos de escala. La revisión reveló que los balances de nutrientes han sido usados ampliamente en el continente. Los resultados de los 57 estudios seleccionados (arbitrados) indicaron, sin embargo, que la mayoría de los balances fueron calculados a escalas de parcela y finca, y generados en África del Este. Los datos confirmaron, como era esperado, una tendencia negativa en los balances de N y K (>75% de los estudios tuvieron promedios por debajo de cero), mientras para el P solo el 56% de los estudios mostraron promedios negativos. Los varios casos existentes de balances positivos indicaron que la extracción excesiva de nutrientes no puede ser generalizada en el continente Africano. Sistemas de uso de la tierra de agricultores ricos o en parcelas cerca a las viviendas presentaron generalmente mayores balances de N y P que aquellos sistemas de agricultores mas pobres ($p<0.001$) y de las parcelas localizadas mas lejos de casa ($p<0.05$). Los balances parciales fueron significativamente ($p<0.001$) mayores que los balances totales calculados para los mismos sistemas, aunque estos últimos traen mayores incertidumbres. El cambio en la magnitud de los balances, desde la escala de parcela a la continental, no mostró ninguna tendencia notable, lo cual desafía las asunciones prevalentes que una tendencia existe. Sin embargo, diferencias metodológicas hicieron difícil una apropiada comparación de los resultados entre las diferentes escalas. De hecho, la revisión ilustró la alta diversidad de los métodos usados para calcular los balances y resaltó las principales limitaciones, especialmente cuando los flujos y balances de nutrientes fueron escalados a otros niveles

espaciales. Efectivamente, la información colectada mostró que a pesar de algunas pocas iniciativas, métodos apropiados para escalar los balances de nutrientes son aún incipientes.

En el capitulo siguiente, el balance de nutrientes fue aplicado en la práctica en el Noreste de Zimbabue. Tres villas de agricultores de pequeña escala localizadas en un área de asentamiento comunal (colonial, de 1948) y en áreas de re-asentamiento (después de la reforma agraria) “viejas” (1987) y “nuevas” (2002), en suelos arenoso-franco, franco-arenoso, y arcilloso, respectivamente, fueron seleccionadas para explorar las diferencias en el manejo de los recursos naturales y la productividad de la tierra. Discusiones enfocadas en grupo y entrevistas fueron realizadas con agricultores. Adicionalmente, agricultores clasificados de acuerdo a su nivel socio-económico en cada villa fueron seleccionados para una evaluación detallada de sus principales sistemas de producción. Los rendimiento de maíz (Mg ha^{-1}) en el área comunal (1.5-4.0) y el nuevo re-asentamiento (1.9-4.3) fueron similares, pero significativamente mayores que en el viejo re-asentamiento (0.9-2.7), a pesar de una menor calidad de los suelos en el área comunal. El uso de nutrientes fue el principal factor controlador de la productividad del maíz en las tres áreas (R^2=59-83%), mientras la fertilidad inherente del suelo solo contribuyó con un 12%. El balance parcial de N (kg ha^{-1} $año^{-1}$) fue significativamente menor en el nuevo (-9.1 a +14.3) y viejo re-asentamiento (+7.4 a +9.6) que en el área comunal (+2.1 a +59.6), debido a las menores aplicaciones de nutrientes. Los balances de P fueron usualmente negativos. Consistentemente, los rendimientos de maíz, las aplicaciones de nutrientes y los balances parciales de N fueron mayores en los agricultores ricos que en los más pobres. Se argumenta que políticas efectivas que soporten una eficiente distribución de fertilizantes y la mejora en las prácticas de manejo, con claros títulos de propiedad a la tierra, son necesarios para evitar la futura degradación de la tierra y mejorar la seguridad alimentaria en Zimbabue, particularmente en las áreas de re-asentamiento.

En el capítulo final, las mismas tres villas en Zimbabue fueron muestreadas para determinar la posibilidad de integrar la espectroscopia del infrarrojo medio (MIRS, por sus siglas en inglés) y geostadística, como medio para facilitar el análisis y monitoreo del paisaje. Un diseño de muestreo anidado y no alineado, con celdas jerárquicas de 750, 150 y 30 m resultó en el muestreo de 432 puntos en las tres villas. En cada punto, una muestra compuesta de suelo fue tomada y analizada por MIRS. Análisis convencionales de laboratorio en 25-38% de las muestras fueron usadas para predecir los valores de las muestras remanentes a través de la aplicación de modelos que usaron MIRS y mínimos cuadrados parciales. Los modelos fueron exitosos ($R^2 \geq 0.89$) en arenas, arcillas, pH, C y N total, Ca y Mg intercambiable, y

CICE; pero no en limos, P disponible, K y Al ($R^2 \leq 0.82$). El tamaño mínimo de muestras requerido para estimar la media de cada propiedad del suelo en cada villa fue menor en el nuevo re-asentamiento que en las otras dos áreas; mientras menos muestras fueron necesarias para estimar pH y arenas. El análisis espacial de las propiedades del suelo en cada villa fue realizado mediante la construcción de semivariogramas isotrópicos estandarizados, los cuales fueron usualmente bien descritos por modelos esféricos. La auto-correlación espacial de la mayoría de las variables fue exhibida en rangos de 250-695 m. La relación "nugget-to-sill" mostró que la variación espacial colectiva de las propiedades del suelo fueron: nuevo re-asentamiento > viejo re-asentamiento > área comunal; lo cual fue atribuido a factores tanto intrínsecos (ej. textura) como a factores extrínsecos (ej. manejo). Como un nuevo enfoque, el análisis geostadístico fue realizado directamente sobre los datos de MIRS, después de un análisis por componentes principales, donde los tres primeros componentes explicaron un 70% de la variabilidad global. Los semivariogramas basados en estos componentes mostraron que la dependencia espacial en cada villa fue similar a la dependencia general identificada en las propiedades individuales del suelo en cada área. El primer componente (explicando 49% de la variación) relaciono bien con las propiedades de suelo de las muestras de referencia (valores de correlación absolutos de 0.55-0.96). Esto demostró que la información de MIRS podría ser directamente vinculada a la geostadística para una amplia y rápida evaluación de la variación espacial de los suelos. La integración de MIRS con análisis geostadísticos es un prometedor enfoque, efectivo y relativamente económico, por ejemplo, en la evaluación, mapeo y monitoreo de la fertilidad de los suelos y el secuestro de carbón a escala de paisaje.

En conclusión, los balances de nutrientes mostraron la urgente necesidad de facilitar a los agricultores Africanos un mejor acceso a fuentes de nutrientes, como una medida para contrarrestar la extracción extensiva de nutrientes del suelo e incrementar los rendimientos de los cultivos. El trabajo en Zimbabue claramente demostró que el efecto de la reforma agraria y la existencia de los diferentes asentamientos de la tierra deberían ser considerados como factores críticos que afectan el manejo de nutrientes y la variación espacial en sistemas agrícolas de pequeña escala en el país. Puede finalmente concluirse que el uso de métodos mixtos (ej. balance de nutrientes e investigación participativa, MIRS y geostatistica) probaron ser un enfoque muy útil para la evaluación de las estrategias en el manejo de los nutrientes, el entendimiento de la extracción de nutrientes del suelo, y en describir la variación espacial de los suelos a través de los diferentes esquemas de asentamiento bajo evaluación.

APPENDIX A. ADDITIONAL PUBLICATIONS

(not related to this thesis but published during the same time frame of doctoral studies)

A.1. Simulating phosphorus responses in annual crops using APSIM: model evaluation on contrasting soil types[v]

Delve RJ[1], Probert ME[2], Cobo JG[3,4], Ricaurte J[4], Rivera M[4], Barrios E[4], Rao IM[4]

[1] *Catholic Relief Services, P.O. Box 49675-00100, Nairobi, Kenya,* [2] *CSIRO Sustainable Ecosystems, 306 Carmody Road, St, Lucia, QLD 4067, Australia,* [3] *TSBF-CIAT, P.O. Box 30677-00100, Nairobi, Kenya,* [4] *TSBF-CIAT, A.A. 6713 Cali, Colombia*

Abstract Crop simulation models have been used successfully to evaluate many systems and the impact of change on these systems, e.g. for climatic risk and the use of alternative management options, including the use of nitrogen fertilizers. However, for low input systems in tropical and subtropical regions where organic inputs rather than fertilizers are the predominant nutrient management option and other nutrients besides nitrogen (particular phosphorus) constrain crop growth, these models are not up to the task. This paper describes progress towards developing a capability to simulate response to phosphorus (P) within the APSIM (Agricultural Production Systems Simulator) framework. It reports the development of the P routines based on maize crops grown in semi-arid eastern Kenya, and validation in contrasting soils in western Kenya and South-western Colombia to demonstrate the robustness of the routines. The creation of this capability required: (1) a new module (APSIM SoilP) that simulates the dynamics of P in soil and is able to account for effectiveness of alternative fertilizer management (i.e. water-soluble versus rock phosphate sources, placement effects); (2) a link to the modules simulating the dynamics of carbon and nitrogen in soil organic matter, crop residues, etc., in order that the P present in such materials can be accounted for; and (3) modification to crop modules to represent the P uptake process, estimation of the P stress in the crop, and consequent restrictions to the plant growth processes of photosynthesis, leaf expansion, phenology and grain filling. Modeling results show that the P routines in APSIM can be specified to produce output that matches multi-season rotations of different crops, on a contrasting soil type to previous evaluations, with very few changes to the parameterization files. Model performance in predicting the growth of maize and bean crops grown in rotation on an Andisol with different sources and rates of P was good (75–87% of variance could be explained). This is the first published example of extending APSIM P routines to another crop (beans) from maize.

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[v] With kind permission from Springer Science. Published in: *Nutrient Cycling in Agroecosystems* (2009), 84: 293–306 (http://www.springerlink.com/content/t0502703g70v6357).

A.2. Decomposition and nutrient release from intra-specific mixtures of legume plant materials[vi]

Cobo JG[1,2], Barrios E[1], Delve R[2].

[1] *Tropical Soil Biology and Fertility-International Center for Tropical Agriculture (TSBF-CIAT), Colombia, Cali, Colombia,* [2] *TSBF- CIAT, Zimbabwe, Harare, Zimbabwe*

Abstract Because farmers use mixtures of leaves and stems as a soil amendment, data of leaves, stems, and a leaf/stem mixture of *Indigofera constricta* and *Mucuna pruriens* from a 20-week litterbag study were analyzed to assess their decomposition, nutrient release, and possible interactions within mixtures. Decomposition and nitrogen (N)– release patterns were leaves ≥ mixtures ≥ stems, whereas phosphorus (P)–release patterns were the opposite ($p < 0.05$). Leaves released 110–130 Kg N ha^{-1}, and mixtures released 30% less. A similar ratio was obtained for P release. This suggests that nutrient release from leaf/stem mixtures is overestimated when only leaves are considered. Decomposition and nutrient-release patterns of mixtures occasionally differed from estimated patterns by 2–5% ($p < 0.05$), indicating that minor interactions took place. However, estimations based on the amount of released nutrients generally showed non significant interactions. This suggests that the impact of low-magnitude interactions within mixtures during its decomposition on soil fertility are negligible when considering total nutrient release.

[vi] With kind permission from Taylor & Francis. Published in: *Communications in Soil Science and Plant Analysis* (2008), 39: 616–625 (http://www.informaworld.com/smpp/content~db=all~content=a790491421).

APPENDIX B. CO-SUPERVISION OF M.SC. AND B.SC. STUDENTS

(during the time frame of doctoral studies)

B.1. At the University of Hohenheim

Mercy Rewe 2008 M.Sc. thesis titled “Development of a mid-infrared spectroscopy based technique utilizing thermal stability of soils and soil organic matter (SOM) removal to assess the quality and quantity of SOM” Institute of Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim

Coral Monje 2007 M.Sc. thesis titled “Factors affecting maize productivity of small-scale farming systems in three resettlement areas in Zimbabwe” Institute of Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim

B.2. At the University of Zimbabwe

Tsitsi Yekeye 2007 M.Sc. thesis titled “Spatial Variability of Vegetation Species Diversity in Woodlands in three resettlement areas in Zimbabwe” Geography and Environmental Science Department, University of Zimbabwe

Lazarus Chapungu 2007 M.Sc. thesis titled “Estimating C sequestration in Savanna Grasslands on small-scale farming systems in Zimbabwe using satellite-based remote sensing” Geography and Environmental Science Department, University of Zimbabwe

Patience Mahembe 2007 B.Sc. thesis titled “Nutrient resource use and management of communal and resettlement areas by smallholder farmers in Zimbabwe” Soil Science Department, University of Zimbabwe

Trylord Gotosa 2007 B.Sc. thesis titled “Evaluating land management diversity in communal and resettlement areas in Zimbabwe” Soil Science Department, University of Zimbabwe

APPENDIX C. COURSES FOLLOWED

(as a requirement for the doctoral program)

1. Methods of Scientific Working (P0001G)
   Prof. Dr. G. Cadisch
   Grade: A-

2. Advanced Crop Production Methods (M5104)
   Prof. Dr. G. Cadisch
   Grade: A-

3. Integrated Agricultural Production Systems (M5106)
   Prof. Dr. R. Schultze-Kraft
   Grade: A

4. Spatial Data Analysis with GIS (M7120)
   Prof. Dr. T. Streck
   Grade: A