Nutr Cycl Agroecosyst (2014) 100:1–18
DOI 10.1007/s10705-014-9632-y

REVIEW ARTICLE

Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa

Regis Chikowo · Shamie Zingore · Sieglinde Snapp · Adrian Johnston

Received: 8 March 2014 / Accepted: 1 August 2014 / Published online: 15 August 2014

Abstract Farm typologies are a useful tool to assist in unpacking and understanding the wide diversity among smallholder farms to improve targeting of crop production intensification strategies. Sustainable crop production intensification will require the development of an array of nutrient management strategies tailored to farm-specific conditions, rather than blanket recommendations across diverse farms. This study reviewed key literature on smallholder farm typologies focusing on three countries (Kenya, Malawi and Zimbabwe), to gain insights on opportunities for crop production intensification, and the importance of developing farm-specific nutrient management practices. Investigations on farm typologies have done well in highlighting the fundamental differences between farm categories, with 3–5 typologies often adequate to represent the wide differences in resource endowment. Resource-endowed farmers have ready access to large quantities of manure and mineral fertilizers, which contribute to higher soil fertility and crop productivity on their farms. Resource-constrained households use little or no manure and mineral fertilizers, and have limited capacity to invest in labour-demanding soil fertility management technologies. These farmers often have to rely on off-farm opportunities for income that are largely limited to selling unskilled labour to their resource-endowed neighbors. The variability in management practices by farmers has resulted in three main soil fertility classes that can be used for targeting soil fertility management technologies, characterized by potential response to fertilizer application as: (1) low-responsive fertile fields that receive large additions of manure and fertilizer; (2) high-responsive infertile fields that receive moderate nutrient applications; (3) poorly responsive degraded soils cultivated for many years with little or no nutrient additions. The main conclusions drawn from the review are: (1) resource constrained farmers constitute the widest band across the three countries, with many of the farmers far below the threshold for sustainable maize production intensification and lacking capacity to invest in improved seed and fertilizer, (2) farm sizes and livestock ownership were key determinants for both farmer wealth status and farm productivity, and (3) soil organic carbon and available P were good indicators

R. Chikowo · S. Snapp
Plant Soil and Microbial Sciences Department, Michigan State University, East Lansing, MI 48824, USA

R. Chikowo
Crop Science Department, University of Zimbabwe, Box MP167, Mt. Pleasant, Harare, Zimbabwe

S. Zingore (✉)
International Plant Nutrition Institute, ICIPE Compound, Box 30772, Nairobi, Kenya
e-mail: szingore@ipni.net

A. Johnston
International Plant Nutrition Institute, 102-411 Downey Road, Saskatoon, SK, Canada

for predicting previous land management, that is also invariably linked to farmer resource endowment.

Keywords Farm types · Nutrient management · Soil fertility variability · Maize

Introduction

A distinctive feature that characterizes smallholder farming systems in much of Sub-Saharan Africa (SSA) is the wide diversity of farming households and marked heterogeneity for both biophysical and socio-economic conditions, at short ranges (e.g. Zingore et al. 2007; Tittonell et al. 2005). Resource availability and the pattern of resource allocation to different activities are determined by household 'wealth', and also depend on household priorities and production objectives. Therefore, the intensity of nutrient use varies between farms of different resource endowment and production orientation, leading to variation in soil fertility status and crop productivity at the farm level. Technological interventions to address the problem of poor productivity of smallholder agricultural systems must be designed to target these socially diverse and spatially heterogeneous farms and farming systems (Tittonell et al. 2010). Implementation of linear and largely top-down approaches, that do not sufficiently recognize such complexity as fundamental, results in agricultural research and development efforts generating lower than expected impacts across much of SSA (e.g. Giller et al. 2011). Technologies developed at research stations have often failed to improve productivity at the farm-scale, due to gross mismatch of highly variable conditions when they are transferred for use by diverse farming households. Part of the problem has been the blanket promotion of single technologies, and failure to address production objectives and constraints across different types of farms. There is, therefore, need for systematic approaches and frameworks that will enable targeting of nutrient management technologies according to farmers' socio-economic circumstances.

Repeating patterns of heterogeneity in the resource endowment among farming households has practical significance regarding soil nutrient management in many smallholder farming communities in SSA. Resource-endowed farmers have access to cash income and use larger amounts of mineral fertilizers (Mtambanengwe and Mapfumo 2005; Tittonell et al. 2005). In addition, farmers in this group own more cattle and thus, have access to manure. In open grazing farming systems, livestock-mediated nutrient flows result in importation of significant quantities of nutrients to resource-endowed farms from communal grazing areas and grazing of crop residues on other farmers' fields during the dry season (Swift et al. 1989). Consequently, nutrients accumulate on wealthier farms, often at the expense of the poorer farms. There is also an important dimension that warrants recognition, related to the large variability among fields within single farms (soil fertility gradients). This arises from preferential nutrient application to certain fields, usually those close to homesteads (Zingore et al. 2007). There is evidence that such variability in soil fertility associated with resource management at the farm level has major effects on nutrient use efficiencies and crop productivity (Smaling and Braun 1996; Giller et al. 2006).

Chambers and Conway (1992) defined a livelihood as comprising the capabilities, assets and activities required for a means of living. The concept of livelihoods revolves around the opportunity offered to an individual or household by their asset endowment and their chosen allocation of those assets across various activities to generate a stream of benefits. Disaggregating farms or farmers into typologies is a useful tool to assist in unpacking and understanding the wide diversity among farms (Giller et al. 2011), enabling identifying of interventions that should be targeted to specific 'livelihood domains'. Substantial progress has already been made on this subject, with several research groups defining farmer classes/livelihoods using criteria whose elements often overlap across regions and agroecological zones (e.g. Tittonell et al. 2010; Mtambanengwe and Mapfumo 2005; Zingore et al. 2007). A review of publications that deal with this subject indicates that the number of farm types generally ranges from 3 to 5, principally defined by farm size, ownership of livestock and other assets, and the degree of dependence on non-farm income (Table 1). Based on literature review, this farm typology synthesis addresses, among other issues, the following key questions:

1. What is the range of methods and approaches used to develop household typologies across studies and geographical regions in SSA?

Table 1 Key studies that formulated farm typologies/farmer resource groups in Kenya, Malawi and Zimbabwe, and the associated characteristics

Study area/site	Number of farm types	Key farm typology/resource group characteristics	References
Kenya	3	High resource endowment (LRE)—>1.6 ha farm size, farmers own at least three cattle, do not have maize grain deficits as annual production >3 t. Annual fertilizer use >120 kg	Shepherd and Soule (1998)
		Medium resource endowment (LRE)—about 0.8 ha farm size, fertilizer use is limited and usually none at all, farmers own a woodlot but often supplement household fuel needs with crop residues. Farmers do not produce any fodder grass	
		Low resource endowment (LRE)—as low as 0.2 ha farm size, farmers do not own any cattle. Farmers do not use any fertilizer and farm annual grain production >900 kg. More than 50 % of farmland is cropped with beans, all the crop residues are used as a source of fuel. Household income from off-farm activities as high as 70 %	
Zimbabwe	3	Type 1—Resource-endowed (RG1)—own house with brick under galvanized iron sheets or asbestos; farm implements include a plough, an ox-drawn cart; livestock ownership >10 cattle; >3 ha arable land; regular contact with extension and employ extension recommendations, through direct training (e.g. the master farmer program); high capacity to secure inputs, use >250 kg fertilizer; generally >20 years farming experience	Mtambanengwe and Mapfumo (2005)
		Type 2—Intermediate (RG2)—varying resource ownership (e.g. may have a plough but not enough draught animals); own ≥4 cattle; include the eager-to-learn type farmers but are limited by resource base -most of the relatively young farming households; Seek to enhance their production through communal social arrangements (e.g. combining draught animals); fair engagement with extension agencies; landholding 2 ha; no regular pattern for hiring-in or hiring-out labour; use 50–150 kg fertilizer	
		Type 3—Resource-constrained (RG3)-lack farming implements, draught power (0–3 cattle) and cash to buy inputs; variable farm size (0.5 to >3 ha) but those with large landholdings typically utilize a small proportion of their arable land; limited or no source of remittances and constituted by a significant number of female-headed and the old (>60 years); usually not members of local social groups and often shy away from community meetings; do not avail themselves for training by extension agencies; often sell their labour to other two groups	
Kenya	5	Type 1—Farms that rely mainly on permanent off-farm employment, farm small pieces of land (0.6–1.1 ha); animal manure used at intensities as high as 8 t ha^{-1} year^{-1}; farms have a net accumulation of C and macronutrients	Tittonell et al. (2005, 2010)
		Type 2—Wealthier farms growing cash crops; farm relatively large land areas (1.6–3.8 ha)	
		Type 3—Medium resource endowment; food self-sufficient farms; farm size intermediate	
		Type 4—Medium to low resource endowment relying partly on non-farm income, farm size intermediate; perennial food deficits	
		Type 5—Poor households with family members employed locally as agricultural laborers by wealthier farmers; farm small pieces of land (0.4–1.0 ha), intensities of use of mineral fertilizers ranges between 0–12 kg ha^{-1}, perennial food deficits	

Table 1 continued

Study area/site	Number of farm types	Key farm typology/resource group characteristics	References
Zimbabwe	4	Type 1—Very rich (RG1): farm size about 3 ha, own more than 10 cattle, own a range of farm implements, afford hiring labour, use large quantities of fertilizers (>500 kg per season) and manure, and market oriented production	Zingore et al. (2007)
		Type 2—Rich (RG2): farm size about 3 ha own <10 cattle, own farm implements but rarely scotch carts, do not regularly hire labour, use fertilizers but <500 kg per season	
		Type 3—Poor (RG3): farm sizes less than 3 ha, livestock limited to goats and chickens, only small implements such as hoes, axes and wheelbarrows; no draught power; grain crops grown for subsistence, little mineral fertilizer use	
		Type 4—Very poor (RG4): Farm sizes <ha, do not own cattle but have goats and chickens, own only small implements such as hoes, grain crops grown for subsistence, do not regularly use mineral fertilizers, sell labour locally	
Malawi	4	Better-resource endowment (RG1)—have iron sheet roofed houses, household assets, own large fields (>5 ha), grow more tobacco for commercial purposes, buy and use more fertilizers, hire in *ganyu* (labour), food secure (bumper yield every year)—any food shortages are mild, own more livestock e.g. cattle, goats, pigs; Have good toilets with good sanitation measures	Kamanga et al. (2009), Kamanga (2011)
		Medium-resource endowment (RG2)—have brick house, grass thatched or iron roofed, household assets, use fertilizer on valuable crops such as tobacco and maize, hire in labour, food secure but may experience periodic or seasonal food insecurity, own livestock e.g. cattle, goats, have good sanitation facilities	
		Less well resource endowment (RG3)—have grass thatched houses, own about 2 ha farm land, grow mostly maize, sell off labour, occasionally use fertilizer (about 10 kg N/ha), limited food (lasts up to August), involved in work for food programs, normally have chickens but may rear goats, have poor sanitary facilities	
		Least-resource endowment (RG4)—have thatched houses, illiteracy very high, have <1 ha land, generally use no fertilizer, chronic food insecure, survive on kinship and *ganyu* labour, no livestock except for chicken or a goat given by others or through *ganyu* labour, no sanitation facilities	

2. What are the key criteria used for the development of farm typologies for different studies and how do the criteria vary for different study sites?
3. What are the implications of spatial and temporal heterogeneity in nutrient management patterns on crop production intensification for various farm typologies?

Study sites

This study was confined to three countries and specific regions of interest—western and central Kenya, central Malawi and northeast Zimbabwe. These regions represent key maize production zones that have good agro-ecological potential, while capturing contrasting socio-economic conditions. A farm typology study conducted in semi-arid western Zimbabwe was also reviewed to assess the potential influence of agroecological potential on farm type conditions.

1. Western and central Kenya: the area covers the densely populated (350–1,000 people km^{-2}), highland and midland humid zones whose land use systems range from strongly market-oriented smallholder coffee, tea and dairy systems, through semi-commercial cereal/legume-based systems, to subsistence oriented maize-based systems.

Farm sizes in the areas of focus, the maize-based smallholder systems, range from as small as 0.3–5 ha and average less than 1 ha. Western Kenya has a bi-modal rainfall distribution characterized by long and short rains, allowing two crops per year, with annual rainfall ranging between 1,200 and 1,800 mm. The densely populated areas lack communal areas for livestock grazing and thus intensive, 'zero-grazing' livestock systems prevail. Population growth has led to gradual depletion of nutrients through crop harvest removal, leaching, and soil erosion, which farmers have been unable to compensate via crop residues, manure and mineral fertilizers. Western Kenya is representative of the situation found in other areas of the East African highlands (Uganda and Ethiopia), with comparable soil types, climate and demography. Nitrogen and phosphorus are the main limiting nutrients to crop production (Tittonell et al. 2005). Soil acidity problems are also widespread.

2. Northeast Zimbabwe: the region is part of the sub-humid maize based integrated crop-livestock farming system. Farm sizes range between 0.9 and 3 ha, excluding communally owned grazing areas. Population densities are mostly <75 persons km^{-2}, much lower than the study sites for western and central Kenya. The area receives unimodal rainfall of 700–950 mm, between November and April. The soils in the area are predominantly granitic sandy soils (Lixisols) with poor inherent fertility. Pockets of more fertile dolerite-derived clay soils (Luvisols) constitute productive hotspots with appropriate management. There is controlled grazing of livestock during the cropping season, and subsequent free grazing after harvest (between May and October). Farmers generally remove crop residues for storage and use them to feed livestock during the dry period, from July to October. If left in the fields after harvest, livestock freely graze these residues.
3. Central Malawi: Malawi has a high human population density, with about 13.1 million people, an annual growth rate of 3 %, and about 4 million ha of arable land (National Statistical Office 2008). This has created considerable pressure on land for agricultural production, given that rainfall is unimodal. Farmers cultivate small fields, largely <1 ha, and there is considerable expansion of agriculture to marginal lands. Nitrogen and phosphorus are known to acutely limit cereal production, with the situation exacerbated by continuous cultivation with little or no use of external inputs by the majority of farmers. Livestock density is low, precluding a large proportion of the farmers from the use of animal manures. Many studies, however, have confirmed low to no response to potassium fertilization (Snapp 1998). Smallholder farmers in Malawi largely till the land using the hand-hoe. The system is based on laborious planting on ridges, which are completely destroyed during the next cropping season and shifted to the previous year furrow position. Crop residues are buried on the ridge position as it is formed. This practice results in considerable soil disturbance annually. Some of the maize residues are used as energy source for cooking.

Key approaches and variables commonly used for farm typology delineation

Farm typology is the systematic classification of farms into groups that have common characteristics. Farm types important for targeting soil fertility management recommendations are typically constructed on the basis of information on resource endowments and production criteria derived from surveys, key informant interviews, focus group discussions and literature on biophysical and socio-economic characteristics of the farming systems (Table 1). Ideally, farm types must readily reflect the potential access of different households to resources for managing their soils. Survey questionnaires that are designed to capture biophysical, socio-economic and managerial aspects of farming households in an area, must capture information on key variables that include characteristics of the household head and family structure, labour availability, main source of household income, farm land use patterns, information on previous participation in marketing (volumes of crop produce sold or bought), use of agricultural inputs, food security, livestock ownership, links to nearby markets, and production orientation (Mtambanengwe and Mapfumo 2005; Tittonell et al. 2005, 2010; Zingore et al. 2007). The specific details include:

household land ownership, family labour available, family members working off-farm, proportion of household income from off/non-farm activities, proportion of production for the market, total number of livestock and months of food self-sufficiency. To complement the formal surveys, farmer participatory wealth ranking and resource flow mapping are usually employed to delineate wealth classes, identify livelihood strategies and categorize household diversity, using farmer-derived indicators and criteria recognizable by the local communities. Principal component analysis (PCA), a common technique for finding patterns in data, is valuable to identify the main drivers of livelihood strategies. Soil characterization across farms is an important feature in farm typology studies. Soil samples from several fields within a single surveyed farm are often collected and analyzed for key variables such as organic carbon, soil pH, total N, plant available P, exchangeable bases, and texture. Further analyses are then done to determine any underlying relationships between the soil variables and identified farm types. This has immediate practical implications to inform better targeting of nutrient resources allocation for farms with different background soil fertility, especially when there are large soil fertility gradients within farms (Zingore et al. 2007).

In addition, some authors refer to two typology development pathways: (1) structural household typologies—a result of clustering households with wealth or resource endowment indicators, which are often used when farmers classify themselves through participatory wealth rankings (e.g. Mango 1999), and (2) functional typologies—that also consider the dynamics of production orientations and livelihood strategies, which they argue, may improve the categorization of households (Tittonell et al. 2010). In the following sections, we present analyses of farm/household typology case studies according to approaches by various research groups. After reviewing a large volume of publications, the synthesis was narrowed down to six publications that had a structured and systematic approach to the subject. Several publications were excluded from our analysis, as they did not analyze variability of farm types and their characteristics in sufficient detail to fully address the objectives of this review. The selected publications are presented chronologically, in the order in which they were published in the three study countries.

Case studies: determinants of farmer typologies relevant for nutrient management

Case study 1: Shepherd and Soule (1998)

Shepherd and Soule (1998) developed three representative farm types in Vihiga district, western Kenya, using participatory techniques, to reflect differences in resource endowments and constraints faced by farmers (Table 2). The average farm size for the area was about 0.65 ha, with some very small farms of 0.2 ha. The analyses were done at the farm scale, as this is the management unit of the farm household. In this site, farm unit boundaries are easily identifiable as they are usually clearly delineated by trees and shrubs. A farm simulation model that runs on a 1-year time step was designed and applied to these three farm types, to assess the long-term impact of existing soil management strategies, on farm productivity, profitability and sustainability. The study established that the low (LRE) and medium (MRE) resource endowment farms, which comprised about 90 % of the farms in the area, had declining soil organic matter and low productivity and profitability. In contrast, the high resource endowment (HRE) category farms had increasing soil organic matter, low soil nutrient losses and were productive and profitable. Crop nutrient yields were 17, 19 and 86 kg N ha^{-1} $year^{-1}$ on LRE, MRE and HRE farms, respectively. Soil C, N and P budgets were negative in LRE and MRE but positive in HRE. In line with later studies in the area (e.g. Tittonell et al. 2010), revenue from the farm activities accounted for only 7 % of the total income for the LRE category of farmers, an indication of poor farm productivity. The proportion of income from farming activities was significantly higher at 63 % for the HRE farms.

The LRE farms did not have a woodlot, and thus such families were forced to use as much as 50 % of their crop residues for fuel and supplemented this with collecting wood on the larger HRE farms where they often worked as casual agricultural laborers. In contrast, the HRE farms had woodlots to provide family fuel wood, enabling them to retain crop residues in fields or using them as livestock fodder. This study also established that the LRE farms did not use any fertilizer, in sharp contrast to fertilizer use of 124 kg ha^{-1} $year^{-1}$ for the HRE farms (Table 2). Self-sufficiency in maize production ranged from 9 %

Table 2 Principal characteristics of low, medium and high resource endowment farms in Vihiga district, western Kenya (after Shepherd and Soule 1998)

Variable and units	Farm resource endowment		
	Low	Medium	High
Farm size (ha)	0.2	0.8	1.6
Number of cattle	0	1	3
Farm area with maize/beans (%)	61	60	27
Farm area in woodlot (%)	0	10	11
Farm area in fodder grass (%)	0	0	38
Crop residues used for fuel (%)	50	25	0
Fertilizer use (kg ha^{-1} $year^{-1}$)	0	0	124
Maize grain productivity (kg ha^{-1} $year^{-1}$)	880	960	3,080
N, P or C balances	–	–	+
Household income from off-farm employment (%)	72	46	38

in LRE to 112 % in HRE. Even if production were to increase by 400 % on LRE farms, the households would still be less than 50 % grain self-sufficiency, partly due to a combination of small farm sizes and low soil fertility. Unsurprisingly, the authors concluded that low land and capital resources constrained the adoption of ecologically and economically sustainable soil management practices on the majority of farms in the area. For the LRE farms, the authors perceived increasing opportunities for off-farm income as the most promising strategy to improve their livelihoods in the short term, and this could also be a potential trajectory for stimulating long-term farm productivity.

While regional as well as farm-scale studies based on only one representative farm type have universally shown negative nutrient balances in Africa (Smaling et al. 1997), this study suggests that disaggregating the nutrient balances by farm type, nutrient balances are actually positive on well resource endowed farms. The HRE farmers show the ability to manage their farms profitably, increase soil organic matter and achieve low levels of nutrient losses. While the technologies and knowledge for sustainable production exist, the major impediment for the poor farmers is the lack of initial capital required to kick-start appropriate farm management (e.g. purchase cows for milk and manure, mineral fertilizers, etc.). To increase the productivity and sustainability of land use, while addressing poverty, low cost but high quality nutrient input interventions must be targeted to the resource poor farmers. Leguminous systems that require low labour inputs (e.g. improved fallows) are a possibility as a cheap source of N input but the problem will remain on how to provide the necessary P inputs at low cost to stimulate large legume biomass production under P-limited soil conditions.

Case study 2: Tittonell et al. (2005, 2010)

Tittonell et al. (2005, 2010) categorized household diversity based on a functional typology of livelihood strategies, and analyzed the influence of such diversity on current soil fertility status and spatial variability on a sample of 250 randomly selected farms from six districts of Kenya. The households were grouped into five farm types: (1) small farms that rely mainly on permanent off-farm employment or pensions, (2) larger, wealthier farms growing cash crops, mainly constrained by labour, (3) medium resource endowment, food self-sufficient farms and generating food surpluses, (4) medium to low resource endowment relying partly on non-farm activities, and (5) poor households with family members employed locally as agricultural laborers by wealthier farmers (Table 3).

Type 1 farms which are generally small (0.6–1.1 ha) represent a category of households that rely mostly on off/non-farm activities, often with the family head or other member permanently employment in skilled jobs. These farmers are able to invest in sustaining their resource base, and in achieving households needs (food security, education). These farms use mineral fertilizers intensively, with an average application rate of about 50 kg ha^{-1}. Type 2 farms represent wealthier farmers owning relatively large farms, growing cash crops and keeping a larger number of livestock, and rely mostly on income generated from farming. Type 3 farms have similar income generation strategies as type 2 but are less endowed in land and/or capital, and some family members may engage in off-farm activities to cover other expenditure such as school fees. Type 4 farms include households with poor to medium resource endowment in which, next to farming, a varying range of off- and non-farm income generating strategies can be observed. Normally, they engage in activities, which require less skill or are poorly remunerated.

Table 3 Commonly used farmers' criteria to classify households in relation to resource endowment and farm management in Western Kenya (adapted from Tittonell et al. 2010)

Criteria	Key indicators
1. Food security	Months of food self-sufficiency (8–12 Class I; 3–5 Class II; 0–2 Class III); having food surplus to market
2. Labour availability	Depending exclusively on family labour, complemented with hired labour or using exclusively hired labour
3. Cash crops	Presence and acreage of tea plantations (> or <1 acre); presence of tobacco, sugar cane, tomatoes; level of input use and maintenance
4. Livestock	Type and number of livestock heads owned (e.g. 3–5 improved dairy cows in Class I) and management system (stall fed, free grazing)
5. Use of fertilisers	Regular, occasional or no use of organic and/or mineral fertilisers; applied in most fields or only in home-gardens; only basal or basal plus
6. Timing of farm operations	Timely planting and weeding, ownership/capacity to hire oxen for ploughing versus hand-hoeing; labour hired for timely weeding
7. Land availability	Farm size (variable acreages across localities); hire-in, use own or hire-out land for cultivation
8. Use of quality seed	Use of certified seeds, maize hybrids; use certified in long rains and local seeds in the short rains
9. Income	Main source of income (on-farm vs. non/off-farm); permanent versus intermittent off-farm income

Type 5 farms, about 0.4–1.0 ha, constitute the poorest category depending largely on off-farm earnings, in which more than one household member is locally employed as a labourer by wealthier farmers. Working on other farmers' fields as an income strategy for these farmers has negative implications on timing of activities in their own fields. Both farm types 1 and 5 rely on off-farm earnings and sell the least amounts of farm produce to the market, though the magnitude of their cash, labour and nutrient flows are very different. Grain production for farm types 4 and 5 is much below annual family requirements, as a result household food is supplemented through grain purchase from richer farmers or other market places.

Data from Tittonell et al. (2005) suggests that proximity to markets and land sizes were factors that strongly influenced fertilizer use across farms–fewer inputs were generally used in areas where markets were more remote and population less dense. Tittonell et al. (2005) observed small differences in the majority of soil fertility variables among different farms in western Kenya, presumably due to overriding effects of inherent properties of the soils. Differences in wealth between farms were reflected mostly by input use intensity, particularly on mineral fertilizer use, and significant differences in soil fertility status between farms belonging to the various farm types in each site were only observed for extractable P (Table 4). Thus, the effects of wealth and production orientation, seen in the magnitude of the nutrient inputs and outputs to and from the farm, were in general not reflected by the soil fertility status at farm scale, except for P. The authors suggested further explanations to this site-specific variability should be sought at more detailed scales of analysis, considering the heterogeneity in nutrient balances and stocks within the farms, and its interaction with factors determining decisions on resource allocation.

A large portion of the variability in soil properties at farm scale is associated with the inherent geological and geo-morphological features of each site. Farms with limited amounts of manure often exhibit more variability in soil fertility indicators (mainly soil C and bases) as these farmers preferentially allocate the limited manure to only some fields. Small farms with larger cattle density tend to have large nutrient stocks due to high rates of manure applied every few years per field. These farmers also readily access cash income to purchase mineral fertilizers. The authors established that in some relatively remote areas of western Kenya, mineral fertilizers were exclusively used by farms of types 1 and 2, the same groups that had high nutrient stocks.

In areas of high population density, the intensity of input use, the proximity to markets and the access to off-farm income were more important factors than inherent biophysical properties in determining the pattern of resource allocation and the magnitude of the soil fertility gradients within farms. Conversely, in areas of sparse population density and/or high

Table 4 Weighted average soil organic C and macronutrient content in the topsoil of 15 case-study farms at three sites (sub-locations) in western Kenya (adapted from Tittonell et al. 2005)

Site	Farm type	Weighted average content			
		Soil organic C (g kg^{-1})	Total soil N (g kg^{-1})	Extractable P (mg kg^{-1})	Exchangeable K^+ ($cmol_{(+)}$ kg^{-1})
Emuhaia	1	9.7	1.1	4.8	0.4
	2	12.0	0.8	6.4	0.4
	3	11.7	1.3	4.3	0.9
	4	13.6	1.3	2.8	0.2
	5	10.6	1.0	2.4	0.4
Shinyalu	1	17.5	1.5	4.5	0.2
	2	17.1	1.7	10.1	0.3
	3	18.7	1.5	2.5	0.5
	4	16.3	1.6	1.8	0.2
	5	17.4	1.6	2.1	0.5
Aludeka	1	10.8	0.6	4.6	0.3
	2	9.1	0.6	5.0	0.2
	3	9.6	0.7	4.0	0.7
	4	6.2	0.4	4.2	0.2
	5	4.8	0.2	2.2	0.2

variability in the inherent biophysical background, perceived land quality determined the resource allocation pattern emerging from farmers' management decisions. Since scarce resources and investments are preferably allocated to less risky land units, such a pattern results in increased within-farm soil fertility variability. Soil fertility variability associated with farmers' nutrient management strategies had profound effects on maize productivity, with yields for both fertilized and unfertilized maize crops decreasing with decreasing soil fertility status (Tittonell et al. 2008).

Case study 3: Mtambanengwe and Mapfumo (2005)

A study involving 120 households from three sites in Zimbabwe identified three farmer classes according to resource endowment: namely, resource endowed, intermediate group and resource-constrained farmers (see Table 1). Two of the sites were old communal areas with >70 years of cultivation in contrast to one of the sites which was formally a large commercial farming area, and had been under smallholder farming for only 20 years. The study also investigated soil fertility status in two fields that each of the farmers had identified as the most productive (rich fields) and least productive (poor fields). Farmer criteria for defining soil fertility included colour, soil structure and crop response following external nutrient inputs. The fertility ranking of fields as identified by the farmers consistently matched with laboratory indices, with fields identified by farmers as 'rich' containing significantly more organic C and nutrients than the corresponding 'poor' fields.

Soil fertility gradients were evident within and across farms belonging to different farmer classes. The mean soil organic C content for rich fields was >6.0 g kg^{-1} compared with <4.6 g kg^{-1} for poor fields (Table 5). The study also established that soil organic C from rich fields belonging to resource-endowed farmers was 28 % more than that from the corresponding rich fields belonging to resource-constrained farmers, confirming differences in organic matter management practices. Differences in fertility status between rich and poor fields were wider in the two study sites which had more than 70 years of cultivation in contrast to the site which had been under smallholder farming for only 20 years, suggesting that the observed fertility gradients are a cumulative effect of years of differential resource management practices by different farmer types. Under the former large commercial farming system, soil fertility management was relatively homogeneous across the different fields.

While the resource-endowed farmers, and to a lesser extent the intermediate farmers, used manure as an integral component of soil fertility management,

Table 5 Soil organic C content for fields belonging farms in three typologies in smallholder farming areas in Zimbabwe (adapted from Mtambanengwe and Mapfumo 2005)

Site	Farm type	Soil organic C (g kg^{-1})	
		Rich fields	Poor fields
Chikwaka	RG1	6.9 ± 0.2	5.0 ± 0.1
	RG2	6.0 ± 0.2	5.0 ± 0.1
	RG3	5.4 ± 0.2	4.4 ± 0.1
Chinyika	RG1	6.5 ± 0.2	4.9 ± 0.1
	RG2	5.6 ± 0.1	4.9 ± 0.1
	RG3	5.6 ± 0.1	4.5 ± 0.1
Zimuto	RG1	7.1 ± 0.2	5.0 ± 0.2
	RG2	6.6 ± 0.2	5.0 ± 0.2
	RG3	5.9 ± 0.1	4.6 ± 0.2

this option was not available to the poor farmers. Carbon input from crop residues was also very low on poor farms, as most of the crop residues were grazed by livestock belonging to rich farmers during the dry season. This results in livestock-mediated export of nutrients from the already depleted fields of poor farmers to farms of relatively better-off farmers. The study concluded that as field-level characterization of soil fertility by farmers and researchers was congruent, the targeting of soil fertility technologies was, in principle, unlikely to be limited by farmers' capacity to identify fields with different soil fertility conditions. Farmers were also able to rank their fields according to productivity despite the general similarity in soils derived from the same parent material. Thus, the criteria used by farmers to identify and classify fields according to productivity potential is holistic and consistent with laboratory-based scientific indices, implying that farmers' criteria could be useful in wide-scale dissemination of site-specific soil nutrient management technologies.

Soils from the three study areas were derived from granite parent material, and had similar textural properties, suggesting that the observed soil fertility gradients were largely a result of management factors rather than inherent soil properties. This is in contrast to farming systems in western Kenya, where soil fertility was largely determined by inherent factors (toposequence and parent material) rather than farmer management practices (Tittonell et al. 2005). While soil fertility differences were evident, overall, the soil organic C contents for both rich and poor field types across the farm classes were poor due to the low capacity of the sandy soils (generally <10 % clay) to physically protect soil organic matter from decomposition (Six et al. 2002), and due to the frequent conventional tillage practiced by smallholder farmers in Zimbabwe.

Case study 4: Zingore et al. (2007, 2011)

Using focus group discussions with farmers in Murewa district, North-east Zimbabwe, Zingore et al. (2007) established four farm types or resource groups (RG) (RG1—very wealthy; RG2—wealthy; RG3—poor; RG4—very poor) based on resource endowment and other characteristics (Table 1). Farmers considered cattle to be the most important indicator of wealth status. The other criteria were ranked in the order: draught power > farm size > farming implements > production orientation (commercial or subsistence) > hire or sell of labour > use of mineral fertilizers. The largest proportion of the farmers was in the RG4 category, whilst the smallest proportion was in the RG1 category. RG4 households were mostly female-headed households. Despite an average cattle ownership of three per household within the village, more than half of the farmers did not own cattle and had no access to manure. Ownership of other resources was also strongly skewed towards the farms in the richer resource groups, as farmers in these groups also owned larger farms and possessed greater quantities of other assets. The wide variability of resource endowment observed indicates strong variability between farms in access to resources and constraints to production. The poorest farmers are faced with multiple constraints, which include small farm size, poor and competing demands for labour, lack of draught power and manure and lack of cash to buy fertilizers.

In line with Mtambanengwe and Mapfumo (2005), this study also traced soil fertility indicators in the different fields of farmers. As expected soil organic C contents were larger on farms located on the clay soils compared with those on the granitic sands, irrespective of farm typology. This is linked to the high capacity for physico-chemical C stabilisation in soils richer in clay and silt, and the resultant higher soil C thresholds that remain stable over time even under poor organic matter input (Feller and Beare 1997; Six et al. 2002).

The study also established that for farms on the same soil type, soil organic C contents in plots closest to the homesteads were significantly larger on farms within the two rich categories, with some dependence on soil texture (Fig. 1). These were in the order: RG1 > RG2 = RG3 = RG4 for sites on the clay soil, and RG1 = RG2 > RG3 = RG4 for the sandy soil sites. Available nutrients were mostly concentrated on 'rich' fields belonging to the resource endowed farms, with steep decline of fertility as distance from the homestead increased, resulting in soil fertility on the fields identified by farmers as their worst fields being similar across different farm categories.

On average cattle owners use between 5 and 10 t manure per farm annually, which provides 50–100 kg N and 15–30 kg P (Zingore et al. 2007). Many farmers in the area used some N and P fertilizers, but the rates applied are lower than the recommended rates of 120 kg N ha^{-1} and 25 kg P ha^{-1}. The resource-endowed farmers (RG1 and RG2) use larger amounts of fertilizers (50–100 kg N and 15 kg P per farm; applied at about 40 kg N ha^{-1} year^{-1} and 10 kg P ha^{-1} year^{-1} across the whole farm area compared with the poor farmers (RG3 and RG4) who use <40 kg N and <10 kg P, applied at rates of about 20 N kg N ha^{-1} year^{-1} and 5 kg P ha^{-1} year^{-1} across the whole farm area.

To derive soil fertility niches meaningful for targeting fertilizer recommendations, Zingore et al. (2011) classified the homefields, midfields and outfields for farms of different wealth categories (14 in total on each soil type) into three fertility zones (FZ1–3) that captured the soil fertility variability within and across farms. FZ1 consisted of the most fertile fields closest to homesteads on RG1 and RG2 farms that received large additions of manure and fertilizer. FZ2 covered medium soil fertility fields that received moderate applications of fertilizer and manure in the past. More than 50 % of the cultivated area in the village fell in the FZ3 category, consisting of infertile fields that were cultivated for long periods with little addition of mineral fertilizers or organic nutrient resources. Maize yields attainable with good management practices decreased from about 6 t ha^{-1} in the FZ1 to 4.5 t ha^{-1} in the FZ2 and 1 t ha^{-1} in the FZ3. The low attainable yields in the FZ3 were associated with soil degradation, multiple constraints to maize productivity, including multiple nutrient deficiencies and soil acidity.

Case study 5: Masvaya et al. (2010)

Most of the studies analysing variability in farm types and soil fertility at farm scale were conducted in humid or sub-humid agroecological zones, where farm sizes are very small (<3 ha) and land use intensive. A study Masvaya et al. (2010) sought to assess the potential implications of climate and land use intensity on farmers' resource endowment, nutrient management strategies, and variability in soil fertility and plant nutrient uptake in smallholder farming systems in Zimbabwe. Study sites were selected in Gokwe, a district located in the semi-arid climatic zone (average rainfall 600 mm year^{-1}) and unreliable rainfall and in Murewa district characterized by sub-humid climate (average rainfall 850 mm year^{-1}). Population was less dense in Gokwe, with 16 persons km^{-1}, compared with Murewa, which had a population density of 41 persons km^{-2}. Maize and cotton were the main crops grown in Gokwe, with maize and groundnut dominant in Murewa. Farm sizes in Gokwe ranged from 5 to 10 ha and fallowing was a common practice. Farm sizes were smaller (1–3 ha) in Murewa and fields had been subjected to continuous cultivation for more than 30 years.

Farms from Gokwe and Murewa were classified into three resource categories (resource-endowed, intermediate and resource-constrained), using a combination of criteria developed by Mtambanengwe and Mapfumo (2005) and Zingore et al. (2007). Although the indicators for generating different farm types based on the type of house, livestock ownership, farming implement owned, farm size, use of fertilizer and manure and hire or sell of unskilled labour were originally developed for sub-humid farming systems; the same indicators were readily applicable under the semi-arid conditions in Gokwe. A detailed analysis of 30 households in Gokwe and 23 households in Murewa randomly selected after a rapid rural appraisal established that the resource-endowed group had the least number of farmers in both sites. Analysis of nutrient management strategies showed large differences in the amounts of manure and fertilizer applied between farms in different resource groups in Murewa, but the differences were very small in Gokwe. In Murewa, the resource-endowed farmers applied 3–9 t manure ha^{-1}, while the intermediate and resource-constrained farmers applied less than 1.5 t manure ha^{-1}.

Different field types were identified using a participatory approach, whereby farmers in the different

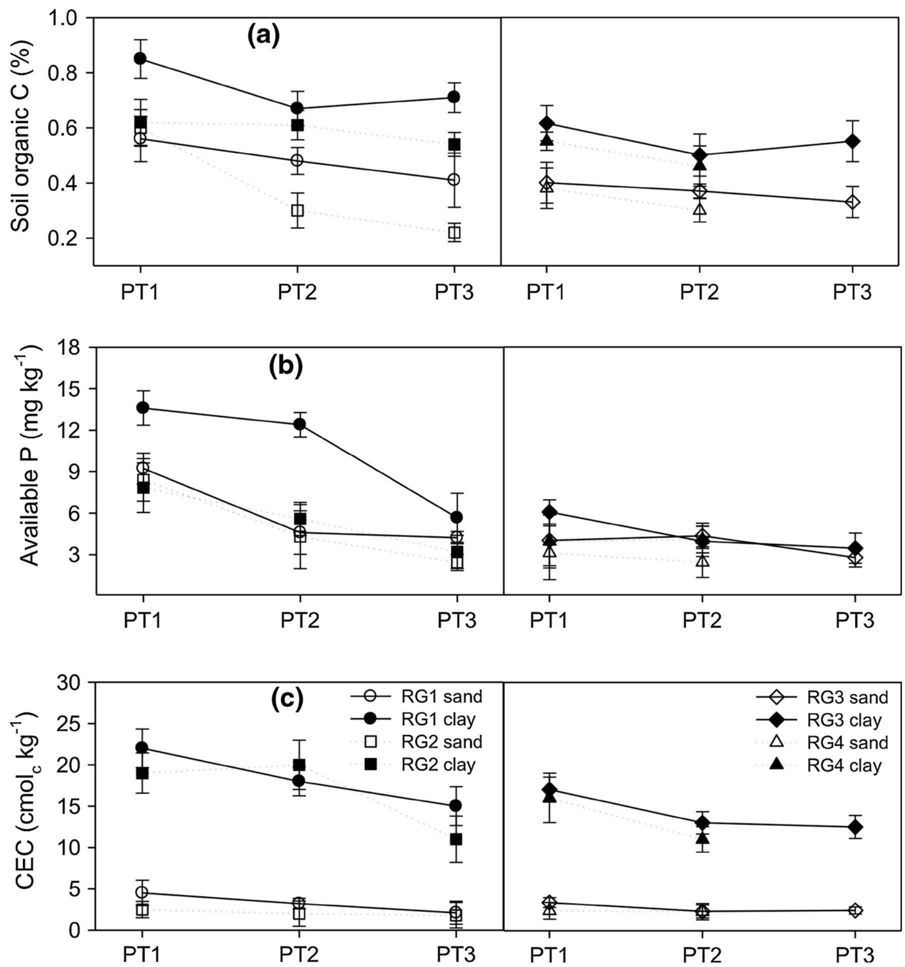

Fig. 1 Variability of soil organic carbon (**a**), available P (**b**) and cation exchange capacity (**c**) with plot type on farms in different resource groups situated on contrasting soil types in Murewa, Zimbabwe

wealth categories were asked to indicate manure and fertilizer allocation patterns and their most productive and least productive maize fields. In line with previous studies, fields belonging to resource-endowed farmers were consistently more fertile than the corresponding fields from poor farmers (Table 6). Consistent with other studies, soil analysis results by Masvaya et al. (2010) showed that within farms in Murewa, the soil fertility levels were higher in homefields than outfields. However, in Gokwe it was observed that fields close to the homesteads were less fertile than field further away, highlighting a strong influence of climate zone on nutrient management patterns at farm-scale. An important finding of this study was that, besides farmers' access to resources, the direction of soil fertility gradients also depended on agro-ecological conditions, which influence resource management strategies. Unlike practices reported in many other related studies, farmers in Gokwe did not target manure to any particular fields. Homefields were continually cultivated, but received the same rates of manure and fertilizer as outfields. However, outfields were less intensively cultivated, as farmers abandoned them once fertility declined and cleared new fields further away from the homestead. This practice resulted in an inverse pattern of resource management intensity that led to higher soil fertility status in outfields than homefields. This resource use pattern is also partly linked to the large landholdings in Gokwe due to a low demographic pressure.

Case study 6: Kamanga et al. (2009), Kamanga (2011)

Using a combination of survey and participatory methods, 136 smallholder farmers from Chisepo,

Table 6 Variation of soil fertility characteristics as influenced by farm typologies for smallholder farmers in Murewa and Gokwe communal areas in Zimbabwe (after Masvaya et al. 2010)

Site	Farm typology	Available P (mg kg^{-1})	SOC (g kg^{-1})	Exchangeable Mg ($cmol_c$ kg^{-1})	Exchangeable K ($cmol_c$ kg^{-1})
Murehwa	RG1	24	9.0	0.5	4.0
	RG2	15	7.2	1.4	2.0
	RG3	4	0.5	0.6	1.1
Gokwe	RG1	20	0.8	5.7	1.6
	RG2	18	0.8	2.0	0.2
	RG3	10	0.6	0.4	0.5

central Malawi, were grouped into four resource groups (RGs), comprising high-resourced (RG1; 5 %), medium resourced (RG2; 10 %), low-resourced (RG3; 47 %) and least-resourced group (RG4; 38 %) (Table 1). The study investigated the link between household access to assets and diversity in livelihood strategies and investments in soil fertility management in central Malawi. Analysis of farmer resources endowment and their relation to soil fertility revealed that soil fertility management is intricately influenced by ownership of assets. RG1 and RG2 farmers owned more resources including cattle, had larger fields (about 5 ha), hired-in labour for timely farm operations, earned more income and invested more in soil fertility improvement. RG3 and RG4, comprising the majority, were resource constrained and did not invest adequately in improving soil fertility, with about 50 % of them owning between 0.5 and 1 ha land. They had large food deficits due to poor crop yields. These farmers supplemented their farm income through *ganyu*, a local practice of casual work on resource-endowed farmers' fields in exchange for food or cash.

This study established that there is a huge variability in fertilizer use linked to farm and field type, with average N application of 44 kg N ha^{-1} for a home-fields in RG1 and but only about 10 kg N ha^{-1} in the same fields belonging to RG3 farmers. Farmers in RG4 applied no fertilizer at all. Farmers' soil fertility management was directly determined by the level of assets of a household, which influence the amounts of resources such as mineral fertilizer and manure a household can use (Orr and Jere 1999). In line with other studies, soil fertility decreased from homefields to remote fields in each farmer group, and also decreased from fields belonging to RG1 to those in RG4 (Table 7). Soil fertility indicators for homefields belonging to resource-constrained farmers (RG4) were low and of similar magnitude to those measured for the remote fields belonging to resource-endowed farmers (RG1).

Experimental results showed that maize grain yields over a 4-year period were greater for RG1 and RG2 than RG3 and RG4 farms. Maize-pigeon pea intercrops gave consistent positive returns across resource groups and were the only technology to provide positive returns to labour for RG4 farmers. Use of pigeon pea was overall the least risky option, and was especially suited to least-resourced farmers. The majority of resource-constrained farmers in Malawi were not able to invest in mineral fertilizers to improve crop yields, and inclusion of grain legumes, such as pigeon pea, offered the best opportunity for these resource-constrained farmers to access protein while improving their soils through litter-fall. This study also established that RG3 and RG4 farmers had less access to legume seed, resulting in less adoption of grain legumes. In general, Malawi's low livestock densities (Benson et al. 2002) limit the use of manure.

General discussion

The importance of farm typologies for site-specific nutrient management practices

While the thresholds for allocating the farmers to different farm types differed between countries, the criteria for typology construction were largely similar across sites (farm size, livestock ownership, hiring in or hiring out of labour, regular off-farm income—Table 1). The key studies reviewed in this study have shown that complex differences in soil fertility and crop response to fertilizer associated with farmer management practices can be summarized into 4

Table 7 Variation of soil fertility indicators by farm typology and field type in a smallholder faring community, central Malawi (after Kamanga 2011)

Field type	Farm typology	pH	SOC (g kg^{-1})	Available P (mg kg^{-1})
Home fields	RG1	6.1	16	9.9
	RG2	5.4	12	7.0
	RG3	5.6	11	7.7
	RG4	5.6	6	6.7
Remote fields	RG1	5.5	9	3.2
	RG2	5.7	7	3.1
	RG3	5.3	6	3.4
	RG4	5.4	4	3.6

categories as follows: (1) low responsive fertile soils that are nutrient saturated; (2) high responsive fertile soils; (3) high responsive infertile soils; and (4) low responsive, degraded and infertile soils. Understanding the extent and distribution of these categories of soil fertility is indispensible to the development of improved nutrient management recommendations for crop production intensification.

Repeating patterns of soil nutrient management practices by smallholder farmers

Across regions, the patterns of soil fertility variability on smallholder farms are reinforced by farmers investing more resources on already fertile fields than on infertile fields. This nutrient management strategy that seemingly cuts across farm typologies, and only differentiated by intensity of nutrient use, suggests that farmers in various resource groups utilize similar resource use strategies. Soil fertility variability between farms on similar soil types is mainly driven by differing access to nutrient resources between farmers of different resource endowment. In open grazing systems, the resource-endowed farmers own more cattle and import significant quantities of nutrients to their farms through grazing on communal land during the cropping season, through grazing of crop residues on other farmers' fields during the dry season (Swift et al. 1989). Therefore, nutrients accumulate on wealthier farms, often at the expense of the poorer farms, accentuating the nutrient limitations for those farmers who have the least capacity to invest in soil fertility management technologies (Zingore et al. 2007). This tends to engrave and perpetuate conditions that favour low farm productivity and poverty on resource-constrained farms.

Resource-endowed farmers have capacity to use best agronomic practices, including early planting, weeding and fertilizer application, and this enhances the yield difference with the resource-constrained farmers who have limited labour. Delays in farm operations are common with resource-constrained farmers, who often have to work on other farmers' fields. This affects the resource-constrained farmers most severely in sub-humid to semi-arid environments, where the there is only a narrow window for getting the right balance of agronomic practices that facilitate high yields.

The agronomic and economic efficiency of preferential targeting of nutrient resources to specific fields depends on site-specific conditions. In limited cases, concentration of nutrients by resource endowed farmers on already fertile fields is associated with poor returns to nutrient investments, as the already fertile fields respond poorly to additional nutrients. Other studies, however, also show that current farmer practices are rational as avoiding poor soils may also mean avoiding application of nutrients in degraded and non-responsive soils (Rowe et al. 2006). While there are major differences to access to nutrient resources among farmer resource groups, few farmers have access to resources to fully exploit the economic attainable yields, including the 'rich' farmer categories.

Targeting nutrient resources based on land quality: local and lab-based fertility indices

Use of local indicators of soil quality by farmers, including application of local terms to ascribe different soil quality features, was often in agreement with laboratory-based soil fertility indices. This knowledge was used across farm typologies, suggesting that farmers are aware of soil quality as a determinant of crop productivity, thus making communication with farmers on site-specific soil nutrient management simpler. Recommendations for nutrient management can therefore be linked to local indicators of soil fertility that farmers can readily relate with. Multiple NPK-based experiments in western Kenya on fields with different soil fertility status indicated clear links between background soil fertility and responses to applied fertilizer (Vanlauwe et al. 2006).

The various soil fertility niches are readily recognisable to farmers, and are often economically viable entities on large farms that often belong to resource-endowed farmers (Mango 1999; Crowley and Carter 2000). However, on resource-constrained farms, productive units are often too small to make an impact on household food security. Even if productivity on these small patches of land were to be increased to the yield potential level determined by the local environment, overall farm production would still remain below the critical threshold required to avert food deficits until the next harvest. The remainder of the farmland is either of intermediate or poor fertility status. While soil fertility restoration technologies exist, and can be applied to improve soil productivity on degraded portions of the farms, this is often impractical or unsuccessful. For example, soil-improving legumes often grow extremely poorly on degraded land and give little benefit to enhancing soil fertility.

Development of site-specific nutrient management strategies that address farm typologies

Current blanket fertilizer recommendations are based on potential yields, as determined by rainfall received, but they ignore heterogeneity in soil fertility at farm scale. Variable responses to mineral fertilizers due to differences in soil fertility and other factors such as seasonal variation in rainfall are inevitable, and are given as major reasons limiting use of mineral fertilizers in smallholder farming systems. There is scope for using strategies that can ensure better nutrient targeting on various farm typologies. To sustainably intensify crop production, both fertilizer use and nutrient use efficiencies have to substantially increase for all farm typologies. The 2006 Abuja Declaration on Fertilizer for an African Green Revolution committed to increase fertilizer use in Africa to 50 kg nutrients ha^{-1} by 2015, in order to improve agricultural productivity and thus food security (Abuja Fertilizer Summit 2006). Progress to achieve this target has been variable across countries. The real opportunity for farmers to increase productivity in the short-term is through efficient targeting of the limited nutrient resources they are currently accessing. While there has indeed been much work on approaches to improve nutrient use efficiencies, the results have largely remained unused, as they failed to address the heterogeneous biophysical and socio-economic conditions on the ground.

Although several analyses indicate that farmers are often doing the best they can with available resources, and within the confines of their current knowledge, most farmers often lack a good understanding of how best to manage resources when they become available. For example, the recent investment in fertilizer in Malawi under the national subsidy program resulted in substantial increases in food production but with an agronomic efficiency of N (defined as unit of grain produced per unit of fertilizer N applied) of only 14 kg grain kg^{-1} N applied (National Statistical Office Malawi Government 2008)—less than half the efficiency that can readily be achieved with good management. Some of the gaps identified for increasing fertilizer use efficiency and the subsidy impacts on crop productivity include improving input distribution logistics to ensure timely delivery of the inputs and improving targeting of beneficiary households and supplying the correct fertilizers for different soil fertility conditions (Dorward and Chirwa 2011).

Many farmers are not using the ‘blanket’ nutrient management recommendations available from national extension services, as they are mostly too rigid for the economic circumstances of the majority of farmers (Sheahan et al. 2013; Jansen et al. 2013). Development of nutrient management recommendations to address soil fertility depletion has often not clearly defined the target groups of farmers that are meant to use them, often resulting in poor adoption (Snapp et al. 2003). There is growing realization that approaches that are more sensitive to the social context underlying the complexity of soil fertility management by farmers may enable effective targeting of soil nutrient management interventions (Giller et al. 2011). There is therefore an opportunity to work towards a more flexible nutrient management recommendation system that responds to the variable soil fertility conditions, farmers’ capacity to purchase fertilizer and the risk associated with droughts, using ‘rules of thumb’ built on farm topology analysis.

Implications of farm-scale socioeconomic and soil fertility variability for future research and development directions

After many decades of low and stagnant crop productivity in SSA, there are renewed development efforts by governments, private sector companies and nongovernmental organizations to support smallholder farmers to increase crop productivity, in particular by increasing access to improved seed varieties and fertilizer. The impact of these efforts will remain limited unless the fundamental issues of improved targeting of technologies to highly variable farms and soil fertility conditions are effectively addressed. The consistent pattern of heterogeneity in smallholder farms highlighted in this review provides a basis for strategic soil fertility management research that identifies effective entry points for increasing agricultural productivity and identifying minimum farm conditions necessary for sustainable crop production intensification. There is need to refocus research direction from approaches that generalize smallholder farms, thereby producing 'best-bet' technologies that do not account for farm-specific opportunities and constraints to adoption of soil fertility management technologies. Greater research emphasis should be placed on improving understanding of recommendation domains at various spatial scales (region, landscape, farm) that enable generation of 'best-fit' technologies that clearly define the socio-economic and biophysical conditions required for their effective implementation.

Major research challenges still exist in the development of effective and practical technologies to manage and restore degraded non-responsive soils. There is currently limited understanding of the key soil factors underlying the non-responsiveness in degraded soils, and there is need for research activities that address the chemical, physical and biological processes underlying the limited crop response to management.

The complex nature of farm-level variability raises the need for decision support tools that can be used by extension systems to evaluate feasibility of technological option for different households. While farm typology decision support tools have been mainly used as a platform for research to improve understanding of the complex smallholder farming systems in SSA, there is increasing scope for simple decision support tools that can be used in guiding the development and dissemination of soil fertility management technologies that are appropriate for various categories of farms. Such targeted research is beneficial not only to increase nutrient use efficiency at the farm level, but also to inform policy makers on matters such as status of land degradation, amounts and formulation of fertilizers required in different regions and targeting farmers for subsidies to improve economics and efficiency of fertilizer use at the regional and country level. Further work to conduct targeted participatory experiments with farmers in different resource endowment categories to evaluate soil fertility management options is necessary to refine the general guidelines for specific sites and farms.

Spatial analysis approaches have proven useful in complementing technology development processes, whether for site-specific fertilizer recommendations based on multi-site fertilizer trials (Snapp and Benson 1995), or for identifying scaling-up recommendation domains for targeting of legume cover crops (Delve et al. 2007). These approaches however are still caught between using limited amounts of data and therefore producing very general recommendations, and the need to generate large volumes of farm and household specific data to make the recommendations truly representative of the diversity of smallholder households that exist. This is one area that has not been successfully managed in soil fertility research, and is a general problem with spatial analysis approaches. Recent developments in soil fertility analysis using infrared spectroscopy allow for rapid, accurate and cost effective large-scale soil analysis and surveillance. This offers opportunities to accelerate data collections for accurate diagnosis of soil fertility constraints and improve targeting of technological options to different farm types (Shepherd and Walsh 2007).

The production of development/recommendation domains is critical for efficient and cost-effective implementation of development programs. These domains are useful for improving decision making on areas/households to target with different interventions, what percentage of a target area (e.g. a country or region) they can be applied to, and more importantly how many smallholders will be able to benefit. Specific farm typology training for extension providers in the locations where soil fertility management options are being disseminated shows the greatest potential for change, and equipping them with the skills to demonstrate them should be a key focus for future development activities.

The process to develop site-specific nutrient management practices takes into account complex factors that not only affect soil–water–crop relations, but also socio-economic factors. The International Plant Nutrition Institute has developed Nutrient Expert® (NE), a robust computer-based decision support tool that integrates complex factors in a simple way and enables strategic formulation of nutrient management guidelines for maize and other crops (Pampolino et al. 2012). We intend to use NE to evaluate and promote site-specific crop and nutrient management practices for crop production intensification that are relevant for the highly variable soil fertility conditions in SSA that have been identified in this review.

Conclusions

Farming systems across SSA show a consistent pattern of farm typologies based on access to resources, which contribute to differences in soil fertility, mostly due to differences in input levels. Analyses of key farm typology studies suggest that soil organic C and available P are the most useful soil fertility indicators separating the fertility levels for farms belonging to different categories. In many cases, home fields belonging to poor farmers have soil organic C and available P that is comparable to levels of nutrients in outfields belonging to richer farmers. It is also clear that there are some households that are in farming but do not regard the enterprise as their primary source of income. The farm is usually subsidized through remittances or pensions. Such farmers are less likely to consider the overall farm efficiency as a defining factor, and will not get involved in labour demanding soil nutrient replenishment innovations. While this review has not attempted any economic analysis, it may well be true that for farms with extra non-agricultural incomes, the agricultural component may be operating unprofitably. The potential for the least resource-endowed farmers to intensify crop production is very limited and off-farm income opportunities in their communities offer the short-term respite.

Acknowledgments This review was done through a grant from The International Maize and Wheat Improvement Center (CIMMYT) to the International Plant Nutrition Institute (IPNI), as part of Consultative Group on International Agricultural Research (CGIAR)'s MAIZE research program.

References

Abuja Fertilizer Summit (2006) Abuja declaration on fertilizer for African Green Revolution. African Union Special Summit of the Heads of State and Government, Abuja

Benson T, Kaphuka J, Kanyanda S, Chinula R (2002) Malawi—an atlas of social statistics. International Food Policy Research Institute, National Statistical Office, Washington, DC, Zomba

Chambers R, Conway G (1992) Sustainable rural livelihoods: practical concepts for the 21st century. IDS discussion paper no. 296. Institute of Development Studies, Brighton, UK, pp 7–8

Crowley EL, Carter SE (2000) Agrarian change and the changing relationships between toil and soil in Maragoli, Western Kenya (1900–1994). Hum Ecol 28:383–414

Delve RJ, Huising JE, Bagenze P (2007) Target area identification using a GIS approach for the introduction of legume cover crops for soil productivity improvement: a case study eastern Uganda. Afr J Agric Res 10:512–520

Dorward AR, Chirwa E (2011) The Malawi Agricultural Input Subsidy Programme: 2005–6 to 2008–9. Int J Agric Sustain 9:232–247

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116

Giller KE, Rowe EC, de Ridder N, van Keulen H (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric Syst 88:8–27

Giller KE, Tittonell P, Rufino MC, Wijk MT, Zingore S, Mapfumo P, Adjei-Nsiah S, Herrero M, Chikowo R, Corbeels M, Rowe EC, Baijukya F, Mwijage A, Smith J, Yeboah E, Burg WJvd, Sanogo OM, Misiko M, Ridder ND, Karanja S, Kaizzi C, K'ungu J, Mwale M, Nwaga D, Pacini C, Vanlauwe (2011) Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric Syst 104:191–203

Jansen J, Wortmann CS, Stockton MC, Kaizzi KC (2013) Maximizing net returns to financially constrained fertilizer use. Agron J 105:573–578

Kamanga BCG (2011) Poor people and poor fields? Integrating legumes for smallholder soil fertility management in Chisepo, central Malawi. PhD thesis, Research School for Resource Studies for Development, Wageningen University

Kamanga BCG, Waddington SR, Robertson M, Giller KE (2009) Risk analysis in maize-legume cropping systems with smallholder farmer resource groups in central Malawi. Exp Agric 46:1–21

Mango NAR (1999) Integrated Soil Fertility Management in Siaya District, Kenya. Managing African soils no. 7, 28 p

Masvaya EN, Nyamangara J, Nyawasha RW, Zingore S, Delve RJ, Giller KE (2010) Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe. Nutr Cycl Agroecosys 88:111–120

Mtambanengwe F, Mapfumo P (2005) Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. Nutr Cycl Agroecosys 73:227–243

National Statistical Office (2008) Malawi in figures. http://www.nso.malawi.net

National Statistical Office Malawi Government (2008) Enhancing agricultural input use efficiency in Malawi. A research report of the National Subsidy Programme Technical Support Workshop in Lilongwe, 15–16 April 2008. Department of Planning, Ministry of Agriculture, Lilongwe

Orr A, Jere P (1999) Identifying smallholder target groups for IPM in Southern Malawi. Int J Pest Manag 45:179–187

Pampolino MF, Witt C, Pasuquin JM, Johnston A, Fisher MJ (2012) Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. Comput Electron Agric 88:103–110

Rowe EC, van Wijk MT, de Ridder N, Giller KE (2006) Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. Agric Ecosyst Environ 116: 60–71

Sheahan M, Black R, Jayne TS (2013) Are Kenyan farmers under-utilizing fertilizer? Implications for input intensification strategies and research. Food Policy 41:39–52

Shepherd KD, Soule MJ (1998) Soil fertility management in west Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agric Ecosyst Environ 71:131–145

Shepherd KD, Walsh MG (2007) Infrared spectroscopy—enabling an evidence based diagnostic surveillance approach to agricultural and environmental management in developing countries. J Near Infrared Spectrosc 15:1–19

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176

Smaling EMA, Braun AR (1996) Soil fertility research in sub-Saharan Africa: new dimensions, new challenges. Commun Soil Sci Plant Anal 7:365–386

Smaling EMA, Nandwa SM, Janssen BH (1997) Soil fertility in Africa is at stake. In: Buresh RJ, Sanchez PA (eds) Replenishing soil fertility in Africa. ASA, CSSA, SSSA, Madison, pp 47–61

Snapp SS (1998) Soil nutrient status of smallholder farms in Malawi. Commun Soil Sci Plant Anal 29:2571–2588

Snapp SS, Benson T (1995) GIS to develop area-specific fertilizer recommendations in Malawi: soil resources, yield potential and decision trees. Agronomy Abstracts 301

Snapp SS, Blackie MJ, Donovan C (2003) Realigning research and extension to focus on farmers' constraints and opportunities. Food Policy 28:349–363

Swift MJ, Frost PGH, Campbell BM, Hatton JC, Wilson KB (1989) Nitrogen cycling in farming systems derived from savanna. In: Clarholm M, Bergstrom L (eds) Ecology of arable land. Kluwer Academic, Dordrecht

Tittonell P, Vanlauwe B, Leffelaar PA, Rowe EC, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya I. Heterogeneity at region and farm scale. Agric Ecosyst Environ 110:149–165

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37

Tittonell P, Muriuki A, Shepherd KD, Mugendi D, Kaizzi KC, Okeyo J, Verchot L, Coe R, Vanlauwe B (2010) The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa—a typology of smallholder farms. Agric Syst 103:83–97

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr Cycl Agroecosys 76:171–182

Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric Ecosyst Environ 119:112–126

Zingore S, Tittonell P, Corbeels M, van Wijk MT, Giller KE (2011) Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nutr Cycl Agroecosys 90:87–103