Field Crops Research 143 (2013) 76–90

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture

Pablo Tittonell[a,*], Ken E. Giller[b]

[a] Farming Systems Ecology, Wageningen University, P.O. Box 563, 6700 AN Wageningen, The Netherlands
[b] Plant Production Systems, Wageningen University, P.O. Box 430, 6700AK Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 23 May 2012
Received in revised form 5 October 2012
Accepted 10 October 2012

Keywords:
Cereal yields
Cassava
Highland banana
Grain legumes
Boundary line analysis
Soil organic matter
Soil degradation
Non-responsive soils

ABSTRACT

Yield gaps are pervasive in African smallholder agriculture, and are large for almost all crops in all regions. There is consensus that poor soil fertility and nutrient availability are the major biophysical limitations to agricultural production in the continent. We identify two major yield gaps: (1) the gap between actual yields (Y_A) and the water-limited yield potential (Y_W), which is the maximum yield achievable under rain-fed conditions without irrigation if soil water capture and storage is optimal and nutrient constraints are released, and (2) The gap between Y_A, and a locally attainable yield (Y_L) which corresponds to the water *and* nutrient-limited yields that can be measured in the most productive fields of resource endowed farmers in a community. Estimates of these two yield gaps are given for major crops, together with a framework for how yield gaps can be estimated in a pragmatic way for different farming systems. The paradigm of ecological intensification which focuses on yield potential, soil quality and precision agriculture is explored for the African context. Our analysis suggests that smallholder farmers are unable to benefit from the current yield gains offered by plant genetic improvement. In particular, continued cropping without sufficient inputs of nutrients and organic matter leads to localised but extensive soil degradation and renders many soils in a non-responsive state. The lack of immediate response to increased inputs of fertiliser and labour in such soils constitutes a chronic poverty trap for many smallholder farmers in Africa. This necessitates a rethink for development policy aimed to improve productivity and address problems of food insecurity.

1. Introduction

The concept of ecological intensification was coined by Cassman (1999) to define the set of principles and means necessary to increase primary productivity in the major cereal agroecosystems of the world. Emphasis was placed on increasing the yield ability of major crops and narrowing yield gaps through implementing forms of precision agriculture, relying on scientific breakthroughs in the field of plant physiology, crop ecophysiology and soil science. Later reinterpretations of this concept, particularly in the context of European agriculture (e.g., Bonny, 2011; Malezieux, 2012), attached a definition that borders those of organic or ecological farming. Ecological intensification is now understood as a means of increasing agricultural outputs (food, fibre, agro-fuels and environmental services) while reducing the use and the need for external inputs (agrochemicals, fuel, and plastic), capitalising on ecological processes that support and regulate primary productivity in agroecosystems. Yet, little has been written on how to achieve this. Single efforts addressing the various challenges facing current agriculture have been often done in isolation rather than holistically. These observations have prompted Doré et al. (2011) to propose new sources of knowledge and methods in agronomy to strengthen the ecological intensification of current agriculture.

The ecological intensification of agriculture has seldom been addressed in the context of the smallholder farming systems that characterise rural Africa. There is no doubt of the concept's relevance to guide farming systems design in the African context: producing more with less external input, while keeping a healthy environment that provides multiple services. However, in view of the importance of agriculture for rural livelihoods and national economies the 'intensification' component, whether ecological or not has been sensed as most urgent for Africa. The need to intensify African agriculture has recently led agricultural research for development in a somehow opposite direction, promoting the use of mineral fertilisers, hybrid seeds, new crops, irrigation, herbicide-based no-till systems, genetically modified cultivars or mechanisation as means to increase productivity (e.g., http://www.agra.org). The sustainable intensification of agriculture through technologies that rely on substantial investment in inputs has been seriously hampered by poorly developed input and

---

* Corresponding author.
E-mail address: pablo.tittonell@wur.nl (P. Tittonell).

0378-4290 © 2012 Elsevier B.V. Open access under CC BY-NC-ND license.
http://dx.doi.org/10.1016/j.fcr.2012.10.007

output markets (Dorward et al., 1998), but often also by the poor performance of technologies in the African context or their inadequacy to fit within local smallholder systems (e.g., Giller et al., 2009, 2011).

Thus, whether deliberately or not, much of African agriculture has remained rather ‘ecological’. Basic supportive and regulatory ecological processes steered through local lay knowledge still constitute the backbone of smallholder agriculture in many places. But despite the genuine attractiveness that surrounds traditional systems and local practices, their inability to sustain Africa’s food sufficiency is self-evident. Yet, there are reasons to believe that supportive and regulatory ecological mechanisms that farmers are able to master can lead to synergetic responses of agricultural systems to external inputs (e.g., Lahmar et al., 2012). This forms the basis for the design of integrated approaches to soil fertility, pest or crop management that build on local knowledge. A large body of evidence shows that labour, water or nutrient use efficiencies are enhanced through the implementation of such knowledge-intensive approaches (e.g., Khan et al., 2010; Vanlauwe et al., 2010; Altieri et al., 2012).

Cassman (1999) distinguished between strategies necessary for ecological intensification under unfavourable (mostly rain-fed) and favourable environments, focusing mostly on the latter. He postulated that the ecological intensification of agriculture in unfavourable rain-fed environments, where lack of water would be the primary constraint, would depend on reducing the reliance on subsistence cereal production, integration with livestock enterprises, greater crop diversification and agroforestry practices that may ensure higher economic value and soil conservation. Although some of these principles may be relevant for the rain-fed production environments that predominate in sub-Saharan Africa, closer examination is necessary. For example, crop productivity in many parts of Africa is limited primarily by nutrient rather than water availability; smallholder cereal production is often oriented to both consumption and the market; the integration of cropping and livestock activities is already a common denominator to many of these systems; in densely populated regions green manures or agroforestry do not always fit the needs and possibilities of smallholders; and so on. Where natural resources have become degraded, farmers may be caught in poverty traps (Marenya and Barrett, 2007), where response to inputs is poor and follows an ‘S-shaped’ curve (De Wit, 1992, 1994). Africa needs a ‘uniquely African’ strategy for the sustainable intensification of its agriculture (cf. Tittonell et al., 2011), capitalising on ecological processes and ensuring efficient use of scarce external inputs.

This paper examines current yield gaps in Africa and the opportunities and challenges that lay ahead for the ecological intensification of smallholder agriculture, placing emphasis on the efficient use of the abiotic resources: light, water and nutrients. We draw on a wide range of experiences from Southern, East, Central and West Africa. We postulate that current approaches to the ecological intensification of smallholder agriculture in Africa: (i) may be deterred by inherent characteristics of these agroecosystems, (ii) lack biophysical references and suitable technical means that embrace local preferences and knowledge, (iii) should not overlook the integrated nature of smallholder systems (e.g., crop-livestock interactions, communally owned resources, etc.) in which decisions are made at scales higher than the field plot, and (iv) will not be achieved without prior efforts to restore productivity of already degraded land. The three pillars that Cassman (1999) identified for the ecological intensification of cereal production, namely yield potential, soil quality and precision agriculture are first analysed for their specificities and suitability in the African context. This is followed by an estimate of the average yield gap of major crops in the continent, attempting to distinguish between yield gaps caused by resource availability from gaps caused by access to technology. We conclude by proposing a framework for yield gap assessment in African agriculture based on biophysical drivers, with the aim of contributing to the delineation of a worldwide yield gap atlas (van Ittersum et al., 2013).

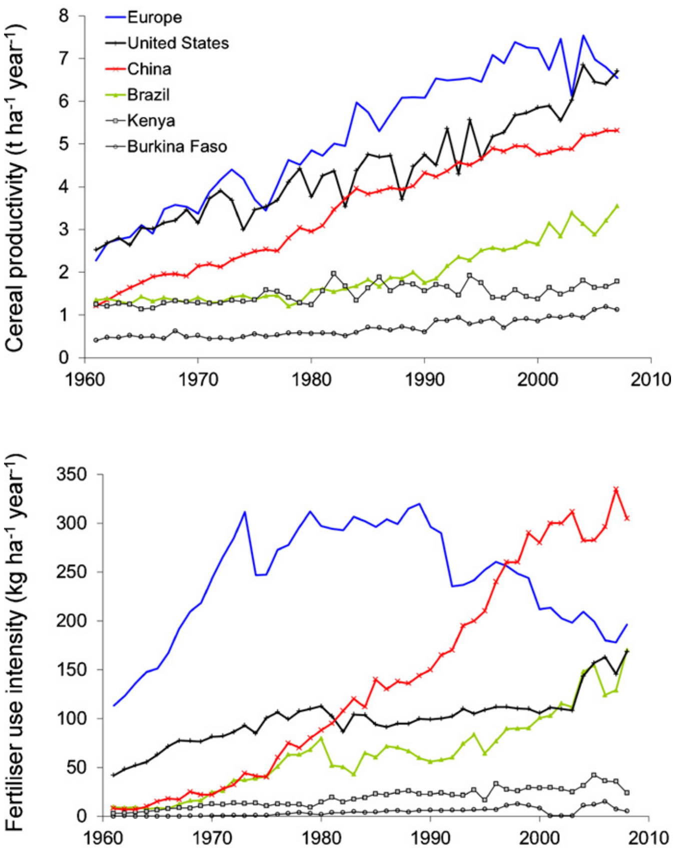


Fig. 1. Average cereal productivity and fertiliser use intensity (total fertiliser use over area cropped) at national level for selected countries between 1961 and 2008. *Source*: FAOstat.

2. The pillars of ecological intensification following Cassman (1999)

2.1. Yield potential

Food production in sub-Saharan Africa is not keeping pace with population growth. Sub-Saharan Africa has the lowest land and labour productivity rates in the world, with annual growth in cereal yields averaging only 10 kg grain ha^{-1} yr^{-1} – about 1% (http://www.earthtrends.wri.org). While cereal yields in most of the developed and developing world increased steadily during the last 50 years, yields in African countries hovered around 1 t ha^{-1} or less (Fig. 1A). Similarly, the average yield of tuber crops (cassava, sweet potato, yam, etc.) is the lowest in the world (around 8 t ha^{-1}), increasing at a rate of 50 kg ha^{-1} yr^{-1} or 0.6% over the same period. Counting growth in harvested area as well, food production in sub-Saharan Africa increases at an annual rate of ca. 2%, while population growth rates average 3%. If Africa seeks to rely on agriculture for economic development, an annual increase of 4–7% in food production is required (Breman and Debrah, 2003). Technological progress in tropical agriculture in combination with more favourable socio-economic contexts allowed food production, and particularly cereal yields to increase substantially in Latin America and Asia during the last two to three decades. Although much of such yield increase may be explained by increased input use (Fig. 1B), genetic progress through plant breeding played a central

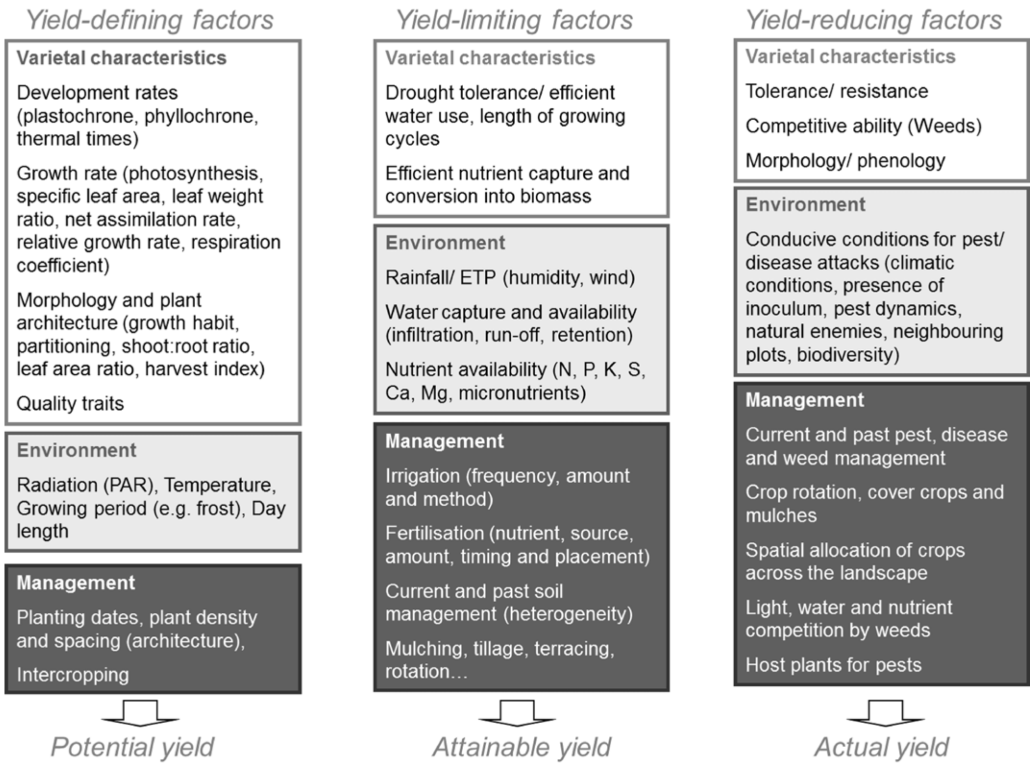


Fig. 2. A representation of yield-defining, yield-limiting and yield-reducing factors determining respectively the potential, attainable and actual yield levels. Factors were grouped into varietal characteristics (G), uncontrolled environment (E) and management (M) to illustrate the increasing importance of the latter as one moves from potential to actual yields.

From: Tittonell (2009).

role (Hall, this volume). As the yield ability of major crop varieties available for tropical environments keeps rising, the stagnating average yield observed in most African countries means that yield gaps are widening across the continent.

(Theoretical) potential yields in sub-Saharan Africa, those that may be achieved under no water or nutrient constraints, vary for the various cereal crops and their cultivars and are defined chiefly by latitude, altitude and cloud cover. Potential yields can be calculated using simulation models that input the length of the growing season, diurnal and nocturnal air temperatures, day length and the total amount of solar radiation received during a season by a given cultivar (e.g., Thornton et al., 2009). In this paper we refer to the water-limited yield potential (Y_W) as defined by van Ittersum et al. (2013), which is the maximum yield achievable under rainfed conditions without irrigation if soil water capture and storage is optimal and nutrient constraints are eliminated. The attainable yield level following the classical definition of production situations by De Wit (1992), corresponds to water *and* nutrient-limited yields. Here, we propose an adaptation of this to the African situation by defining a locally attainable yield level (Y_L), which is the maximum yield achievable by resource endowed farmers in their most productive fields. Two yield gaps can be then calculated: a yield gap 1, between Y_W and Y_L, and a yield gap 2, between Y_L and actual farmers yield levels (Y_A).

2.1.1. The $(G \times E \times M)_{FS}$ interaction

Taking de Wit's definitions, the relative importance of management decisions with respect to the genotype or the uncontrolled environment increases as we move from yield-defining to yield-reducing factors, from potential to attainable and actual yields (Fig. 2). There is consensus that nutrient supply, rather than water, is the main yield-limiting factor in sub-Saharan Africa (Penning de Vries and Ditèye, 1991; Breman and Debrah, 2003). However, whilst fertiliser use has expanded in some countries such as Kenya, it remains anecdotal in many parts of the continent. Where land is not limiting, the area cultivated is a more important determinant of household food security than the yield per unit area. In such cases, farmers often prioritise investments to hire labour or ox-ploughing rather than purchasing fertilisers or improved seeds to intensify production (Tittonell et al., 2010a). Cultivating large areas with limited labour available often leads to late planting, exposing bare soil to the first torrential rains of the season, or to late or inefficient weeding during the season. In some cases, however, extended periods of sowing may be a strategy to deal with erratic rainfall, minimising the risk of complete crop failure in space and time (Milgroom and Giller, 2013). Thus probably more than anywhere else, potential yields under African smallholder conditions are the result of a tight interaction between the genotype, the environment *and* the local farming practice (i.e., *FS* in the $G \times E \times M$ model).

2.1.2. Local reference yields

Although it may be hard to estimate the achievable yields of local varieties under local circumstances and management practices, approximations are necessary in order to quantify current yield gaps. An example is the use of boundary-line analysis (e.g., Shatar and McBratney, 2004) of large yield datasets across sites, seasons and management practices. Boundary lines may reveal ceiling yields for a given crop in a certain environment. Ceiling yields may sometimes represent the maximum achievable yields under farmer management, or locally attainable yield Y_L, or be close to the water-limited yield potential Y_W when yields are measured under controlled conditions. An alternative is to use simulation models to establish the reference yield Y_W, or an approximation to the locally attainable (water and nutrient-limited) yield Y_L when proper model calibration and validation are possible (e.g., Affholder et al., 2013). Such an exercise is illustrated in Fig. 3A for

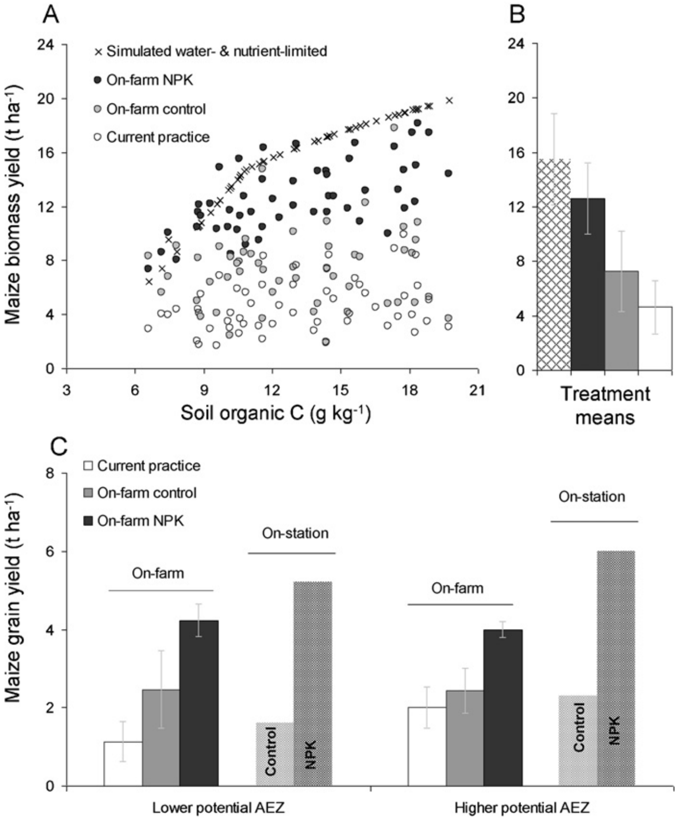


Fig. 3. (A) On-farm maize biomass yields in farmers' fields (current practice) and in researcher-managed micro-plots established on the same fields with or without mineral fertilisers (NPK, control), and yields simulated for each field with the model DYNBAL (Tittonell et al., 2006); (B) means and standard deviations in each case (first column from the left is average simulated yields); (C) comparing average grain yields on-farm (current practice and researcher-managed) against yields obtained in nearby experimental stations (control, NPK), with the observations grouped according to proximity to two stations located in lower and higher potential agro-ecological zones (AEZ) in western Kenya.

maize (*Zea mays* L.) grown in the highlands of Kenya, using aboveground biomass as a measure of productivity (harvest indices were highly variable under farmer management). Simulated water and nutrient-limited biomass yields (corresponding to Y_L) are plotted against soil organic carbon together with biomass yields measured on farmers' fields under their own management (current practice) and under researcher management with (NPK) or without (control) fertilisers. Soil C (0–20 cm) is used here as a surrogate of inherent and current soil fertility, with soil clay contents varying from 18 to 44%, altitude from 1100 to 2100 masl and rainfall from 1300 to 1900 mm in the study area.

Across this environmental range, the simulated attainable biomass yields varied from ca. 5 to 20 t ha^{-1} (15.5 on average), and the respective gaps between 2 and 15 t ha^{-1} under farmer practices, between 0 and 14 in control plots, and between 0 and 8 t ha^{-1} with a full NPK fertiliser application. The average response to a full NPK fertilisation was in the order of 5.3 t ha^{-1} of aboveground biomass. It is striking that researcher-managed plots receiving no fertilisers yielded on average better than the same fields under farmer management, which may include using organic and/or mineral fertilisers. The effect of germplasm was more difficult to unravel, given that the hybrid used under research management was also often seen in farmers' fields. When examining grain yields (Fig. 3C), such differences were wider for the fields grouped in the lower potential zone (dominated by ferric-Acrisols, 1300–1500 mm) than in the higher potential zone (Nitosols and humic-Ferralsols, 1500–1900 mm). Yields under controlled management with fertiliser were greater on nearby experimental stations than in farmer's fields (although not during the same season), and such difference was also wider in the high potential zone. The potential yields simulated with the soil-crop model DYNBAL (Tittonell et al., 2006, 2007b) in response to water and nutrient availability varied between 10.8 and 11.4 t ha^{-1} grain (22.6 and 24.5 t ha^{-1} aboveground biomass) for this environmental range (Fig. 3), cutting through one of the areas of highest agricultural potential in sub-Saharan Africa.

2.1.3. Non-cereal crops

Although the analysis of Cassman (1999) focuses on the yield potential of major cereal crops, the economy of large areas of sub-Saharan Africa depends also on other, equally important staple or cash crops. Yield gaps for cassava (*Manihot esculenta* Crantz) grown in vast areas of medium to marginal agro-ecological potential may also be analysed with respect to management practices or single limiting factors, and reference ceiling (rather than potential) yields be derived through boundary line analysis (Fig. 4A). Maximum fresh root yields obtained on eastern Uganda farms were in the order of 25 t ha^{-1}, while yields of 50–60 t ha^{-1} have been obtained under experimental conditions in East Africa (Ntawuruhunga et al., 2006) and as high as 75–90 t ha^{-1} in Colombia or India (El-Sharkawy, 2004). Fermont et al. (2009) analysed the yield gap of cassava in the East African highlands and determined the individual yield gains and synergies that may be expected from improved agronomy, cultivar choice or fertiliser use. Although it is generally believed that cassava responds poorly to fertilisers, this research showed once again that responses were substantial when proper agronomic (establishment and weeding) practices were in place. The incremental contribution of these different factors to narrowing the yield gap on farmers' fields was 1.5 t ha^{-1} for improved crop implantation (from an average yield of fresh cassava roots 8.6 to 10.1 t ha^{-1}), 3.5 t ha^{-1} for improved cultivar choice (from 10.1 to 13.6 t ha^{-1}) and 7.2 t ha^{-1} with fertiliser use (from 13.6 to 20.8 t ha^{-1}). The choice of cultivars with resistance to cassava mosaic virus was crucial.

For an indeterminate crop such as cotton (*Gossypium hirsutum* L.), the engine of rural economies across regions of West, Central and Southern Africa, the relationships between single limiting factors and yield are more elusive. Examining data from a number of research trials established across the cotton growing area of southern Mali, Cretenet (1994) arrived at establishing yield thresholds with respect to soil indicators such as exchangeable K (Fig. 4B) or organic C contents, to rainfall or to sowing dates using a similar boundary-line approach. Cotton has a relatively strong K demand. A negative K balance of 200 kg ha^{-1} over a certain period of time, which corresponds to a change in 0.025 cmol$_{(+)}$ kg^{-1} of K in the first 40 cm of the soil, results in a reduction of up to 570 kg ha^{-1} in the attainable seed-cotton yield. Each day of delay in the date of planting, or each day of reduction in the rainy period led to an average reduction of 16 kg ha^{-1} in the attainable seed cotton yield, irrespective of fertiliser use. More difficult to predict in the case of cotton is the potential quality of the fibre obtained, which has a strong impact on the price received by the farmer.

The examples above illustrate the use of boundary line analysis to study the effect of single abiotic, yield-limiting factors such as water, nutrients or dates of planting. Similarly, the method can be used to study the effect of biotic yield-reducing factors such as weeds, pest and diseases. The East African highland banana (*Musa* spp., AAA-EA genome) is a staple crop in large areas of Burundi, the Democratic Republic of Congo, Rwanda and Uganda. In a detailed investigation on plots on 159 smallholder farms in Uganda, yields of highland banana were significantly greater

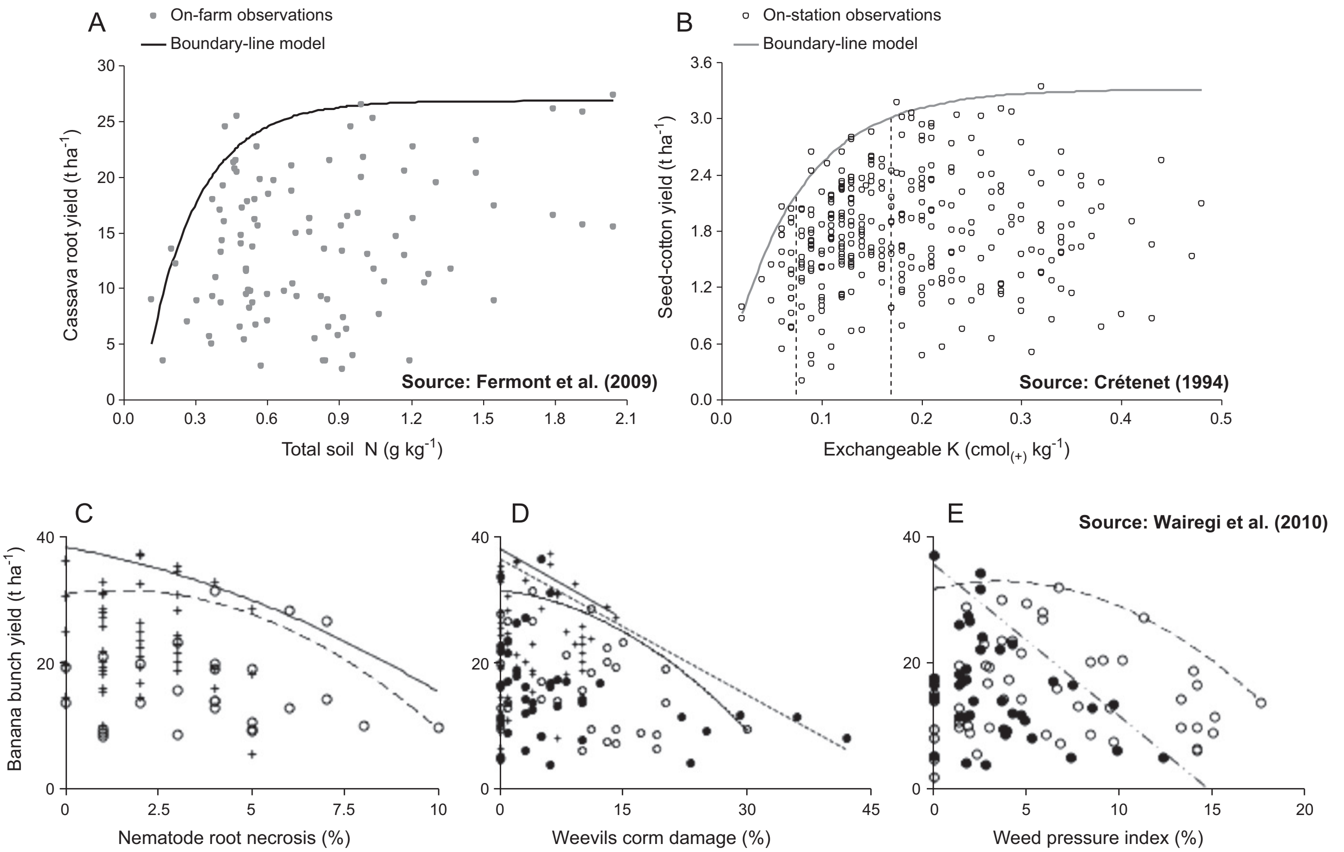


Fig. 4. Examples of using boundary line analysis to establish ceiling, or locally attainable yields as a function of different explanatory variables. (A) Cassava yield in Uganda and Kenya against total soil N; (B) Cotton yield in Mali against soil exchangeable K; (C–E) Highland banana yield against different biotic constraints. Boundary line models fitted to the maxima at each level of the independent variable are represented by (continuous or dashed) lines.

in the Southwest region (20 t ha^{-1} year^{-1}) than in the Central (12 t ha^{-1} year^{-1}) and South (10 t ha^{-1} year^{-1}) (Wairegi et al., 2010) whereas the estimated national average yield in 2007 was only 5.5 t ha^{-1} year^{-1} (FAOSTAT). On the same farms demonstration plots yielded 3 to 10 t ha^{-1} year^{-1} more when (on average) 71 N, 8 P and 32 K kg ha^{-1} year^{-1} was applied (Wairegi et al., 2010). Using the boundary line approach (Fig. 4C–E) they found that the yield gap expressed as percentage of attainable yield in the Central region was caused by pests (nematodes 10% loss, weevils 6%) and suboptimal crop management (mulch 25%) indicating that past research efforts were mistaken in neglecting abiotic constraints.

2.2. *Soil quality*

The second pillar of ecological intensification proposed by Cassman (1999) was the maintenance or improvement of soil quality, defined as the capacity of soils to sustain biological productivity while ensuring environmental, plant and animal health. Both severe and subtle forms of soil degradation are associated worldwide with the practice of agriculture, even under favourable production environments. Four soil degradation phenomena may be distinguished: water erosion, wind erosion, deterioration of physical properties, and chemical degradation. The latter includes nutrient depletion and loss of organic matter, salinisation, acidification, and chemical pollution. The relationship between poverty and land degradation has been highlighted for sub-Saharan Africa (e.g., Scherr, 2000; Sanchez, 2002), and many of the forms of degradation listed take place simultaneously in the continent. Rather than cataloguing the extent of land degradation, as recently done (cf. Vlek et al., 2008), we focus on the particularities of the degradation processes taking place in sub-Saharan Africa, and on their implications for the design of strategies to rehabilitate degraded land. Soil nutrient depletion and loss of organic matter are treated as integrative measures of land degradation, which reflect the combined effect of management practices, inherent soil fertility and other forms of degradation.

Two decades ago Stoorvogel and Smaling (1990) published alarming figures on negative nutrient balances at country level for sub-Saharan Africa. Since then, nutrient balances calculated in different ways have been used extensively as indicators of soil nutrient depletion and of the long-term sustainability of agricultural systems at scales ranging from the individual field plot to entire regions or countries (e.g., Smaling et al., 1993; Stoorvogel et al., 1993). Nutrient balances calculated at regional and/or national scales provide coarse but relevant information for policy makers. For example, it was estimated that, every day, up to 100 trucks with a payload of 6 tonnes of cooking bananas enter the capital city of Uganda, Kampala, representing an annual export from rural areas of over 1.5 million kg K and 0.5 million kg N (van Asten et al., 2004). However, less than 5% of banana farmers in Uganda use any type of mineral fertiliser (Bekunda and Woomer, 1996). Estimations of nutrient balances at field scale, by different authors and through slightly different methods show almost always negative values in different African farming systems. For continuous cereal cropping in the central highlands of Kenya, De Jager et al. (2001) calculated nitrogen balances as negative as −44 to −75 kg N ha^{-1} year^{-1}, clearly contrasting with the values presented for other African systems that were calculated using the same method (cf. Table 1). One of the weakest points in the calculation of nutrient balances is the estimation of flows that are difficult

Table 1

N balances (kg ha^{-1} season^{-1}) at field scale across African farming systems calculated using comparable methods and assumptions.[a] Inputs and outputs consider only those mediated by farmers (e.g., fertilisers, harvest of crop residue, etc).

Case study	Farming system	Variability component	Total N inputs	N removal in harvest	N balance	Calculation procedure	Source
Central Zimbabwe	Integrated cereal-livestock systems, free grazing	Best plots	26	24	−38	Complete balance using NUTMON	Zingore et al. (2007)
		Average plots	22	18	−34		
		Worst plots	5	11	−31		
Western Kenya	Integrated cereal-livestock systems, zero grazing	Home gardens	28	28	+21	Complete balance using dynamic simulation	Tittonell et al. (2005b)
		Close fields	43	36	−22		
		Mid-distance fields	11	25	−17		
		Remote fields	4	12	−24		
Eastern Uganda	Cereal-based farming systems	(Averaged for a representative farm)	86	138	−48	Complete balance using static model	Nkonya et al. (2005)
Northwest Tanzania	Banana-based farming systems	Kibanja (banana)	18	26	−8	Partial balance using NUTMON	Baijukya et al. (2005)
		Kikamba-maize	4	13	−9		
		Kikamba-S. potato	1	6	−5		
		Kikamba-Cassava	0	2	−2		
Northern Ghana	Cereal-based farming systems	Mucuna/maize		72.4	+26	Complete balance using a modified NUTMON	Anthofer and Kroschel (2002)
		Sole maize (burning)	0	118	−120		
Southern Mali	Cereal/cotton/pastoral systems	Village settlings	58	45	−15	Complete balance using NUTMON	Ramisch, 2005
		Hamlet settlings	81	47	−3		
		Fulawere settlings	128	41	+21		

[a] When results were presented for farms of different wealth classes, only the middle class farms were considered.

to measure, such as losses by leaching or erosion, or the flows generated by denitrification, wet/dry deposition and N_2-fixation (Faerge and Magid, 2004). For instance, N losses by leaching assumed by different authors in African conditions were widely variable: 8–15 kg N ha^{-1} year^{-1} (Grimme and Juo, 1985), 10 kg N ha^{-1} year^{-1} (Akonde et al., 1997), 11–26 kg ha^{-1} year^{-1} (Ramisch, 2005) or 36–153 kg N ha^{-1} year^{-1} (Poss and Saragoni, 1992). Estimations remain uncertain, and may often lack quantitative rigour (Faerge and Magid, 2004). Nonetheless, the work of Stoorvogel and Smaling (1990) was highly influential in bringing attention to the problem and in prioritising research agendas on soil fertility management. Fortunately the nutrient balances they predicted were not always realised, for if they were, agriculture would by now have disappeared from one third of the continent.

Soil fertility zoning is a well-known process in the savannah-derived agroecosystems of West Africa, in which nutrients tend to be concentrated in the village fields to the detriment of the fertility of the so-called bush fields (e.g., Prudencio, 1993). Tittonell et al. (2005a,b) found a similar relationship between the magnitude and sign of nutrient balances, as determined by management decisions, and the creation of patterns of spatial soil heterogeneity within *individual* farms in the highly fragmented landscapes of western Kenya. Large differences in input use (e.g., 0.7–104 kg N ha^{-1} year^{-1}), food production (e.g., 0.6–2.9 t DM ha^{-1} year^{-1}), partial C (e.g., −570 to 1480 kg ha^{-1} year^{-1}) and N (e.g., −92 to 57 ha^{-1} year^{-1}) balances were observed between home- and outfields located less than 50–100 m apart, which showed also wide differences in extractable P (e.g., 2.1–19.8 mg kg^{-1}) and exchangeable K (e.g., 0.14–0.54 cmol$_{(+)}$ kg^{-1}) contents in their soils. Differential management of the various fields of the farm led to the establishment of gradients of soil fertility, notably decreasing with distance from the homestead. Farmers tended to allocate their scarce nutrient and labour resources in the fields they perceived as most fertile or less risky, or in fields around the homestead where high value crops were better protected from marauding livestock or theft. A close interaction was also found between soil fertility gradients and topography in these highly dissected landscapes, with homesteads located on the upper positions of the slope. Such interactions between inherent soil-landscape variability, historical and current management, nutrient balances and current soil fertility were later documented for smallholder systems in different parts of Africa; e.g., in Zimbabwe (Zingore et al., 2007), Ghana (Adjei-Nsiah, 2006) and Uganda (Ebanyat, 2009).

Losses of organic matter from agricultural soils are the result of the imbalance between inputs as plant litter or animal manure and outputs through decomposition and soil erosion. This balance is regulated by environmental conditions, soil type, litter quality and management practices. Vegetation clearance for cultivation, as practiced in the African savannahs triggers positive feedback loops – or vicious cycles – characterised by the disturbance of soil physical properties, increased erosion, accelerated decomposition rates and gradually decreasing C inputs to the soil in the form of crop residues due to declining crop yields (e.g., Kintché et al., 2010). Such process may be counterbalanced by application of organic fertilisers such as animal manures, or further aggravated when crop residues are removed from the fields or grazed by livestock. The magnitude of soil carbon losses would vary for different soil types and environments, and be affected by the characteristics of the local farming (or natural resource management) system. Abrupt productivity losses (a fast responding variable) take place during the first 5–10 years after woodland clearance, especially on sandy soils or under intensive double-cropping in areas with a bimodal rainfall regime (Fig. 5). During the first decade of maize cultivation in Gagnoa, Ivory Coast maize yields decreased to about one fifth of their initial level when no nutrient input was applied, but yields could be sustained with application of large amounts of mineral and organic fertilisers, or both combined (Guibert, 1999). Soil organic carbon (a slow variable) decreased in about 20% over the same period in soils that did not receive organic amendments. These results and similar ones from long-term experiments in West Africa indicate that the magnitude of the yield gap increases substantially after the first five years of cultivation of soils cleared from savannah vegetation.

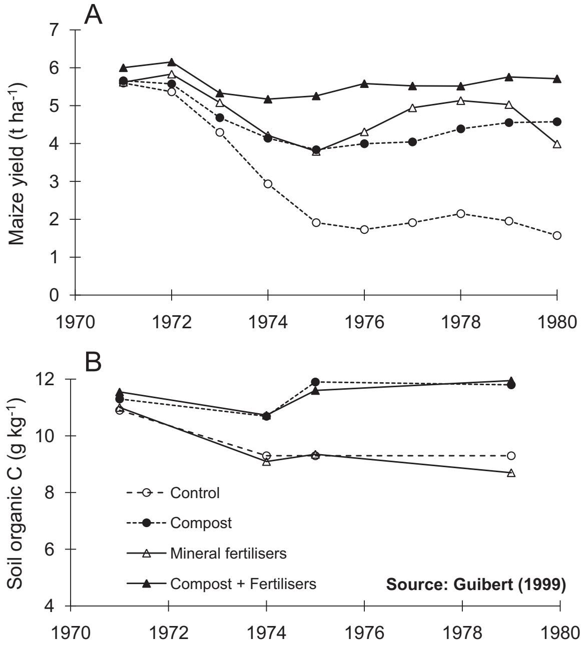


Fig. 5. Results of the first 10 years of a long-term trial conducted in Gagnoa, Ivory Coast illustrating how yield gaps increase in time (years of cultivation) due to soil fertility depletion when no nutrient inputs are used (control). (A) Maize grain yields; (B) soil organic carbon.

Source: Guibert (1999).

Rehabilitating soils that have become degraded often requires substantial investment. The amounts of manure necessary to restore productivity of degraded outfields on the granitic sandy soils of Zimbabwe were as much as 17 t ha^{-1} year^{-1}, complemented with 100 kg ha^{-1} year^{-1} of N as mineral fertiliser (Zingore et al., 2007). Earlier calculations indicated that an equivalent of 30 ha of grazing land would be necessary to sustain productivity in one hectare of cropping land on these soils through annual application of 8 t ha^{-1} of manure (Rodel and Hopley, 1973). Analysis at village scale indicated that only one third of the village cropland could be covered with the manure produced with its livestock population, in equilibrium with the carrying capacity of local grasslands (Zingore et al., 2011). A quick glance at livestock population densities in Africa shows that sustaining soil fertility exclusively through manure applications is not a viable option in most places (Fig. 6). Cattle (as much as human population) densities are greatest in the highland regions, where soils are inherently more fertile and agriculture most intensive. Although crop productivity may be sustained through use of mineral fertilisers coupled with restitution of crop residues, this does not appear to be sufficient to maintain the soil organic matter contents needed (i.e., soil C output is larger than C input, resulting in soil C decline – cf. Fig. 5). As a consequence, yields often plummet when fertiliser applications are interrupted.

Discontinuous, insufficient or no fertiliser application over a certain period of time may lead to severe soil degradation through nutrient depletion and loss of organic matter. When fertiliser or organic matter applications restart after a certain period of cultivation without them soils may not respond immediately. Often crop productivity may not be raised back to the yields attained before

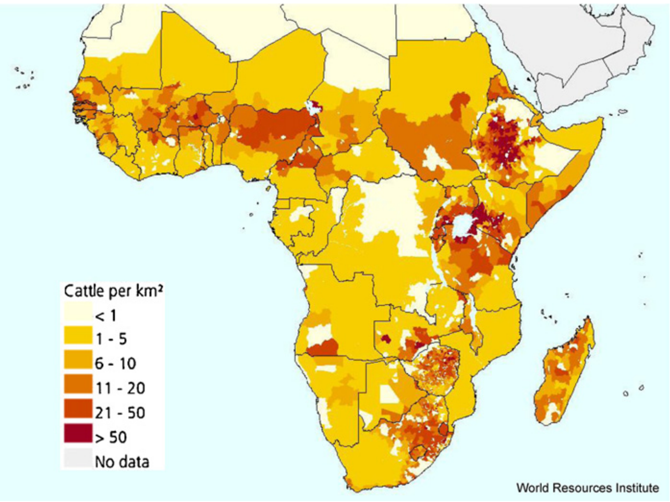


Fig. 6. Cattle densities in sub-Saharan Africa (World Resources Institute; http://www.earthtrends.org). Denser cattle populations (between 20 and more than 50 cattle per km^2) are distributed across an east-west band of northern grassland, and along a northeast-southeast band of eastern grassland. Countries with the highest densities include Ethiopia, Kenya, Uganda, Tanzania, Zambia, Zimbabwe, South Africa, and Madagascar.

fertilisation was interrupted, creating a new system state at lower equilibrium and consequently a very resilient yield gap (Tittonell et al., 2012). The two states, responsive and non-responsive soils do not necessarily represent a continuum. Reversibility may be lost when a certain threshold of soil degradation is surpassed. The magnitude of the distance between these two alternate states is known as hysteresis. This is a concept common in ecology, but it has also been used to characterise phases of land rehabilitation (e.g., Lal, 1997; Tittonell et al., 2008a). In the francophone literature, it has been termed the '*memoire du sol*' and related to the parameters that define response curves to fertilisers by crops (Cretenet and Tittonell, 2010). In a long-term experiment in southern Benin ceiling maize yields fluctuated between 3 and 4 t ha^{-1} when large amounts of mineral and organic fertilisers were applied together, and crop residues incorporated into the soil every year. Control yields without fertilisers coupled with residue removal dropped from about 1 t ha^{-1} to practically nothing after 8 years. When the same fertiliser and residue management regimes were applied to these control fields from the 10th year maize yields recovered gradually, but hardly achieved the ceiling yields after a decade. Current research aims at characterising the determinants of such soil memory, and ways to overcome it to ensure hysteretic soil rehabilitation, for different types of soils and cropping systems.

2.3. *Precision agriculture*

Precision agriculture was proposed by Cassman (1999) as a means of ensuring a more efficient use of applied agricultural inputs, reducing losses and thus environmental pollution. Although this may seem rather foreign to the reality of subsistence agriculture, smallholder farmers in sub-Saharan Africa practice several forms of precision agriculture. To start with, farmers recognise niches of soil fertility to which they ascribe different local names. Thus the pervasive localised soil heterogeneity is much more than a curiosity. The efficiency with which nutrients added as fertilizer or manure are captured and used by crops is strongly reduced by soil degradation (Giller et al., 2006; Tittonell et al., 2007a). Farmers recognise the existence of soil fertility gradients. They tend to plant crops earlier and more densely, weed earlier and more frequently, and apply nutrients as fertilisers and manure to the plots that are already more fertile (Tittonell et al., 2005b). Thus the resulting differences in yields are due to gradients of management intensity rather than soil fertility alone (Tittonell et al., 2007b). Such decision-making patterns, local soil classification and soil quality indicators may form the basis of a new form of precision agriculture adapted to the African smallholder context. To ensure efficiency this new form of precision agriculture should recognise and target resources:

(i) To diverse regions and agricultural contexts.
(ii) To diverse rural livelihood systems.
(iii) To agro-ecological, cropping systems and soil fertility niches.
(iv) Through concentration of limited resources in space and time.
(v) In synchrony with crop demands.

Cassman (1999) points out that in most cases technical solutions are available, but that socio-economic factors deter their implementation. We listed some of such factors relevant for African agriculture in the introductory paragraphs, and many publications deal with issues such as diversity of livelihood strategies, land tenure, integration of crop-livestock activities, climate change and other risks. Likewise, there is an important body of literature concerning means to improve the synchrony between crop nutrient demands and nutrient release from different organic resources used in Africa (Myers et al., 1997; Palm et al., 2001; Singh et al., 2001), and/or with micro-dosing and point-placed application of nutrient sources (Aune and Bationo, 2008; Hayashi et al., 2008).

Point (iii) deserves most attention in the context of yield gaps and their biophysical causes. Fig. 7 illustrates the challenges in moving from recommendations based in on-station trials to decision rules for niches of soil fertility within heterogeneous farms. Fertiliser experiments provide information on crop responses to nutrient inputs. Based on this, a range of sensible input rates can be identified that ensure biophysically efficient input use, avoiding negative externalities to the environment. Theory indicates that the amount of inputs to be added depends on the balance between necessary investments and economic returns (both affected by market conditions). However, adding nutrient inputs may result in highly variable crop responses across spatially heterogeneous farms. In smallholder farms as small as 0.5 ha efficiencies will vary enormously from poorly responsive fertile fields (normally the home fields), to responsive or poorly responsive infertile fields (normally the outfields). Applying nutrient inputs in the most responsive fields of the farm will ensure most efficient use of them. Fertile home gardens may be managed with 'maintenance fertilisation', whereas poor fields should be rehabilitated with long-term additions of organic matter before they can respond to nutrient inputs. This means also that the impact of input use should be analysed considering time horizons longer than a single season.

A major challenge in designing such forms of precision agriculture resides in identifying these three categories of fields in the landscape, responsive, non-responsive but productive and non-responsive degraded. Soil fertility and physical condition are the result of history of land use and current management, of inherent geology and geomorphology, and of farmer resource endowment (Tittonell et al., 2005a,b). Ebanyat (2009) documented niche management of soil fertility by smallholder farmers in eastern Uganda, where they shifted their *kraals* (corrals) every number of years to create islands of fertile soils to grow crops. Finger millet (*Eleusine coracana* (L.) Gaertn.) yields ranged between 0.6 and 2.2 t h^{-1} in old-kraal sites and between 0.3 and 1.4 in other fields. Obviously the presence of old-kraals sites is closely associated with farmer resource endowment, as only the wealthier farmers in the community possess livestock. Table 2 provides an example of soil fertility zoning across farm types in the vicinities of Murewa, Zimbabwe (Zingore et al., 2011). From this data it is possible to roughly assume that all households in the poorest resource categories farm on

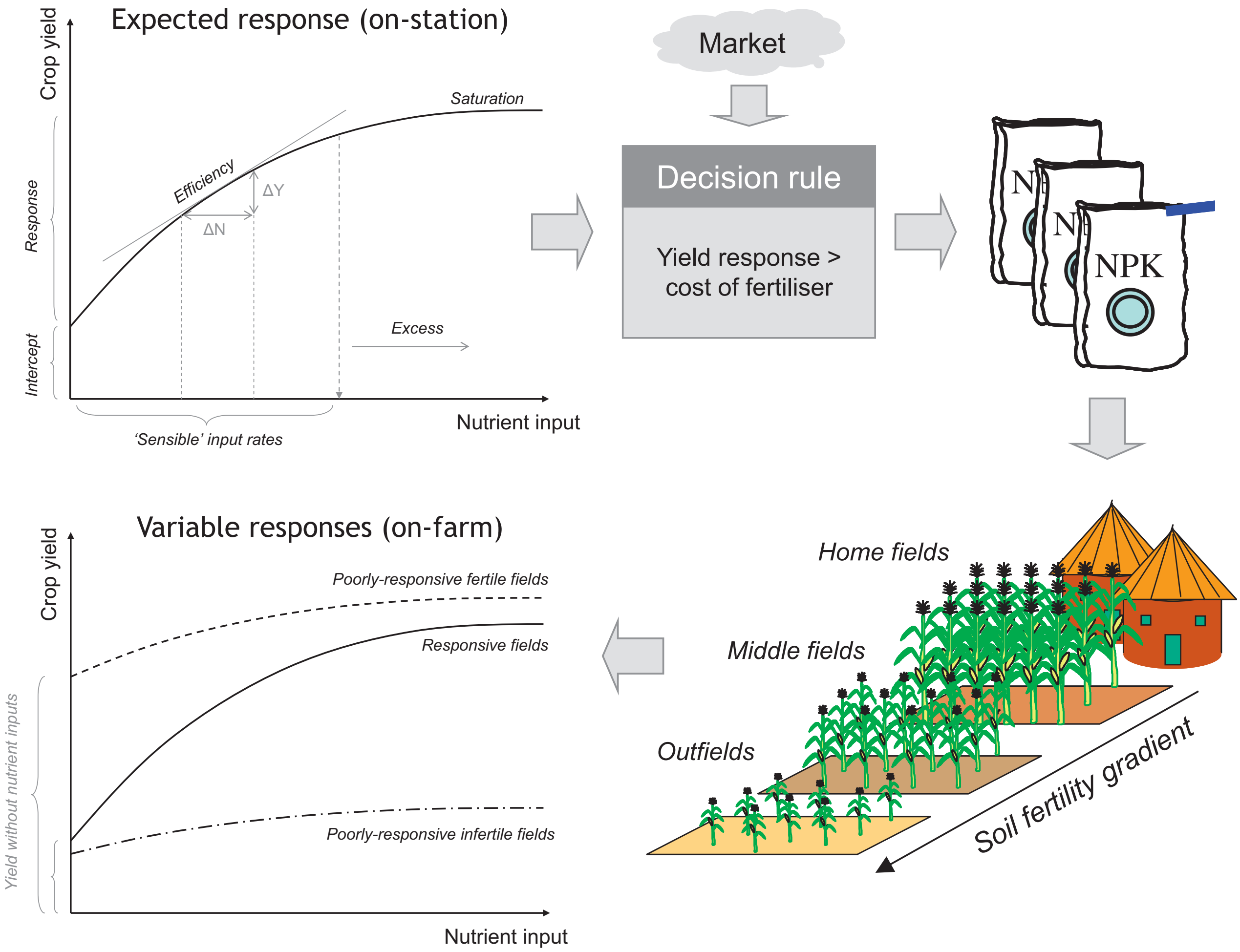


Fig. 7. An illustration of the challenges in moving from recommendations based in on-station trials to decision rules for niches of soil fertility within heterogeneous farms. The diagram must be read clockwise starting from the top-left corner.

non-responsive soils (zone 4). This is however not always the case, and more complex interactions between soil fertility and resource endowment have been documented (e.g., Giller et al., 2011).

An extra source of complexity that contributes to the existence of niches for technologies (and also to explain yield gaps) within smallholder farms is the diversity of cropping systems in space and time. Intercropping and crop rotations are most common in traditional agricultural systems in the continent. The residual benefits of N_2-fixing grain legumes on the yields of subsequent cereals and other crops are well documented (e.g., Adjei-Nsiah et al., 2008; Bationo and Ntare, 2000). Apart from the direct N benefit derived from the legumes, rotational benefits arise due to other factors such as suppression of the parasitic "witchweed" or *Striga* which can devastate cereal crops (Franke et al., 2006; Rusinamhodzi et al., 2012). Table 3 illustrates the effect of intercropping with cowpea on the yield of maize, which dropped from 2.4 t ha^{-1} in sole cropping to 1.6 t ha^{-1} when intercropped at a 1:1 ratio (in spite of the fact that the land equivalent ratios were in all cases favourable). The combination of all these elements means that actual yields in farmer fields are highly variable, in space and time. Precision agriculture needs to consider such variability, as responses to inputs and technologies and therefore their efficiency are also likely to vary.

The different factors responsible for yield variability are interdependent, and their interaction often leads to reinforcing synergistic effects. We can expect thresholds to exist in relationships between yield and management or soil fertility variables, leading to non-linearities. Analysis of such interactions requires application of multivariate analysis methods and an ability to deal with non-linear relationships. Farm survey data sets that can be used to determine actual yields are normally characterised by a mixture of continuous and categorical variables, highly skewed data, and large numbers of missing observations, adding to the complexity of the analysis. Classification and regression tree (CART) analysis has been used to unravel within-farm yield variability (e.g., Tittonell et al., 2008b). Fig. 8 shows an example of classification of maize yield data measured in 150 farmer fields in western Kenya. From about 30 possible explanatory variables describing agro-ecological, soil and management factors only five were retained in a CART analysis as meaningful: resource use intensity, plant density, planting dates, total soil N and available P. The 150 observations were classified in six homogeneous groups (Terminal nodes), which can be interpreted: e.g., fields cropped with no inputs and planted late were the majority, and these fields exhibited low to very low soil P availabilities. CART is a powerful method to categorise yield variability, to estimate actual yields in yield gap analysis, and to link variability back to its underlying causes.

3. Yield gaps of major food crops in Africa

Here we provide a first attempt to estimate the current yield gaps of major food crops in Africa, illustrating with examples the diversity of factors that should be considered when estimating both

Table 2
Description of the different zones of fertility on smallholder farms in Murewa, Zimbabwe; (A) their occurrence and soil properties, and (B) proportion of the area covered by zones of fertility on farms differing in wealth status.

Soil fertility zoning		Sandy soils				Clay soils			
		Village area	SOC (g kg^{-1})	N (g kg^{-1})	Avail. P (mg kg^{-1})	Village area	SOC (g kg^{-1})	N (g kg^{-1})	Avail. P (mg kg^{-1})
A									
Zone 1	Uncultivated woodland soils. Mainly used as communal grazing lands.	53.6%	12	1.2	14	14.0%	21	1.6	18
Zone 2	Most fertile fields where large amounts of manure were applied, typical homefields on wealthier farms.	5.6%	8	0.8	12	1.5%	16	1.2	12
Zone 3	Fields with moderate fertility where small amounts of manure were used, mid-fields and outfields of wealthier farms.	6.1%	5	0.6	7	1.6%	10	0.8	10
Zone 4	Fields with low fertility mostly cultivated with little fertilizer inputs, most fields of poorer farms and outfields of mid to wealthier farms.	14.6%	3	0.3	3	3.9%	7	0.5	5

Farm type	Area in zone 2 (%)	Area in zone 3 (%)	Area in zone 4 (%)
B			
Resource Group 1 (wealthiest)	32	68	0
Resource Group 2	42	21	37
Resource Group 3	0	0	100
Resource Group 4 (poorest)	0	0	100

From Zingore et al. (2007).

Table 3
Crop yields and land equivalent ratios (LER) for different cowpea-maize intercrops at Ibadan, Nigeria.

Cowpea:maize ratio	Yield		Relative yield		
	Cowpea (kg ha^{-1})	Maize (kg ha^{-1})	Cowpea (Y_c)	Maize (Y_m)	LER ($Y_c + Y_m$)
0:100	n/a	2439	n/a	n/a	n/a
25:75	181	2158	0.43	0.88	1.31
50:50	327	1653	0.78	0.68	1.46
75:25	291	1167	0.70	0.48	1.18
100:0	322	n/a	n/a	n/a	n/a

Modified from Olufemi Pitan and Odebiyi (2001).

actual and attainable yields. A coarse but useful first approximation to average crop yields per country is the FAOStat database. Table 4 presents a comparison of yield ranges of major food crops reported in the literature – mostly from on-farm experiments – and the average country-level yield over the last 10 years calculated from the FAO data. In spite of the wide coverage of the country average, which includes diverse agro-ecological regions and production situations within each country, its value is not far from the mid-range yield reported in the scientific literature for crops such as maize, sorghum or millet, and for some grain legumes. The FAO average yields for cassava and highland banana are closer to the lower end of the yield range found in the literature – which is likely to be the case in reality. Yet, yields from the literature exhibit wide ranges of variability, which are not uncommon in farmers' fields. Perhaps one of the most useful elements of the FAO database is the time series, which provides a rough indication of inter-annual yield variability.

These general trends are only indicative of the magnitude of yield gaps but say little about their causes and local variation. At local scale, and based on all the evidence presented in the previous section, soil fertility gradients must be considered in any yield gap assessment. Table 5 presents a first attempt to quantifying maize yield gaps across soil fertility gradients in regions of countries where maize is grown and important, using data from a diversity of (comparable) sources. Locally attainable yields varied between roughly 4 and 7 t ha^{-1} across regions. Average yields in farmers' fields varied widely across soil fertility gradients. On average, however, relative yields were in the order of 40–60% of the locally attainable yields in the most fertile fields, and in most cases they ranged between 10 and 20% in poorest fields. Rainfall use efficiencies ranged from 1 to 2 kg ha^{-1} mm^{-1} on poor fields to more than 5 kg ha^{-1} mm^{-1} on fertile fields. These efficiencies are calculated with respect to seasonal rainfall (note that two cropping seasons per year are possible in some of these sites). On the basis of a large number of model simulations, Tittonell et al. (2010b) proposed a simple equation to estimate water-limited maize yields:

$$\text{WLY}\ \ (\text{kg ha}^{-1}) = \text{Rainfall}\ \ (\text{mm}) \times 20\ \ (\text{kg ha}^{-1}\,\text{mm}^{-1}) \times \text{HI} \quad (1)$$

where HI is the crop harvest index or the ratio between grain to total above-ground biomass. The potential rainfall use efficiency for biomass production, of 20 kg ha^{-1} mm^{-1} in this case, is obviously a rough estimate and a coefficient that can be easily calibrated against data. When rainfall is 800 mm (e.g., NE Zimbabwe) and HI = 0.5, the water limited yield potential of maize would be 8 t ha^{-1}. Such yields are rarely realised by smallholders, but may be attainable in commercial farming. Similar simple equations could be easily derived for sorghum (e.g., ≈12 kg ha^{-1} mm^{-1}) and millet (e.g., ≈10 kg ha^{-1} mm^{-1}), and perhaps also for non-cereal crops such as cassava or banana. The fact that the water limited yield could be greater for sorghum than for millet does not always reflect what farmers experience in reality. Particularly in dry environments millet often yields better than sorghum (e.g., Murungweni et al., submitted for publication).

Table 4
Examples of yield ranges for major food crops on smallholder farmers' fields in four countries of East and Southern Africa.

Crop	Yield ranges from literature (t ha^{-1})			Country, region	Current yield from FAOstat
	Low	Medium	High		(t ha^{-1})
Cereals					
Maize	0.57	1.30	5.67	Zimbabwe, central	1.51
Sorghum	0.11	1.03	3.92	Zimbabwe, North	0.94
Millet (pearl)	0.16	0.72	1.93	Zimbabwe, S. East	0.83
Millet (finger)	0.29	1.49	2.15	Uganda, East	n/a
Legumes					
Common bean	0.14	0.34	0.76	Kenya, West	0.64
Cowpea	0.16	0.40	0.81	Kenya, West	0.64
Groundnut	0.22	0.55	0.98	Zimbabwe, S. East	0.79
Soyabean	0.35	0.87	2.15	Malawi, central	0.95
Perennial crops (Fresh weight)					
Cassava	8.60	13.60	20.80	Uganda, East	9.13
Banana	5.50	9.40	38.40	Uganda, S. West	7.78

References: Zingore (2006), Ojiem (2006), Fermont (2009), Nyombi (2010), Murungweni (2011), Baudron (2011), and Kamanga (2011).

4. A framework for yield gap assessments in African smallholder agriculture

When the intention is to assess yield gaps across countries and regions in Africa, at least three major sets of biophysical drivers should be considered (Fig. 9). First, the climatic zone, as determined by the length of the growing season, radiation, maximum and minimum temperatures (altitude) and rainfall (amount and distribution). This information, together with information on the start and end of the typical growing season allows estimating a water-limited yield potential (Y_W). This is equivalent to the yield that can be estimated with Eq. (1), or calculated with a simple crop growth model simulating potential yields, correcting the crop growth rate by the daily (or seasonal, according to data available) ratio between actual and potential evapotranspiration, or rainfall vs. potential evapotranspiration. Note that this calculation does not include soil hydrological characteristics – which were seldom measured in African soils – and so the water-limited yield thus calculated may differ from values cited in literature. This yield level should approximate the maximum yields attainable under controlled conditions in experimental stations, during a favourable growing season.

The second set of physical drivers corresponds to the dominant soil types, as determined by their geological, geomorphological and pedological features. In particular soil texture, soil depth and field slope play an important role in water capture, retention and availability to crops. These elements plus the inherent soil fertility define locally attainable yield levels (Y_L), which are also affected by the characteristics of the cropping system (e.g., intercropping, agroforestry, and rotations). This yield level corresponds to the maximum yield that can be obtained on farmers' fields when management is optimised (or in researcher-managed on-farm trials – cf. Tittonell et al., 2008c), or to the 95th percentile yield in a farmer yield survey (cf. van Ittersum et al., 2013). Digital soil maps, if sufficiently accurate, could provide the input required to characterise soil properties (Minasny and Hartemink, 2011). When data are available for parameterisation, calibration and testing, this yield

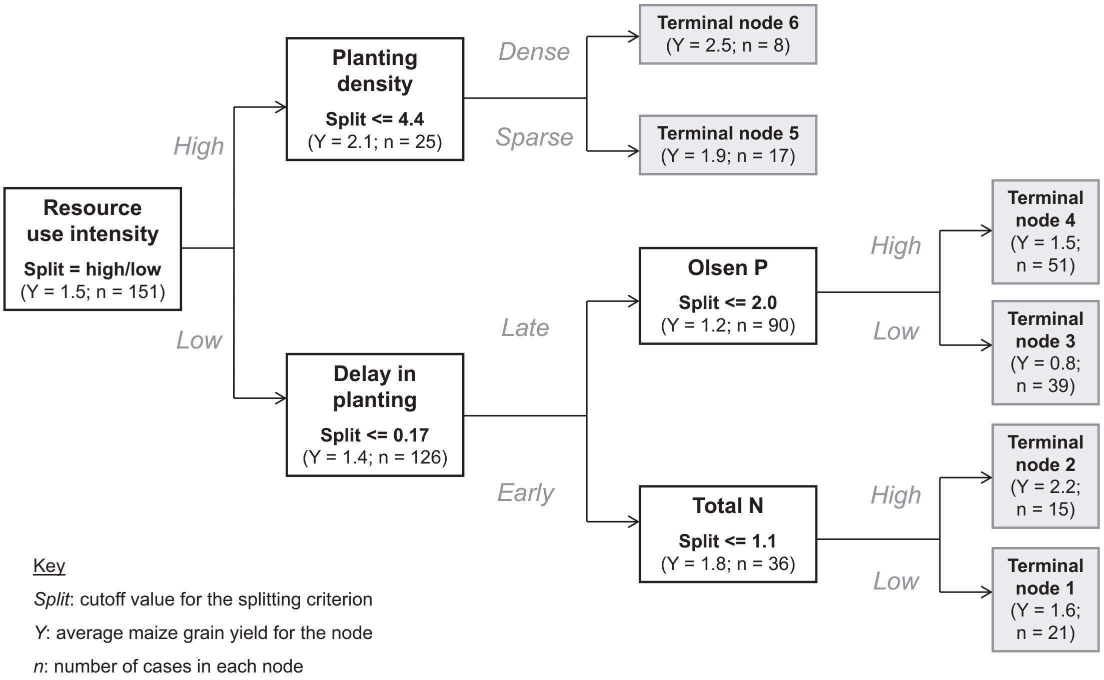


Fig. 8. Results of a classification and regression tree analysis of 151 maize grain yield observations across 60 households in Kenya. Of the almost 30 candidate explanatory variables included in the analysis (including rainfall), only five were selected: the intensity of nutrient resource use (organic and mineral fertilisers), the planting date and density, total soil N and extractable P (Tittonell et al., 2008b).

Table 5
Current average maize grain yields (t ha^{-1}) across soil fertility gradients on smallholder farms, locally attainable yields (maximum yields in on-farm trials or 95th percentile farmers' yields), relative yields and rainfall use efficiency in selected regions of countries where maize is an important staple crop.

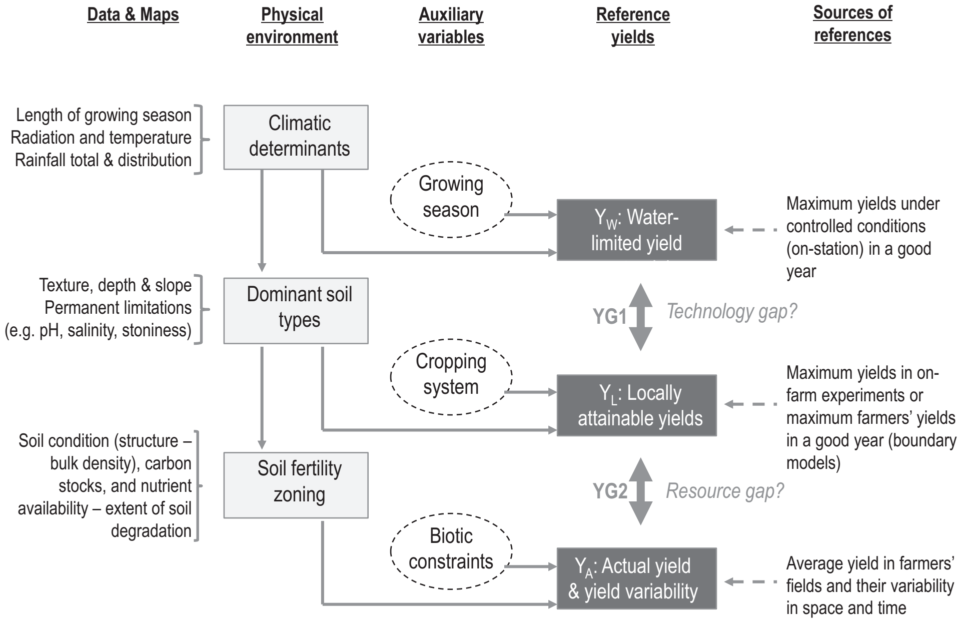
Country/region	Agro-ecological niche	Current farmers' yields	Locally attainable yield[a]	Relative yield (% of locally attainable)	Rainfall use efficiency (kg ha^{-1} mm^{-1})
Kenya, Kakamega	NFS	2.8	6.9	41	4.2
	RS	1.4		20	2.1
	NPS	0.9		13	1.4
Uganda, Tororo	NFS	1.7	4.8	35	3.7
	RS	1.0		21	2.2
	NPS	0.7		15	1.5
Zimbabwe, Murewa	NFS	2.1	6.2	34	2.8
	RS	0.7		11	0.9
	NPS	0.2		3	0.3
Tanzania, Kibera	NFS	2.6	5.1	51	2.9
	RS	1.5		29	1.7
	NPS	0.8		16	0.9
Mozambique, Manika	NFS	2.1	6.1	34	2.7
	RS	0.9		15	1.2
	NPS	0.5		8	0.8
Ghana, Kumasi	MF	1.5	4.2	36	1.7
	DS	0.4		10	0.4
Ivory Coast, Gagnoa	MF	3.8	6.2	61	5.8
	DS	1.6		26	2.4
Togo, terres de barre (S)	MF	1.8	3.7	49	3.5
	DS	0.3		8	0.6
Benin, Aplaoué	MF	2.1	4.5	47	4.2
	DS	0.5		11	1.0

NFS: non-responsive fertile fields; RS: responsive soils; NPS: non-responsive soils; MF: moderately fertile; DS: degraded site

[a] In most cases, these correspond to yields in on-farm experiments receiving full fertiliser application rates.

level can be calculated with a crop-soil simulation model as shown in Fig. 3, equivalent to the water- and nutrient-limited yield level defined by De Wit (1992). This yield level can also be approximated through boundary line models fitted to data on farmers' yields that include favourable rainfall years. When boundary lines or 95th percentile farmer yields are considered, the difference between locally attainable yields and the water-limited yield potential, or yield gap 1 in Fig. 9 may be partly – and sometimes almost exclusively – explained by the degree of technology used for crop cultivation, notably by the use of improved germplasm and/or agrochemicals.

The last set of physical drivers is the most elusive and concerns drivers of yield variability within farms, chiefly soil fertility gradients. Zones of soil fertility are defined by soil management history, and reflect the proportion of responsive and non-responsive



Adapted from Tittonell (2009)

Fig. 9. A framework for definition and estimation of reference yields and yield gaps in African smallholder agriculture, indicating minimum data needs and possible sources of yield references. It is hypothesised that while the yield gap 1 (YG1) is largely attributable to access to (and availability of) adequate technologies, the yield gap 2 (YG2) reflects differences in farmers' resource endowment.

soils in agricultural landscapes. Thus the yield gap cannot be estimated on an aggregated basis without a spatial analysis to estimate the proportion of fields that are in a degraded state. If detail on individual farms is aimed for, the granularity of such spatial analysis should be fine enough to identify small plots of 0.2 ha or less given the patchwork patterns of fields found in densely populated areas. This could be done using kriging methods, although the density of sampling required may be prohibitive. In view of this, we recommend using remote sensing techniques to estimate the proportion of different categories of fields (or zones of fertility) within an area (cf. Table 2). This information, together with knowledge about major biotic constraints (weeds, pest and diseases – cf. example of highland banana in Section 2.1) in a certain location can be used to estimate actual yields and their variability, not for each individual farm, but for the entire area (cf. Fig. 8). While yield estimates are still likely to show strong stochasticity, the relevant area unit to estimate yield gaps is likely to vary across regions depending on inherent spatial variability and demographic patterns. Well calibrated simulation models of the cropping system (cf. Fig. 3A), allowing for correction factors due to weed, pest or disease pressure could be used to estimate actual yields – although obtaining the necessary data to parameterise such models would be often more demanding than measuring yields in a rigorously identified sample of farmers' fields.

For yield gaps to be informative at this scale of analysis it is not only important to consider average yields in farmers' fields but also their strong variability in time. The method proposed by Lobell (2013) of comparing the average yield of the last one, two, three, four and five years to assess yield differences would be most pertinent here, as this provides a measure of variability. Lobell's interpretation does of the resulting patterns of variability to infer their possible causes is however questionable. For instance, if these averages were calculated for the yields in the control treatment in Fig. 5, their value would vary enormously depending on the 5-year period considered, whether 1971–1976, 1973–1978, or 1975–1980, while in all these periods the underlying cause of yield decline was the same. We hypothesise that the gap between actual and locally attainable yields is largely attributable to farmer resource endowment and access to nutrient inputs, and a categorisation of yield ranges across farm types and production environments will provide very good approximation of this yield gap and its space-time variability within smallholder African farms.

5. Discussion and conclusions

Yield gaps in African smallholder farming are among the largest in the world. Given demographic projections that the human population in Africa will grow most rapidly of all continents in the coming years, there is an urgent need for productivity to increase. The underlying causes of poor productivity of African agriculture are diverse, but the challenges faced by farmers often include the lack of access to agricultural inputs, the intense labour demands caused by lack of mechanisation, the small size and increasing fragmentation of farms and the lack of capital to invest in building productive soils in harsh environments. Thinking about yield gaps or yield ceilings makes much sense when examining current yields in the most productive agroecosystems of the world, where actual yields are constantly narrowing the gap with respect to the yield potential. In the case of African smallholder agriculture, we believe that the concept of yield gaps can be meaningful when at least two main components of the total absolute gap can be distinguished and studied separately: (1) the gap between the water-limited yield potential (Y_W) and the locally attainable yield (Y_L: or best yields attained in farmers' fields), which provides a measure of yield gap attributable largely to access to adequate technologies, and (2) the gap between Y_L and the average yields (Y_A) farmers obtain across their heterogeneous farms, which differences across farms and largely attributable to access to resources.

Given the context of poor agricultural productivity, of about 1 Mg ha^{-1} year^{-1} of cereal grain across much of sub-Saharan Africa, increasing resource use efficiency means increasing crop primary productivity per unit resource invested. In other terms, radiation interception in space and time and its conversion through photosynthesis are the obvious ecological processes that need to be addressed first. Of the three pillars of ecological intensification proposed by Cassman (1999), yield potential, soil quality and precision agriculture, the second is the most urgent in Africa. Little or no productivity gain can be expected by raising the yield potential when current yields fluctuate around only 20% of that achievable (cf. Tables 4 and 5). Degraded and poorly responsive soils cover large areas of Africa, and represent the majority of poor farmers' fields in certain regions (cf. Table 2). Yet poorly responsive soils are hidden due to the patchwork of productive and unproductive soils across landscapes, coupled with the location of more fertile fields closer to roads and homesteads which can mislead those conducting rapid and superficial assessments. The fertilisers that are generally available simply do not work on degraded soils. Substantial investment to build soil organic matter is needed to restore such soils to a responsive state. A form of precision agriculture, as a means of making an efficient use of natural resources and agricultural inputs, can be redefined for Africa as a practical approach for targeting technologies across scales. There is a need for targeting in a "best fit" approach from a basket of options, rather than pushing best-bet approaches or "silver bullet" solutions (Giller et al., 2011).

The water-limited yield potential seems to be a more sensible reference to calculate yield gaps than the yield potential determined by radiation and temperature in such rainfed African farming systems. However, the use of such theoretical yield levels may yet mask important yield differences within and across farms. For instance, doubling on-farm cereal yields from 0.5 to 1 t ha^{-1} year^{-1} may have a substantial impact on local livelihoods; but such changes may be barely detectable when relative yields are calculated against a yield potential of e.g., 12 t ha^{-1} year^{-1} (from 4.1 to 8.3%). Likewise, yield gaps calculated with respect to yields obtained in experimental stations may also be misleading as they are often located in the most productive environments, overestimating attainable yields under farmer conditions. Hence, we recommend effort should be invested in deriving sound estimates of *locally* attainable yields, Y_L, which as the maximum yields attainable in farmers' fields over years are a more meaningful reference. We suggest a framework for yield gap analysis that recognises the heterogeneous farming systems and landscapes of smallholder agriculture (cf. Fig. 9). A sound understanding and accurate measurements of yield variability is essential for estimating yield gaps (cf. Fig. 8), and probably more challenging to achieve than estimates of water-limited yield potentials which can be derived using simulation models.

The importance of genotype × environment interactions is undeniable, and plant breeding has an important role in enhancing nutritional quality as well as adaptation, resistance and resilience in the face of abiotic and biotic stresses. Yet cultivar choices of sub-Saharan Africa smallholders are also highly influenced by local food habits, markets and traditions. For instance, some of the local varieties cultivated in the highlands of Kenya, although poorly yielding when compared with current tropical hybrids, are highly appreciated for their early maturity that allows harvesting green cobs for roasting at a time of food scarcity (Tittonell et al., 2010a). Discussing the choice of maize cultivars with local farmers, Figueroa Gomez de Salazar et al. (2008) found that grain yield was pondered against other criteria such as the amount of fodder biomass harvestable, yield reliability under water, nutrient or biotic stresses, the size of the cobs or even some aesthetic features of the cultivar (vigour, colour and height) when maize is grown around the homesteads. In other regions with prolonged dry seasons, post-harvest storage properties may be more important than the potential yield of a genotype (Kydd, 1989). Switching from local varieties to hybrids is not always seen as the most sensible strategy in resource-poor, risky environments.

Our analysis suggests that an important fraction of the yield gap may be reduced through proper agronomic management (planting dates, spacing, cultivars, early weeding, etc.) even when fertilisers are not applied. Essentially sound agronomic management is a prerequisite for efficient use of fertilisers and other inputs. Paradoxically, the lack of investment of farmers' labour in agriculture may in turn be caused by the lack of agricultural inputs required to allow efficient returns to labour, and the local soil degradation that requires large investment to achieve response to inputs of fertilizer and labour – a so-called 'poverty trap' (Carter and Barrett, 2006; Marenya and Barrett, 2007) – rather than due to lack of knowledge. This is important for policy setting by governments and their development funding partners. Actions to implement the "Abuja declaration" to ensure efficient use of fertilisers and enhance labour productivity (e.g., http://www.agra-alliance.org) need concomitant attention to restoration of exhausted soils to a healthy and responsive state (Tittonell et al., 2012).

Due either to resource limitations, to local preferences in the choice of genotypes, or to access to technologies current agriculture in sub-Saharan African is far from being able to profit from the ongoing genetic gains in yield potential. Estimating the relative importance of resource limitations ($Y_L - Y_A$) versus inadequate access to technologies ($Y_W - Y_L$) across agro-ecological zones is a good initial step to inform strategies aimed at ultimately narrowing the current yield gaps. However, yield gaps in Africa remain wide and likely to increase further if soil degradation is not reverted, keeping poor farmers confined within recurrent poverty traps.

Acknowledgements

We thank Lotte Klapwijk for help with compiling background data. This research was partially funded by the European Union through the project ABACO, Agroecology-based aggradation-conservation agriculture (DCI-FOOD 2010/230-178).

References

Adjei-Nsiah, S., 2006. Cropping Systems, Land Tenure and Social Diversity of Wenchi, Ghana: Implications for Soil Fertility Management. Wageningen University, Wageningen.

Adjei-Nsiah, S., Kuyper, T.W., Leeuwis, C., Abekoe, M., Cobbinah, J., Sakyi-Dawson, O., Giller, K.E., 2008. Farmers' agronomic and social evaluation of productivity, yield and N_2-fixation in different cowpea varieties and their subsequent residual effects on a succeeding maize crop. Nut. Cycl. Agroecosyst. 80, 199–209.

Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E., Tittonell, P., 2013. The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modelling. Field Crop Res. 143, 106–118.

Akonde, T.B., Kuchne, R.F., Steinmueller, N., Leihner, D.E., 1997. Alley cropping on an ultisol in sub-humid Benin. Part 3: nutrient budget of maize, cassava and trees. Agrofor. Syst. 37, 213–226.

Anthofer, J., Kroschel, J., 2002. Partial macronutrient balances of Mucuna/maize rotations in the forest Savannah transitional zone of Ghana. In: Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R. (Eds.), Integrated Plant Nutrient Management in Sub-Saharan Africa: from Concepts to Practice. CAB International, Wallingford, Oxon, UK.

Altieri, M.A., Funes-Monzote, F.R., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Dev. 32, 1–13.

Aune, J., Bationo, A., 2008. Agricultural intensification in the Sahel – the ladder approach. Agric. Syst. 98, 119–125.

Baijukya, F.P., de Ridder, N., Masuki, K.F., Giller, K.E., 2005. Dynamics of banana-based farming systems in Bukoba District, Tanzania: changes in land use, cropping and cattle keeping. Agric. Ecosyst. Environ. 106, 395–406.

Bationo, A., Ntare, B., 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. J. Agric. Sc. (Camb.) 134, 277–284.

Baudron, F., 2011. Agricultural intensification – saving space for wildlife? PhD thesis. Wageningen University, Wageningen.

Bekunda, M.A., Woomer, P.L., 1996. Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda. Agric. Ecosyst. Environ. 67, 187–195.

Bonny, S., 2011. Ecologically intensive agriculture: nature and challenges. Cah. Agric. 20, 451–462.

Breman, H., Debrah, S.K., 2003. Improving African food security. SAIS Rev. XXIII, 153–170.

Carter, M.R., Barrett, C.B., 2006. The economics of poverty traps and persistent poverty: an asset-based approach. J. Dev. Stud. 42, 178–199.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. U.S.A. 96, 5952–5959.

Cretenet, 1994. Expérimentation des systèmes de culture dans les pays tropicaux. Cas des zones cotonnières d'Afrique noire (Systems Oriented Research in Agriculture and Rural Development). CIRAD, Montpellier, 5 pp.

Cretenet, M., Tittonell, P., 2010. Discontinuous fertiliser use affects soil responsiveness and widens yield gaps in cotton-based cropping systems of N Cameroon. In: AGRO2010 – The Scientific International Week around Agronomy, August 29–September 03, Montpellier, France.

De Jager, A., Onduru, D., van Wijk, M.S., Vlaming, J., Gachini, G.N., 2001. Assessing sustainability of low-external-input farm management systems with the nutrient monitoring approach: a case study in Kenya. Agric. Syst. 69, 99–118.

De Wit, C.T., 1992. Resource use efficiency in agriculture. Agric. Syst. 40, 125–151.

De Wit, C.T., 1994. Resource use analysis in agriculture: a struggle for interdisciplinarity. In: Fresco, L.O., Stroosnijder, L., Bouma, J., van Keulen, H. (Eds.), The Future of the Land: Mobilising and Integrating Knowledge for Land Use Options. John Wiley, Chichester, UK, pp. 42–55.

Doré, T., Cadoret, K., Makowski, D., Malézieux, E., Munier-Jolain, N., Tchamitchian, M., Tittonell, P., 2011. Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur. J. Agron. 34, 197–210.

Dorward, A., Kydd, J., Poulton, C., 1998. Smallholder Cash Crop Production under Market Liberalisation: A New Institutional Economics Perspective. CAB International, Wallingford.

Ebanyat, P., 2009. A Road to Food: Efficiency of Nutrient Management Options Targeted to Heterogeneous Soilscapes in the Teso Farming System, Uganda. Wageningen University, Wageningen.

El-Sharkawy, M.A., 2004. Cassava biology and physiology. Plant Mol. Biol. 56, 481–501.

Faerge, J., Magid, J., 2004. Evaluating NUTMON nutrient balancing in sub-Saharan Africa. Nut. Cycl. Agroecosyst. 69, 101–110.

Fermont, A.M., 2009. Cassava and soil fertility in intensifying smallholder farming systems of East Africa. PhD thesis. Wageningen University, Wageningen.

Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: an analysis from smallholder farms in East Africa. Field Crop Res. 112, 24–36.

Figueroa Gomez de Salazar, B., Tittonell, P., Ohiokpehai, O., Giller, K.E., 2008. The contribution of traditional vegetables to household food security in two communities of Vihiga and Migori Districts, Kenya. In: International Symposium Underutilized Plant Species for Food, Nutrition, Income and Sustainable Development, Arusha, Tanzania, 3–7 May 2008.

Franke, A., Ellis-Jones, J., Tarawali, G., Schulz, S., Hussaini, M., Kureh, I., White, R., Chikoye, D., Douthwaite, B., Oyewole, B., Olanrewaju, A., 2006. Evaluating and scaling-up integrated *Striga hermontica* control technologies among farmers in northern Nigeria. Crop Prot. 25, 868–878.

Giller, K.E., Rowe, E., 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, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 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.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res. 114, 23–34.

Grimme, H., Juo, S.S.R., 1985. Inorganic nitrogen losses through leaching and denitrification in soils of the humid tropics. In: Kang, B.T., van der Heide, J. (Eds.), Nitrogen Management in Farming Systems in Humid and Sub-humid Tropics. Institute for Soil Fertility Research, Haren, The Netherlands, pp. 57–71.

Guibert, 1999. Evolution de la matière organique et de la capacité d'échange cationique des alfisols tropicaux cultivés. Ph.D. thesis, INPL, Nancy, France, 206 pp.

Hayashi, K., Abdoulaye, T., Gerard, B., Bationo, A., 2008. Evaluation of application timing in fertilizer micro-dosing technology on millet production in Niger, West Africa. Nut. Cycl. Agroecosyst. 80, 257–265.

Kamanga, B.C.G., 2011. Poor people and poor fields? Integrating legumes for smallholder soil fertility management in Chisepo, Central Malawi. PhD thesis. Wageningen University, Wageningen.

Khan, Z.R., Midega, C.A.O., Bruce, T.J.A., Hooper, A.M., Pickett, J.A., 2010. Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. J. Exp. Bot. 61, 4185–4196.

Kintché, K., Guibert, H., Sogbedji, J.M., Levêque, J., Tittonell, P., 2010. Carbon losses from savannah soils under cotton–cereal rotations in semiarid Togo. Plant Soil 336, 469–484.

Kydd, J., 1989. Maize research in Malawi: lessons from failure. J. Int. Dev. 1, 112–144.

Lahmar, R., Bationo, B.A., Lamso, N.D., Guéro, Y., Tittonell, P., 2012. Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. Field Crop Res. 132, 158–167.

Lal, R., 1997. Degradation and resilience of soils. Phil. Trans. R.Soc. 1356, 997–1010.

Lobell, D.B., 2013. The use of satellite data for crop yield gap analysis. Field Crops Res. 143, 56–64.

Malezieux, E., 2012. Designing cropping systems from nature. Agron. Sust. Dev. 32, 15–29.

Marenya, P., Barrett, C., 2007. Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. Food Pol. 32, 515–536.

Milgroom, J., Giller, K.E., 2013. Courting the rain: rethinking seasonality and adaptation to recurrent drought in semi-arid southern Africa. Agric. Syst., in press.

Minasny, B., Hartemink, A.E., 2011. Predicting soil properties in the tropics. Earth Science Reviews 106, 52–62.

Murungweni, C., 2011.Vulnerability and resilience of competing land-based livelihoods in South Eastern Zimbabwe. PhD thesis. Wageningen University, Wageningen.

Murungweni, C., Smaling, E.M.A., Van Wijk, M.T., Giller, K.E. Enhancing crop production in semi-arid areas through increased knowledge of varieties, environment and management factors. Agric. Syst., submitted for publication.

Myers, R.J.K., van Noordwijk, M., Vityakon, P., 1997. Synchrony of nutrient release and plant demand: plant litter quality, soil environment and farmer management options. In: Cadisch, G., Giller, K.E. (Eds.), Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, pp. 215–229.

Nkonya, E., Kaizzi, C., Pender, J., 2005. Determinants of nutrient balances in a maize farming system in eastern Uganda. Agric. Syst. 85, 155–182.

Ntawuruhunga, P., Ssemakula, G., Ojulong, H., Bua, A., Ragama, P., Kanobe, C., Whyte, J., 2006. Evaluation of advanced cassava genotypes in Uganda. Afr. Crop Sci. J. 14, 15–27.

Nyombi, K., 2010. Understanding growth of East Africa Highland Banana: experiments and simulation. PhD thesis. Wageningen University, Wageningen.

Ojiem, J.O., 2006. Exploring socio-ecological niches for legumes in smallholder farming systems of Western Kenya. PhD thesis. Wageningen University, Wageningen.

Olufemi Pitan, O.R., Odebiyi, J.A., 2001. The effect of intercropping with maize on the level of infestation and damage by pod-sucking bugs in cowpea. Crop. Prot. 20, 367–372.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42.

Penning de Vries, F.W.T., Ditèye, M.A., 1991. La Productivité des Pâturages Sahéliens: Une Étude des Sols, des Végétations et de l'Exploitation de cette Ressource Naturelle. Pudoc, Wageningen.

Poss, R., Saragoni, H., 1992. Leaching of nitrate, calcium and magnesium under maize cultivation on an Oxisol in Togo. Fert. Res. 33, 123–133.

Prudencio, C.F., 1993. Ring management of soils and crops in the West African semi-arid tropics: the case of the Mossi farming system in Burkina Faso. Agric. Ecosyst. Environ. 47, 237–264.

Ramisch, J.J., 2005. Inequality, agro-pastoral exchanges, and soil fertility gradients in southern Mali. Agric. Ecosyst. Environ. 105, 353–372.

Rodel, M.G.W., Hopley, J.D.H., 1973. Investigations into systems of farming suitable for tribal trust land. Rhod. Agric. J. 70, 1–18.

Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crop Res. 136, 12–22.

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295, 2019–2020.

Scherr, S.J., 2000. A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. Food Pol. 25, 479–498.

Shatar, T.M., McBratney, A.B., 2004. Boundary-line analysis of field-scale yield response to soil properties. J. Agric. Sci. (Camb.) 142, 553–560.

Singh, U., Giller, K.E., Palm, C.A., Ladha, J.K., Breman, H., 2001. Synchronizing N release from organic residues: opportunities for integrated management of N. Scient. World 1, 880–886.

Smaling, E.M.A., Stoorvogel, J.J., Windmeijer, P.N., 1993. Calculating soil nutrient balances in Africa at different scales. II. District scale. Fert. Res. 35, 237–250.

Stoorvogel, J.J., Smaling, E.M.A., 1990. Assessment of the Soil Nutrient Depletion in Sub-Saharan Africa, 1983–2000. Winand Staring Centre, Wageningen, The Netherlands.

Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., 1993. Calculating soil nutrient balances in Africa at different scales. II. Supra-national scale. Fert. Res. 35, 227–235.

Thornton, P.K., Jones, P.G., Alagarswamy, G., Andresen, J., 2009. Spatial variation of crop yield response to climate change in East Africa. Global Environ. Change 19, 54–65.

Tittonell, P., 2009. Propriétés, diversité et variabilité spatio-temporelle des agroécosystèmes. Implications pour leur conception, leur analyse et leur gestion intégrée. Mémoire d'HDR (Habilitation à Diriger des Recherches), École doctorale SIBAGHE, Université de Montpellier II, 47 pp.

Tittonell, P., Vanlauwe, B., Leffelaar, P., Rowe, E., Giller, K., 2005a. 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., Leffelaar, P., Shepherd, K., Giller, K., 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya – II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric. Ecosyst. Environ. 110, 166–184.

Tittonell, P., Leffelaar, P.A., Vanlauwe, B., van Wijk, M.T., Giller, K.E., 2006. Exploring diversity of crop and soil management within smallholder African farms: a dynamic model for simulation of N balances and use efficiencies at field scale. Agric. Syst. 91, 71–101.

Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M., Giller, K.E., 2007a. Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: Exploring management strategies across soil fertility gradients. Field Crop Res. 100, 348–368.

Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007b. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agric. Syst. 94, 376–390.

Tittonell, P., Corbeels, M., van Wijk, M.T., Vanlauwe, B., Giller, K.E., 2008a. Combining organic and mineral fertilizers for integrated soil fertility management in smallholder farming systems of Kenya – explorations using the crop-soil model FIELD. Agron. J. 100, 1511–1526.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008b. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya – an application of classification and regression tree analysis. Agric. Ecosyst. Environ. 123, 137–150.

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008c. Yield gaps, nutrient use efficiencies and responses to fertilisers by maize across heterogeneous smallholder farms in western Kenya. Plant Soil 313, 19–37.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010a. 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.

Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2010b. FIELD – a summary simulation model of the soil-crop system to analyse long-term resource interactions and use efficiencies at farm scale. Eur. J. Agron. 32, 10–21.

Tittonell, P., Vanlauwe, B., Misiko, M., Giller, K.E., 2011. Targeting resources within diverse, heterogeneous and dynamic farming systems: towards a 'uniquely African green revolution'. In: Bationo, et al. (Eds.), Innovations as Key to the Green Revolution in Africa. Springer Science + Business Media B.V., pp. 747–758, http://dx.doi.org/10.1007/978-90-481-2543-2_76.

Tittonell, P., Scopel, E., Andrieu, N., Posthumus, H., Mapfumo, P., Corbeels, M., van Halsema, G.E., Lahmar, R., Lugandu, S., Rakotoarisoa, J., Mtambanengwe, F., Pound, B., Chikowo, R., Naudin, K., Triomphe, B., Mkomwa, S., 2012. Agroecology-based aggradation-conservation agriculture (ABACO): Targeting innovations to combat soil degradation and food insecurity in semi-arid Africa. Field Crop Res. 132, 168–174.

van Asten, P.J.A., Gold, C.S., Okech, S.H., Gaidashova, S.V., Tushemereirwe, W.K., De Waele, D., 2004. Soil quality problems in East African banana systems and their relation with other yield loss factors. Infomusa 13, 20–25.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance – a review. Field Crop Res. 143, 4–17.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E.M.A., Woomer, P.L., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24.

Vlek, P.L.G., Quang Bao, L., Lulseged, T., 2008. Land Decline in Land-rich Africa – a Creeping Disaster in the Making. CGIAR Science Council Secretariat, Rome, Italy, 63 pp.

Wairegi, L.W.I., van Asten, P.J.A., Tenywa, M.M., Bekunda, M.A., 2010. Abiotic constraints override biotic constraints in East African highland banana systems. Field Crop Res. 117, 146–153.

Zingore, S., 2006. Exploring diversity within smallholder farming systems in Zimbabwe: nutrient use efficiencies and resource management strategies for crop production. PhD thesis. Wageningen University, Wageningen.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 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., Wijk, M.T., Giller, K.E., 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nut. Cycl. Agroecosyst. 90, 87–103.