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56% of studies showed negative mean balances. Several cases with positive nutrient balances indicated that soil nutrient mining cannot be generalized across the continent. Land use systems of wealthier farmers mostly presented higher nitrogen and phosphorus balances than systems of poorer farmers ($p<0.001$). Plots located close to homesteads also usually presented higher balances than plots located relatively farther away ($p<0.05$). Partial nutrient balances were significantly higher ($p<0.001$) than full balances calculated for the same systems, but the later carried more uncertainties. The change in magnitude of nutrient balances from plot to continental level did not show any noticeable trend, which challenges prevailing assumptions that an increasing trend exists. However, methodological differences made a proper inter-scale comparison of results difficult. Actually, the review illustrated the high diversity of methods used to calculate nutrient balances and highlighted the main pitfalls, especially when nutrient flows and balances were scaled-up. Major generic problems were the arbitrary inclusion/exclusion of flows from the calculations, short evaluation periods, and difficulties on setting of spatial-temporal boundaries, inclusion of lateral flows, and linking the balances to soil nutrient stocks. The need for properly describing the methods used and reporting the estimates (i.e. appropriate units and measure of variability and error) were also highlighted. Main challenges during scaling-up were related to the type of aggregation and internalization of nutrient flows, as well as issues of non-linearity, and spatial variability, resolution and extent, which have not been properly addressed yet. In fact, gathered information showed that despite some few initiatives, scaling-up methods are still incipient. Lastly, promising technologies and recommendations to deal with these challenges were presented to assist in future research on nutrient balances at different spatial scales in Africa and worldwide.

Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress

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Abstract

Nutrient balances are useful tools as indicators of potential land degradation and for optimizing nutrient use, and are thus highly relevant in the African context. A comprehensive literature review on nutrient balances in Africa was carried out to illustrate the main approaches, challenges, and progress, with emphasis on issues of scale. The review showed nutrient balances being widely used across the continent. The collected dataset from 57 peer-reviewed studies indicated, however, that most of the balances were calculated at plot and farm scale, and generated in East-Africa. Data confirmed the expected trend of negative balances in the continent for nitrogen and potassium, where >75% of selected studies had mean values below zero. For phosphorus only 56% of studies showed negative mean balances. Several cases with positive nutrient balances indicated that soil nutrient mining cannot be generalized across the continent. Land use systems of wealthier farmers mostly presented higher nitrogen and phosphorus balances than systems of poorer farmers ($p<0.001$). Plots located close to homesteads also usually presented higher balances than plots located relatively farther away ($p<0.05$). Partial nutrient balances were significantly higher ($p<0.001$) than full balances calculated for the same systems, but the later carried more uncertainties. The change in magnitude of nutrient balances from plot to continental level did not show any noticeable trend, which challenges prevailing assumptions that an increasing trend exists. However, methodological differences made a proper inter-scale comparison of results difficult. Actually, the review illustrated the high diversity of methods used to calculate nutrient balances and highlighted the main pitfalls, especially when nutrient flows and balances were scaled-up. Major generic problems were the arbitrary inclusion/exclusion of flows from the calculations, short evaluation periods, and difficulties on setting of spatial-temporal boundaries, inclusion of lateral flows, and linking the balances to soil nutrient stocks. The need for properly describing the methods used and reporting the estimates (i.e.

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Key words

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1. Introduction

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

Nutrient balances have been used extensively for improving natural resource management and/or for policy recommendations over the last decades (e.g. Smaling and Braun, 1996; Defoer *et al.*, 1998; Smaling and Toulmin, 2000; De Jager, 2005; Grote *et al.*, 2005). However, caution must be taken due to the often uncritical interpretation of the results, as several methodological complexities and uncertainties exist with this approach (Bationo *et al.*, 1998; Scoones and Toulmin, 1998; Færge and Magid, 2004; Hartemink, 2006a). For example, it has been pointed out that scaling-up[1] nutrient balances in the spatial hierarchy can introduce bias and major errors in the results if flows are not properly extrapolated (Oenema and Heinen, 1999; Schlecht and Hiernaux, 2004). This is partially due to detailed data needed for the calculations (e.g. erosion losses, N_2-fixation, etc.) are generally based on small-scale experiments or observations at plot level (Sheldrick and Lingard, 2004).

The nutrient balance approach in Africa became relevant since the pioneering study of Stoorvogel and Smaling (1990), and the research is still on the agenda (e.g. Vitousek *et al.*, 2009). However, regardless that the knowledge base on the topic has been increasing and some challenges have been recognized, information is fragmented and varies widely (Grote *et al.*, 2005). Although some attempts have been made to integrate the information of nutrient

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

balances in Africa (e.g. Smaling and Braun, 1996; Bationo *et al*., 1998; Nandwa *et al.*, 1998; Schlecht and Hiernaux, 2004), these initiatives included just few case studies, and their assessments were usually restricted to particular regions (e.g. West Africa; East and Southern Africa). Moreover, despite early reports on highly negative nutrient balances across the continent heading to an environmental disaster (e.g. Stoorvogel and Smaling, 1990; Smaling *et al.*, 1993, 1997), more recent evidence has shown that nutrient balance calculations have been often inaccurate and respective results have been misinterpreted (e.g. Faerge and Magid, 2004; Muchena *et al.*, 2005). However, as alternate solutions are still lacking, the original approach of Stoorvogel and Smaling (1990) is still currently being widely used (Lesschen *et al*., 2007). Therefore, improvements in the calculation and a proper interpretation and reporting of nutrient balances for its use as indicator of land degradation at different spatial scales are required. This paper intends to contribute to this goal by: a) integrating peer-reviewed information on nutrient balances in Africa, b) describing the state of the art on the topic based on this comprehensive literature review, c) determining main trends in the results on nutrient balances in Africa for corroborating or demystifying some of the narrative on the topic, d) identifying main methodological differences and limitations between studies, e) identifying pit-falls on scaling-up nutrient balances' approaches by using the compiled information, and f) deriving some recommendations for guiding future studies on nutrient balances at different scales. Although the spotlight is on Africa, principles and methodologies discussed here are not restrictive to this continent, and results are thus generically applicable.

2. Data retrieval criteria and analyses

Data on nutrient balances in African land use systems from studies published in peer-reviewed journals were selected as the population of interest for an objective analysis and comparison among results. The selection was based on a search in the Scopus database (www.scopus.com), which firstly, used as key words “soil” AND different synonyms (singular and plural forms) of "nutrient balances" or “nutrient flows”. Use of the word “soil” narrowed the search to studies assessing land use systems, as nutrient balances are also used in other disciplines (e.g. marine sciences, hydrology, molecular biology, etc.). Subsequently, “Africa” was added as a keyword. Next, “Africa” was sequentially replaced for each of the 53 African countries. Finally, results of previous phases were merged. This final exercise came up with 144 hits. However, after an initial revision 49 studies were excluded as they dealt with subjects beyond the scope of this study. From the remaining 95 studies, 57 reported original data on nutrient balances. Therefore, information regarding their objectives, study sites, methodological approaches, and experimental classificatory variables were tabulated for their characterization. Additionally, reported data on nutrient balances were extracted from the text, tables or figures, and classified by the scale(s) of evaluation and the type of study, as well as by the type of balances (partial or full balances), depending on the flows considered. Partial nutrient balances are the difference between the inflows to a system from mineral and organic fertilizers, and its respective outflows from harvested products and crop residues removed (Cobo *et al.*, 2009); while full nutrient balances include additionally environmental flows (i.e. inputs from wet/atmospheric deposition, nitrogen fixation and sedimentation; and outputs from leaching, gaseous losses, and soil erosion) (Haileslassie *et al.*, 2005). Double data entry was avoided and the units for expressing nutrient balances were standardized when possible (i.e. kg ha^{-1} season^{-1} when only seasonal assessments were done; kg ha^{-1} yr^{-1} when the evaluation was carried out for one or more entire years). Once all data were organized, box-and-whisker plots were constructed for each study as well as for the main spatial scales of evaluation. This helped to understand the distribution of the data in each study and to visualize whether a trend on the magnitude of balances existed across the spatial hierarchy. Box-and-whisker plots displayed the interquartile range (box), the 90th and

10th percentiles (whiskers), outliers (circles) and the mean and median (thick and thin horizontal line inside the box, respectively). To determine differences within farmers' typologies (rich *versus* poor farmers) and within field types (classified according to the distance to homestead) corresponding data pairs per study, for the same system under evaluation (for making them comparable), were plotted against each other by using scatter plots. Thus, only the extreme levels in the categories (i.e. poor vs. rich farmers; closest fields vs. furthest ones) were included in the comparisons; while intermediate levels (e.g. medium wealth class; middle fields) were omitted. This assured a relative comparison between contrasting groups, since farmers' typologies and field types are known to be site and/or study-specific. Differences between the types of balances (partial versus full balances) were also illustrated in a similar way, but including only data from studies reporting both types of balances simultaneously for the same system under analysis. All comparisons were further tested for statistical significance by carrying out paired t-tests for related samples according to Cody and Smith (1997). Box-and-whiskers plots and the t-tests were performed in SAS version 8 (SAS Institute Inc., 1999). Additionally to the peer-reviewed studies selected in Scopus, any other source of publication worldwide was used for the discussion of results.

3. Results and discussion

3.1. Nutrient balances in Africa

The present review confirms that nutrient balances have been widely used as indicators of soil nutrient mining in Africa. The overview presented in Table 1, however suggests that it has been in Kenya where most of the research on nutrient balances has been carried out (19 out of 57 studies), which is more than two times than in the succeeding countries, Ethiopia, Mali and Uganda. Most of the studies (42 out of 57) have been carried out for assessing the condition of different agroecosystems, but nutrient balances have been also calculated from experimental plots (13 studies) and after scenario simulations (8 studies). Nearly all studies (55 out of 57) assessed nitrogen (N) balances, while phosphorus (P) and potassium (K) balances received less attention (Table 1). Few studies (7) dealt with calcium and magnesium, and only four considered carbon (data not shown). Nutrient balances were mainly expressed in kg ha^{-1} yr^{-1} (53% of studies) or in kg ha^{-1} (42% of studies), but were also presented in kg ha^{-1} season^{-1}, in amount of nutrient per system (e.g. kg farm^{-1}) or nutrient per system per unit of time (e.g. kg farm^{-1} yr^{-1}) (Table 1). This depended mainly on the spatial-temporal boundaries of the study and their specific objectives. For the purposes of this study, however, units of balances were uniformized where possible (e.g. kg ha^{-1} per year or season), as previously mentioned.

Nutrient balance results from all 57 selected studies, irrespective of the type of balances, spatial scale, and units (Figure 1), indicated that most systems had negative N and K balances (i.e. 85 and 76% of studies showed negative means, respectively). For P the trend was less noteworthy (i.e. only 56% of studies presented means below zero). These observations are broadly consistent with the general claim of nutrient mining across the continent (e.g. Smaling *et al.*, 1996, 1999; Sanchez and Leakey, 1997; Hartemink, 2006a), at least for N and K. As input use in Africa is the lowest in the world (Nandwa and Bekunda, 1998; Place *et al.*, 2003; Bayu *et al.*, 2005; Muchena *et al.*, 2005), soil nutrient balances are often negative (Bationo *et al.*, 1998; Scoones and Toulmin, 1998; Wortmann and Kaizzi, 1998; De Jager, 2005). This situation can be critical in regions where land users are extensively mining soil resources for their livelihoods. For example, according to Nkonya *et al.* (2005) and Esilaba *et al.* (2005) between 95-100% of studied farmers in Eastern Uganda were soil miners. Based on nutrient balances results and associated socio-economical information De Jager *et al.* (1998a) and van der Pol and Traore (1993) calculated for Kenya and Mali, respectively, that

30-40% of farm income came from soil mining. De Jager *et al.* (2001) even argued that this proportion for subsistence-oriented farmers in Kenya is as high as 60-80%.

Despite the overall negative trend on nutrient balances in Africa, positive balances could also be found on the continent. This is evidenced in Figure 1, especially for P and where mean values from 44, 24 and 15% of the studies (for P, N and K, respectively) were above zero, as well as in all positive observations from many of the studies. In fact, land use systems of wealthier farmers usually had higher nutrient balances than respective systems from poorer farmers (i.e. 52 cases out of 67 for N; 51 cases out of 52 for P) (Figure 2A). This is usually explained by the extended possibilities (in terms of cash, labor, livestock) of wealthier farmers for investing in soil fertility (Cobo *et al.*, 2009), sometimes at the expense of poorer farmers (Zingore *et al.*, 2007). In a similar way, fields near to the homestead (infields) usually had higher nutrient balances than plots of same farmers located relatively further away (outfields) (43 cases out of 48 for N, 11 cases out of 14 for P) (Figure 2B), as farmers frequently allocate their resources and effort to the closest fields (Tittonell *et al.*, 2007). These situations, however, are not always the case (e.g. data pairs below the 1:1 line in Figure 2), as differences within wealth classes and within field types are usually dependent on the crop grown, field/farm size and the related particular soil management practices, among other factors (Elias and Scoones, 1999; Ramisch, 2005; Haileslassie *et al.*, 2007). An extreme case of positive balances is reported by Graefe *et al.* (2008) for urban and peri-urban gardens in Niger, where the use of nutrient-loaded wastewater for irrigation increased N, P and K partial balances up to excessive levels of +7.3, +0.5 and +6.8 Mg ha^{-1} yr^{-1}, respectively, indicating high pollution risks. Cases showing positive nutrient balances are an indication that some farmers, in a conducing environment (as exemplified before), have managed to overcome soil degradation by adapting existing resources and technologies to challenging situations (De

Jager, 2005). Moreover, these examples support the premise of other researchers (De Ridder *et al.*, 2004; Mortimore and Harris, 2005; Muchena *et al.*, 2005; Vanlauwe and Giller, 2006) that the simple narrative of African soil fertility being universally in danger is in reality more complex and therefore must be re-analyzed and treated with more caution.

3.2. Methodological approaches and limitations

Basically, most of the work done on nutrient balances in Africa has followed the approach of Stoorvogel and Smaling (1990), in which five major inputs (mineral fertilizers, organic fertilizers, wet and dry deposition, nitrogen fixation and sedimentation) and five major outputs (harvested crops, crop residues removed, leaching, gaseous losses and soil erosion) have been considered. As several of these fluxes are difficult to measure (e.g. leaching, erosion), transfer functions are commonly used (Smaling and Fresco, 1993; Stoorvogel, 1998; Bindraban *et al.*, 2000; Lesschen *et al.*, 2007). Transfer functions, however, are only approximations as site-specific conditions are not correctly applied in many cases and resulting estimates are rarely checked against field measurements (Færge and Magid, 2004; Hartemink, 2006a). In fact, from the 57 studies evaluated, 39 studies worked with full balances, while 31 studies estimated partial balances (Table 1). Partial balances only consider flows ‘easy’ to measure or estimate (Smaling and Toulmin, 2000; FAO, 2004), like inputs from mineral and organic fertilizers, and outputs from crop yields and residues. A partial balance approach permits to better discuss with farmers the potential implications of the results, as considered flows are ‘visible’ and ‘easily managed’ by farmers (Defoer *et al.*, 1998). However, a shortcoming of partial balances is that excluded flows (e.g. N fixation, erosion) could have a high relative importance, especially in low external input agriculture (Janssen, 1999). Differences between partial and full nutrient balances were evident once both types of balances for the same land use systems were compared (Figure 3). This comparison showed that partial balance estimates were significantly higher than their respective full balances (t values: 4.1 to 9.3, $p<0.001$), especially for N and K (89 and 99% of the cases, respectively); while for P this was less remarkable (only 66% of the cases were higher). This is possibly due to the fact that P is less mobile in soils than N and K, making it less susceptible to losses (e.g. leaching). The difference between partial and full balances clearly suggests that both types of balances must be treated separately, as they are simply different indicators. Therefore, they must be discussed accordingly, but this basic distinction is sometimes not explicitly stated in the literature.

Even when a specific type of balances (full or partial) is chosen, some authors often decide arbitrary to include or exclude some flows, or estimate them differently. For example, both Nkonya *et al.* (2005) and Wortmann and Kaizzi (1998) calculated full balances for farming systems in eastern Uganda. However, while the first study considered all flows, the second study excluded sedimentation, despite it being a substantial process in the system. Additionally, Nkonya *et al.* (2005) estimated most flows by transfer functions, while Wortmann and Kaizzi (1998) estimated leaching, volatilization, and denitrification by the CERES-maize model. Flows rarely considered in the computation of nutrient balances are inputs by livestock urine (FAO, 2003), inputs from seeds (Hartemink, 1997) and nutrient losses and deposition by wind erosion (Visser *et al.*, 2005; Visser and Sterk, 2007), with the last one being a considerable scale-dependent flow in semi-arid areas (Stoorvogel *et al.*, 1997b; Warren, 2007). At large spatial scales, processes like river-basin sediment transport and forest burning are rarely considered (FAO, 2003). Of prime importance is the inclusion of livestock-related nutrient flows, especially in integrated crop-livestock systems, as manure is an essential nutrient source in Africa (Harris, 1999, 2002; Sheldrick *et al.*, 2003). However, the fact that in Africa most livestock graze not only in communal areas but also inside cropping lands after harvest, together with a varied management of the animals and manure, complicates the estimations (Oenema and Heinen, 1999; Schlecht and Hiernaux, 2004).

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

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

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

Even if measurements and calculations are correct, nutrient balances alone are not sufficient as indicators of land degradation. Negative balances, for example, do not directly imply an immediate decline in crop production as nutrient-rich soils (those with high soil nutrient stocks) can still support continued cultivation for several years (Stoorvogel and Smaling, 1998; Vanlauwe and Giller, 2006). Hence, the dynamics of soil fertility decline (i.e. nutrient mining) or recovery (i.e. nutrient accumulation) would be better estimated as a rate of change (proportion) of the total soil nutrient stocks (Bindraban *et al.*, 2000). Unfortunately, the number of studies that link nutrient balances to soil nutrient stocks are limited (i.e. 23 studies out of 57, Table 1). In fact, not always do soil fertility studies include measurements of soil bulk density, which are necessary to express nutrient stocks in the same units that balances are calculated (Hartemink, 2006a); and when included usually different soil depths are considered for the calculations (Schlecht and Hiernaux, 2004). In any case, an accurate determination of soil nutrient pools is very difficult to achieve due to the dynamic and stochastic characteristics of soil system processes (van Noordwijk, 1999; Singh *et al.*, 2001).

3.3. Nutrient balances at different spatial scales

Nutrient balances for Africa, as well as worldwide, have been calculated at different spatial scales, ranging from plot to continental level. Most of the assessments, however, have been carried out at plot and farm level (i.e. 53 and 39% of studies, respectively); while only 12, 11, 11 and 5% of studies have been done at village/watershed, region/district, nation, and continental level, respectively (Table 2). Whereas the number of studies at plot and farm level was similar for partial and full balances, full balances studies dominated (two-to-five times) at higher scales (data not shown). In any case, nutrient balances are usually grouped (e.g. by crop type, wealth class) according to the specific objectives of each study (see Table 3). Differences in nutrient balances among systems, system components, sites and seasons can be attributed to a great diversity of factors, which typically depend on the spatial scale of the study. Based on the hierarchy theory in ecology (O'Neill *et al.*, 1991), lower spatial scales are mainly dominated by natural processes acting at plant level, and climate and geomorphology usually dominate higher spatial scales (Veldkamp *et al.*, 2001). Nevertheless, social, cultural, economical, and political conditions are also important drivers of variation on nutrient flows and balances at different scales (e.g. de Jager, 2005). For example, differences in nutrient balances between plot and farm types are usually associated to landscape position and specific soil fertility management practices (Haileslassie *et al*., 2007); but also to farmers' wealth class and even land tenure (Cobo *et al*., 2009). However, these factors may have less influence at a regional scale where main soil types, access to markets and climate are usually more influential (Haileslassie *et al*., 2007). At large scales, policy is usually a dominant force (e.g. Urban, 2005). Policy, however, can influence a wide variety of other factors, from specific soil fertility management practices to markets and institutional conditions (de Jager, 2005) thereby having significant impact across the whole spatial hierarchy. In fact, most factors affecting environmental processes usually operate at several spatial scales (Heuvelink, 1998); but then, they usually act differently at each spatial level (e.g. Veldkamp *et al.*, 2001).

Having different spatial scales of evaluation for nutrient balance studies actually allows scientist to achieve diverse objectives as well as to reach different users (Stoorvogel, 1998; Bindraban *et al.*, 2000). For example, nutrient balances from plot to farm level can be carried out for improving soil fertility management and nutrient use, and targeted to farmers as it is at these levels that they operate (Table 4). Balances at national and continental levels, on the other hand, can be carried out for performing national and global budgeting to guide decision- and policy making on agricultural sustainability and environmental protection issues. Likewise, units on which nutrient balances are expressed can be used differentially across the spatial hierarchy to match knowledge and preferences of potential users. For instance, while most farmers would prefer nutrient balances expressed in terms of fertilizer equivalents than corresponding estimates expressed as, e.g., kg ha^{-1} yr^{-1}, policy makers would find them more influential in terms of yield loss and monetary values (Lesschen *et al.*, 2007). All this means that it would be simply impossible to conceive a generic optimal spatial scale for nutrient balances studies (Haileslassie *et al*., 2007); although optimum spatial scales for different objectives and users could be proposed (e.g. Table 4).

Given the limited number of studies at scales higher than the farm (Table 2), and considering methodological differences, we refrained from a detailed comparison of results between scales, but plotted the data from only those studies that assessed full balances and whose results could be expressed in kg ha^{-1} yr^{-1} to look for a noticeable trend (Figure 4). A similar exercise using partial balances could not be performed due to the limited number of observations per category at higher spatial levels. The data did not reveal a major trend in the magnitude of N, P and K balances by increasing the spatial scale from plot to continental level. This is in apparent contradiction to Haileslassie *et al.* (2007), Schlecht and Hiernaux (2004), and Onduru and Du Preez (2007) who claimed a trend of increasingly negative nutrient balances with increasing scale of observation; although their statements were based on a limited number of cases only. Even though our sample size is relatively larger and coherent in the type of balances and units, a limitation of results in Figure 4 is that the diversity of systems assessed and the inclusion of sub-levels within main scales could increase variability. Therefore, evidence seems inconclusive, and new studies aiming to validate the impacts of spatial scale on nutrient balance estimations are required. Possibly the only way to perform a rigid comparison would be if the same methodology is applied at each different scale and carried out under the same biophysical and socio-economical conditions.

However, in practice this would be difficult as the input data for nutrient balances studies, as well as the data collection strategy, strongly depend on the scale of evaluation, available resources and the location, hence calculations of nutrient balances usually vary accordingly (Scoones and Toulmin, 1998; Bindraban *et al.*, 2000; FAO, 2003, 2004).

3.4. Scaling-up challenges

The issue of scale takes even greater relevance when nutrient flows and balances are scaled-up. A problem with scaling-up is that the bulk of understanding of biological processes and its dynamics usually resides at lower scales (Urban, 2005). In fact, soil nutrient balances at any scale usually depend on plot scale measurements, as this is the lowest level where most of the flows are based or determined (Stoorvogel and Smaling, 1998). Thus, great attention must be paid to the way flows are extrapolated, as different procedures can be used which may lead to loss of information and/or to bias in the results (Oenema and Heinen, 1999; Scoones and Toulmin, 1998). Aggregation can be carried out as a linear function of the components or based on non-linear functions, depending on the interactions among system components, like in the case of substantial lateral fluxes, as explained previously (van Noordwijk, 1999; Dalgaard *et al.*, 2003). The internalization of flows (which refers to their qualification as internal to a system at a specific spatial scale) is also a critical factor, as once a flow is internalized, it would be not considered or considered only partially in the nutrient balance calculation (Schlecht and Hiernaux, 2004; Smaling and Dixon, 2006). For example (Table 5), organic fertilizers are a net input to the plots; but if the organic inputs have been produced within the farm (e.g. by composting crop residues) these flows should be internalized in a farm gate level approach. A similar effect would happen for crop products. While all yields go out of the plot at plot scale, home consumption must be accounted for at the farm level, so this flow must be partially internalized. Therefore, the higher the scale where boundaries are established, the more likely a flow must be internalized (Table 5). Hence, different types of aggregation and internalization would produce different results, and this is usually a function of the degree of heterogeneity and resolution of the system under analysis and the process in consideration (Heuvelink, 1998; van Noordwijk, 1999). Unfortunately, but expected, aggregation and internalization of flows can mask important differences within the lower levels (Haileslassie *et al.*, 2007), as up-scaling and loss of information are closely connected (van der Hoek and Bouwman, 1999; FAO, 2003). In fact, by decreasing the resolution of assessment and increasing its extent, the identification of key processes and factors usually turns more difficult (Kok and Veldkamp, 2001). Moreover, as system heterogeneity and complexity increase with scale, precision and accuracy of nutrient balances calculations usually decrease (Stoorvogel and Smaling, 1998; FAO, 2003).

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

Heuvelink, 1998). Thus, information is usually found for scaling-up exercises comprising only few (1-2) levels. Scaling up is evidently more difficult when several scales are included. Three main approaches, therefore, could be broadly distinguished according to the scaling-up procedures carried out in practice, as outlined below:

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

Scaling-up to the farm scale has been carried out frequently in Africa (Table 2). For example, Zingore *et al.* (2007), estimated farm level balances by taking “the difference between total nutrient inputs and total outputs from all plots on a farm” and later dividing it by the total area, where “direct movements of nutrients between plots were considered as internal”. In fact, farm scale balances are mostly carried out by direct measurements or estimations of flows from the plots or administrative units from which the farm is composed, which is followed by a linear aggregation of data (internal flows excluded). Although the method is quite straightforward and typically used by most of the studies in Africa, a major problem is the existence of non-linear effects due to the high level of interacting flows among plots and other farm components (Stoorvogel and Smaling, 1998); which is usually more noteworthy on farms with several plots and which are highly diversified (Haileslassie *et al.*, 2007). Choosing the basic spatial unit to be used in the study (plot or administrative unit) is also important, as this would affect the internal variability within units, as well as the amount of local interactions (van Noordwijk, 1999). Including non-linear effects in the calculations, however, would require detailed information of related fundamental processes within the farm (e.g. Dalgaard *et al.*, 2003). Modeling and spatial statistics (see section 3.5) could help overcome this problem. In any case, a proper internalization of flows at this spatial level and the inclusion of home gardens, homestead, fallows, and hedgerows should be also considered.

Scaling-up to the village or communities, on the other hand, has been carried out to a lesser extent than at farm level (Table 2). Selecting the study of Ramisch (2005) as illustration, up-scaling to the community level was achieved by “the sum of all the balances for all the plots within the relevant sub-region or [household] class, averaged over the total area of those plots”. This approach seems also straightforward, although it suffers from issues of non-linearity among plots (as explained for the farm scale), but also among farms, which make it more complex. Another critical issue relates to whether calculations are based on an ‘average farm’ (e.g. Shepherd and Soule, 1998) instead of farm typologies, as this would influence until which extent diversity between farms is accounted for. If a farm typology is selected, emphasis should be placed on how well it is capturing the differences among farms (e.g. resource endowments), and this would depend further on the indicators (criteria) chosen for the classification. Selecting an ‘average’ farm for extrapolation would only be acceptable when no significant differences among farming systems in the area under observation occur, which is exceptionally rare in Africa. Manlay *et al.* (2004a), on the other hand, calculated balances at village level in an apparently similar way, but included in the calculations not just cropping fields but also fallow areas, woodlands, grasslands, and livestock-mediated flows. This is important, as rangelands and fallows at village scale (and higher levels) are generally excluded from the assessments despite their importance as sources of nutrients for agricultural land (Harris, 1999; Smaling and Toulmin, 2000), as well as sinks or traps for nutrients from erosion (Warren, 2007). Therefore, a cautious interpretation of results must be carried out, as negative balances from agricultural land do not necessarily mean that nutrients leave the area completely, as they can be deposited on adjacent ecosystems (Haileslassie *et al.*, 2006). In fact, scaling-up nutrient flows and balances are especially critical when substantial lateral flows (e.g. soil, nutrients, water) are involved (van Noordwijk, 1999b; van Noordwijk *et al.*, 2004). As lateral flows are scale-dependent, and this scale-dependency is very difficult to quantify, they are generally ignored in the calculations, which usually results in overestimations of the final budget (De Ridder *et al.*, 2004). For example, flows due to soil erosion and deposition are an example of lateral flows most affected by the scale (Stoorvogel and Smaling, 1998; Schlecht and Hiernaux, 2004) as actual losses by erosion at scales beyond the plot level are considerably smaller than those ones usually estimated at the plot scale due to re-deposition (De Ridder *et al.*, 2004; Visser and Sterk, 2007). Unfortunately, few studies have been conducted to determine the proper contribution of soil erosion/deposition processes to nutrient balance studies at different scales (Visser *et al.*, 2005). Moreover, methodologies for scaling-up data of run-off and erosion are still not available (De Ridder *et al.*, 2004), despite the fact that scaling-up methods are even more relevant for erosion model building than the actual measurements (Hashim *et al.*, 1998). In this regard, the use of LAPSUS (LandscApe ProcessS modeling at mUltidimensions and Scales) is apparently a better alternative than USLE (the Universal Soil Loss Equation), as it includes a feedback between erosion and sedimentation (FAO, 2003; Haileslassie *et al.*, 2005; Lesschen *et al.*, 2007). Moving from farm to higher scales also implies that not one farmer but the community is responsible for natural resource management; therefore, common property land management and use become an issue as well. This would be especially important in the case of communities with restricted access to grazing and forested areas, as potential conflicts could arise which would affect nutrient flows into the system. In section 3.5 some alternatives for dealing with this issue are presented.

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

The levels of province, district, region, or agro-ecological zone are a suitable entry point for policy-making at sub-national level, as well as for private sector interventions (FAO, 2003). Here the main problem is that very few input data at the required resolution and quality actually exist (Bekunda and Manzi, 2003; FAO, 2004). Therefore, data must be scaled-up from plot, farm or village levels (by aggregation of data), and/or scaled down from higher scales (by disaggregation). The “mesolevel” study from FAO (2004) in Ghana, Kenya and Mali clearly showed this problem, especially in Ghana where less data were available. This study “involved establishing relations between land use and soils in order to compensate for the lack of spatial data”, and calculations were finally made in a tabular form. Thus, data from lower levels (e.g. surveys, weather stations) and higher scales (e.g. national statistics, international databases) were used to feed the multiple functions in the calculations. The problem with aggregating data from lower scales is that usually not the entire range of bio-physical and socio-economical conditions can be practically covered, and results would depend on the criteria used during extrapolation (van der Hoek and Bouwman, 1999). The issue with disaggregating data from macro-scale studies, on the other hand, is that in this process “variability should be added instead of being leveled out and this is generally considered a difficult problem” (Heuvelink, 1999). Therefore, uncertainties may be propagating from both the micro and macro -scales, and thus several of the problems identified earlier in point 3.4.1 and in the next point would also apply.

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

National, supra-national and continental assessments of nutrient balances in Africa strongly depend on the collection of national or international studies and databases, which are already aggregated (De Jager *et al.*, 1998b). For example, Lesschen *et al*. (2007) calculated spatially-explicit nutrient balances at national level for Burkina Faso. They based their methodology on a land use map, produced via qualitative land evaluation (a FAO methodology), which used diverse biophysical databases and statistical data for the allocation of crops over the generated map units at 1-km resolution. Nutrient balances were later calculated for each grid unit and results aggregated (by simple averaging) to 20-km grid cells for final presentation. From a spatial point of view, the approach was roughly similar to the macro-scale study of FAO (2004) in Kenya, Ghana and Mali; and essentially differed from earlier approaches (spatially-explicit, e.g. Folmer *et al.*, 1998; and non-spatially-explicit, e.g. Stoorvogel *et al.*, 1993) in which grid cells were used as the basic spatial units for the estimation of balances, instead of using coarser land use classes. Although the approach included several innovations (e.g. improvement of some pedotransfer functions, estimation of uncertainties), due to the higher scale of evaluation complexities were inevitable. For example, macro-scale assessments are typically limited by the availability of data to be used in the calculations, as these vary per country (Stoorvogel, 1998; Bindraban *et al.*, 2000). This is why Lesschen *et al*. (2007) had to use fertilizer input data from Mali and Senegal, as there was none available for Burkina Faso. Moreover, due to data limitations, a great variety of datasets, maps and information from different times, sources, qualities and resolutions are typically used. Use of GIS is assumed to solve the problem of convergence among different data. However, for the calculations to being accurate, biophysical and socio-economical information must be collected at the same spatial units, sampling designs and times (Schreier and Brown, 2001), which has been hardly ever carried out. Moreover, most applications in GIS assume data to be proportional to the area they occupy for extrapolation (van Noordwijk, 1999) which, as it has been discussed previously, is usually not the case. In Lesschen *et al*. (2007), erosion-deposition process were included by using the LAPSUS model. However, this model was developed at watershed level making its results at higher scales uncertain. Another important issue refers to the internalization of the flows, which at these levels is rarely considered (Schlecht and Hiernaux, 2004). Balances calculated from national to continental levels also traditionally refer to arable land (excluding thus fallows and rangelands), thus redistribution of nutrients out of the boundaries (as discussed previously) is seldom considered (Haileslassie *et al.*, 2007). In any case, the wide diversity of agricultural systems in Africa makes it very difficult to obtain a general meaningful value at these scales. These estimates should be better expressed as broad qualitative classes due to their typically low accuracy and uncertainty (Table 4).

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

3.5. Vanguard techniques for nutrient balances' studies

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

Due to the increasing need for understanding the spatial variation of soil processes and phenomena, coupling models with GIS for a spatially-explicit quantification of nutrient balances across different scales seems even more promising (Schlecht and Hiernaux, 2004; Hartemink, 2006a). In fact, recent advances in remote sensing and the accessibility to new geographical databases (on climate, soils, etc.) and software make all these tasks nowadays easier than before. The macro-scale studies cited in section 3.4.2 are a good example of this. A decision support system approach has also been proposed by Singh *et al.* (2001), which integrates nutrient balance calculations, crop simulation models, bio-economic databases, and GIS. A similar approach but linking dynamic nutrient balance models to land use change models is even envisaged in the near future to be able to explore the different effects of land use and land cover dynamics in nutrient flows and balances with time, which would be highly relevant in agroecological research (Lesschen *et al.*, 2007). In any case, (spatially-explicit) models and decision support systems should further allow soon the integration of off-site effects at different scales, as well as the actions of different stakeholders into the systems

(Schlecht and Hiernaux, 2004). In the first case, the use of fractal approaches for incorporation of lateral flows has been proposed by van Noordwijk *et al.* (2004) in which a fractal dimension (with self-similar properties at different scales) is identified and applied across different scales where its rules operate. This approach, however, has not been apparently applied yet in nutrient balances studies in Africa. Multi Agent Systems (MAS), on the other hand, would have the potential of incorporating management decisions of actors or groups of actors in the agroecosystems, which would be especially important when dealing with communal resource management (e.g. grazing areas, forests) at the scale of village and beyond Schlecht and Hiernaux, 2004). The experiences from Schreinemachers *et al.* (2007) in Uganda with this kind of approach are encouraging.

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

4. Conclusions and further recommendations

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

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

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

Despite methodological limitations and uncertainties, nutrient balances have been proven to be useful methodological tools for natural resource management assessments in Africa. Nutrient balances clearly illustrate the impact of human intervention on soil fertility (FAO,

2003) and allow the identification of problematic land use systems and flows where corrective land-use strategies should be properly adopted (e.g. Bindraban *et al*., 2000; Haileslassie *et al*., 2007). In fact, at lower spatial scales, nutrient balance exercises seem more appropriate for comparing how different systems and technologies potentially impact nutrient mining or recovery, and which and where prospective measures for tackling imbalances are most likely to be successful. At higher spatial scales, the assessment should focus more on creating awareness for policy recommendations on food security and land degradation. The challenge for Africa still resides in providing more external agricultural inputs (nutrients) while building-up systems' soil organic matter, inside a policy framework that facilitate these interventions, and even supports monitoring pathways of change across time (Vitousek *et al.*, 2009). Editors and reviewers also have an important role, as recurring errors in soil nutrient balance studies are still present in the recent literature (see Table 6 for a list of usual errors on nutrient balances studies and recommended solutions), which could lead to misleading information for the different target groups. Hence, if the scientific community wants to encourage African farmers to adopt more sustainable soil management practices and/or to convince African policy makers to enhance governmental strategies to reduce soil mining, the calculations, interpretation, and presentation of nutrient balances as indicators of land degradation at different spatial scales must be improved.

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6. References

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Table 1. Main methodological characteristics of selected nutrient balance studies in Africa (n=57). Data show the number and proportion of studies per each category.

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

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

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

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

Table 2. Methodological issues related to the scale of the study and scaling-up from selected nutrient balance studies in Africa (n=57). Data show the number and proportion of studies per each category.

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

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

Table 3. Examples of different spatial scales and sub-levels at which nutrient balances studies in Africa have been carried out.

Scale or sub-level*	Description of the scale or sub-level	Study used as example	Units of analyses
Plot (field)	Different plots in a farm	Harris (1998)	Field$_1$, field$_2$… field$_n$
Plot types	Grouping of plots according to a common feature	Tittonell *et al.* (2007)	Infields vs. outfields
Crop (primary production unit, land use type)	A crop or crop activity consisting of one or more crops grown deliberately	Baijukya *et al.* (2005)	Maize, potato, cassava
Production systems (activity level, farm-subsystems)	Grouping of units within farm according to production objectives or farming activities	Esilaba *et al.* (2005b)	Crop production system, animal production system, household
Farm (household)	Different farms in a village or region	Bekunda and Manzi (2003)	Farm$_1$, farm$_2$… farm$_n$
Farm typologies (wealth class, soil fertility managers)	Stratification of households by biophysical and/or socio-economical conditions	Zingore *et al* .(2007)	Very rich, rich, poor, very poor farmers
Farm management system (farming system)	Grouping of farms or areas under same farming systems	Haileslassie *et al.* (2006)	Enset system, teff system
Village (community)	One or several villages in a region	Manlay *et al.* (2004a)	Sare Yorobana village (Senegal)
Watershed, Catchment	One or several watershed or catchment in a region	Kanyama-Phiri *et al.* (1998)	Songani Watershed (Malawi)
Land cover	Different land covers in a district or region	Powell *et al.* (1996)	Rangelands, Croplands
District, Region	One or several districts or regions in a nation	Smaling *et al.* (1993)	Kisii District, Southwestern Kenya
Production system, Land use system	Stratification of areas by crop inside units of similar cropping systems and use intensity	Folmer *et al.* (1998)	Maize in Small or large scale rain-fed or irrigated farming
Crop type (cropping systems)	Grouping of crops within farm according to a common feature	Haileslassie *et al.* (2005)	Permanent crops, vegetables, pulses, oil crops, cereals
Land water class, Agro-ecological zone	Stratification of areas by units of similar production potential	Stoorvogel *et al.* (1993)	(Rain-fed, flooded, irrigated land) * (high, medium, low soil fertility)
Nation (country)	One or several countries	Sheldrick and Lingard (2004)	All countries in Africa
Sub-continent	A specific area or region inside a continent	Stoorvogel *et al.* (1993)	Sub-Saharan Africa
Continent	A continent as a whole	Sheldrick *et al.* (2002)	Africa

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

Table 4. Potential objectives, users, resolution accuracy, and units of nutrient balance studies across main spatial scales. Modified from (Bindraban *et al.*, 2000) and (Stoorvogel, 1998).

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

*Under similar availability of resources and same time period.

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

Table 5. Internalization of main nutrient flows during their scaling-up by using the main scale as the system boundary. The type of internalization (N: none, P: partial, T: total) in some cases would depend on the specific characteristics of the system under study.

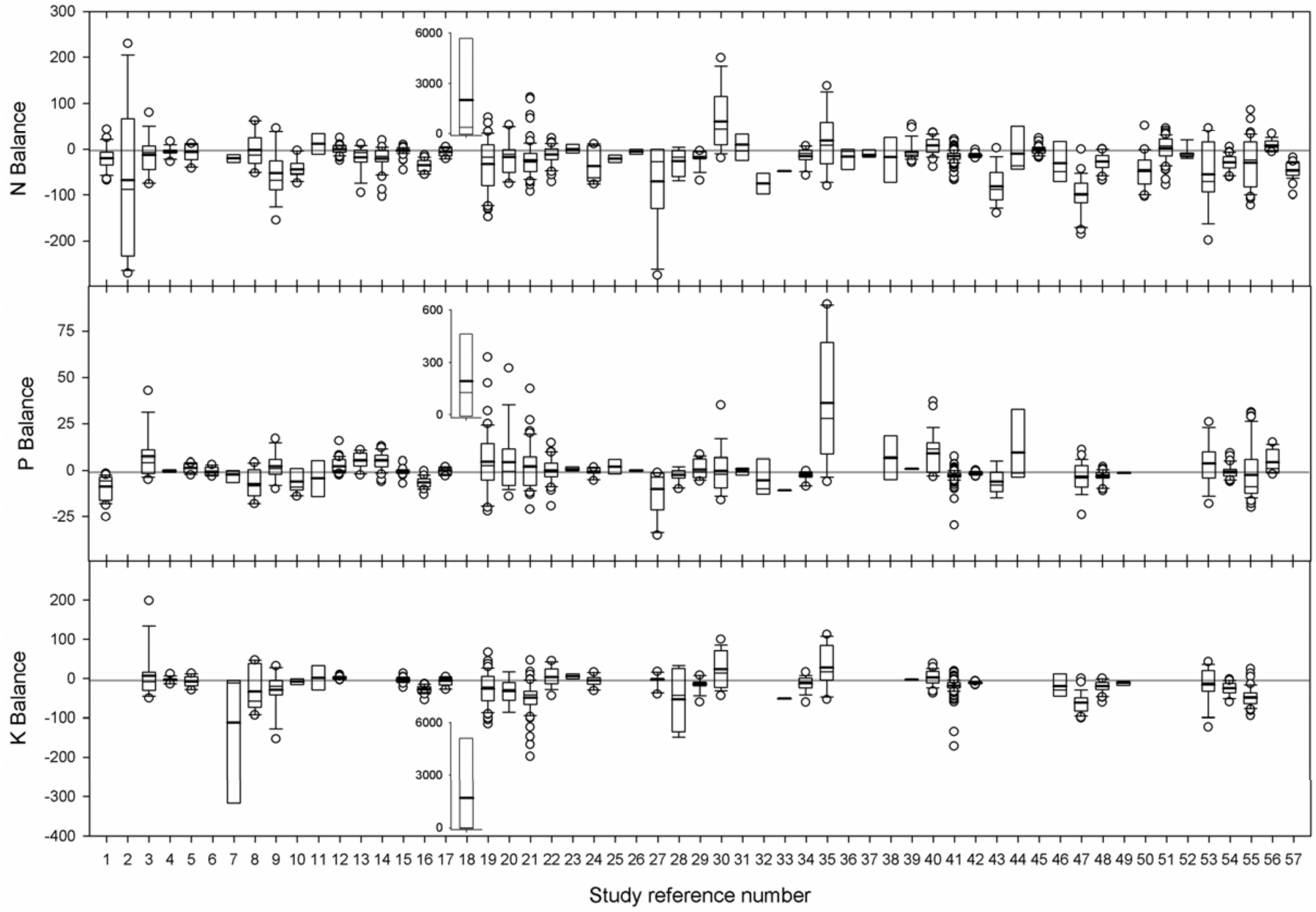
	Main spatial scale						
Flow description	Plot	Farm	Village	Region	Nation	Continent	Global
Mineral fertilizer	N	N	N	N	P	P/T	T
Organic fertilizer	N	N/P	N/P/T	P/T	T	T	T
Purchased food and feed	N	N	P/T	P/T	P/T	P/T	T
External grazing	N	N/P	P/T	P/T	T	T	T
Wet and dry deposition	N	N	N	N	N	N/P	T
N fixation	N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

Table 6. Typical errors found in studies reporting nutrient balances at different scales in Africa and recommendations for its rectification

Error	Solution
Errors during estimations of flows and/or calculations of nutrient balances:	
- Transfer functions are used under different conditions from where they were developed	- Estimates of parameters must be checked against field measurements or data from (at least) similar sites. Transfer functions without validation should be avoided.
- Some flows are excluded from the calculations, despite its acknowledged importance	- If full balances need to be calculated, the excluded flows need to be included. On the contrary, uncertainties must be acknowledged or partial balances must be used
- Partial N balances are used on N_2-fixing ecosystems	- Input from N_2-fixation must be accounted for
- Flows are not properly internalized when up-scaled	- Total or partial internalization of flows must be carried out accordingly
- Direct extrapolation of erosion measurements from plot to higher spatial levels are carried out	- Soil re-deposition across spatial scales must be accounted for; thus particular scaling-up procedures for erosion versus soil deposition processes must be properly reported
- Nutrient balances are not linked to soil nutrient stocks	- Samples for bulk density must be taken together with soil fertility determinations for being able to link them accordingly

Table 6 (cont.)

Error	Solution
Errors in reporting the methods used:	
- No clear definition of land use systems studied	- As nutrient balances studies can assess only cropping fields or include additionally rangelands and/or fallows, this must be properly mentioned in the methodology
- Time frame of the study is not mentioned	- The time frame as well as the year or season of study must be clearly stated
- Units of balances are not mentioned or used erroneously	- Balances should be presented in kg per units of space and time, unless they are needed to calculate necessary inputs to a system (e.g. kg farm^{-1} or country^{-1} per year or season)
- No proper explanation of how flows are estimated	- An explicit methodology explaining the specific procedures done must be stated
- No clear distinction of type of balances used	- Partial or full balances must be clearly defined and interpreted accordingly
- Resolution of the assessment is not clear	- The basic unit where the calculation of balances took place (plot, field, administrative unit, cell, etc.) must be clearly stated
- Scale of evaluation of nutrient balances is not mentioned	- The scale, as well as the sub-levels used for the assessment, must be clearly mentioned in the methodology
- Methods used during scaling-up flows and balances are not properly explained	- The specific way how flows are extrapolated, aggregated and internalized must be clearly mentioned in the methodology
- Variability of estimates are not shown	- A measure of dispersion or uncertainty must accompany the reported results


N Balance
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57
Study reference number

Figure 1. Box-and-whiskers plots of reported nutrient balances from 57 peer-reviewed studies in Africa, irrespective of the type of balances. Balances are expressed in kg ha^{-1} yr^{-1} with the exception of studies no. 23 and 25 (kg ha^{-1}), and 14, 15, 17, 28, 34, 35, 39, 40, 45, 50, 51 and 52 (kg ha^{-1} season^{-1}). Study no. 18 was out of the range and is presented with its own y-axis. Study reference numbers: 1: Adu-Gyamfi et al., 2007, 2: Akonde et al., 1997, 3: Baijukya and De Steenhuijsen, 1998, 4: Baijukya et al., 2005, 5: Bekunda and Manzi, 2003, 6: Bontkes and Van Keulen, 2003, 7: Brand and Pfund, 1998, 8: Carsky and Toukourou, 2005, 9: De Jager et al., 1998b, 10: De Jager et al., 2001, 11: Defoer et al., 1998, 12: Dougill et al., 2002, 13: Elias and Scoones, 1999, 14: Elias et al., 1998, 15: Esilaba et al., 2005, 16: Folmer et al., 1998, 17: Gachimbi et al., 2005, 18: Graefe et al., 2008, 19: Haileslassie et al., 2005, 20: Haileslassie et al., 2006, 21: Haileslassie et al., 2007, 22: Harris, 1998, 23: Harris, 1999, 24: Kanmegne et al., 2006, 25: Kanyama-Phiri et al., 1998, 26: Krogh, 1997, 27: Laclau et al., 2005, 28: Lehmann et al., 1999, 29: Lesschen et al., 2007, 30: Lupwayi and Haque, 1999, 31: Manlay et al., 2004b, 32: Mathuva et al., 1998, 33: Nkonya et al., 2005, 34: Onduru and Du Preez, 2007, 35: Onduru et al., 2007 (Napier data omitted), 36: Poss and Saragoni, 1992, 37: Powell et al., 1996, 38: Radersma et al., 2004, 39: Ramisch, 2005, 40: Saïdou et al., 2003, 41: Sheldrick and Lingard, 2004, 42: Sheldrick et al., 2002, 43: Shepherd et al., 1996, 44: Shepherd and Soule, 1998, 45: Singh et al., 2003, 46: Smaling and Fresco, 1993, 47: Smaling et al., 1993, 48: Stoorvogel et al., 1993, 49: Stoorvogel et al., 1997a, 50: Tittonell et al., 2005, 51: Tittonell et al., 2006, 52: Tittonell et al., 2007, 53: Van den Bosch et al., 1998, 54: van der Pol and Traore, 1993, 55: Wortmann and Kaizzi, 1998, 56: Zingore et al., 2007, 57: Zougmore et al., 2004.

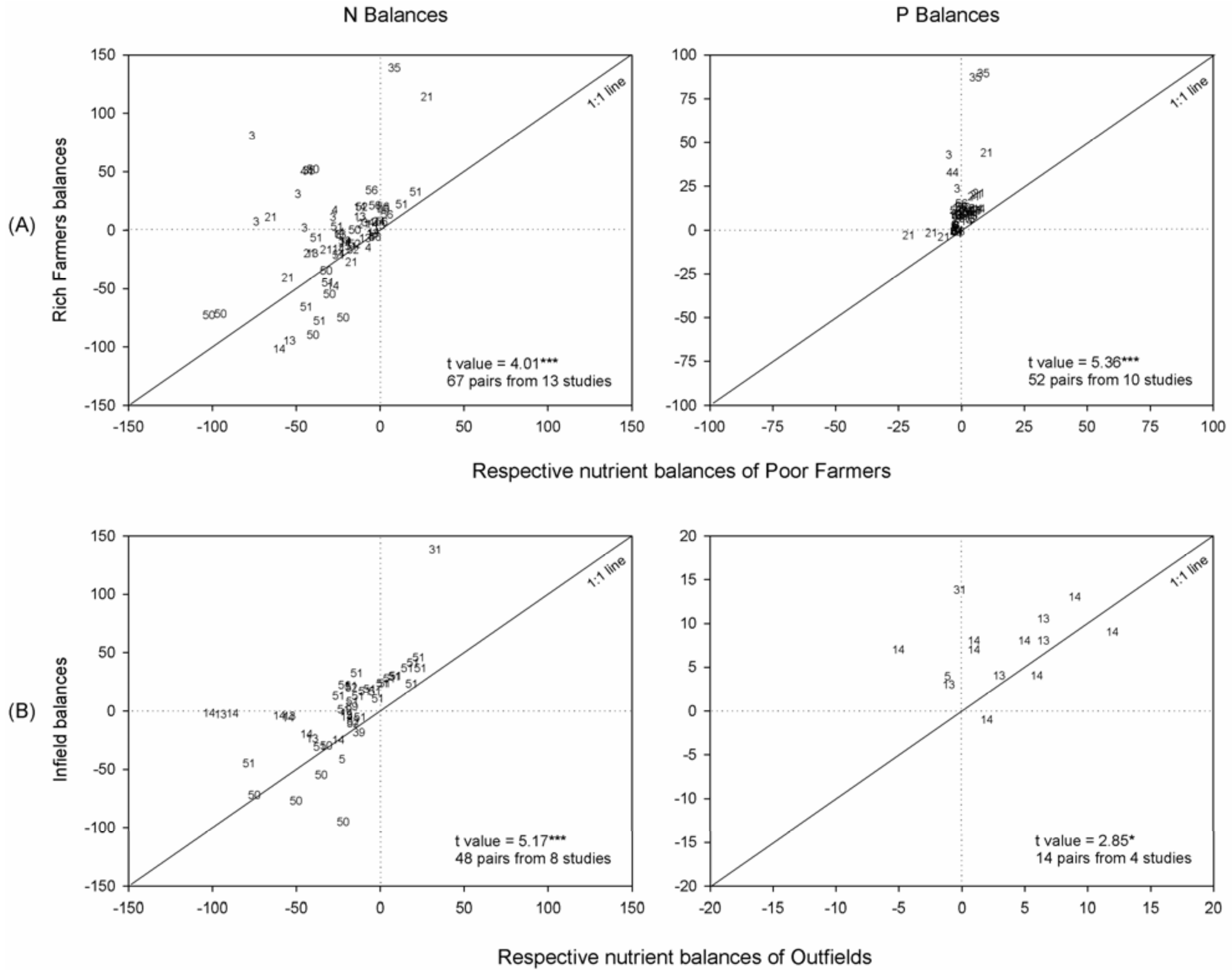

Figure 2. Comparisons within (A) farmers' resource endowment (rich *versus* poor farmers) and (B) within field types (infields *versus* outfields) for N and P balances (in kg ha^{-1} yr^{-1} or kg ha^{-1} season^{-1}) from different studies in Africa. For the comparisons to be valid, only data pairs per study, for the same system under evaluation, were plotted against each other. Results of the paired t-test for related samples are shown (*** : *p*<0.001, * : *p*<0.05). All data pairs are represented by its study's reference number according to Figure 1.

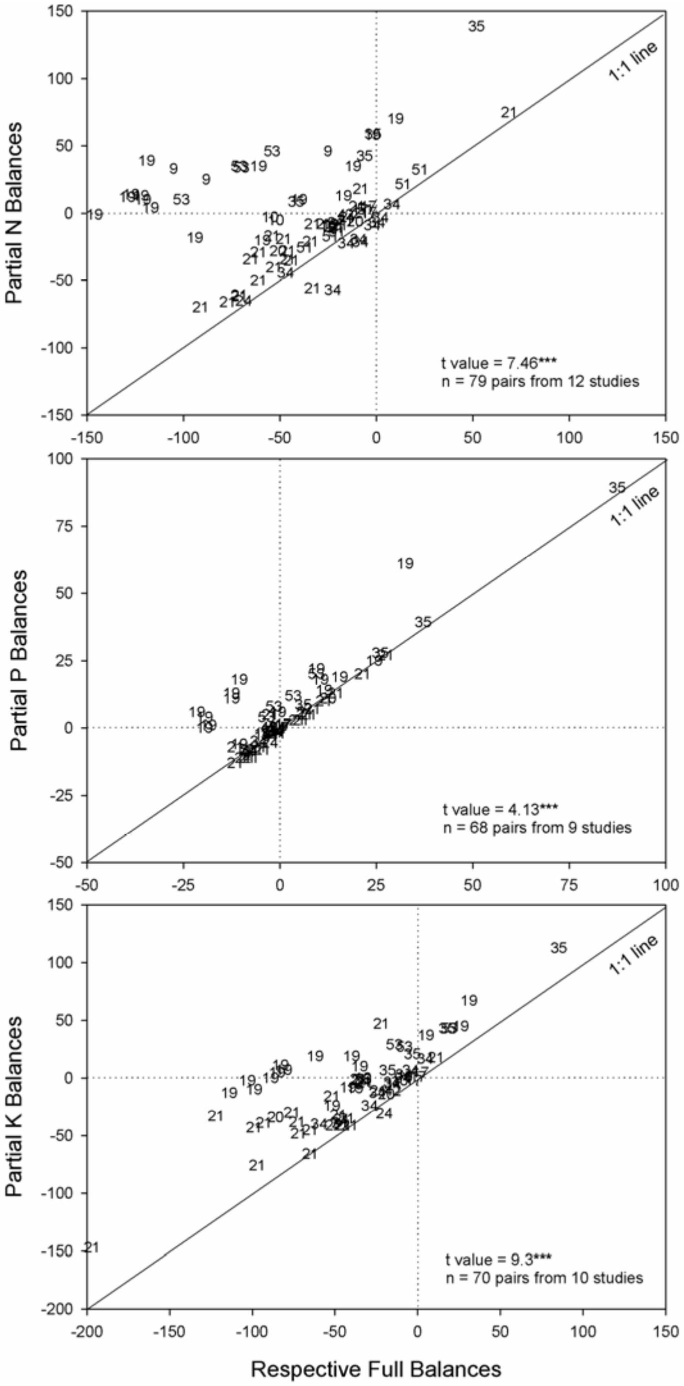

Figure 3. Comparison between partial and full balances (in kg ha^{-1} yr^{-1} or kg ha^{-1} $season^{-1}$) for studies in Africa reporting both types of balances simultaneously for the same system under evaluation. Results of the paired t-test for related samples are shown (*** : $p<0.001$). All data pairs are represented by its study's reference number according to Figure 1.

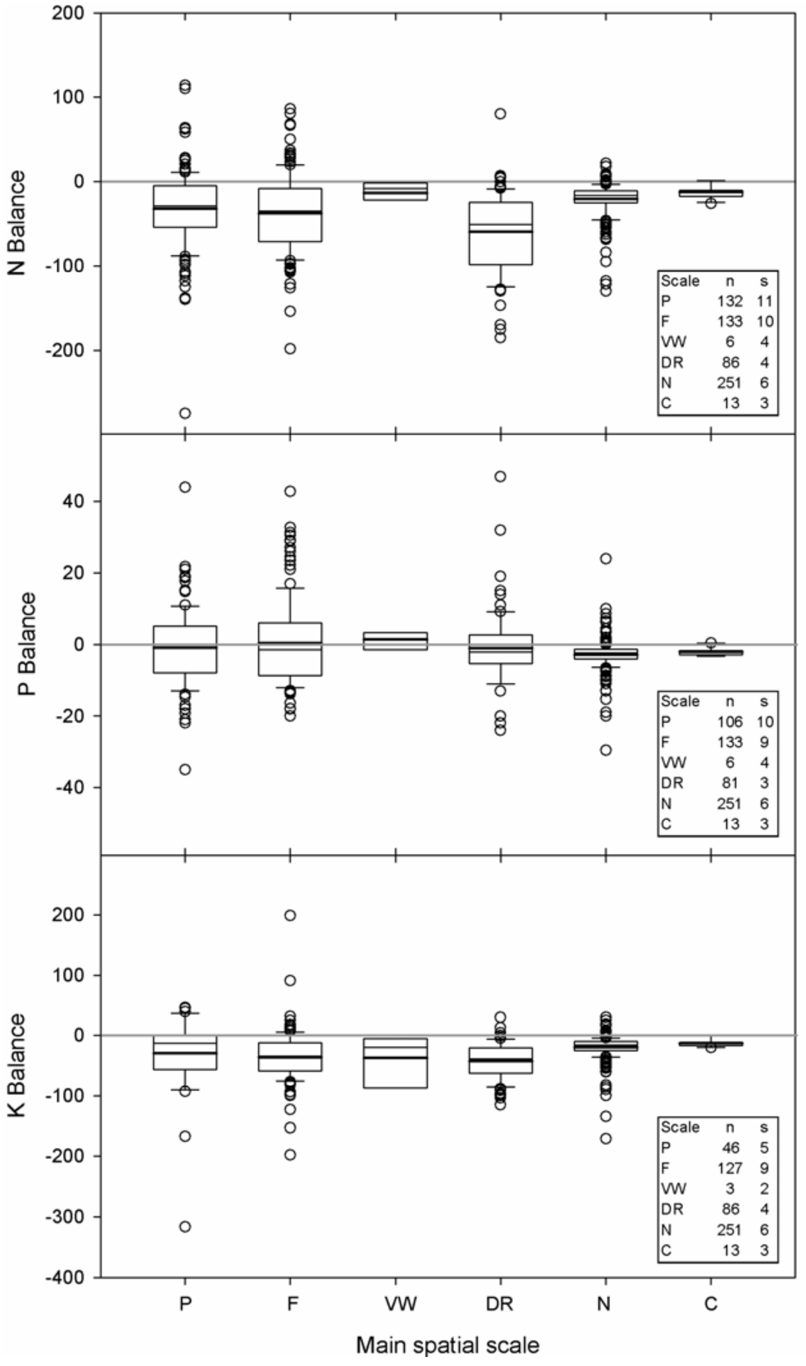

Figure 4. Nutrient balances at main spatial scales from different studies in Africa (P: plot, F: farm, VW: village & watershed, DR: district & region, N: nation, C: continent). Only data expressed as kg ha^{-1} yr^{-1} and derived from full nutrient balances studies were plotted for the comparison. Number of observations (n) and studies (s) per category are shown in the rectangles.