Nutrient Balance Studies: General use and perspectives for SE Asia

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Abstract

The principles behind nutrient balance studies and the comparison of inputs and outputs from a system have been at the heart of the development of plant nutrition as a science and the development of world agriculture. Only in relatively recent times, however, has there been much interest in using nutrient balance approaches to assess the status of agroecosystems and ecosystems in general.

Nutrient balances can be used across a wide range of scales - from a farmer's field to global – and for a wide range of reasons – for recommendations to farmers through to national policy making. A primary objective of nutrient budgeting has been to develop appropriate recommendations for management, particularly for the use of fertilizers, with the aim of increasing productivity. However, there is increasing use of nutrient balances for assessing a component of the sustainability of agroecosystems, as well as for broad scale policy decision-making.

The methods of estimating nutrient balances vary significantly, depending on the scale of the study and its objectives. Many studies, particularly those at higher scales namely, national and supranational rely almost solely on the use of secondary data. Most studies use some secondary or published data, while only a few, particularly those aimed at better understanding of the underlying processes, rely solely on measurements. The quality of the data that are used has a significant impact on the accuracy and precision, and thus the usefulness, of the calculated balance

Many of the nutrient balances that are calculated are partial balances in that they do not include all component inputs and outputs of the system. These must be interpreted with great care, such that the impacts of the component nutrient flows that are not included are not ignored completely. Even those nutrient balances that do attempt to include all component pathways must be interpreted carefully as the assumptions involved in estimating different flows can have significant impact on the results. Despite these potential weaknesses, both complete and partial nutrient balances can provide very useful information for a wide range of end-users. In most cases, decisions on the completeness of the calculated balances involves a trade-off between a more accurate assessment of a full balance, which may be very specific or very time-consuming and/or expensive, and a partial balance, which may be quicker, cheaper, and less specific, albeit with more significant caveats. A number of nutrient balance exercises, from different scales, and with different complexities, are briefly outlined as examples.

Introduction

Nutrient budgets and early developments in agriculture

Principles of assessing nutrient balance or nutrient budgets, being the comparison of inputs and outputs, have been at the heart of the development of plant nutrition and of agriculture more broadly. Many important examples of the early use of such analyses are outlined in the introductory section of "Soil Conditions and Plant Growth" (Russell, 1961). One of the earlier studies into how plants grow was the experiment of Woodward in 1699, in which he grew spearmint in different quality water. By measuring the mass of plant growth with different amounts of contaminants (Table 1) he concluded that the plants were "not formed of water, but of a certain peculiar terrestrial matter" and that the plants were "more or less augmented in proportion as the water contains a greater or lesser quantity of that matter". Hence, although not appreciating the exact nature of the "terrestrial matter", Woodward did appreciate the relationship between plant growth and inputs.

Table 1. Comparison of relative growth rates (RGR) of spearmint grown in water of different quality from the experiment of John Woodward in 1699.

Water source	RGR relative to control
Rainwater (control)	1.0
River Thames	1.5
Hyde Park conduit	2.0
Hyde Park conduit + garden mould	5.0

Another major advance in the development of the science of agriculture, which used nutrient balance approaches, were the experiments of Jean Baptiste Boussingault in the 1830s, which were the first real agricultural field experiments undertaken. In these experiments, a balance sheet was drawn up for different nutrients and plant constituents for a range of crops grown in different rotations. The uptake by the crops was compared to the input in manure and those derived from other sources, with the recognition that the relative balance affected the enrichment or depletion of the soil. These studies led to those of Liebig in the 1840s and to his conclusion that "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in nature." and, subsequently, to his "Law of the Minimum" that "by the deficiency or absence of one necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which that one constituent is indispensable".

Nutrients and agricultural expansion

Direct or indirect assessment of nutrient budgets continued at the heart of expansion in agricultural production, with movement from areas of low or reduced fertility to areas of greater fertility and, more recently, as fertilizer technologies allowed for previous limitations to be overcome. The development of early phosphorus fertilizers, based on the use of basic slag, enabled the intensification and expansion of agriculture. Subsequently, as phosphorus became non-limiting in agricultural systems in Europe and North America, the artificial N fertilizers were developed and adopted broadly. In contrast, the late 20th century intensification and expansion of food and fibre production, particularly in the developing world, was driven by the use of nitrogen fertilizers, with the subsequent mining of other nutrients, particularly K and P, to the point that their under-use has become a concern.

In between these changes in the use of fertilizers for macronutrients, improved understanding of other plant nutrients led to increased agricultural production on previously unused or under-utilized areas for which micronutrients such as copper, zinc, and molybdenum, were recognized as the primary limitations.

Increased interest in Nutrient Balance studies

The need for increased agricultural production

The rapid expansion of agricultural production in the last four decades of the 20th century managed to outpace the increase in population, with the net result that average per capita consumption of food increased. These gains resulted from a combination of factors, namely an increase in the area of land cultivated, the development of higher yielding varieties of the major staple foods, particularly wheat, rice, and maize, and increased use of irrigation, fertilizers, pesticides, and herbicides, which enabled at least some of the potential of the higher yielding varieties to be reached.

Despite these overall improvements, the average increase was insufficient and the gains were unevenly distributed throughout the developing world. The continued increase in population, particularly in the developing world and most particularly the cities of the developing world, the current number of poor, and the current level of malnourishment combine to pose a significant challenge for agricultural production in the early 21st century.

Population pressure: Using the example of the 10 ASEAN countries demonstrates easily the pressure of population growth on the demand for agricultural production. The total population approximately doubled, from 240 million to 500 million, during the 35 years from 1965 to 2000, and is expected to almost double to approximately 720 million in the 35 years to 2035 (Figure 1).

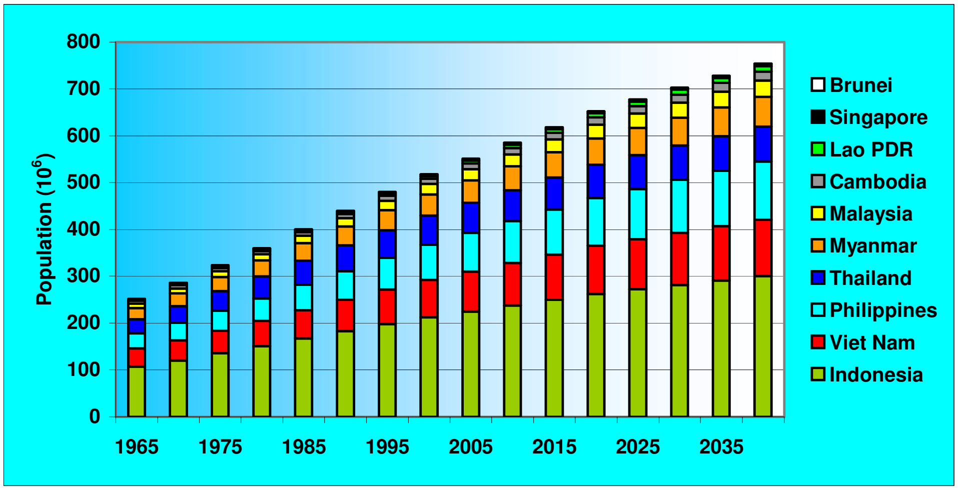

Figure 1. The change in population of 10 Southeast Asia nations for the period from 1960 to 2040 (Source: FAOSTAT)

Available land: The reserves of unutilized but potentially arable land are not distributed evenly throughout the world (Alexandratos, 1995). The majority of unused land is in just 10 countries, with the largest reserves in Brazil and the Congo. There are limited reserves in Asia, with Indonesia having the largest reserves in SE Asia. Even where agriculture can expand to unused areas, in general, the quality of the remaining land is much lower than the land in use at present. In addition, much of the current agricultural lands are being lost to degradation.

With production being the product of yield and land area, it is possible to estimate current production (current average yield x current land area) and current potential production (estimated maximum yield x estimated potential arable land) and compare these with projected production and projected potential production estimates (Penning de Vries, 2001). Average yields can be expected to increase with time, although land degradation is likely to cause a reduction in both the potential yields and the potential area of land for agriculture. Although such analyses must be interpreted with great care, such an analysis for East Asia and the Pacific, for 2000 and 2025, indicates significant potential for expansion of agricultural production, but with very limited potential for further increase, through expansion or increased yield, after 2025. These analyses differ for different regions of the world, with variations in land reserves and/or yields.

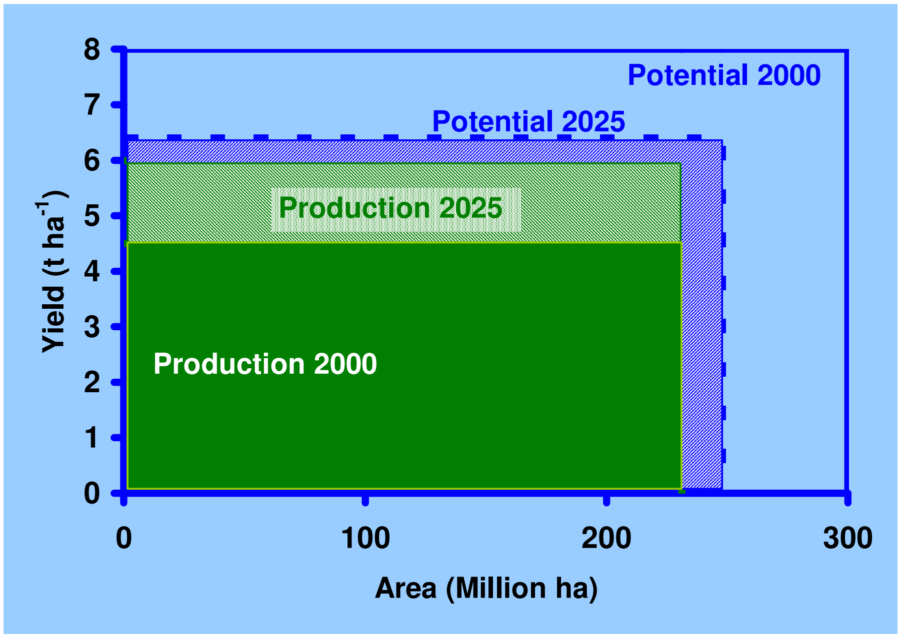

Figure 2. Agricultural production and potential production for East Asia and the Pacific in 2000 and 2025

Global fertilizer use: The recent expansion of agricultural production has been concomitant with a large increase in the use of fertilizers. In fact, the differential increase in agricultural production in different regions can be related fairly directly to the expansion in fertilizer use, which has been greatest in parts of Asia, especially China, and least in sub-Saharan Africa. Analysis of the changes in global fertilizer use shows that the vast majority of the increase has been as nitrogen fertilizer, with much lower increases, and some recent decline, in the use of potassium and phosphorus fertilizers (Figure 3).

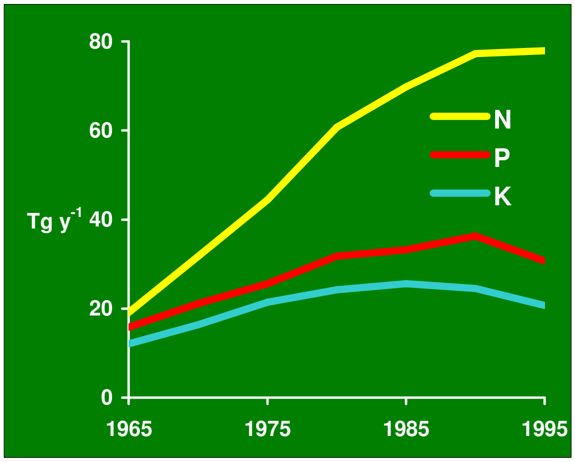

Figure 3. Global trends in the use of nitrogen, phosphorus, and potassium fertilizers (Tg y^{-1}) from 1965 to 1995

To meet the challenges of providing an adequate food supply to all regions of the world, it is clear that agricultural production must increase substantially and that land degradation must be reduced and eventually reversed. This will require much greater efficiency of resource utilization and the development of more sustainable production systems. While there are many aspects of production systems that will need to be addressed, the efficient use of nutrients is critical, which explains the greater interest in nutrient balance analysis in recent times.

Nutrient Balance Analyses

How and why

Nutrient balance analyses or nutrient budgeting can be undertaken at very different scales, with different aims, and using different methods. Clearly the scale of the analysis can vary enormously, depending on the use to which the results will be put. There are no fixed scale categories, but the main scale groups are analyses carried out at the field or farm level, at the district, province or country level, and at the regional or global level. These different scale classes are likely to have different uses in terms of the management of inputs, particularly fertilizers, and in terms of the use for management and the impact on sustainability. Such examples include the following:

Scale:	*field/farm*	*district/country*	*region/global*
Fertilizers/inputs:	*recommendations*	*distribution*	*production/trade*
Management tool:	*farm sustainability*	*infrastructure/policy*	*trade/aid*

A major interest in undertaking nutrient balance analyses is for management of fertilizers and other nutrient source inputs. At the local level, particularly at the field and farm level, such analyses can be part of the process of developing recommendations or decision support systems for the applications of inorganic and organic fertilizers. At a slightly higher level, the results of nutrient budgets can be useful in planning the geographic distribution of inputs, such as fertilizers, so that the temporal and absolute level of supply meets the likely demand. At an even higher level, such information is invaluable for developing strategies for the production and/or importation of fertilizers.

In a related, but slightly different way, nutrient balance analyses are management tools for different scales. At the field and farm level such analyses can be utilised to develop land use plans, including annual and multi-annual/perennial cropping patterns, the management of cultivation, irrigation, and fertilizers, and as part of economic analyses. At a higher level, they are a management tool for developing infrastructure (roads, storage, etc.) and government or government/private policies. At an even higher, supra-country level, they can be used for planning trade and aid policies.

Another important use for nutrient balance analyses, which follows the earlier examples of Woodward, Boussingault, and others, is the understanding of process. As such, nutrient budgeting is undertaken to increase our understanding of nutrient, carbon, and hydrologic cycles, again at different scales, with different levels of accuracy and precision, and with different aims.

The mechanics of nutrient balance analyses

Depending on scale, interest, and the capacity to make measurements or estimates, different parts of the nutrient cycles are included in different analyses. The main input and output factors that are included are listed in Tables 2 and 3, with a qualitative indication of the ease with which these characteristics can be monitored for the nutrient balance exercise and managed within the farming systems. For instance, the amount of nutrients applied in fertilizer can be both monitored accurately and managed easily. In contrast, the application of organics can be managed fairly easily, although the monitoring is slightly more difficult due to difficulties in estimating accurately the amount of material applied and the nutrient content. Other input and output factors, such as irrigation, erosion, and sedimentation can be affected by management, but are very difficult to monitor. Further, the quantity of rainfall can be measured relatively easily, but the nutrient content is measured less frequently, and there is no practical way to manage either of these characteristics.

Table 2. The main Inputs used in nutrient balance analyses and estimates of the ease with which they can be monitored and managed

Input	Characteristic	Monitor	Manage
Fertilizer	rate / source	✓✓	✓✓
Organics	residues / rate / quality	✓	✓✓
BNF	cropping system	✓	✓✓
Irrigation	quantity / concentration	?	✓
Rainfall	quantity / concentration	?	-
Sedimentation	quantity / concentration	?	✓
	Sum of inputs	?	?

✓✓ = can be monitored/managed easily; ✓= can be monitored/managed;
? = limited capacity to monitor/manage; - = cannot be monitored/ managed

Table 3. The main Outputs used in nutrient balance analyses and estimates of the ease with which they can be monitored and managed

Outputs	Characteristic	Monitor	Manage
Product	Harvest	✓	✓✓
Residues	residue recycling	✓	✓✓
Runoff	cropping system / tillage	?	✓
Erosion	mulch / groundcover	?	✓
Leaching	Irrigation	?	?
Gaseous	fertilizer/water management	?	✓
	Sum of outputs	?	?

✓✓ = can be monitored/managed easily; ✓= can be monitored/managed;
? = limited capacity to monitor/manage; - = cannot be monitored/ managed

Types of nutrient balance analyses

In addition to, and within the variations in the scale of the analyses (from field to global) and the objectives of the studies (from management, to policy, and to understanding process), there are a number of further variations in the types of analyses.

Complete or partial: The budgeting exercises can vary in their completeness both in terms of the number of nutrients included and, more importantly, in the number of input and output factors included. Considering the variation within which the various factors can be monitored and managed, as indicated in Tables 2 and 3, in some cases it is recognised that it may be more useful to undertake a more accurate partial analysis, including only the input and output factors that can be measured (and managed) with reasonable accuracy, than a less accurate estimate of all the factors. In the case of a partial budget, the interpretation needs to be done with care, in acknowledgement of the factors that have been excluded, whereas in a complete budget the interpretation needs to be done with care in acknowledgement of the different accuracies with which different factors have been measured. In many ways, a more accurate partial budget may be less at risk of misinterpretation than a complete budget in which the completeness implies an accuracy that does not exist.

Temporal aspects: Nutrient analyses can be conducted as a one-off analysis that provides a "snapshot" of the situation. In most cases, this is all that is required, however, where the aim is to understand the underlying processes a more continuous monitoring is required, so as to capture the dynamic nature of nutrient cycles.

Data sources: The information required for nutrient balance analyses can come from a mixture of sources. Clearly, the most accurate will involve direct measurements of the amounts of nutrients transferred in and out through each factor. Many of these factors can be estimated with reasonable accuracy by using a combination of observations, interviews, and secondary data. The accuracy with which such estimates can be made is closely related to the rankings in Tables 2 and 3. For instance, interviews can provided good estimates of the amounts of fertilizer applied and secondary data, rather than measurements, provide the amounts of nutrient or nutrients applied for a given weight of fertilizer. Nutrients applied in organic matter are less easy. While the amount, usually the volume, applied can be ascertained with reasonable accuracy the dry matter content and the nutrient content are less easily estimated and may require laboratory-based determination. Many farmers can provide reasonable estimates of crop yield and secondary data can be used with reasonable accuracy as default information on nutrient contents, especially if the secondary data is for similar growth conditions and varieties.

The same is not true for nutrient removal in residues as few farmers can provided good estimates of the amounts of crop residue, let alone the nutrient content, and although they are related to crop yield, the relationship is far from direct. Some of the other factors, such as inputs in biological nitrogen fixation, irrigation, rainfall, and sedimentation, and offtake or losses in runoff, erosion, leaching, and gaseous losses are both more difficult to measure and, to estimate.

Examples of nutrient balance analyses

Biogeochemical cycles

Detailed analyses of global nutrient cycles have been used in many instances to study environmental and ecological impacts of human activities. Particular examples have looked at the natural and anthropogenic cycles of nitrogen and sulphur, which have included studies at different scales, from the atmospheric, the continental, and the local, and for different ecosystems and agroecosystems (Galloway et al., 1985; Howarth et al., 1992). These and related studies on carbon cycles and emissions of greenhouse gases are central to the appreciation of global warming.

NUTMON in Sub-Saharan Africa

The NUTMON model developed in Wageningen (Smaling and Fresco, 1993) has been the basis for one of the better known series of studies on nutrient balances. In one of the earlier studies, N, P, and K balances were estimated on a country basis in Sub-Saharan African using secondary data sources (Stoorvogel and Smaling, 1990). Their analysis divided the 38 countries analysed into four main categories of annual nutrient depletion rates (Table 4).

Table 4. Categories of annual nutrient depletions (kg ha^{-1}) in Sub-Saharan Africa

	N	P	K
Average	22	2.5	15
Low	<10	<1.7	<8.3
Moderate	10 - 20	1.7 - 3.5	8.3 - 16.6
High	20 - 40	3.5 - 6.6	16.6 - 33.2
Very High	>40	>6.6	>33.2

Clearly, such national level assessments have little value for developing fertilizer recommendations, but they can assist in policy and management at the national level. Drechsel and Gyiele, (1999) re-expressed these country-level N, P, and K balances in economic terms by expressing the nutrient losses as a percentage of agricultural GDP, with an average cost in nutrient loss across the 38 countries of 7% of agricultural GDP. The NUTMON analyses have been continued for other regions, particularly Central America, and at different scales, such that within and between regional variations in nutrient balances have been compared (Stoorvogel and Smaling, 1998).

Partial Sulphur balances in Indonesia, Malaysia, and Thailand

In an analysis of the partial balance of sulphur (S) in Indonesia, Malaysia, and Thailand (Blair and Lefroy, 1987), which compared the S applied in fertilizer with that removed in crop products and residues, again based largely on secondary data sources, large differences were found in the extent of the national balances of S, from very negative in Indonesia to very positive in Thailand (Table 5).

Further analysis of the different agricultural sectors indicated that in Indonesia the industrial crops sector had a positive S balance, while the food crop sector had a very large negative balance between the S applied as fertilizer and the S removed in crop and residue (Table 6). This indicates one of the dangers of over-interpretation of country wide data.

Table 5. Partial S balances (Mg) for Indonesia, Thailand, and Malaysia in 1983

Country	Product	Residue	Fertilizer	Balance
Indonesia	79,574	53,295	85,806	-47,063
Thailand	46,761	35,350	255,000	+172,889
Malaysia	30,032	2,147	123,211	+91,032

Table 6. Partial S balances (Mg) for different agricultural sectors in Indonesia in 1983

Sector	Product	Residue	Fertilizer	Balance
Food crops	59,393	44,675	21,452	-82,616
Industrial crops	18,241	8,620	64,354	+37,493
Animals	1,940	0	0	- 1,940

While such partial analyses have to be assessed with care, because many important inputs and losses are ignored, they can only be utilized to contribute to policy developments. A workshop held in Indonesia in 1989 reviewed the status of fertilizer production, importation and use in the country, agricultural research work on sulphur nutrition, and the current fertilizer recommendations for different agricultural crops. An outcome of this workshop was the development of a relatively simple set of recommendations aimed at utilizing the same amount of sulphur fertilizer but with much greater efficiency in terms of addressing the sulphur requirements for different crops, soil types and climatic situations (Blair and Lefroy, 1990). Positive S partial balances at the district level indicated over-use of S fertilizer for major crops in much of Java, which were confirmed by soil S measurements. At the same time, there was a great deal of evidence for S deficiency on the outer islands of the Indonesian archipelago. The recommendations were to reduce the S applications in Java to the maintenance applications that were required to balance S off take and then distribute the remaining S to the outer islands. Thus, through a reasonably crude assessment of S balances without further refinement of S fertilizer recommendations to be highly site-specific, the majority of deficiencies could be overcome without increasing the importation of S.

Impact of S in rain on fertilizer requirement in Malaysia

While many of the major inputs and losses from systems are reasonably well understood, the impact of some parts of the various nutrient cycles are not so well understood. The input of S from rain is known to be important and even damaging in certain circumstances, particularly inputs from heavily industrialised areas. However, t in many agricultural systems there is relatively little appreciation of the importance of S inputs via rainfall. A relatively cheap and efficient ion-exchange collection system was developed and installed at 31 sites on peninsular Malaysia in an attempt to assess this part of the S cycle (Lefroy and Hussin, 1991). Cumulative accessions of S in rainfall in two-monthly periods were collected and an annual S accession map developed, with accessions ranging from approximately 1 to 30 kg S $ha^{-1}y^{-1}$ (Figure 4). The S accessions indicated that marine and anthropogenic inputs were the main sources and that they each exhibited different temporal and geographic variations.

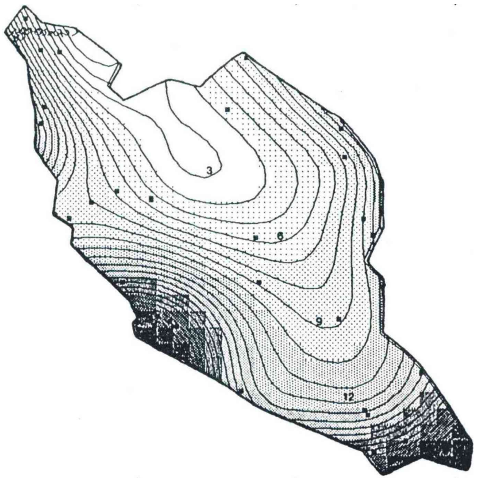

Figure 4. S accessions in rainfall for peninsular Malaysia (kg S $ha^{-1}y^{-1}$).

When S offtake for major crops (Table 7) were compared to inputs of S in rainfall, it was possible to develop basic S fertilizer recommendations that could be modified for local conditions, such as likely losses by leaching. As such, the low requirement of rubber would be met everywhere by the S in rainfall. The moderately high S requirement of coconut and tea would not be met everywhere, but would be met for coconuts in the coastal areas, but would not be met for tea in the central highlands, hence the need for S fertilizer applications for tea. The high S requirement of oil palm requires S applications in all areas, while those for cocoa, coffee, and rice are more complex, especially for rice, where the non-perennial nature and inputs from irrigation make a simple balance less easy to interpret.

Table 7 S removal (kg ha^{-1}) for different crops at average yields.

Crop	S content (kg t^{-1})	Yield (t ha^{-1})	S offtake (kg ha^{-1})
Rubber	0.15 - 0.4	1.5	0.2 - 0.6
Coffee	3.7	1	3.7
Cocoa	5.6	1	5.6
Rice	2.25	4	9
Coconut	4.5	2.5	11.25
Tea	4	3	12
Oil Palm	1.1	20	22

Complete nutrient balances as Decision Support Systems

The examples of S partial balance studies demonstrate how fertility management can benefit from improved understanding of specific parts of nutrient cycles, such as fertilizer applications, S in rainfall, etc., without attempting to measure or estimate the whole nutrient cycle. In other cases, studies of the specific components have been combined into complete balances to be used as nutrient management decision support systems. The study of Dobermann and White (1999), in which N, P, and K inputs and losses are estimated for a lowland rice system that yields between 4 and 6 t ha^{-1} of grain, is an example of such a combined study. This style of complete (or more complete) nutrient balance is the forerunner of the decision support systems that are being developed to enable more site-specific nutrient management that uses available knowledge and expert systems, rather than extensive on-site measurements.

Conclusions

The principles of nutrient budgeting have been used increasingly for a range of purposes and scales, from ecological to agricultural, from policy to research on underlying mechanisms, and from global to field level. In the agricultural realm, nutrient balances, even partial balances, can provide very useful insights and information on productivity and sustainability at different scales. Perhaps the two main areas of interest will remain at the field and farm level, for improved nutrient use, economic return and sustainability, and at the country level, for developing and monitoring policy on agricultural production and support services, such as fertilizers, principally importation, production, distribution and subsidies.

While precise and accurate measurement of all nutrient inputs and outputs can be undertaken and justified in studies of the mechanisms of nutrient dynamics, in the majority of cases the critical part of the budgeting process is to achieve an appropriate level of accuracy with minimal complexity in measurement or data gathering. Herein lie the greatest weaknesses of nutrient balance studies; either the inaccuracy of measurements or estimates of included component inputs or outputs, especially in complete balance studies, are too great, or accurate partial balances are invalidated because of the exclusion of critical parts of the nutrient cycles. The key is in the interpretation of the nutrient budgets. In some cases, a more accurate partial balance that is interpreted with appropriate caveats is more useful than a much less accurate complete balance that has relied on poor estimates of certain components. In other cases, a loss of overall accuracy in the balance, but with inclusion of all parts of the cycle, may be more useful. In the former case, the risk is that caveats will be ignored, in the latter case, the risk is that too much accuracy will be ascribed to the total balance figure. In general, it is important that nutrient balances should not be used in isolation, whether partial or complete, for policy or for farm-level fertility management recommendations.

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