Nutrient balance changes as an indicator of sustainable agriculture

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Abstract

Annual nutrient (N, P, and K) balances for Republic of Korea (ROK), Vietnam, and China for the period 1961-1998 were established using a recently-developed nutrient audit model. A current annual surplus of all three nutrients was found for ROK, with potentially serious depletion rates for K (approximately 60 kg $ha^{-1}y^{-1}$) obtained in both Vietnam and China. Year-to-year fluctuations in the annual nutrient balances were often large, indicating that 'one-off' or 'snapshot-in-time' data can give misleading information for nutrient depletion. To avoid this, time series data are required.

To assess the likely impact of nutrient depletion on nutrient status, data obtained from nutrient balances should be integrated with those for nutrient stocks. It is possible to have the same rate of nutrient depletion in two soils but a different impact on nutrient status because of differences in opening stocks. Nutrient balances and nutrient stocks should be assessed at the same scales and it is likely that the field is the largest unit at which this can be done, given that nutrient stocks in soils are site specific, and the difficulties of data acquisition, handling, and interpretation at larger scales.

Nutrient-based indicators for agricultural systems are being included into sustainability evaluation procedures; these could include nutrient balances, which are modified to take account of soil nutrient stocks. Nutrient balances, calculated at the national level are probably the most useful for providing information on trends in nutrient depletion/enrichment which can be used to formulate nutrient management strategies, including those relating to fertilizer production, importation, and use. They are unlikely to find specific application in sustainability assessment procedures.

Keywords: nutrients, nutrient balance, depletion, indicator, sustainability

Introduction

Soil degradation is a key factor affecting the sustainability of agricultural systems. It is a complex process, having physical, chemical, and biological dimensions. Of the chemical processes involved in soil degradation, nutrient depletion is one of the most important (Syers, 1997). Because soil nutrient supply is vitally important for crop production, unchecked nutrient depletion has major implications for the sustainability of agricultural systems and future world food supplies.

Quantification of the rate of nutrient depletion involves measurement and/or estimation of nutrient inputs and outputs. Much of the initial emphasis on nutrient balances was directed towards sub-Saharan Africa (SSA). The work of Stoorvogel and

Smaling (1990) and Smaling (1993) assessed the extent of soil nutrient depletion in 35 SSA countries for the year 1983 (with estimates for 2000) and showed that nutrient depletion was widespread and likely to present a serious problem for future food production.

In Asia, Mutert (1996) reported negative nutrient input/output balances for major crops and for rice alone in lower-income countries with large and growing populations and an oversupply (positive balances) in higher-income economies with relatively smaller and stagnant populations. Other studies have shown that the potassium (K) balance is in deficit in several Asian countries (Dobermann *et al.*, 1995), particularly in China (Sheldrick *et al.*, 2002b), consistent with widespread K deficiency in that country (Xie *et al.*, 1998).

Smaling *et al.* (1996) have suggested that 'nutrient budgets' (positive minus negative nutrient flows) and nutrient stocks are quantifiable indicators of agricultural sustainability and have used this information to classify agro-ecosystems. Relatedly, nutrient balances have been proposed as an indicator for assessing land quality (Pieri *et al.*, 1995).

The present paper considers nutrient balance changes for arable land plus plantation crops in Republic of Korea (ROK), Vietnam, and China. The need for time-series data to assess trends in nutrient depletion is emphasised, as is the need to relate nutrient depletion data to soil nutrient stocks. The potential for using nutrient balance changes as an indicator of the sustainability of agricultural systems is briefly discussed.

Methods

A nutrient audit model has recently been developed (Sheldrick *et al.*, 2002a) which provides nutrient balance information at the national level. It is a conceptual, mass balance model which contains coefficients for estimating nutrient outputs and inputs, and uses crop and animal production data from the FAO Internet data base (FAOSTAT, 1999). This is an important feature of the model because the FAO data are readily and freely available. The comparison between nutrient outputs and inputs is referred to as a nutrient balance. The process by which this exercise is conducted is referred to as a nutrient audit. The nutrients considered are nitrogen (N), phosphorus (P), and potassium (K) for land use involving arable and permanent crops between 1961 and 1998.

The model produces a time-series of nutrient outputs and inputs, which are used to calculate balances. When used with data obtained over a reasonable period of time, say 20 years, robust and reliable trends for nutrient depletion/enrichment are obtained.

Results and Discussion

Annual nutrient balances

The N, P, and K balances are presented for ROK, Vietnam, and China between 1961 and 1998 to illustrate the often very large differences that can occur between nutrients, between countries, over periods of time, and even from year to year.

Republic of Korea

An annual surplus of N, P, and K now exists (Figure 1) in ROK; this occurred consistently after 1984 for N, after 1988 for P, and after 1992 for K. Mutert (1996) has pointed to the oversupply of N, P, and K in ROK but has commented that this has been associated with high and sustained rice yields during the last 10 years.

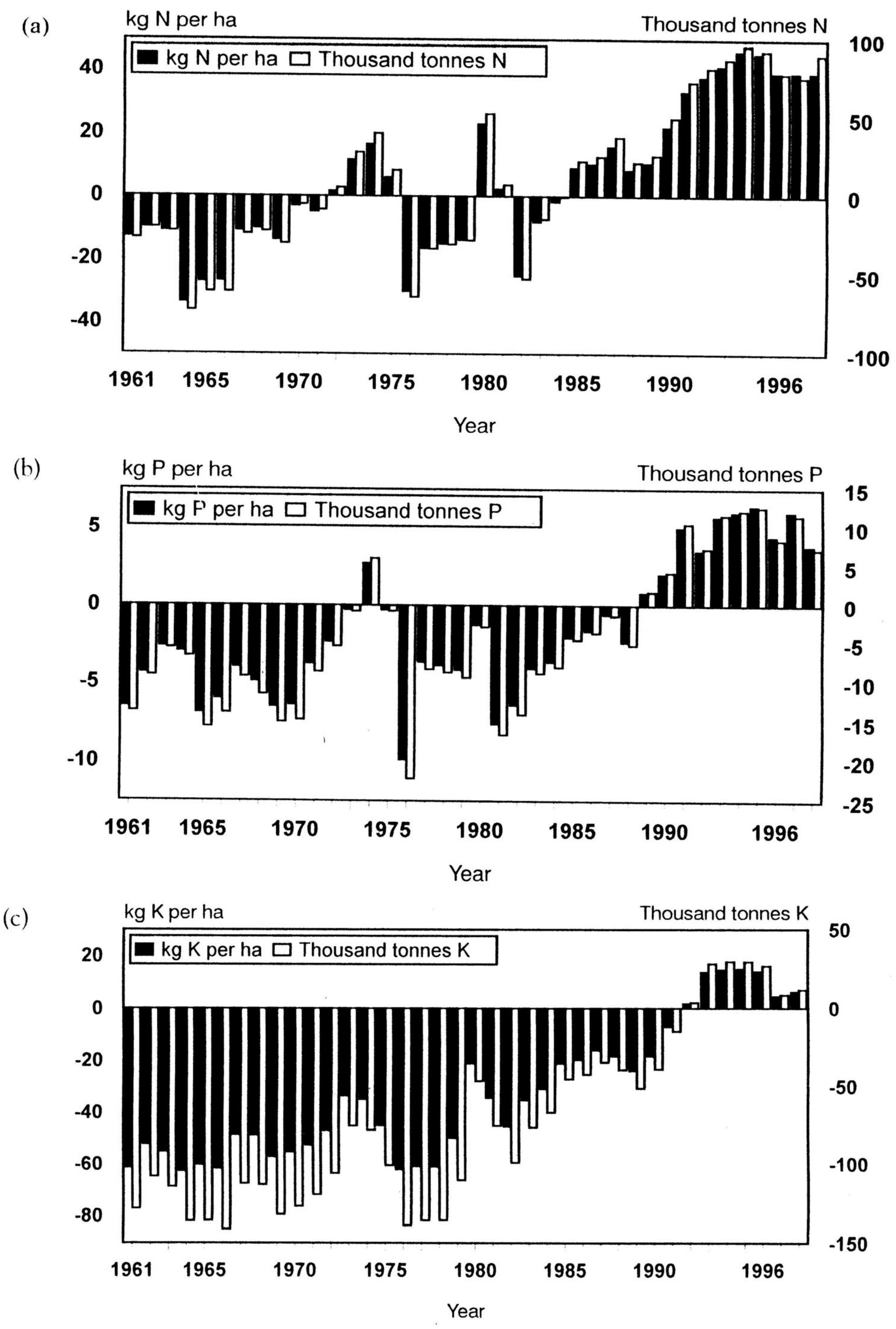

Figure 1 Nutrient balances for repubic of Korea between 1961 and 1998 for (a) nitrogen, (b) phosphorus and (c) potassium.

Agricultural production has decreased by approximately 15% in the last decade in ROK but the input of N and P has been maintained. Significantly, the amount of nutrients supplied in manure increased by some 50% during the last ten years, with major implications for water quality.

There was a serious annual K deficit of up to 85 kg ha^{-1} between 1961 and 1985. This was progressively reduced and converted to a small surplus, which since 1988 ranged from 5 to 15 kg ha^{-1} As for Japan (data not presented), but unlike most other Asian countries, ROK achieved high cereal yields by maintaining well-balanced inputs of N, P, and K, although the current high annual N surpluses of 35-40 kg ha^{-1} raise questions about the environmental sustainability of agriculture in ROK.

Vietnam

In Vietnam, the annual N balance increased gradually from a peak deficit of approximately 25 kg ha^{-1} in 1980, corresponding to a large increase in agricultural production in the late 1970's when hostilities ceased, to a surplus of approximately 25 kg ha^{-1} in 1998 (Figure 2). This was largely due to substantial imports of urea. Currently, the fertilizer N application rate is 179 kg N ha^{-1}y^{-1} the highest in the region. There was an annual surplus of N since 1994. As for N, there was a large increase in the annual P deficit in the late 1970's and this remained at a high value of around 7 kg ha^{-1} between 1980 and the mid 1990's. This has progressively been reduced (it is now 5 kg ha^{-1}) by recent imports of DAP and may be eliminated when the planned new P fertilizer plants, with a capacity of 400,000 t y^{-1} are built.

In contrast, the K balance results show a progressive and substantial increase in the annual deficit since 1968. This peaked in 1996 at a very high value of around 70 kg K ha^{-1}y^{-1} Large fertilizer K imports between 1996 and 1998 have reversed this trend but in 1998 the annual K deficit was still some 360,000 tonnes of K, corresponding to 58 kg K ha^{-1} Mutert (1996) reported results for the available K content of five soils from northern Vietnam, which showed a very large decline in values from the early 1960's to 1993, reaching a deficiency level in each case.

China

The annual N deficit in China between 1961 and 1976 varied from 20 to 30 kg ha^{-1} (Figure 3). With the rapid expansion of domestic fertilizer N production in the late 1970's and the importation of large amounts of urea, the annual deficit was gradually eliminated; since 1987 N has approximately been in balance. The annual P deficit increased progressively from around 6 to 11 kg ha^{-1} between 1961 and 1983. As the phosphoric acid industry has been developed the annual P deficit has gradually been reduced until in 1998 it was approximately 6 kg ha^{-1} It has been suggested (Sheldrick *et al.*, 2002b) that the annual P deficit will be eliminated within a few years, given current rates of production and consumption.

As for Vietnam (Figure 2), the K deficit in China has increased progressively since 1961, although it has been more consistent in China and there has been no recent reduction. The K deficit in 1998 was more than 8 million tonnes, which amounts to 62 kg ha^{-1} a figure very similar to that of the 58 kg ha^{-1} for Vietnam.

The results indicate often very large year-to-year changes in the annual nutrient balance, for example the decrease in the P balance in ROK from approximately zero in 1975 to a deficit of around 10 kg ha^{-1} in the following year. There was also a large decrease in the N balance in ROK between the same period. There were some large changes in the annual nutrient balances for Vietnam, particularly for P in the 1970's and the mid-1990's.

In contrast, the year-to-year changes for K were much less pronounced and until 1996, were remarkably small. These results point to the importance of having time-series data and the potential danger of using ‘one-off,’ ‘snapshot-in-time’ balances.

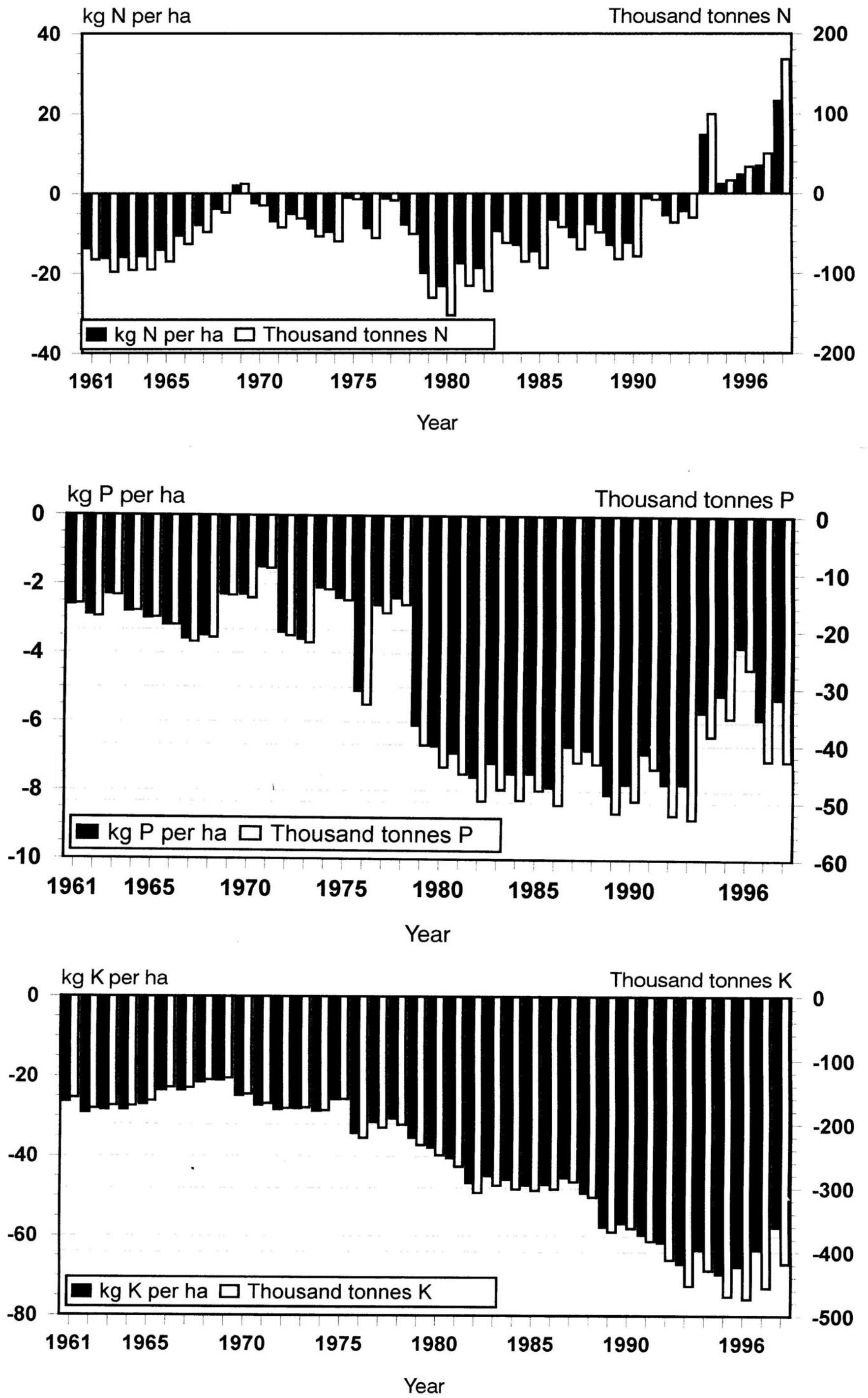

Figure 2 Nutrient balances for Vietnam between 1961 and 1998 for (a) nitrogen, (b) phosphorus and (c) potassium.

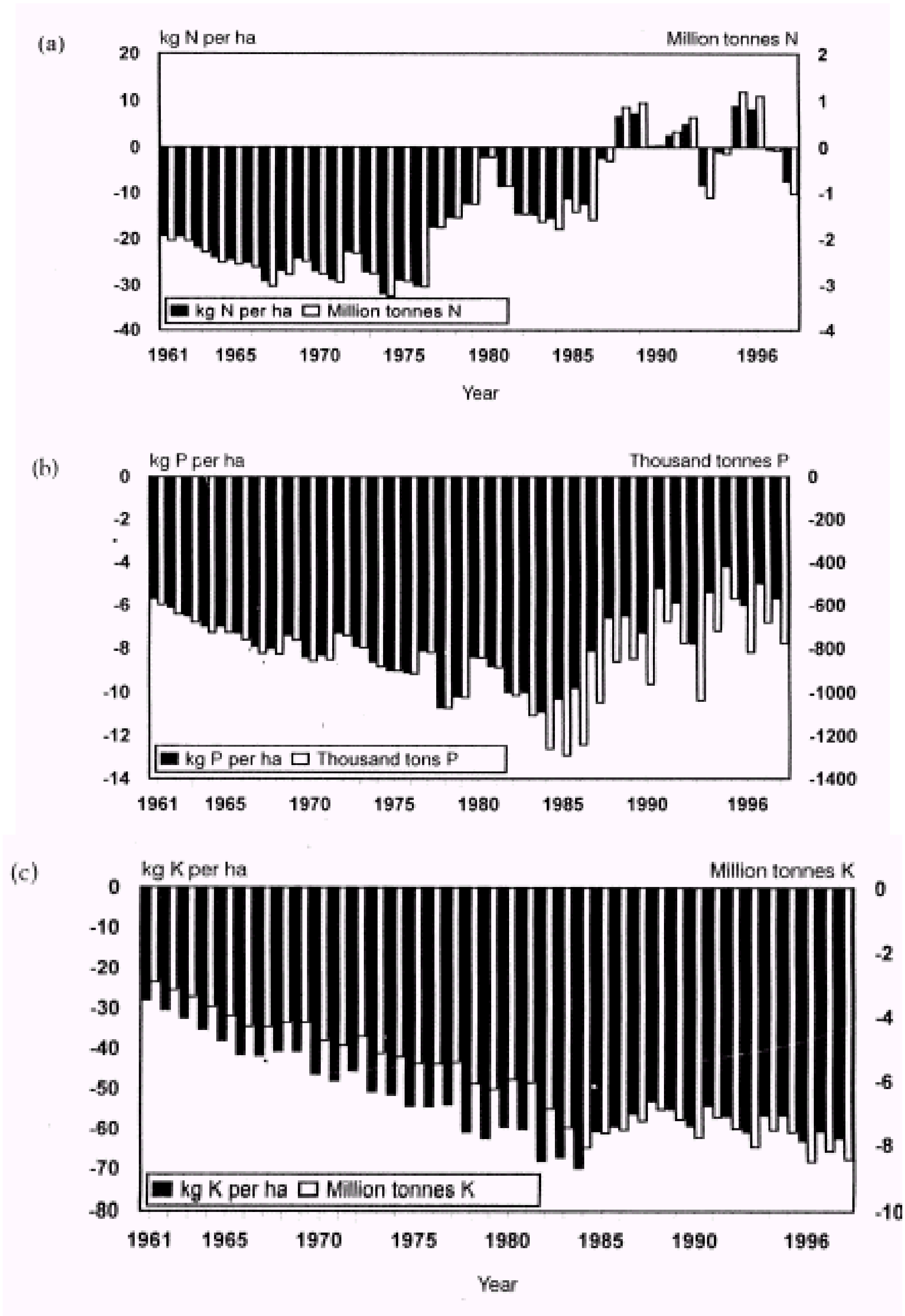

Figure 3 Nutrient balances for China between 1961 and 1998 for (a) nitrogen, (b) phosphorus and (c) potassium.

Accounting for soil nutrient stocks

In assessing the impact of nutrient depletion rate on soil nutrient status it is essential to take account of nutrient stocks. This is shown in Figure 4. The rates of nutrient depletion are the same for the two soils, because the slopes of the two lines relating soil nutrient stock with time are the same. However, soil B has a lower (but not nutrient limiting) opening stock and will become nutrient limiting over time, whereas soil A does not. In the absence of information on nutrient stocks, it is not possible to determine whether a soil will be deficient in a particular nutrient, based on depletion rate alone.

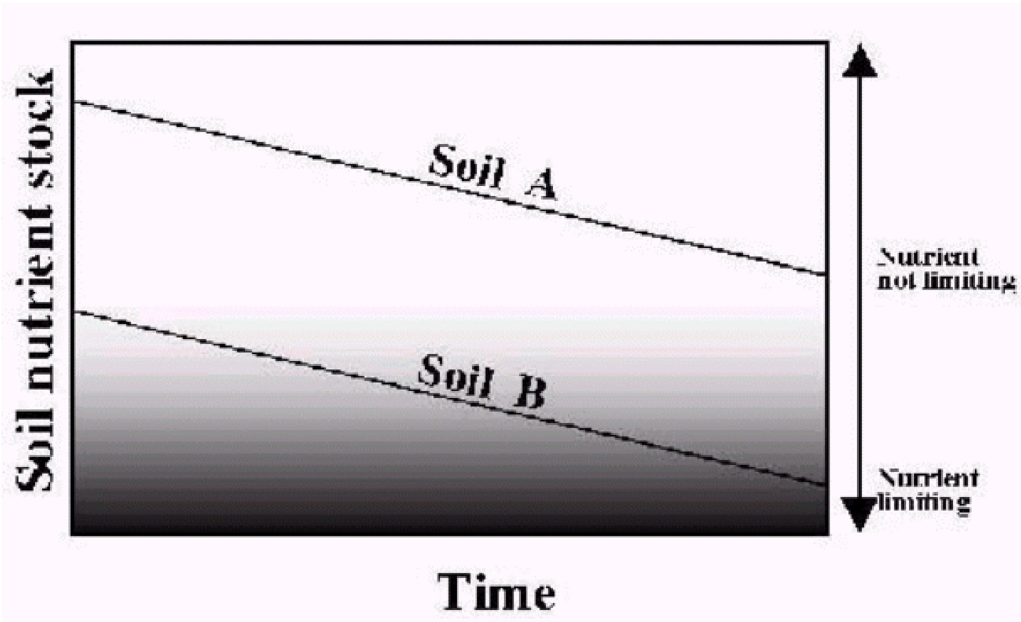

Figure 4 Effect of soil nutrient stock on nutrient limitation over time for two soils having the same depletion rate (redrawn from Stoorvogel (1998)).

Soil scientists are often reluctant to estimate soil nutrient stocks because of the complexities surrounding nutrient forms and their dynamics. In most situations and over short periods of time (say 5-10 years), the total amount of nutrient present in a soil will overestimate the nutrient stock, because the weathering of primary minerals and the mineralization of organic forms occur over a longer time. Nevertheless, an ‘upper-limit estimate’ of nutrient stock can be based on the total amount of nutrient present. At the other extreme, because initially less-readily available nutrients can become available with time, soil-testing data, used to assess the amount of plant-available nutrient in a soil, will underestimate soil nutrient reserves. Somewhere between the two estimates lies the reality.

Potassium offers the most promise for making meaningful estimates of soil stocks, partly because it does not enter into organic combination (unlike N and P), and also because its chemistry in soils is comparatively simple. However, there are still uncertainties in making the calculations.

Assuming an average total K content of 0.8% (this may be higher for weakly-weathered soils (say 1.2%) and lower for strongly-weathered soils (say 0.4%), and that the upper 50 cm depth contains 5.0 x 10^6 kg soil, then 40,000 kg ha^{-1} of total K are present. Exchangeable K is the most widely-used estimate of plant-available K in soils (Syers, 1998), with estimated amounts varying from 40 to 500 mg kg^{-1} (Barber, 1984); these give values of 200 and 2500 kg K ha^{-1}, respectively. Over time, all of this K is likely to be plant available. Taking an annual depletion rate of 60 kg K ha^{-1} as found for both Vietnam and China, all of this K would be depleted in 3 to 40 years, respectively, assuming that only exchangeable K was depleted; this is unlikely. In soils which contain weathered micaceous minerals, K can be present in a slowly-exchangeable form (often referred to as 'fixed' K) and this is an important source and sink of plant-available K (Syers, 1998). Slowly-exchangeable K in soils is not commonly determined and so there is little information on the amounts present over a wide range of soils. In some soils at Rothamsted Experimental Station (UK) the amounts of slowly-exchangeable K were more than double those of exchangeable K (Syers, 1998). Extrapolating this observation to a situation where annual K depletion is 60 kg ha^{-1}, a period of 9 to 120 years would be required to deplete all of the exchangeable plus slowly-exchangeable K. There is an urgent need to develop a better understanding of the amounts and plant availability of slowly-exchangeable K in soils. Over time, K present in the lattice structure of K-containing primary minerals can contribute to plant-available K, but this will only be important where exchangeable K and slowly-exchangeable K are present in small amounts.

Reconciling annual nutrient balances with nutrient stocks

Nutrient balances can be estimated at a range of scales, i.e., plot, field, farm, community, district, provincial, national (as here), sub-regional, regional, and global.

Nutrient stocks in soils are site specific, being determined by inherent soil properties and previous management and can not be assessed at the national level. Probably the largest unit at which nutrient stocks can be estimated, with any reliability is the field, and that assumes limited variability. The same may be the case for nutrient balances, unless generalizations and aggregations are accepted (Stoorvogel and Smaling, 1998). Establishing nutrient balances over time and accounting for nutrient stocks should be done at the same scale and this might be quite small, unless major inaccuracies are accepted.

The 'life time' of soil nutrient stocks can be estimated by dividing the nutrient stock by the annual rate of depletion. However, given the limitations of scale, such information is likely to be of academic rather than of practical interest.

Assessing sustainability

As suggested above, the loss of nutrients obtained from the nutrient balance, is unlikely to be a good indicator for assessing sustainability. A similar conclusion was reached by Stoorvogel (1998). In discussing a basis for evaluating the effect of nutrient stocks on the nutrient balance, Smaling *et al.* (1997) indicated that only the ratio of the (negative) balance of available nutrients to total nutrient stock, and not a balance based on total nutrients, could be meaningful. Jansson (1999) further considered this proposal, pointing to the need to correct for the conversion of incoming available nutrients to forms which are not immediately available and for the estimation (rather than measurement) of some of the nutrient outputs. Jansson (1999) concluded that the uncertainties are such that 'it does not make sense to use nutrient balances as a possible land quality indicator. This is consistent with the earlier suggestion of Gomez *et al.*, (1996) that the nutrient balance may be too difficult to measure directly for assessing sustainability, even at the farm level.

It appears that the most useful function of time-based, national nutrient balances is the provision of information on trends in nutrient depletion/enrichment which can inform policy makers, planners, and other stake holders in the development of strategies relating to nutrient management, particularly the production, importation, and use of fertilizers. In a broad sense this relates to agricultural sustainability but not to sustainability assessment, in the narrower sense, and the use of indicators.

Conclusions

Nutrient balances can be established at different scales. The nutrient audit model used in this study incorporates readily-accessible data from the FAO Internet data base and has produced trends for nutrient depletion/enrichment covering the period 1961-1998 for ROK, Vietnam, and China. Quite large differences were obtained between the annual budgets for N, P, and K between the three countries and over time, in some cases even between years, pointing to the need for long runs of data if reliable assessments are to be made.

Data for soil nutrient stocks are required if the impact of annual rates of nutrient depletion (from nutrient balances) on nutrient status is to be evaluated. Data for nutrient balances and nutrient stocks should be obtained at the same scale. Given the constraints on data acquisition (reliability achieved and assumptions made), handling (aggregation), and interpretation, it is suggested that the field is the largest level at which this can be done, also considering the site specificity of nutrient stock evaluation. National nutrient balances are likely to be the most useful for assisting with the development of policies and strategies relating to nutrient management, particularly those relating to fertilizers.

Except in a research context, it is unlikely that nutrient balances can be used specifically for sustainability assessment, and then only at a small scale. There are too many uncertainties and difficulties in obtaining sufficiently reliable data for their routine use.

References

Barber, S.A. 1984. Soil Nutrient Availability. A Mechanistic Approach. Wiley Interscience, New York. 398 p.

Dobermann, A., P.C. Santa Cruz, and K.G. Cassman. 1995. Potassium balances and soil potassium supplying power in intensive irrigated rice ecosystems. 24th Colloqium of the International Potash Institute, Chiang Mai, Thailand. pp.199-229.

FAOSTAT (1999). http//www.fao.org

Gomez, A.A., D.E. Swete Kelly, J.K. Syers and K.J. Coughlan. 1996. Measuring sustainability of agricultural systems at the farm level, pp. 401-410. *In* Methods of Assessing Soil Quality. Soil Science Society of America Special Publication 49, Madison, Wisconsin.

Jansson, B.H. 1999. Basics of budgets, buffers, and balances of nutrients in relation to sustainability of agroecosystems, pp. 27-56. *In* E.M.A. Smaling, O. Oenema and L.O. Fresco (eds.). Nutrient Disequilibria in Agroecosystems. CAB International, Wallingford.

Mutert, E. 1996. Plant nutrient balance in Asia and the Pacific region: facts and consequences for agricultural production. APO-FFTC Seminar on Appropriate Use of Fertilizers. pp.730-112.

Pieri, C, J. Dumanski, A. Hamblin and A Young. 1995. Land Quality Indicators. World Bank, Washington, DC. 63 p.

Sheldrick, W.F., J.K. Syers and J. Lingard. 2002a. A conceptual model for conducting nutrient audits at national, regional, and global scales. Nutrient Cycling in Agroecosystems 62:61-72.

Sheldrick, W.F., J.K. Syers and J. Lingard. 2002c. Soil nutrient audits for China to estimate nutrient balances and output/input relationships. Agriculture, Ecosystems and Environment (in press).

Smaling, E.M.A. 1993. The soil nutrient balance: an indicator of sustainable agriculture in sub-Saharan agriculture, p. 18. *In* Proceedings of the Fertilizer Society 340.

Smaling, E.M.A., L.O. Fresco and A. De Jager. 1996. Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio. 25:492-496.

Smaling, E.M.A., S.M. Nandwa and B.H. Jansson. 1997. Soil fertility in Africa is at stake, pp. 47-61. *In* Replenishing Soil Fertility in Africa. Special Publication. Soil Science Society of America, Madison.

Stoorvogel, J.J. 1998. Land quality indicators for sustainable land management: nutrient balance. http://www.ciesin.org/lw-kmn/nbguidl2/nbguidl2.htm.

Stoorvogel, J.J. and E.M.A. Smaling. 1990. Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28, Winand Staring Centre for Integrated Land Soil and Water Resources (SC-DLO), Wageningen, The Netherlands. 137 p.

Stoorvogel, J.J. and E.M.A. Smaling. 1998. Research on soil fertility decline in tropical environments: integration of spatial scales. Nutrient Cycling in Agroecosystems 50:151-158.

Syers, J.K. 1997. Managing soils for long-term productivity. Philosophical Transactions Royal Society of London(B) 352:1011-1021.

Syers, J.K. 1998. Soil and Plant Potassium in Agriculture, p. 32. *In* Proceedings of the Fertilizer Society 411.

Xie, J.C., W.Y. Xing and J.M. Zhou. 1998. Current use of and requirement for nutrients for sustainable food production in China, pp. 267-277. *In* A.E. Johnston and J.K. Syers (eds.). Nutrient Management for Sustainable Crop Production in Asia. CAB International, Wallingford.