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Assessing Soil Fertility Decline in the Tropics Using Soil Chemical Data

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Soil fertility decline is perceived to be widespread in the upland soils of the tropics, particularly in sub-Saharan Africa. Most studies have used nutrient balances to assess the degree and extent of nutrient depletion; these have created awareness but suffer methodological problems as several of the nutrient flows and stocks are not measured. This chapter focuses on the assessment of soil fertility decline using soil chemical data (pH, organic C, total N, available P, cation exchange capacity (CEC), and exchangeable cations) that are routinely collected in soil surveys or for the assessment of fertilizer recommendations. Soil fertility decline can be assessed using a set of properties from different periods at the same site or from different land-use systems with the same soils. The former is easier to interpret; the latter can be rapidly collected but differences may be due to inherent differences and not have resulted from soil management. This study provides an analytical framework for the assessment of soil fertility decline and shows pitfalls and how they should be handled. Boundary conditions are presented that could be used in future studies on soil fertility management and crop productivity in the tropics.

I. INTRODUCTION

Crops remove nutrients from the soil through the agricultural produce (food, fiber, wood) and crop residues. This may result in declining soil fertility if replenishment with inorganic fertilizers or manure is inadequate. A decline in soil fertility implies a decline in the levels of soil organic C, pH, CEC, and plant nutrients. Soil fertility decline includes nutrient depletion (larger removal than addition of nutrients), nutrient mining (large removal of nutrients and no inputs), acidification (decline in pH and/or an increase in exchangeable Al), the loss of organic matter, and an increase in toxic elements such as aluminum (Hartemink, 2003).

Several studies in the 1990s indicated that soil fertility decline is a problem in many tropical countries and, particularly, in sub-Saharan Africa (Brand and Pfund, 1998; Folmer *et al.*, 1998; Hartemink, 1997a; Henao and Baanante, 1999; Nandwa and Bekunda, 1998; Pieri, 1989; Probert, 1992; Rhodes, 1995; Stoorvogel and Smaling, 1990; van der Pol and Traore, 1993). Most of these studies were based on nutrient balances or budgets in which fluxes and pools were estimated from published data, data derived from pedotransfer functions, or some other method. The studies were conducted mostly on the country or subcontinental level. One influential study was conducted by Stoorvogel and Smaling (1990) who calculated budgets for N, P, and K for the arable soils of 38 countries in sub-Saharan Africa for the years 1983 and 2000. The nutrient inputs were less than the outputs in nearly all countries in sub-Saharan Africa.

In recent years, there has been criticism of such studies—on the way the study was conducted as well as on the extent and impact of soil fertility decline (Hartemink and van Keulen, 2005). Some researchers consider nutrient depletion to be a serious problem (Koning and Smaling, 2005; Muchena *et al.*, 2005) hindering agricultural development; others argue that the problem is exaggerated and that farmers have found ways to deal with dwindling soil fertility (Fairhead and Scoones, 2005; Mortimore and Harris, 2005; Niemeijer and Mazzucato, 2002). They see evidence in farmers' practices and yield patterns over time that do not match the widely perceived soil fertility decline.

These contradictions are in part due to lack of fundamental knowledge, differences in perceptions, differences in research methodology, and the scale of observation. In some areas, soil fertility has declined because of reduced fallow period in shifting cultivation systems and little or no inorganic fertilizer inputs. In other areas, soil fertility may have been maintained or improved at the expense of land elsewhere, that is, through biomass transfer. Where such differences are explored in more detail, there are complex explanations including non-agronomic aspects like infrastructure, access to markets, political stability, land tenure, and investments. A detailed analysis of causes and effects requires a multidisciplinary effort of which soil scientists need to be part. However, they need to be equipped with arguments and data to feed the discussion. A rigorous analysis and assessment of soil fertility decline requires solid scientific methodologies and approaches.

As mentioned, most of the discussion has been fueled by nutrient balance studies. Relatively little use has been made of soil chemical data from different periods or land-use systems, although such data are available from soil surveys, soil fertility evaluations and fertilizer programs. They may be available from long-term experiments of which there are several in tropical regions (Bekunda *et al.*, 1997; Greenland, 1994a; Laryea *et al.*, 1995; Pieri, 1995; Singh and Goma, 1995; Smyth and Cassel, 1995; Steiner and Herdt, 1993). Recent rapid assessment of soil fertility properties using spectroscopy (Shepherd and Walsh, 2002; Shepherd *et al.*, 2003) greatly increase the amount of data on tropical soils. Moreover, there is increase access to soil testing databases through the internet (Motavalli *et al.*, 2002). Although there are several techniques to derive soil properties using pedotransfer functions or soil inference systems (McBratney *et al.*, 2002; Pachepsky and Rawls, 2005), the need remains for reliable data to validate and further develop our models and increase the understanding of soil behavior and human-induced soil changes.

This chapter reviews the major aspects of using soil chemical data for the assessment of soil fertility decline in soils of the tropics. Such assessment is needed to adequately address the issue of sustainable land management for increased food production and the alleviation of hunger in many parts of the

tropics. To assess soil fertility decline, it is necessary to define the spatial and temporal boundaries of the systems under study, the data types that are available and their spatial and temporal variation, and proper soil sampling procedures and analysis to obtain meaningful results. In the final part of this paper interpretation of results including resilience and reversibility is discussed.

II. CHANGES IN SOIL CHEMICAL PROPERTIES

The total amount of a nutrient in the soil declines when the output exceeds the input over a given period of time, soil depth, and at a certain location. To ascertain whether nutrient levels, pH, or soil organic C have declined, spatial and temporal boundaries must be chosen. A spatial boundary is, for example, the plot. A temporal boundary might be the period during which the plot was cultivated. When such boundaries are properly set it is possible to conclude, for example, that the soil fertility has declined in a wheat field between 1980 and 2005. Such a simple conclusion involves various complicated steps and these are discussed later.

The soil can be considered a box from which nutrients are removed (output) and in which nutrients are entered (input). The box is the pool of nutrients (nutrient stock) whereas input and output of nutrients are fluxes or flows. This approach has been adopted in agricultural and ecological research since the seminal work of Nye and Greenland (1960). When the pool is measured over a period of time, no changes may have occurred: the soil is in a steady-state condition in which the properties are in dynamic equilibrium (Yaalon, 1971). Such a condition is exceptional and there is increasing evidence that, even under natural conditions, nutrient losses occur (Poels, 1989; Stoorvogel *et al.*, 1997). The steady-state condition does not imply that losses are absent and provides no information on the environmental impact of a land-use system.

The second possibility is that the pool has increased due to nutrient inputs exceeding nutrient outputs, or because the output of nutrients is decreased whereas the inputs remained the same, or a combination of the two. Higher inputs may also mean higher outputs but, as long as total input exceeds output, the soil fertility builds up. This has occurred in the Pleistocene sandy areas of the Netherlands, Germany, and Belgium where plaggen soils, or Anthrosols, developed through centuries of applications of a mixture of manure, sods, litter, and sand (Pape, 1970). Similar soils occur in Russia (Giani *et al.*, 2004) and several other European countries. The buildup of nutrients continues to the present day through high applications of animal manure and inorganic fertilizers to agricultural soils of several Western

European countries (de Walle and Sevenster, 1998). As a result, nutrients may be leached into surface and groundwaters potentially causing environmental problems. This is an important drive for manure legislation and precision agriculture (Neeteson *et al.*, 2002; Pierce *et al.*, 1999; Robert, 2002). There are also several examples in the tropics where soil fertility has built-up as a result of long-term applications of organic materials (Lima *et al.*, 2002; Sandor and Eash, 1995) including household waste and manure (FAO, 2001b).

The third possibility is that the pool decreases and soil fertility declines. This occurs when nutrient output exceeds input over a given period due to increasing outputs when inputs remain the same. This may occur, for example, when there is a sudden increase in the rate of erosion or leaching because of high rainfall events. Decreased inputs may also imply decreased outputs, but the net difference between nutrient input and output determines whether there is a decline in soil fertility.

A. Additions, Removals, Transformations, and Transfers

Factors affecting soil fertility decline are essentially the same as those in pedogenesis: additions, removals, transformations, and transfers. In natural ecosystems, additions of nutrients occur through atmospheric deposition, biological nitrogen fixation (BNF), and sedimentation whereas removals include leaching, gaseous losses (denitrification, volatilization), and through soil erosion. In agricultural ecosystems, nutrients are also removed with the crop yield and crop residues, whereas nutrients may be added with animal manure, inorganic fertilizers or other amendments. There are important differences in the rates of soil processes between natural and agricultural ecosystems. In agro-ecosystems there is periodic disturbance, including tillage, weeding, and the application of soil amendments, which determine the additions and removals of nutrients. Also nutrient removal through erosion and leaching is generally higher in agricultural ecosystems (Logan, 1990).

Some of the additions and removals in a nutrient balance are difficult to quantify. For example, leaching is governed by intrinsic soil properties (porosity) in relation to climate (periodic excess of rainfall over evapotranspiration), cropping systems (rooting system), and soil management (inorganic fertilizer applications, organic matter content). The fact that several interacting factors are involved explains why quantifying leaching losses is difficult (Addiscott, 1996). Denitrification is also difficult to quantify, but it is generally assumed to be low in upland soils of the humid tropics (de Klein *et al.*, 2003; Grimme and Juo, 1985). Volatilization has been studied particularly in relation to the efficiency of N fertilizers (Harrison and Webb, 2001; Raun and Johnson, 1999). Quantification of BNF has received much attention in

Table I
Additions, Removals, Transformations, and Transfer of Nutrients in Soils Under Natural and Agricultural Ecosystems

	Factors in natural ecosystems	Additional factors in agricultural ecosystems
Additions (input)	Dust, nutrients in the rainfall, symbiotic and asymbiotic N fixation, sedimentation	Inorganic fertilizers, organic manure
Removals (output)	Leaching, volatilization, denitrification, erosion	Removal of nutrients in economic produce and crop residues
Transformations	Mineral weathering, organic matter decomposition, fixation	None
Transfer	Deep uptake, clay eluviation and illuviation	None

tropical ecosystems as it is considered to be a viable way of increasing the N status of soils in the tropics (Boddey *et al.*, 1997; Giller *et al.*, 1997; Greenland, 1985).

A transformation of nutrients is a change from an organic into an inorganic form or *vice versa*. Mineral weathering releasing cations and organic matter decomposition releasing N, P, and S are transformation of nutrients. Other examples are P fixation by sesquioxides and allophane, or N immobilization due to additions of organic matter with high lignin content. These are neither a loss nor an output but a transformation into a form that is not directly available for plant growth. The transformations may imply that the nutrient is not available for crop production for long periods (>100 years).

Transfer of a nutrient refers to replacement within the soil like deep uptake by tree roots, or the eluviation of organic matter or K-rich clay minerals into deeper soil layers. Both deep uptake and eluviation are not a removal of nutrients but a transfer of nutrients to other soil layers.

Table I summarizes additions, removals, transformations, and transfer of nutrients in soils under natural and agricultural ecosystems. As mentioned, the rate and direction of these processes is different under natural ecosystems compared to agricultural ecosystems.

B. Spatial Boundaries

The boundaries of the box need to be defined before measurements are made and soil fertility changes can be assessed. If the box has unrestricted depth, deep uptake and leaching are a transfer of nutrients but gaseous

losses and runoff are outputs because nutrients depart from the box. Replenishment of nutrients can take place only through inputs, that is, animal manure, inorganic fertilizers, and biological nitrogen fixation. Deep uptake can be considered as a nutrient input only when the box has a horizontal boundary at some depth. Deep uptake is important not only in agricultural systems with a tree component but also in natural forests (Hartemink *et al.*, 1996; Lehmann *et al.*, 2004; Poszwa *et al.*, 2002).

In addition to the depth of the box, the width and length are important boundaries. If the box is large, then losses of nutrients by erosion and subsequent deposition in a lower position of the landscape are a transfer of nutrients. The same applies for nutrients transported by subsurface flow. When soil fertility changes are evaluated for an entire catchment, it may be found that nutrients in the upper part of the catchment are being lost whereas there is net gain in the lower part. The net changes within the catchment may be nil, whereas differences between the sampling sites are large.

The transfer of nutrients from one area or spatial scale to another is natural, as for example, the deposition of nutrient-rich sediments in alluvial plains and river deltas, or the Harmattan dust from West Africa which reaches Europe (Simonson, 1995). It shows that the spatial scale or boundary affects the conclusions of a soil fertility decline evaluation. There are methods available to use soil fertility data at different scales (McBratney, 1998; Stoorvogel and Smaling, 1998), but universally applicable scaling rules are to be developed.

C. Temporal Boundaries

Monitoring soil chemical properties implies that observations are made at different time steps. Soil fertility data can be compared for the different times, and it provides some information on what has happened between the two sampling periods (Hartemink, 2003). If there are only two sampling periods then no information is collected on the exact pattern of change (see Section VII). For example, in shifting cultivation systems the level of exchangeable cations may be low prior to cutting the fallow vegetation but increases when the vegetation is cleared and cations are released from the burning of the biomass (Lal, 1986; Nye and Greenland, 1960). The higher levels of exchangeable cations are usually followed by a rapid decrease due to losses and crop uptake (Sanchez *et al.*, 1983). In such dynamic systems, different conclusions are reached when measurements and observations are made at different time steps.

The soil science literature is flooded with short-term observations, by which transient phenomena can be missed or misinterpreted (Pickett, 1991).

In general, observations made over a long period allow more rigorous analysis. If, however, long-term observations also imply large time steps, it may mask what has happened during the period of observation. Therefore, the best approach is long-term monitoring with relatively short time steps (Hartemink, 2003).

Also the soil property chosen and the techniques used for its analysis affects the assessment of soil fertility decline. Changes in the microbial population occur within hours or days, whereas a significant difference change in CEC may require years of cultivation between the measurements. A related problem is that some soil parameters fluctuate during the day or between seasons and detecting changes may therefore be confounded with the natural variability (see Section IV).

III. DATA TYPES

Some soil degradation features like soil erosion and salinization can be observed and assessed by remote sensing (Cresswell *et al.*, 2004; Goossens and Van Ranst, 1998; Howari, 2003; Servenay and Prat, 2003). Such techniques cannot yet be used to adequately assess a decline in soil nutrient levels. In the literature on soil fertility decline, three different data types are used to assess soil chemical changes caused by agricultural production systems: expert knowledge, nutrient balances, and the monitoring of soil chemical properties (Hartemink, 2006). Some of these data can be collected relatively easily, whereas others require long-term commitment. Each data type has specific advantages and disadvantages; the type of data collected is determined by the research plan, and the financial conditions.

A. Expert Knowledge

Traditionally, soil science has used several qualitative measures of soil properties like soil color and field texture. Soil mapping also has qualitative aspects including the delineation of mapping units. Qualitative approaches have greatly contributed to our knowledge on soil resources and form the base for what can be called expert knowledge systems. Also farmers and other users of the land have expert knowledge about soils; this is loosely described as indigenous soil knowledge or ethnopedology (Barrios and Trejo, 2003; Krasilnikov and Tabor, 2003; Sillitoe, 1998; Warkentin, 1999; WinklerPrins and Sandor, 2003). Indigenous soil knowledge has different characteristics from knowledge gained by the scientific study of the soil.

Farmers' empirical knowledge is not soil process or data-oriented but yield or management-oriented (Bouma, 1993). Yield decline, as observed by a farmer could be caused by a variety of factors including soil fertility decline, adverse weather conditions, invasion of weeds, soil physical deterioration, or a combination of factors. Therefore, farmers' knowledge of soil fertility decline is difficult to interpret if not augmented by other types of data, like for example crop yield, weather conditions, or information on pests and diseases (Hartemink, 2003).

The annotated bibliography on ethnopedology Barrera-Bassols and Zinck (2000) lists more than 900 references and abstracts and the bibliography provides a wealth of information on how farmers perceive soil fertility. This perception is almost universally qualitative and, as mentioned, could be affected by many biophysical and management factors including the memory or political motives of the farmer. For example, in a land degradation study in Burkina, Faso Gray (1999) found that the perception of local farmers was frequently socially constructed and politically mediated. Perceptions of degradation were related to ethnic conflicts over land. Environmental development projects offered tangible benefits for farmers who perceive their resource base is degraded (Gray, 1999). In other words, it was beneficial to exaggerate the situation.

A good example of expert knowledge was the first approximation to assess and map soil degradation at a global scale—GLASOD (Oldeman *et al.*, 1991). More than 200 soil and environmental scientists worldwide were asked to give their opinion on the types, degrees, and areal coverage of human-induced soil degradation in their regions. Two categories of soil degradation were distinguished: the first relates to displacement of soil material (soil erosion by water and wind) and the second was soil deterioration *in situ* like chemical and physical degradation. GLASOD showed that loss of nutrients (i.e., soil fertility decline) was severe in Africa and South America but less a problem in the upland soils of Asia.

Expert knowledge is largely qualitative, may have political motives, and is not useful for the quantitative assessment of soil fertility decline. Nonetheless, such knowledge can be useful in selection of sampling sites or for additional information. There are examples where expert knowledge was used to investigate long-term changes in soil fertility (Peters, 2000; Sillitoe and Shiel, 1999).

B. The Nutrient Balance

Another approach to investigate changes in soil fertility is the nutrient balance approach, which in essence is an accounting procedure. Inputs

(e.g., fertilizers, manure) are compared to nutrient outputs (crop removal, leaching etc.) over a given time span that is mostly one cropping season or 1 year. Nutrient balances are a convenient and biologically meaningful way to investigate what is known about a system's biogeochemical cycles. It can give insight into the processes that regulate nutrient cycling, and nutrient balances may help to formulate system management decisions and direct the course of research (Hartemink, 2005; Robertson, 1982). In several countries, nutrient balance studies have been used in studies on food crop production and the maintenance of the soil resource base (Johnston and Syers, 1998).

Nutrient balances have been used mostly at national or supranational scale, although some studies have been conducted at the district scale (Smaling *et al.*, 1993; van der Pol and Traore, 1993) or farm scale (Shepherd *et al.*, 1996; Van den Bosch *et al.*, 1998; Wortmann and Kaizzi, 1998). In the national or supranational studies, existing soil data are combined with pedotransfer functions to estimate the decline in soil fertility at a given location (Stoorvogel and Smaling, 1990). This is a mechanistic modeling approach in which expert knowledge is also important. Such studies are not to replace soil-monitoring but to be seen as the best possible way of getting the most out of available data (Hartemink, 2003). The outcome of such studies provides qualitative, comparative, and spatial information on the difference between nutrient input and output. The maps may raise more awareness amongst the public and policy makers than facts and figures collected by soil monitoring.

1. Methodological Problems

Nutrient balance studies in tropical regions have been influential—both agronomically and politically—but there are some methodological problems (Faerge and Magid, 2004; Sheldrick *et al.*, 2002). Some of the input and output data in the supranational or national nutrient balances were easily obtained whereas others were hard to quantify or relied heavily on FAO soil and crop databases, which are not always accurate. Yield data from FAO databases were multiplied by standard nutrient uptake data of crops (Cooke, 1982). Nutrient uptake data are variable. For example, Hartemink (1995) showed that, based on 11 literature sources, nutrient removal of *Agava sisalana* varied from 27–33 kg N ha^{-1}, 5–7 kg P ha^{-1}, and 59–69 kg K ha^{-1} per ton of fiber produced. This variation may be attributed to differences in sampling techniques, sampling period, inherent soil conditions, fertilizer applications, and analytical methods. Multiplying the uptake values with the range of yields in the FAO databases gives a range in calculated nutrient removal, which is often the largest factor in nutrient balance studies.

In the absence of sufficient data, several factors were estimated using pedotransfer functions. Denitrification in the sub-Saharan Africa nutrient balance study was estimated from studies conducted in Puerto Rico (Dubey and Fox, 1974), which may not hold for the range of soils and climates in Africa. Nitrogen inputs by BNF and wet deposition were estimated from average annual rainfall whereas such inputs vary greatly between regions and seasons (Clark *et al.*, 1998; Walley *et al.*, 2001). Faerge and Magid (2004) concluded that the transfer functions in nutrient balance studies tend to overestimate losses and that no check has been made to assess whether the modeled losses are consistent to empirical measurements. In the supranational study of Stoorvogel and Smaling (1990), nutrient depletion in Gambia for the year 2000 was estimated to be −17 kg N, −3 kg P, and −24 kg K ha^{-1}. Henao and Baanante (1999), who used a similar approach to Stoorvogel and Smaling, estimated the nutrient balance for Gambia over the years 1993–1995 to be: −30 kg N, −5 kg P, and −18 kg K ha^{-1} $year^{-1}$. However, a nationwide soil fertility evaluation in 1992 and 1998 showed that available P and exchangeable K levels had actually increased in soils under the main food crops (Peters, 2000). This shows that nutrient balance studies need to be combined with field measurements for accurate assessment of soil fertility decline.

When all factors in a nutrient balance are considered and accumulated errors are calculated, the difference between the nutrient outputs and inputs may show a wide range of values. For example, if the sum of nutrient inputs is on average 150 kg ha^{-1} (range: 125–175 kg ha^{-1}) and the sum of nutrient output is on average 200 kg ha^{-1} (range: 175–225 kg ha^{-1}), the difference between the averages is −50 kg ha^{-1}. If the range of values is considered, the difference could be 0 or as large as −100 kg ha^{-1}. There are, however, no nutrient balance studies in which standard errors or the range of values of different factors are given. Moreover there may be a difference between years depending on the weather and other factors. As a result, the average annual nutrient balance may be negative, but it may largely differ between years (Sheldrick *et al.*, 2003).

An overview of sources of biases in nutrient budgets was prepared by Oenema and Heinen (1999). Possible biases in the budget could be personal (conceptual interpretation and simplification of the system and its flows), sampling biases of nutrient pools and flows, data manipulation biases through generalization, averaging, and upscaling. Biases may also be due to fraud that could occur when nutrients budgets are being used as a policy instrument to enforce a nutrient management strategy with possible economic consequences for farmers and other stakeholders.

It should be mentioned that the authors never ignored the inherent methodological problems with the nutrient balance but justified the overall simplifications because of the lack of data (Smaling, 1993).

2. Recent Efforts

Most nutrient balance studies have been at the macro level (e.g., national, supranational) or the micro level (farm). They have provided data for decision makers and farmers. They have ignored an intermediate level that is operating at the level of a province, agro-ecological zone, or agro-economic system and this level has been termed the mesolevel (FAO, 2004). Compared with earlier studies, the mesolevel approach by FAO is more quantified and used more accurately, which were not available in the early 1990s. Most of the input and output factors could be better quantified and also dynamic landscape models were used. The results, however, are not very different. For three countries (Ghana, Kenya, Mali) nutrient depletion rates were similar to those presented in the studies from the 1990s. However, linking the results with food security or poverty maps using GIS appeals to policy makers (FAO, 2004). Further quantification of the nutrient balance allows for spatially explicit assessment of soil fertility decline at a range of scales, and the well-quantified approach of this study appears to be the way ahead for future nutrient balance studies.

C. Measured Change in Soil Chemical Properties: Type I Data

Two approaches have been used to investigate changes in soil chemical properties. First, soil properties can be monitored over time at the same site, which is called chronosequential sampling (Tan, 1996) or Type I data (Sanchez *et al.*, 1985). Type I data show changes in a soil chemical property under a particular type of land-use over time. The original level is taken as the reference level to investigate the trend. It is most useful if trends are also followed under other land-use systems, for example, under cultivation, secondary regrowth, and natural forest over the same period; these data expose differences more accurately because natural forest ecosystems are not stable *per se*, especially under marginal conditions (Poels, 1987; Stoorvogel *et al.*, 1997).

Soil chemical data can be derived from stored samples that are analyzed at the same time as the newly collected soil samples, but the storage of soil samples may affect their chemical properties (Chapman *et al.*, 1997; Jones and Shannon, 1999; Slattery and Burnett, 1992). Alternatively, data from samples analyzed in the past can be compared to newly collected and analyzed soil samples provided analytical methods as well as laboratory errors are the same (see Section IV).

Type I data have been used for quantifying soil contamination by comparing soil samples collected before the intensive industrialization period with recent samples taken from the same locations (Lapenis *et al.*, 2000). Type I data are useful to assess the sustainability of land management

practices in the tropics (Greenland, 1994b), but few data sets exist because they require long-term research commitment and detailed recordings of soil management and crop husbandry practices (Hartemink, 2003).

D. Measured Change in Soil Chemical Properties: Type II Data

In the second approach to investigate changes in soil chemical properties, soils under adjacent different land-use systems are sampled at the same time. This is called biosequential sampling (Tan, 1996), Type II data (Sanchez *et al.*, 1985), or "sampling from paired sites" in the soil science literature from Australia (Bramley *et al.*, 1996; Garside *et al.*, 1997). It has also been named the "space-for-time" method (Pickett, 1991) and the "inferential method" (Ekanade, 1988).

The underlying assumption is that the soils of the cultivated and uncultivated land are the same and that differences in soil properties can be attributed to differences in land-use and management. Obviously, this is not always the case; the uncultivated soil may have been of inferior quality and therefore not planted. Also, spatial variability may be confounded with changes over time (Sanchez *et al.*, 1985). Other confounding factors are differences in clay content, soil depth, or unknown history of land-use.

In ecology, Type II data studies have often proven to be misleading as functional parameters like nutrient availability and plant–animal interactions have been conspicuously underrepresented (Pickett, 1991). When carefully taken, however, Type II soil samples can provide useful information, and this sampling strategy has been followed in many studies investigating the effects of cultivation on soils.

Table II summarizes the different data types. Each data type has its own merits and drawbacks but the most comprehensive and effective characterization of soil behavior is obtained when all three data types are available.

E. Minimum Data Sets

How much data are required and which soil attributes should be measured to assess that at a given location the soil fertility has declined? In the literature, these questions have been discussed in relation to the assessment of sustainable land management (Smyth and Dumanski, 1995) and in relation to such concepts as "soil quality" and "ecosystem health" (Doran and Parkin, 1996; Greer and Schoenau, 1997; Sposito and Zabel, 2003). Determining what data are to be included depends on the type of study and its objectives. For example, if the effects of continuous wheat on soil organic matter is to be examined, then measurements of soil organic C, light fraction, and particulate organic matter as well as mineralisable C, microbial

Table II
Data Types in Soil Fertility Decline Studies and Their Main Advantages and Disadvantages

Data type	Short description	Advantages	Disadvantages	Examples
Type I Chronosequential	Monitoring soil properties over time	Accurate, unequivocal, using existing data	Slow, contamination of monitoring sites, spatial and temporal variability, problems with soil sample storage, consistent laboratory procedures required, costly	Gray, 1999; Peters, 2000; Sobulo and Osiname, 1986
Type II Biosequential	Comparing soil properties under different land-use	Easy to obtain, rapid	Soils at sampling sites may differ, unknown land-use history of sites, spatial and temporal variability	Ayanaba *et al.*, 1976; Islam and Weil, 2000; Koutika *et al.*, 2000
Nutrient balance, nutrients budgets	Combination of existing data with pedotransfer functions or models	Using existing data, fairly rapid, indicative, appealing outcome	Several unknown or unmeasured fluxes and pools, hard to follow changes over time	Henao and Baanante, 1999; Stoorvogel and Smaling, 1990

Partly after Hartemink (2003).

biomass, and soil carbohydrates and enzymes should be included. Also bulk density and soil texture are needed. If it is to be determined whether leguminous crops enhance soil acidity, then the soil pH, buffering capacity, CEC, and exchangeable cations and soil acidity should be measured. These are, however, specific types of studies and for soil fertility decline studies the standard set of soil chemical properties suffice.

Soil organic matter is a key component of soil fertility (Chantigny, 2003; Woomer *et al.*, 1994). It is an essential soil property in soil fertility decline studies and Gregorich *et al.* (1994) considered assessment of soil organic matter as a valuable step towards identifying the overall quality of a soil. Other soil properties that should be included in a minimum data set are: soil pH (easily measured indicator) and levels of plant nutrients (total N, inorganic N, available and total P, exchangeable Ca, Mg, K). Existing data (soil surveys, soil fertility evaluation programs, long-term agronomic experiments, and reflectance spectral libraries) can be combined with newly collected data. More and more soil data are available through the internet (Motavalli *et al.*, 2002) and the number of soil studies in which existing data are used is increasing (Hartemink *et al.*, 2001). Quality verification is essential but modeling and statistical tools allow for more rigorous analysis than ever before.

IV. SOIL SAMPLING, SOIL ANALYSIS, AND ERRORS

For the monitoring of soil properties (both Types I and II data) soil chemical data are required, which are obtained by sampling and analyzing soils. Soil sampling procedures and analytical techniques have continually improved since the beginning of the twentieth century (Schuffelen, 1974; Sparks, 2003). Soil analysis is undertaken to assess the potential for a certain type of land-use, to characterize mapping units in a soil survey, and as a basis for fertilizer recommendations. Most soil analysis is undertaken for diagnosing soil constraints for agriculture. Usually the analysis is for chemical properties, and biological and physical tests are more rare (McLaughin *et al.*, 1999). An increasing number of soil chemical measurements is undertaken to assess the risk for ecological and human health and for environmental regulations (Sparks, 1996). To a lesser extent, soil chemical analysis is undertaken for building or road construction. Three sources of errors can be distinguished: (i) during the sampling and handling of the soil samples, (ii) during the laboratory analysis, and (iii) in the interpretation of the results.

A. Errors in Soil Sampling

Errors in soil sampling have been well documented and are generally greater than errors in the actual soil analysis (Cline, 1944; Tan, 1996).

A key problem is that soil volumes, not areas, are sampled. Results are nearly always expressed as units per mass and not on a volume or area base, which would require measurement of bulk density. Sampling depth should be in line with the depth of soil horizons or the rooting depth of the crop. The extent that a soil sample represents the population sampled depends upon the soil variability, the number of sampling units contributing (i.e., the number of subsamples or cores), and the method of soil sampling (Cline, 1944). The problem is that soil variation is not known until soil samples have been taken and analyzed. Much progress has been made in the quantification of soil variability and how many samples should be taken to characterize soil properties (McBratney *et al.*, 2000). Soil sampling equipment is also a potential source of error when it is difficult to clean (contamination) or take cores or slices with different volumes. Also variation in sampling techniques between individual samplers may introduce errors that could be as large as 6% (Kulmatiski and Beard, 2004).

The number of subsamples or cores is an important consideration and the minimum number to cope with soil variability differs per soil chemical property, soil type, and cropping system. Based on a review of studies in Australia, Brown (1999) suggested a minimum of 5–10 cores to characterize organic C and total N; 10–20 cores for pH and exchangeable cations; 20–30 cores for extractable P, and larger numbers when inorganic fertilizer or lime is applied (Table III).

B. Errors in Soil Handling and Storage

Soil properties may change during transport to the laboratory, but little work has been carried out on the effects of temperature, moisture, etc. on soil samples in transit from the field to the laboratory (Brown, 1999). Biological activity continues so that there can be rapid changes in soil nutrient contents.

In most cases, soils are air dried at ambient temperature and humidity in the laboratory, which affects some soil properties. Both temperature (Molloy and Lockman, 1979) and method of drying (Payne and Rechcigl, 1989) affect soil chemical properties. Tan (1996) and Landon (1991) listed the effects of air-drying based on earlier works. Air-drying will not affect total C or total N but affects NO_3–N and NH_4–N. The pH may be lowered by air-drying and is strongly altered in soils rich in S. Drying can cause changes in P-fixation, which is related to changes in Al and Fe chemistry. In soils with a low pH, P soluble in diluted acid tends to increase, whereas P levels tend to decrease in high pH soils. Potassium may be fixed or released from the fixed form during drying, but it depends on the type of clay minerals present. During drying exchangeable K tends to increase in soils low in exchangeable K, whereas more K becomes fixed in soils with moderate or high K content.

Table III
Soil Parameters, Their Variation and Number of Subsamples Required

Property	Vertical changes	Variation	Recommended number of samples	Random error (Landon, 1991)
pH	Often increases with depth. In strongly leached soils, acidity increases with depth	SD = 0.03–0.90; 80% of studies SD < 0.5	30–40 but 10–20 where site is uniform and lime never applied	0.2 units
Organic C	Highest near the surface sometimes accumulating as mat; may be high in subsoils of podzols and buried profiles	CV = 6–74%; 80% of studies CV < 15%	5–10, but larger number is required when surface organic matter varies	5%
Total N	Closely associated with organic C	CV = 1–85%; 80% of studies CV < 20%	As for organic C	5%
Extractable P	Almost always concentrated in the topsoil, or where fertilizer P applied in bands or drill rows	CV = 8–126%; 80% of studies CV < 90%	30–40, or 50–60 where fertilizer recently spread or banded or in paddocks with high stocking rates	10%
Exchangeable cations	Generally increases when clay content increases or where organic matter is high	CV = 3–224%; 80% of studies CV < 70%	30–40, or 10–20 where site is uniform and no amendments are applied	5%

Modified from Brown (1999) and Landon (1991).

Storage of soil samples is needed for Type I data when samples taken in the past are reanalyzed and compared to newly collected soil samples. Except for air-dried soils, samples may also be stored refrigerated but this cannot be recommended for long-term storage because of possible shifts in microbial community and the potential development of anaerobic conditions. Freezing at temperatures below −20 °C can be suitable for long-term storage, given that microbial activity is effectively minimized, although it has some drawbacks. Freezing promotes desiccation, lyses microbial cells and disrupts soil organic matter structure, and it may alter exchangeable ammonium and soluble P concentrations. Typically there is a flush of biological activity in thawed soils due to the decomposition of soil microbial cells lysed by the freezing (Boone *et al.*, 1999).

Air-dried soil samples, which are not kept in airtight containers, may absorb NH_3, SO_3, or SO_2 gases and, therefore, the container should be made of materials that will not contaminate the soil samples (Tan, 1996). Even in airtight containers soil changes occur during prolonged storage. An important change that may occur in stored soil samples is an increase in surface acidity and increased solubility and oxidizability of soil organic matter (Bartlett and James, 1980). Research on Australian soils, however, showed that the pH (in water) of soils that were stored for 7 years was 0.55 units higher; there was no relationship between soil type and pH change due to storage of soils (Slattery and Burnett, 1992). Overall, the effects of soil storage are important for the long-term study of soil changes, but available literature on this subject is limited. There seems to be no storage condition that is perfect and the absence of a storage effect on soil properties should be checked rather than assumed (Boone *et al.*, 1999). However, in reports on long-term agricultural and ecological studies storage methods and conditions of soil samples are seldom reported.

Storage is not relevant for soil samples that were analyzed in the past and which plots were resampled. For such samples, however, it is necessary that the analytical laboratory has a consistent, systematic error (Kempthorne and Allmars, 1986), which means that it should not change over time and the error should be quantified. With analytical apparatus and personnel changes, it may be difficult to keep the error constant in a soil laboratory (Kulmatiski and Beard, 2004).

C. Errors in Soil Analysis

Most soil tests have been calibrated for topsoil properties. After a series of pot trials and field trials, the quantity of nutrients measured by soil tests can be expressed in terms of deficient, adequate, or toxic for the crop considered. The quantity of nutrients extracted from the soil differs from

that accumulated by the crop. Variation in soils and soil properties versus consistency of analytical methods has been a matter of concern since the beginning of the twentieth century. International soil classification systems (FAO-Unesco, WRB, Soil Taxonomy) require that soils are analyzed by standard methods in order to compare results from different parts of the globe. This implies that some soil data are almost meaningless, like for example the CEC determined by NH_4OAc at pH 7.0 in highly weathered soils. In such very acid soils there may be a considerable portion of pH dependent charge, which results in a gross overestimation of the CEC.

The selection of an inappropriate analytical method could be termed a fundamental error and it is generally perceived that selecting the right procedure is more difficult than performing the actual analysis (Tan, 1996). Most errors arise from the fact that soil variation is insufficiently dealt with, but errors could also be made in the actual analysis. In the past decades, several international programs have been developed to check laboratory errors through exchange of soil and plant samples (e.g., LABEX, WEPAL), which has improved the accuracy of many soil analytical laboratories. There are also several handbooks on soil analytical techniques (Rayment and Higginson, 1992; Sparks, 1996; Van Ranst *et al.*, 1999), and guidelines have been developed for quality management in soil laboratories (van Reeuwijk, 1998). Although the standard set of soil testing procedures is widely used, a range of new analytical techniques have emerged that allow for rapid and accurate characterization of soil chemical properties (Sparks, 2001).

D. Soil Variation

Soil varies in space (between two points) and in time (between two sampling times at the same site) and across a range of scales for both space and time. Variation in soil properties between two sampling points or sampling times can be enhanced by cultivation. Soil fertility research has dealt with variation by taking a sufficiently large number of soil samples in order to differentiate treatment effects from random variance.

1. Variation by Soil Chemical Property

Variation in soil chemical properties is affected by a range of factors including the parent material from which the soil is derived, microrelief and climate, soil fauna, litter inputs, and the effects of individual plants. In agricultural systems amendments, tillage, cropping sequences, animal dung, and manure as well as artificial drainage and irrigation cause soil variation.

The degree of variation differs per soil chemical property and some properties vary more than others, both in time and space. Table III summarizes the analysis of 44 studies on soil variation in Australia (Brown, 1999) supplemented with some general information from Landon (1991).

The data from Brown (1999) were from a large number of studies with a variety of sampling methodologies and agro-ecological conditions, which explains the large variation. Moreover, there were banded applications of inorganic fertilizers. The errors quoted by Landon (1991) show that 5–10% is common for the major soil chemical properties, but these errors cannot be directly linked to the standard deviations and coefficients of variation found by Brown (1999).

Soil chemical properties may vary from year to year, between seasons in a year, or even between days depending on weather conditions and management factors. Several studies have been carried out in an attempt to find seasonal or climatic patterns in this variation, but many studies have failed because insufficient attention was given to spatial variation or laboratory variation. In soil science, spatial variation has been given more attention than temporal variation. Fewer data sets are available to study temporal variation possibly because observations over a period of time may be affected by weather, management, and unknown factors. It has been suggested that seasonal variation on some soil properties may mask differences due to soil management. Therefore, characterization of some soil chemical properties requires more than one soil sample per year (Brown, 1999), but for most standard soil chemical properties (pH, organic C, total N, etc.) short-term temporal variation is relatively small.

The number of soil samples to characterize a soil chemical property is site-specific and affected by land-use. Prasolova *et al.* (2000) used a spatial analysis of soil chemical properties to calculate the number of samples required in two araucaria plantations (Table IV). The calculations were based on experimental estimates of the mean differences between the means for sampling dates and variance estimates of the soil properties. The

Table IV
Sample Size Required for Estimation of the pH, Organic C, Total N, and CEC at Different Levels of Error at Two Sites Under *Araucaria cunninghamii* Plantations in Subtropical Australia

	Site 1				Site 2			
	pH	Organic C	Total N	CEC	pH	Organic C	Total N	CEC
10% error	5	29	32	19	7	35	66	15
20% error	3	9	10	7	4	11	19	6

Modified from Prasolova *et al.* (2000).

results demonstrated that there were considerable differences between the two sites in the number of samples required.

2. Variation Due to Cultivation

Natural soil variability is affected by cultivation and the cropping system. Some grain crops are sown by broadcasting over the field and usually no row effects exist, that is, localized nutrient extraction or addition. Tropical crops like maize, sugarcane, or oil palm are grown in rows, which determines the rooting pattern and extraction of water and nutrients (Hartemink, 1998c). This is further influenced by soil management like the application of inorganic fertilizers in rings around trees (oil palm), which induces spatial variability (Tinker, 1960). Soil variation under oil palm is illustrated in Table V, which depicts the pH and exchangeable K values of a Typic Paleudult in an oil palm field in Malaysia (Kee *et al.*, 1995). The oil palm was fertilized with 210 kg N and 520 kg K ha^{-1} $year^{-1}$ in the form of ammonium chloride and muriate of potash, respectively. The fertilizers were applied in a ring around the palm, which caused significant acidification and an increase in the levels of exchangeable K as compared to the interrow (between two rows of palms) and frond piles (area where pruned oil palm leaves are piled up).

Field scale heterogeneity may be created when crop residues are piled up and burned creating "hot spots" or concentrations of soil fertility. Soil sampling should thus consider the spatial arrangement of the crops that might have created field scale heterogeneity in soil properties. Although the cultivation-induced variation can be taken into account when the crops are still growing, it is difficult to consider such variation when the previous crop has been slashed and a new crop is planted. For example, when oil palm fields are replanted, the hotspots created by the inorganic fertilizer applications (Table V) still affect the soil sampling results. Also old tree rooting

Table V
Field Scale Heterogeneity in pH and Exchangeable K ($n = 4$) in a 20-Year Old Oil Palm Plantation in Malaysia

Sampling depth (m)	pH (1:2.5 w/v)			Exchangeable K ($mmol_c$ kg^{-1})		
	Palm circles	Interrows	Frond piles	Palm circles	Interrows	Frond piles
0–0.15	3.4	4.4	4.3	8.4	3.1	2.9
0.15–0.30	3.5	4.2	4.4	8.8	2.8	3.4
0.30–0.45	3.5	4.1	4.2	8.5	2.3	3.1

Only circles around the palm received N and K fertilizer. Modified from Kee *et al.* (1995).

Table VI
Soil Fertility Status Under Sugarcane (Within and Interrow)

	Sampling depth (m)	Sugarcane within rows	Sugarcane interrows
pH (1:5, water)	0–0.15	6.1 ± 0.3	6.2 ± 0.4
	0.15–0.30	6.4 ± 0.2	6.6 ± 0.2
Organic C (g kg^{-1})	0–0.15	34.1 ± 3.6	32.0 ± 2.4
	0.15–0.30	29.0 ± 2.8	22.0 ± 7.4
Total N (g kg^{-1})	0–0.15	2.3 ± 1.6	1.8 ± 0.3
	0.15–0.30	1.4 ± 0.2	1.2 ± 0.5
Available P (mg kg^{-1})	0–0.15	22 ± 10	22 ± 11
	0.15–0.30	17 ± 10	11 ± 7
Exchangeable Ca ($mmol_c$ kg^{-1})	0–0.15	278 ± 73	280 ± 49
	0.15–0.30	280 ± 61	249 ± 74
Exchangeable Mg ($mmol_c$ kg^{-1})	0–0.15	104 ± 16	91 ± 12
	0.15–0.30	104 ± 19	93 ± 26
Exchangeable K ($mmol_c$ kg^{-1})	0–0.15	10.8 ± 4.9	10.3 ± 5.5
	0.15–0.30	6.4 ± 5.8	4.1 ± 1.8

Values are the arithmetic mean of five samples ± 1 SD. Modified from Hartemink (1998b).

patterns affect the results of soil sampling replanted fields (Dockersmith *et al.*, 1999).

As mentioned, crops grown in rows cause localized nutrient removal and create soil heterogeneity. Table VI shows soil chemical data from a sugarcane field whereby samples were take in between the plants (in the rows) and between the rows (Hartemink, 1998b). Soil chemical properties differ between and within the rows, and to a large extent this was due to differences in rootability and soil physical factors.

V. SOIL CHEMICAL CHANGES AND NUTRIENT REMOVAL

In agro-ecosystems most nutrient output takes place by the crop removal. Different crops remove different quantities of nutrients in different ratios. Nutrient removal data by the crop are sometimes the only quantified nutrient output in nutrient balance studies.

A. Annual and Perennial Crops

There is a wide range in nutrient removal for annual crops (Table VII) and this is related to differences in cultivars, time of sampling, and agro-ecologies, which affect yield and thus nutrient removal. Variation is also the

Table VII
Nutrient Removal (kg ha^{-1}) by Annual Crops

Crop	Yield (kg ha^{-1})	Nutrients in kg ha^{-1}					Reference
		N	P	K	Ca	Mg	
Maize (grain)	1000	18–77	2.2–9.7	8–72	5–14	3.3–10.7	(Boxman and Janssen, 1990)
	1100	17	3	3	0.2	1	(Cooke, 1982)
	2500	40	9	33	7.5	5.0	(Sanchez, 1976)
	12,500	298	55	247	nd	nd	(IPI, 1995)
Cassava	8000	30	10	50	20	10	(Sanchez, 1976)
	11,000	25	3	65	6	nd	(Cooke, 1982)
	45,000	202	32	286	nd	nd	(IPI, 1995)
Yam	11,000	38	3	39	0.7	nd	(Cooke, 1982)
Sweet potato	16,500	72	8	88	nd	nd	(Sanchez, 1976)
	34,500	175	34	290	nd	nd	(IPI, 1995)
Groundnut	800	30	2.2	5	1	1	(Cooke, 1982)
	1000	51–62	2.8–3.5	7–17	12–19	4.0–6.7	(Boxman and Janssen, 1990)
Soybean	1000	49	7.2	21	nd	nd	(Sanchez, 1976)
	1000	79–97	6.4–7.8	46–60	nd	4.7–5.4	(Boxman and Janssen, 1990)
	3400	210	22	60	nd	nd	(Cooke, 1982)

nd, no data.

result of different crop parts that are measured. In the literature, it is not always indicated what was included in the measurements, and husks and cobs are sometimes included whereas in other studies the nutrients in these plant parts were excluded. Also nutrients in belowground biomass other than harvested parts are seldom reported.

Nutrient removal data for some perennial crops are given in Table VIII. There are several woody perennials that are heavy K-consumers (oil palm, coffee) whereas other crops remove mostly N. Bananas, sugarcane, and sisal are also heavy K-consumers. Nutrients in the yield of perennial crops are a fraction of the nutrients immobilized in the above- and belowground biomass, as was shown for cocoa (Hartemink, 2005).

Nutrient accumulation in the belowground biomass should be considered as a transformation of nutrients—not as a loss. This applies to both annual and perennial crops although the time scale is different. At the end of a crop cycle in a perennial crop system, the trees are slashed and burned or left to decompose. The nutrients in the above- and belowground biomass are returned to the soil. During the crop cycle the nutrients have been withdrawn from the soil solution. The withdrawal is only temporary, that is, 10 years for sisal, 20–30 years for oil palm or other perennial crops grown in the tropics. Some of the nutrients taken up are recycled during the crop cycle,

Table VIII
Nutrient Removal (kg ha^{-1}) by Perennial Crops

Type	Crop	Yield (kg ha^{-1})	Nutrients in kg ha^{-1} N	P	K	Ca	Mg	Reference
Woody perennial crops	Oil palm	2500 (oil)	162	30	217	36	38	(Cooke, 1982)
		15,000	90	8.8	112	28	nd	(Sanchez, 1976)
		24,600	193	36	249	nd	nd	(IPI, 1995)
	Rubber	1100	7	1	4	nd	nd	(Cooke, 1982)
	Cocoa	500	10	2.2	5	1	1	(Sanchez, 1976)
		1000	19.3	4.6	10.9	1.3	3.4	(Heuveldop *et al.*, 1988)
		1200	24	4	36	nd	nd	(Cooke, 1982)
	Coffee	2000	253	19	232	nd	nd	(IPI, 1995)
	Tea	600	31	2.3	15	2	nd	(Sanchez, 1976)
		1300	60	5	30	6	3	(Cooke, 1982)
	Coconut	1400	62	17	56	6	12	(Cooke, 1982)
Herbaceous perennial crops	Sugarcane	88,000	45	25	121	nd	nd	(Cooke, 1982)
	Bananas	45,000	78	22	224	nd	nd	(Cooke, 1982)
		30,000	85	10	226	72	90	(Sanchez, 1976)
	Pineapple	12,500	9	2.3	29	3	nd	(Sanchez, 1976)

nd, no data.

like litterfall and throughfall, which can be very high (particularly for K) in tree crop systems (Parker, 1983).

Overall, the concept of nutrient uptake, removal, and recycling is no different in perennial crop systems but important differences are the time scale or the length of the crop cycle and the much greater biomass in perennial crops.

B. Nutrients in the Roots and Crop Residues

In most field crop studies, root biomass production and nutrient removal by the roots receive little attention. The reasons are obvious: the root system is hidden from direct observation and the quantification of roots is tedious and difficult because of problems in extracting roots from the soil. It is also complex because of the spatial and temporal variability of roots in the soil matrix. Despite these problems various destructive and nondestructive methods have been developed to study roots of field crops (Taylor *et al.*, 1991) in addition to sampling schemes for their quantification (van Noordwijk *et al.*, 1985). Much of the research on roots is conducted in the temperate regions and information on root biomass and its nutrient content in tropical crops is limited, with the exception of agroforestry research (Govindarajan *et al.*, 1996; Jama *et al.*, 1998; Suprayogo *et al.*, 2002).

Table IX
Nutrient Uptake (kg ha^{-1} ± 1 SD) of Sweet Potato at Two Sites in the Humid Lowlands of Papua New Guinea

Site	Plant part	Fresh yield (Mg ha^{-1})	Nutrients in kg ha^{-1}				
			N	P	K	Ca	Mg
Hobu	Marketable tubers	18.2 ± 3.7	30 ± 6	12 ± 2	93 ± 20	5 ± 1	5 ± 1
	Nonmarketable tubers	4.0 ± 1.0	8 ± 2	3 ± 1	25 ± 6	1 ± 0.5	1 ± 0.5
	Vines	26.2 ± 4.8	80 ± 8	18 ± 2	180 ± 30	61 ± 13	20 ± 2
	Total		118 ± 10	33 ± 3	298 ± 46	67 ± 12	26 ± 2
Unitech	Marketable tubers	9.0 ± 3.8	15 ± 17	7 ± 3	39 ± 19	4 ± 2	2 ± 1
	Nonmarketable tubers	2.9 ± 1.3	5 ± 5	2 ± 1	12 ± 5	1 ± 0.5	1 ± 0.5
	Vines	30.1 ± 8.2	590 ± 21	22 ± 2	189 ± 15	37 ± 8	10 ± 2
	Total		79 ± 40	31 ± 5	241 ± 23	42 ± 10	13 ± 3

Hobu soils were classified as Typic Eutropepts and the soils at Unitech were Typic Tropofluvents (Hartemink *et al.*, 2000).

In annual crops only part of the total amount of nutrients taken up is removed by the economic produce viz. the grain of wheat, the tubers of sweet potato, or the seeds of soybean. An important portion of the nutrients taken up may be returned to the soil with the cropping residues. Table IX gives the total nutrient uptake of sweet potato tubers and vines (= above-ground biomass); less than one-third is found in the marketable tubers (= economic produce). Farmers only remove the tubers from the field and the vines remain behind as crop residues. As vines decompose, nutrients become available for the subsequent crop. Less than 25% of the total N and K uptake was found in the economic produce. It is generally recognized that crop residues are extremely important for recycling of nutrients in many cropping systems in the tropics (Giller *et al.*, 1997; Kumar and Goh, 2000).

VI. PRESENTATIONS OF RESULTS

For Type I data (monitoring soil properties over time) it is essential that the methods of soil analysis have not changed, that is, comparing soil organic C determined by the Walkley & Black method in 1970 to values obtained from the same field using a dry-combustion analyzer in the year 2000 is less than ideal. Provided analytical methods are unchanged, simple *t*-tests or analyses of variance can be used to detect statistically significant differences. An example of Type I data are given in Table X, whereas Type II

Table X
Topsoil Chemical Properties of Fluvents and Vertisols Between 1979 and 1996 (Arithmetic Mean ± 1 SD) of a Sugarcane Plantation in Papua New Guinea

	Year	Number of samples	pH 1:2.5, water	Organic C (g kg^{-1})	Available P (mg kg^{-1})	CEC pH 7 ($mmol_c$ kg^{-1})	Exchangeable cations ($mmol_c$ kg^{-1})			Base saturation (%)
							Ca	Mg	K	
Fluvents	1979	15	6.5 ± 0.4	58 ± 15	nd	389 ± 43	228 ± 78	93 ± 41	13.0 ± 5.0	79 ± 17
	1982	14	6.2 ± 0.1	nd	36 ± 4	459 ± 55	275 ± 35	113 ± 24	12.9 ± 2.0	87 ± 2
	1983	44	6.3 ± 0.1	nd	37 ± 10	435 ± 48	256 ± 35	100 ± 16	12.4 ± 2.8	85 ± 3
	1984	9	6.1 ± 0.1	nd	42 ± 10	437 ± 52	266 ± 45	102 ± 21	12.9 ± 3.8	87 ± 4
	1994	12	5.9 ± 0.1	35 ± 6	28 ± 9	384 ± 65	232 ± 47	101 ± 22	10.8 ± 2.3	90 ± 5
	1996	8	5.8 ± 0.2	31 ± 7	28 ± 12	374 ± 33	220 ± 30	99 ± 13	8.0 ± 2.0	88 ± 8
Vertisols	1979	6	6.6 ± 0.1	52 ± 9	nd	421 ± 21	293 ± 69	123 ± 39	15.5 ± 2.7	93 ± 17
	1982	17	6.2 ± 0.1	nd	43 ± 5	490 ± 29	286 ± 22	131 ± 16	16.1 ± 2.9	89 ± 2
	1983	40	6.3 ± 0.2	nd	40 ± 13	477 ± 94	290 ± 83	114 ± 33	12.9 ± 2.3	87 ± 9
	1986	7	6.2 ± 0.2	nd	37 ± 18	490 ± 108	307 ± 77	112 ± 37	12.3 ± 5.6	88 ± 3
	1994	12	5.9 ± 0.1	32 ± 3	32 ± 11	452 ± 79	273 ± 50	129 ± 34	13.4 ± 3.9	92 ± 5
	1996	12	5.8 ± 0.2	32 ± 6	28 ± 11	421 ± 102	276 ± 73	115 ± 38	9.0 ± 3.0	92 ± 8

nd, no data.
Type I data modified from Hartemink (1998c).

Table XI
Soil Analytical Data of Under Bush Vegetation and Permanent Cropping in Northeast Tanzania

	Oxisols		Ultisols		Psamments		Inceptisols on limestone	
Land-use system[a]	Bush vegetation	Permanent cropping	Bush vegetation	Permanent cropping	Bush vegetation	Permanent cropping	Bush vegetation	Permanent cropping
pH 1:2.5, water	6.2	5.2	6.1	4.6	6.3	5.3	7.5	7.4
Organic C (g kg^{-1})	21	17	15	11	7	7	19	34
Available P (mg kg^{-1})	3	3	3	<0.5	3	2	9	4
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	125	88	157	110	98	60	310	310
Exchangeable Ca ($mmol_c$ kg^{-1})	68	13	38	11	27	12	161	140
Exchangeable Mg ($mmol_c$ kg^{-1})	26	5	23	5	14	4	70	36
Exchangeable K ($mmol_c$ kg^{-1})	5	1	5	3	3	2	3	1
Base saturation (%)	80	21	45	24	47	28	76	58
Exchangeable Al ($mmol_c$ kg^{-1})	0	9	0	nd	0	0	0	0
Al saturation (% ECEC[b])	0	32	0	–	0	0	0	0

Type II data modified from Hartemink (1997b).
[a]Sampled sites were within 100 m distance.
[b]Aluminium saturation of the ECEC is calculated as: (Al/Ca + Mg + K + Na + H + Al) * 100.
nd, no data.

data are given in Table XI. Both these comparisons allow for conclusions on the effects of continuous cultivation on soil chemical properties (Hartemink, 2003). There are other methods to use soil chemical data to assess soil fertility decline including calculations on the rates of change and using paired sequential samples—these methods are discussed in a later section.

A. Rates of Change

For each soil chemical property (χ) measured over a given time span (t), the following can be calculated:

the absolute difference: $\chi_1-\chi_2$,
the change per year: $(\chi_1-\chi_2)/(t_1-t_2)$,
and the rates of change in soil chemical properties: $[(\chi_1-\chi_2)/\chi_1]/(t_1-t_2) \times 100$,

which gives the change in percentage per year of the initial level t_1.

Very few studies have been conducted in which rates of change in soil chemical properties were calculated. Calculating the rate of change in percentage per year using two data points assumes a linear change in a soil property. However, many soil chemical processes are nonlinear and the rate of change therefore differs at different periods (Jenny, 1980). For example, an average decline in organic C at a rate of -0.3 g kg^{-1} year^{-1} observed between 1980 and 2000 may have been -0.8 g C kg^{-1} year^{-1} in the 1980s, but less than -0.2 g C kg^{-1} year^{-1} in the 1990s. This is further discussed in Section VII.

A different method is to assume that loss of a nutrient, χ, is a first order kinetic process that can be fitted to single exponential model. The first order process is:

$$d\chi/dt = kt,$$

whereby the rate factor k can be calculated from plotting $\ln\chi/\chi_0$ versus t whereby k represents the slope of the line. Calculating the k-factor gives insight in the rates of change in a property. This was suggested by Nye and Greenland (1960) and first order kinetics have been widely used in crop residue and organic matter decomposition studies. First order kinetics were used by Arnason *et al.* (1982) in a study of soil fertility decline in Belize: Table XII lists the results and shows the k-factor and the relative change in soil chemical properties of Rendols under permanent cropping in Belize. For the use of the single exponential model, several data points and relatively short time-steps are needed. This method cannot be used when soil fertility studies have only single time steps (t_1 and t_2). First order kinetics fit well for C and N but less well for exchangeable cations or pH. Overall this method provides necessary input for scenario studies on how soil fertility changes over time.

Table XII
Decline of Soil Fertility in Relative Values (Percentage per Year) and Calculated *k*-factor Based on First Order Kinetics

Soil chemical property	Relative rate of decline (% per year)	*k*-factor (per year)
pH	1.2	0.013
Available P	10	0.11
Total N	4.8	0.05
Exchangeable Ca	16	0.19
Exchangeable K	3.9	0.035

Modified from Arnason *et al.* (1982).

B. Paired Sequential Samples

In some studies, several paired samples are available but all of them with different single time steps. This is the case when various fields are being sampled at different times, for example, some fields may have been sampled in 1987 and again in 2003 whereas other were sampled in 1992 and again in 2000. The data set from such a sampling scheme has several values of a soil property with different time steps. It is possible to calculate from such data the rate of change whereby the difference in years between the initial sample (t_1) and the second sample at (t_2), is plotted against the difference in the measured soil property values. Based on a large number of sample pairs, the decline in a soil chemical property can be calculated whereby t_1 is the initial value and t_2 the value of the second sampling. Thus, it can be calculated whether a soil property had increased or not changed (i.e., value at t_2 minus value at $t_1 \geq 0$) or whether there has been a decline (i.e., value at t_2 minus value at $t_1 < 0$).

From a sugarcane plantation in Papua New Guinea, pH data were available from 80 fields sampled at different sampling times. The difference in years between the initial sample at t_1 and the second sample at t_2, was plotted against the difference in the measured pH values. It appeared that the decline in pH was related to the initial pH value (Fig. 1). Although the data are scattered, a larger decline occurred when the initial pH was high. This relation does not take into account the time elapsed between the pH measurements. Based on the 80 sample pairs, the decline in pH with time was calculated whereby t_1 was the initial value and t_2 the pH value of the second sampling. In only a few samples the pH_w increased or had not changed (i.e., pH at t_2 minus pH at $t_1 \geq 0$) but in the majority of the sample pairs there was a decline in pH (i.e., pH at t_2 minus pH at $t_1 < 0$). The largest decrease in pH

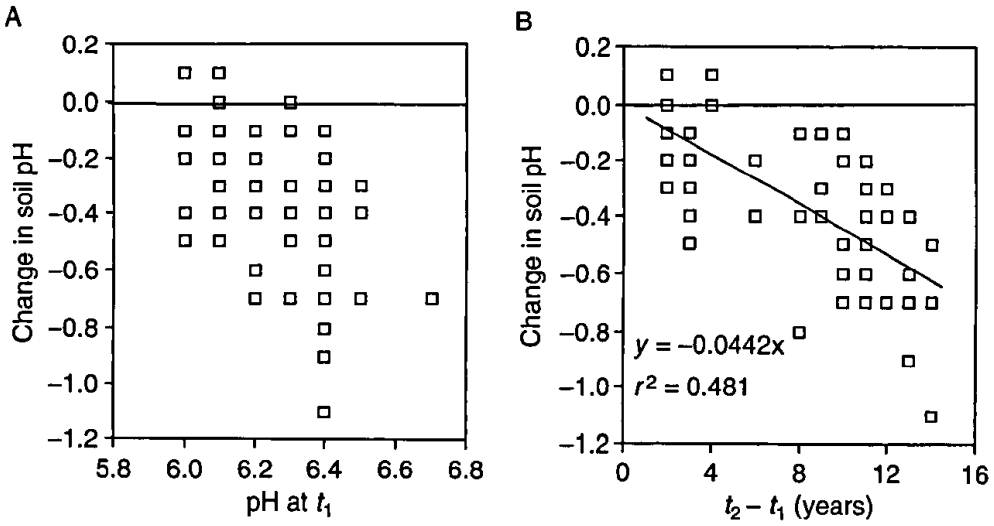

Figure 1 Changes in topsoil pH (0–0.15 m) in relation to the initial pH at t_1 (A), and the change in topsoil pH with time (B). Based on 80 sample pairs. Type I data. Modified from Hartemink (1998a).

occurred after 10 years ($t_2 - t_1 \geq 10$), and nearly 50% of the variation was explained by the linear function:

$$\Delta\text{pH} = -0.444 \times (t_2 - t_1).$$

This method proved useful to quantify rates of change in a soil property using paired sequential sample data with different time steps.

C. Bulk Density

Cropping brings about changes in soil physical and soil biological properties and these also influence soil chemical properties. For example, changes in the soil moisture or temperature regime affect soil microbial biomass, which influences mineralization of organic matter and other processes. Measured changes in soil chemical properties are a net effect of these processes but such changes also depend on the bulk density of the soil, which may alter under cropping. In the previous section, changes in soil chemical properties were mostly expressed as concentrations, for example, $mmol_c\ kg^{-1}$ or $g\ kg^{-1}$. Nutrient concentration can be expressed as nutrient content ($kg\ ha^{-1}$), which can be used in nutrient balance studies and translated in nutrient replacement by inorganic fertilizers or other amendments.

Suppose an Alfisol cropped with millet contained 1.5 g N kg^{-1} in the topsoils (0–0.20 m) in 1990, and 1.2 g N kg^{-1} in 2000. The rate of change in total N content is 0.03 g N kg^{-1} $year^{-1}$. If the topsoil has a constant bulk density of 1.3 Mg m^{-3}, the decrease of 0.03 g N kg^{-1} $year^{-1}$ is equivalent to

a loss of 78 kg N ha^{-1} $year^{-1}$. This figure is easy to deal with, particularly when it is expressed as inorganic fertilizer: the loss of N from the topsoil is equivalent to 170 kg urea or 390 kg sulphate of ammonia. A further step is to translate this nutrient loss into economic terms (Alfsen *et al.*, 1997; Drechsel and Gyiele, 1999; FAO, 2001a).

As this example showed, expressing soil chemical properties in kg nutrient ha^{-1} requires soil bulk density values, which are rarely measured in soil fertility studies. Moreover, many soil chemical properties are determined by an extraction method and the values are expressed in terms of availability. Available means that the nutrient is susceptible to absorption by plants, whereas availability means effective quantity (Black, 1993). The amount of available nutrients extracted may hold little relation with the total amount of the nutrient in the soil and its availability over a given time span. The availability aspect is irrelevant for C and N because total pools are measured. Bulk density measurements thus improve the quantification of C and N loss as it would be possible to relate N loss to the total N pools. For P, K, or Ca that is not possible unless the total element concentrations were determined.

D. Bulk Density Effects on Nutrient Stocks

Bulk density is likely to change under cropping, which has several effects. In annual cropping systems where no mechanization is used, increases in bulk density are not so likely to occur. Increases may be caused by people in the field or occur naturally; generally these increases are not spectacular. In mechanized annual cropping systems, where tractor traffic is common, substantial compaction may occur (Soane, 1990), which may affect the outcome of nutrient stock calculations. It may severely reduce nutrient availability (Arvidsson, 1999; Lipiec and Stepniewski, 1995) because rooting is restricted which limits the volume of soil from which nutrients can be extracted. In compacted soils the crop also becomes susceptible to water stress, which may have a larger impact than the reduced nutrient availability. It is difficult to distinguish these factors and their effects on crop productivity. When the soil is more compacted the thickness of the layer decreases. This means that, if the sampling depth remains the same, part of the subsoil is being sampled, which affects calculations on nutrient contents. So sampling should be corrected for decrease in the thickness of the compacted layer (Dias and Nortcliff, 1985).

An increase in bulk density does not mean that nutrient content is reduced. Table XIII shows the nutrient concentration and nutrient content of an Oxisol cropped with sugarcane. The nutrient content was calculated for three depths using bulk densities determined in 1978 and 1983. Absolute and relative differences in the nutrient concentration and nutrient content

Table XIII
Nutrient Concentration and Nutrient Content of Oxisols Under Sugarcane in 1978 and in 1983

Sampling depth (m)	Soil property	Nutrient concentration		Difference		Nutrient content (kg ha^{-1})		Difference	
		1978	1983	Absolute	Percentage	1978	1983	Absolute	Percentage
0–0.12	BD (Mg m^{-3})	0.76	1.02	+0.26	+34				
	Organic C (g kg^{-1})	68.2	41.3	−26.9	−39	62,198	50,551	−11647	−19
	Total N (g kg^{-1})	4.0	1.9	−2.1	−53	3,648	2,326	−1322	−36
	Total P (g kg^{-1})	1.1	0.9	−0.02	−18	1,003	1,102	+99	+10
	Ca (mmol$_c$ kg^{-1})	29.0	9.1	−19.9	−69	530	223	−307	−58
	Mg (mmol$_c$ kg^{-1})	2.9	1.6	−1.3	−45	32	24	−8	−26
	K (mmol$_c$ kg^{-1})	3.0	1.2	−1.8	−60	107	57	−50	−46
0.30–0.40	BD (Mg m^{-3})	0.86	1.06	+0.20	+23				
	Organic C (g kg^{-1})	7.1	10.9	+3.8	+54	6,106	11,554	+5448	+89
	Total N (g kg^{-1})	1.2	1.0	−0.2	−17	1,032	1,060	+28	+3
	Total P (g kg^{-1})	0.9	1.1	+0.02	+22	774	1,166	+392	+51
	Ca (mmol$_c$ kg^{-1})	1.6	4.0	+2.4	+150	28	85	+57	+208
	Mg (mmol$_c$ kg^{-1})	0.5	0.4	−0.1	−20	5	5	0	0
	K (mmol$_c$ kg^{-1})	0.6	0.5	−0.1	−17	20	21	+1	+3
0.70–0.80	BD (Mg m^{-3})	1.01	1.10	+0.09	+9				
	Organic C (g kg^{-1})	3.6	3.0	−0.6	−17	3,636	3,300	−336	−9
	Total N (g kg^{-1})	0.5	0.5	0	0	505	550	+45	+9
	Total P (g kg^{-1})	1.1	1.1	0	0	1,111	1,210	+99	+9
	Ca (mmol$_c$ kg^{-1})	2.0	2.2	+0.2	+10	40	48	+8	+20
	Mg (mmol$_c$ kg^{-1})	0.4	0.2	−0.2	−50	5	3	−2	−46
	K (mmol$_c$ kg^{-1})	0.3	0.5	+0.2	+67	12	22	+10	+82

Calculated from data in Masilaca *et al.* (1985).

were calculated for both periods. No correction was made for the decrease of soil layer thickness due to the increased bulk density. In the topsoils bulk density increased from 0.76 to 1.02 Mg m^{-3} between 1978 and 1983. There was a relatively lower decrease in nutrient content than in nutrient concentration. As a result of the increase in bulk density, different conclusions would be reached with regard to total P in the topsoils: total P decreased from 1.1 to 0.9 g kg^{-1} whereas the P content of the topsoil increased by 99 kg ha^{-1} due to the 34% increase in topsoil bulk density. Similar discrepancies can be found in some other soil chemical properties. Annual losses of total N from the topsoil exceed 200 kg ha^{-1} but a slight increase in N contents of the subsoils was found, which may have been caused by leaching.

A second example on the effects of bulk density on soil nutrient contents is from Nigeria where Aina (1979) sampled Alfisols that had been cropped for 10 years and Alfisols that had been fallowed for 20–25 years (Table XIV). Nutrient concentration and content drastically decrease in permanently cropped soils, but the relative decrease in nutrient contents was lower. The relative decrease in soil nutrient contents is lower than the decrease in nutrient concentration with the exception of NO_3–N, which varies greatly with time.

VII. INTERPRETATION OF RESULTS

The interpretation of soil chemical data for the assessment of soil fertility decline is complex and particular to each situation. Factors affecting the interpretations are the agro-ecological conditions, the spatial and temporal boundaries of the study, the type of data, and how they were collected. Soil fertility decline must be differently appraised for soils in different agro-ecologies, but some common rules apply and these are discussed here.

A. Resilience and Reversibility

Resilience is the ability of the soil to recover from a period of stress—as for example, the cultivation of agricultural crops (Greenland and Szabolcs, 1994; Lal, 1997). Some soils withstand cultivation and quickly recover after a period of cultivation whereas others lack such capacity. This resilience is an intrinsic property of the soil. Therefore, different soils require different appraisal. Also individual soil chemical properties require a different appraisal depending on the type of land-use. For example, a decrease in exchangeable K may have more effect on potato production than a similar rate of decrease in total N. Likewise, the decrease in soil organic C may have no direct yield effect but could drastically reduce the resistance of the soil to physical deterioration, or to supply N or P to the crop.

Table XIV
Nutrient Concentration and Nutrient Content (0–0.15 m depth) of Alfisols Under Fallow and 10 Years of Cropping

Soil property	Nutrient concentration		Difference		Nutrient content (kg ha^{-1})		Difference	
	Fallow	Cropped	Absolute	Percentage	Fallow	Cropped	Absolute	Percentage
BD (Mg m^{-3})	1.24	1.58	+0.34	+27				
NO_3–N (g kg^{-1})	19.3	2.3	−17.0	−88	36	5	−30	−85
Available P (g kg^{-1})	15.4	6.0	−9.4	−61	29	14	−14	−50
Ca (mmol$_c$ kg^{-1})	45.1	15.0	−30.1	−67	1681	712	−969	−58
K (mmol$_c$ kg^{-1})	2.4	0.9	−1.5	−63	174	83	−91	−52

Calculated from data in Aina (1979).

The removal of nutrients in relation to the size of the nutrient pool could be considered when evaluating soil fertility decline (Janssen, 1999). Much depends not only on how the size of the pool is measured, that is, the bioavailability concept in soil fertility, but also on the bulk density. Since Liebig it has been generally assumed that input of nutrients needs to match the output in order to sustain crop production (van Noordwijk, 1999), or in other words, replace what was lost. However, the time frame at which the replacement is required is different for different soils. Inherently fertile soils might compensate for the drain of nutrients and remain productive for a considerable period of time (the resilience concept) but, at some stage, these soils require replenishment of what was removed or lost. Inherently poor soils might need nutrient replenishment before a second crop is grown and their soil fertility declines quickly when permanently cultivated. The annual nutrient balance may largely differ between years or seasons (Sheldrick *et al.*, 2003), which should be taken into account in the replenishment concept.

Another aspect that affects the interpretation of results is the degree of reversibility of a change in a soil property. A decreasing level of exchangeable K may be less of a problem than a large decrease in soil organic C. Potassium may be replaced by inorganic fertilizers, whereas a doubling of the soil organic C content to its original level is very difficult. A strongly acidified topsoil may be easy to correct by the judicious application of lime, but it may be much harder to raise the pH of a strongly acidified subsoil (Sumner and Yamada, 2002). So the reversibility is different for the various soil attributes and it is also important to consider the depth to which the soil chemical changes have occurred.

B. The Time-Lag Effect

To assess whether soil fertility decline has occurred depends on what properties are measured and the rates at which the properties change. Fairly rapidly changing properties include organic C, N, and pH, and these properties usually reach dynamic equilibrium within 100 years in undisturbed ecosystems. The second group of features changes slowly and appear to be at equilibrium mainly because their rate of change is so slow (Yaalon, 1971).

Some soil processes, once established, continue for some time despite changes in the environment and the resistance to change may be related to what has been termed "pedogenic inertia" (Bryan and Teakle, 1949; Chadwick and Chorover, 2001). An example of a lag is the soil temperature, both diurnal and annual, which invariably lags behind the atmospheric temperature wave (Yaalon, 1971). By analogy, soil fertility may continue to decline for some time even if the cause of the decline (permanent cropping

without nutrient inputs) has been removed and the soil has been left fallow. Not all soil properties would show this effect and at the same pace.

C. Frequency, Period, and Time of Observation

The frequency of phenomena that affect soil properties is important. For example, a single and destructive soil erosion event may take place once every 10 years and could have substantial impact on the soil fertility. On the other hand, there are very gradual processes like soil acidification (Pickett, 1991). For both rare events and slow phenomena to be recorded, long-term observations are needed.

Besides the pace of soil change, another factor is the period during which the observations are made. Whether a declining trend in a soil chemical property can be quantified depends on the property itself and the period and time of observation. This is illustrated in Fig. 2, which shows the trend in a fictitious soil chemical property over time. In Fig. 2A the soil property shows some noise or short-term variation, which may have been the result of weather conditions or management factors. This could be the variation in soil pH over the years, but on a different time scale it could be the variation in a soil property during a single day following the warming of the soil, or directly after rain or inorganic fertilizer applications. Soil chemical properties show variation at different time scales, but for most of the standard soil tests, long-term variation is of greater importance than the diurnal or short-term variation. The decline of the soil property in Fig. 2A (i.e., an interpolated line) is more or less linear.

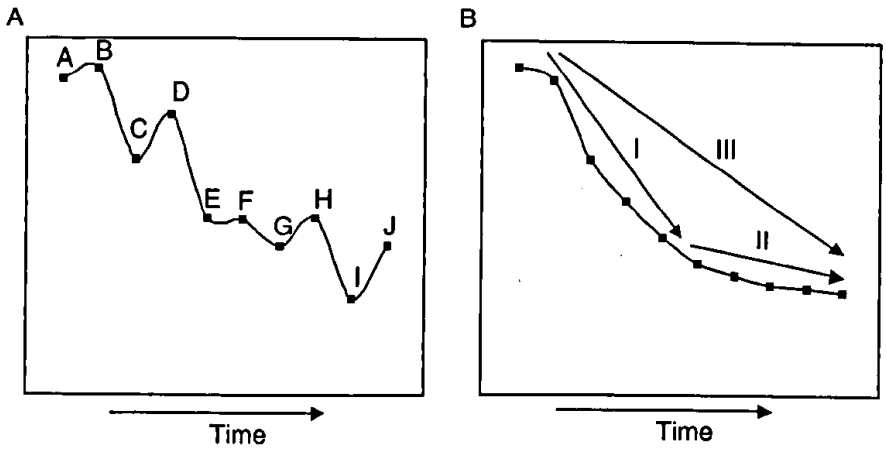

Figure 2 Theoretical changes in soil chemical properties over time when no amendments are made and the soils are permanently cropped: (A) noise and trend, and (B) exponential decline. See text for explanation (Hartemink, 2003).

A gradual decline in a soil chemical property is shown in Fig. 2B. This may represent a decline in exchangeable K in unfertilized and permanently cropped soils. Assessing of the rate of decline depends on the period and time of observation. In the beginning the decline is fast (arrow I) but, since the decline is nonlinear, the rate of decline (Δt^{-1}) is decreasing with time (arrow II). If observations would be made over time I, the rate of decline is different compared to time II even though the period of observation is the same. Rates of decline over the whole period (arrow III) would again give a different rate and this would largely ignore the nonlinearity of the relationship. It is not necessarily the case that the decline based on III is half the sum of I and II. To assess a nonlinear decline in a soil chemical property measurements at relatively short time steps are required. If time steps are large, it should be known whether period I, II, or III is evaluated.

The pattern in Fig. 2A may result in different conclusions when two points in the curves are compared. This is exemplified in Table XV where long-term, medium-term, and short-term comparisons are grouped. Comparisons were termed long-term when they exceeded five data points of the x-axis (time), medium-term when there were three to four data points, and short-term when there were two or less between two data points.

The general pattern emerging is that long-term observations yield a stronger decline in soil fertility whereas short-term observations yield no clear pattern. Due to short-term variation there is also a difference within the periods of comparison. A large decrease in the soil property was found in 20% of the long-term comparisons, whereas 70% of the comparisons yielded

Table XV
Changes in a Soil Property Between Different Sampling Times (A, B, C, D, etc.)—Based on Fig. 2A

	B	C	D	E	F	G	H	I	J	
A	+/–	–	+/–	–	–	–	–	–	–	Long-term comparison
B		+	+/–	–	–	–	–	–	–	
C			+	–	–	–	+/–	–	+/–	
D				–	–	–	–	–	–	
E					+/–	+/–	+/–	–	+/–	Medium-term comparison
F						+/–	+/–	–	+/–	
G							+/–	–	+/–	Short-term comparison
H								–	+/–	
I									+	

– – Large decrease +/– no change
– Moderate decrease + Moderate increase
From Hartemink (2003).

a moderate decrease (Table XV). In 10% of the long-term comparisons, no change was apparent. Medium-term comparisons yielded a large decrease in 9% of the cases, whereas in more than 25% of the comparisons no change was found. Short-term comparisons yielded no change in soil properties in almost half of the cases and a moderate increase in 15% of the comparisons.

VIII. SUMMARY AND CONCLUSIONS

In this chapter, both theoretical and practical aspects for the assessment of soil fertility decline are critically reviewed. Evaluating soil fertility decline can be addressed with different types of data. There are data from measured soil chemical properties, and such data can be from the same plot at different times (Type I data), or from plots under different land-use (Type II data). Both data types have their merits and drawbacks: data are either quickly collected and indicative of what is going on, or the collection is more tedious but the data may be easier to interpret and more meaningful.

Whatever data are collected, it is important that the boundary conditions are properly set. This means that the study should indicate whether soil fertility decline is assessed for a point, catchment, region, country, etc. At the catchment level, soil fertility may decline in one soil, but it may increase in a lower part of the catchment, which illustrates the need for the delineation of spatial boundaries. Soil fertility decline studies should also have temporal boundaries. In general, long-term observations yield better results. This review has also shown that frequency of observations is dependent on the type of study and is different for various soil chemical properties.

An important aspect in soil fertility decline studies is the spatial and temporal variation in soil properties. Soil spatial variation has been sufficiently tackled by research and various methods exist to quantify the variation. Temporal variation is a more difficult issue and fewer studies are available. As with spatial variation, it requires sufficient samples before rigorous conclusions can be drawn. Temporal variation may also be confused with other trends in the data and some soil chemical properties are more vulnerable to temporal variation than others.

Soil fertility decline studies depend on soil sampling, soil analysis, and interpretation of the results. Errors are possible in all three steps, although most errors are generally being made during soil sampling because soil variation is insufficiently dealt with and insufficient samples are taken. The choice of the analytical technique in relation to the soil property or soil type is another potential source of errors. The effects of soil sample storage and a constant laboratory error are relevant for long-term studies on soil change, but data on storage effects and laboratory errors are scarce.

Bulk density is an important factor to consider in soil fertility studies. It is needed to calculate nutrient concentrations into nutrient contents that can be used in nutrient balance studies. The decrease in the thickness of a soil layer should be considered when soils have been compacted: small deviations in bulk densities have a significant effect on the outcome of the nutrient content calculations. Nutrient removal by the economic produce is also an important component in nutrient balance studies. Published values on nutrient removal vary greatly according to differences in cultivars, measured plant portion, age of the crop, soil type, and the soil nutrient status.

For the interpretation of studies on soil fertility decline, resilience and reversibility are important concepts that reflect the ability of the soil to withstand stress and the ability to reverse changes brought about by cropping. The frequency at which observation are made also determines the interpretation of the results since some phenomena rarely occur whereas others take place gradually. The period of observation should be long enough to accommodate slow phenomena and rare events but, also, to deal with temporal variation. Due to noise in the data caused by temporal or other sources of unknown variation, different conclusion can be reached—even if the period of observation is substantial. The pattern of decline, the time of observation and the size of the time steps are important for accurately quantifying soil fertility decline.

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REFERENCES

Addiscott, T. M. (1996). Measuring and modelling nitrogen leaching: Parallel problems. *Plant Soil* **181**, 1–6.

Aina, P. O. (1979). Soil changes resulting from long-term management practises in Western Nigeria. *Soil Sci. Soc. Am. J.* **43**, 173–177.

Alfsen, K. H., Bye, T. A., Glomsrod, S., and Wiig, H. (1997). Theory and applications. Soil degradation and economic development in Ghana. *Environ. Dev. Econ.* **2**, 119–143.

Arnason, T., Lambert, J. D. H., Gale, J., Cal, J., and Vernon, H. (1982). Decline of soil fertility due to intensification of land use by shifting agriculturists in Belize, Central America. *Agro-Ecosystems* **8**, 27–37.

Arvidsson, J. (1999). Nutrient uptake and growth of barley as affected by soil compaction. *Plant Soil* **208**, 9–19.

Ayanaba, A., Tuckwell, S. B., and Jenkinson, D. S. (1976). The effects of clearing and cropping on the organic reserves and biomass of tropical forests soils. *Soil Biol. Biochem.* **8**, 519–525.

Barrera-Bassols, N., and Zinck, J. A. (2000). "Ethnopedology in a worldwide perspective: An annotated bibliography," International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede.

Barrios, E., and Trejo, M. T. (2003). Implications of local soil knowledge for integrated soil management in Latin America. *Geoderma* **111**, 217–231.

Bartlett, R., and James, B. (1980). Studying dried, stored soil samples: Some pitfalls. *Soil Sci. Soc. Am. J.* **44**, 721–724.

Bekunda, M. A., Bationo, A., and Ssali, H. (1997). Soil fertility management in Africa: A review of selected research trials. *In* "Replenishing Soil Fertility in Africa" (R. J. Buresh, P. A. Sanchez, and F. Calhoun, Eds.), pp. 63–79. SSSA Special Publication Number 51, Madison, WI.

Black, C. A. (1993). "Soil fertility evaluation and control." Lewis Publishers, Boca Raton, FL.

Boddey, R. M., Sa, J. C. D., Alves, B. J. R., and Urquiaga, S. (1997). The contribution of biological nitrogen fixation for sustainable agricultural systems in the tropics. *Soil Biol. Biochem.* **29**, 787–799.

Boone, R. D., Grigal, D. F., Sollins, P., Ahrens, R. J., and Armstrong, D. E. (1999). Soil sampling, preparation, archiving, and quality control. *In* "Standard Methods for Long-Term Ecological Research" (G. P. Robertson, D. C. Coleman, C. S. Bledsoe, and P. Sollins, Eds.), pp. 3–28. Oxford University Press, Oxford.

Bouma, J. (1993). Soil behavior under field conditions: Differences in perception and their effects on research. *Geoderma* **60**, 1–14.

Boxman, O., and Janssen, B. H. (1990). Availability of nutrients and fertilizer use. *In* "Mechanized Annual Cropping on Low Fertility Acid Soils in the Humid Tropics. Wageningen Agricultural University Papers 90–5" (B. H. Janssen and J. F. Wienk, Eds.), pp. 73–99. Veenman, Wageningen.

Bramley, R. G. V., Ellis, N., Nable, R. O., and Garside, A. L. (1996). Changes in soil chemical properties under long-term sugar cane monoculture and their possible role in sugar yield decline. *Aust. J. Soil Res.* **34**, 967–984.

Brand, J., and Pfund, J. L. (1998). Site and watershed-level assessment of nutrient dynamics under shifting cultivation in eastern Madagascar. *Agr. Ecosys. Env.* **71**, 169–183.

Brown, A. J. (1999). Soil sampling and sample handling for chemical analysis. *In* "Soil Analysis: An Interpretation Manual" (K. I. Peverill, L. A. Sparrow, and D. J. Reuter, Eds.), pp. 35–53. CSIRO Publishing, Collingwood, Victoria.

Bryan, W. H., and Teakle, L. J. H. (1949). Pedogenic inertia - A concept in soil science. *Nature* **164**, 969.

Chadwick, O. A., and Chorover, J. (2001). The chemistry of pedogenic thresholds. *Geoderma* **100**, 321–353.

Chantigny, M. H. (2003). Dissolved and water-extractable organic matter in soils: A review on the influence of land use and management practices. *Geoderma* **113**, 357–380.

Chapman, P. J., Shand, C. A., Edwards, A. C., and Smith, S. (1997). Effect of storage and sieving on the phosphorus composition of soil solution. *Soil Sci. Soc. Am. J.* **61**, 315–321.

Clark, K. L., Nadkarni, N. M., Schaefer, D., and Gholz, H. L. (1998). Atmospheric deposition and net retention of ions by the canopy in a tropical montane forest, Monteverde, Costa Rica. *J. Trop. Ecol.* **14**, 27–45.

Cline, M. G. (1944). Principles of soil sampling. *Soil Sci.* **58**, 275–288.

Cooke, G. W. (1982). "Fertilizing for Maximum Yield," 3rd ed. Collins, London.

Cresswell, R. G., Dent, D. L., Jones, G. L., and Galloway, D. S. (2004). Three-dimensional mapping of salt stores in the southeast Murray-Darling Basin, Australia. 1. Steps in calibration of airborne electromagnetic surveys. *Soil Use Manage.* **20**, 133–143.

de Klein, C. A. M., Barton, L., Sherlock, R. R., Li, Z., and Littlejohn, R. P. (2003). Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. *Aus. J. Soil Res.* **41**, 381–399.

de Walle, F. B., and Sevenster, J. (1998). "Agriculture and the Environment: Minerals, Manure and Measures." Kluwer Academic Publishers, Dordrecht.

Dias, A. C. C. P., and Nortcliff, S. (1985). Effects of two land clearing methods on the physical properties of an Oxisol in the Brazilian Amazon. *Trop. Agr.* **62**, 207–212.

Dockersmith, I. C., Giardina, C. P., and Sanford, R. L. (1999). Persistence of tree related patterns in soil nutrients following slash-and-burn disturbance in the tropics. *Plant Soil* **209**, 137–156.

Doran, J. W., and Parkin, T. B. (1996). Quantitative indicators of soil quality: A minimum data set. *In* "Methods for Assessing Soil Quality" (J. W. Doran and A. J. Jones, Eds.), pp. 25–37. SSSA, Madison, WI.

Drechsel, P., and Gyiele, L. A. (1999). "The Economic Assessment of Soil Nutrient Depletion. Analytical Issues for Framework Development." IBSRAM, Bangkok.

Dubey, H. D., and Fox, R. H. (1974). Denitrification losses from humid topical soils of Puerto Rico. *Soil Sci. Soc. Am. Proc.* **38**, 917–920.

Ekanade, O. (1988). The nutrient status of soils under peasant cocoa farms of varying ages in southwestern Nigeria. *Biol. Agric. Hortic.* **5**, 155–167.

Faerge, J., and Magid, J. (2004). Evaluating NUTMON nutrient balancing in Sub-Sahara Africa. *Nutr. Cycl. Agroecosys.* **69**, 101–110.

Fairhead, J., and Scoones, I. (2005). Local knowledge and the social shaping of soil investments: Critical perspectives on the assessment of soil degradation in Africa. *Land Use Policy* **22**, 33–41.

FAO. (2001a). "The Economics of Soil Productivity in Sub-Saharan Africa." FAO, Rome.

FAO. (2001b). "Lecture Notes on the Major Soils of the World." FAO, Rome.

FAO. (2004). "Scaling Soil Nutrient Balances: Enabling Mesolvel Applications for African Realities. FAO Fertilizer and Plant Nutrition Bulletin 15." FAO, Rome.

Folmer, E. C. R., Geurts, P. M. H., and Francisco, J. R. (1998). Assessment of soil fertility depletion in Mozambique. *Agr. Ecosyst. Environ.* **71**, 159–167.

Garside, A. L., Bramley, R. G. V., Bristow, K. L., Holt, J. A., Magarey, R. G., Nable, R. O., Pankhurst, C. E., and Skjemstad, J. O. (1997). Comparisons between paired old and new land sites for sugarcane growth and yield and soil chemical, physical, and biological properties. *Proc. Aus. Soc. Sugarcane Technol.*, 60–66.

Giani, L., Chertov, O., Gebhardt, C., Kalinina, O., Nadporozhskaya, M., and Tolkdorf-Lienemann, E. (2004). Plagganthrepts in northwest Russia? Genesis, properties and classification. *Geoderma* **121**, 113–122.

Giller, K. E., Cadish, G., Ehaliotis, C., Adams, E., Sakala, W. D., and Mafongoya, P. L. (1997). Building soil nitrogen capital in Africa. *In* "Replenishing Soil Fertility in Africa" (R. J. Buresh, P. A. Sanchez, and F. Calhoun, Eds.), pp. 151–192. SSSA Special Publication Number 51, SSSA, Madison, WI.

Goossens, R., and Van Ranst, E. (1998). The use of remote sensing to map gypsiferous soils in the Ismailia Province (Egypt). *Geoderma* **87**, 47–56.

Govindarajan, M., Rao, M. R., Mathuva, M. N., and Nair, P. K. R. (1996). Soil-water and root dynamics under hedgerow intercropping in semiarid Kenya. *Agron. J.* **88**, 513–520.

Gray, L. C. (1999). Is land being degraded? A multi-scale investigation of landscape change in southwestern Burkina Faso. *Land Degrad. Dev.* **10**, 329–343.

Greenland, D. J. (1985). Nitrogen and food production in the tropics: Contributions from fertilizer nitrogen and biological nitrogen fixation. *In* "Nitrogen Management in Farming Systems in Humid and Subhumid Tropics" (B. T. Kang and J. van der Heide, Eds.), pp. 9–39. IB-Haren & IITA-Ibadan.

Greenland, D. J. (1994a). Long-term cropping experiments in developing countries: The need, the history and the future. *In* "Long-Term Experiments in Agricultural and Ecological Sciences" (R. A. Leigh and A. E. Johnston, Eds.), pp. 187–209. CAB International, Wallingford.

Greenland, D. J. (1994b). Soil science and sustainable land management. *In* "Soil Science and Sustainable Land Management in the Tropics" (J. K. Syers and D. L. Rimmer, Eds.), pp. 1–15. CAB International, Wallingford.

Greenland, D. J., and Szabolcs, I. (Eds.) (1994). "Soil Resilience and Sustainable Land Use," 1994CAB InternationalWallingford, pp. 1–561. CAB International, Wallingford.

Greer, K. J., and Schoenau, J. J. (1997). Toward a framework for soil quality assessment and prediction. *In* "Soil Quality for Crop Production and Ecosystem Health" (E. G. Gregorich and M. R. Carter, Eds.), pp. 313–321. Elsevier Science, Amsterdam.

Gregorich, E. G., Carter, M. R., Angers, D. A., Monreal, C. M., and Ellert, B. H. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Can. J. Soil Sci.* **74**, 367–385.

Grimme, H., and Juo, A. S. R. (1985). Inorganic nitrogen loss through leaching and denitrification in soils of the humid tropics. *In* "Nitrogen Management in Farming Systems in Humid and Subhumid Tropics" (B. T. Kang and J. van der Heide, Eds.), pp. 57–71. IB-Haren & IITA-Ibadan.

Harrison, R., and Webb, J. (2001). A review of the effect of N fertilizer type on gaseous emissions. *Adv. Agr.* **73**, 65–108.

Hartemink, A., and van Keulen, H. (2005). Soil degradation in Sub-Saharan Africa. *Land Use Policy* **22**, 1.

Hartemink, A. E. (1995). "Soil Fertility Decline Under Sisal Cultivation in Tanzania." ISRIC, Wageningen.

Hartemink, A. E. (1997a). Input and output of major nutrients under monocropping sisal in Tanzania. *Land Degrad. Dev.* **8**, 305–310.

Hartemink, A. E. (1997b). Soil fertility decline in some major soil groupings under permanent cropping in Tanga region, Tanzania. *Geoderma* **75**, 215–229.

Hartemink, A. E. (1998a). Acidification and pH buffering capacity of alluvial soils under sugarcane. *Exp. Agr.* **34**, 231–243.

Hartemink, A. E. (1998b). Changes in soil fertility and leaf nutrient concentration at a sugar cane plantation in Papua New Guinea. *Commun. Soil Sci. Plan.* **29**, 1045–1060.

Hartemink, A. E. (1998c). Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. *Geoderma* **85**, 283–306.

Hartemink, A. E. (2003). "Soil Fertility Decline in the Tropics: With Case Studies on Plantations." ISRIC-CABI Publishing, Wallingford.

Hartemink, A. E. (2005). Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: A review. *Adv. Agr.* **86**, 227–253.

Hartemink, A. E. (2006). Soil fertility decline: Definitions and assessments. *In* "Encylopedia of soil science." (R. Lal, Ed.), pp. 1618–1621. Dekker, New York.

Hartemink, A. E., Buresh, R. J., Jama, B., and Janssen, B. H. (1996). Soil nitrate and water dynamics in sesbania fallows, weed fallows, and maize. *Soil Sci. Soc. Am. J.* **60**, 568–574.

Hartemink, A. E., McBratney, A. B., and Cattle, J. A. (2001). Developments and trends in soil science: 100 volumes of Geoderma (1967–2001). *Geoderma* **100**, 217–268.

Hartemink, A. E., Poloma, S., Maino, M., Powell, K. S., Egenae, J., and O'Sullivan, J. N. (2000). Yield decline of sweet potato in the humid lowlands of Papua New Guinea. *Agr. Ecosyst. Environ.* **79**, 259–269.

Henao, J., and Baanante, C. (1999). "Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa." IFDC, Muscle Shoals.

Heuveldop, J., Fassbender, H. W., Alpízar, L., Enríquez, G., and Fölster, H. (1988). Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poro (*Erythrina poeppigiana*) in Costa Rica. II. Cacao and wood production, litter production and decomposition. *Agroforestry Systems* **6**, 37–48.

Howari, F. M. (2003). The use of remote sensing data to extract information from agricultural land with emphasis on soil salinity. *Aus. J. Soil Res.* **41**, 1243–1253.

IPI. (1995). "Potassium in Asia: Balanced Fertilization to Increase and Sustain Agricultural Production. 24th Colloquium of the International Potash Institute." IPI, Basel.

Islam, K. R., and Weil, R. R. (2000). Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agric. Ecosyst. Environ.* **79**, 9–16.

Jama, B., Buresh, R. J., Ndufa, J. K., and Shepherd, K. D. (1998). Vertical distribution of roots and soil nitrate: Tree species and phosphorus effects. *Soil Sci. Soc. Am. J.* **62**, 280–286.

Janssen, B. H. (1999). Basics of budgets, buffers and balances of nutrients in relation to sustainability of agroecosystems. *In* "Nutrient Disequilibria in Agroecosystems: Concepts and Case Studies" (E. M. A. Smaling, O. Oenema, and L. O. Fresco, Eds.), pp. 27–56. CABI Publishing, Wallingford.

Jenny, H. (1980). "The soil resource. Origin and behavior." Springer-Verlag, New York.

Johnston, A. E., and Syers, J. K. (1998). Working group reports and conference summary. *In* "Nutrient Management for Sustainable Crop Production in Asia" (A. E. Johnston and J. K. Syers, Eds.), pp. 375–382. CAB International, Wallingford.

Jones, D. L., and Shannon, D. (1999). Mineralization of amino acids applied to soils: Impact of soil sieving, storage, and inorganic nitrogen additions. *Soil Sci. Soc. Am. J.* **63**, 1199–1206.

Kee, K. K., Goh, K. J., and Chew, P. S. (1995). Effects of NK fertiliser on soil pH and exchangeable K status on acid soils in an oilpalm plantation in Malaysia. *In* "Plant Soil Interactions at Low pH" (R. A. Date, R. J. Grundon, G. E. Rayment, and M. E. Probert, Eds.), pp. 809–815. Kluwer Academic, Dordrecht.

Kempthorne, C., and Allmars, R. R. (1986). Errors and variability of observations. *In* "Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods," 2nd ed. (A. Klute, Ed.), pp. 1–31. ASA-SSSA, Madison, WI.

Koning, N., and Smaling, E. (2005). Environmental crisis or 'lie of the land'? The debate on soil degradation in Africa. *Land Use Policy* **22**, 3–11.

Koutika, L. S., Chone, T., Andreux, F., and Cerri, C. C. (2000). Carbon decomposition of the topsoils and soil fractions under forest and pasture in the western Brazilian Amazon basin, Rondonia. *Biol. Fert. Soils* **30**, 284–287.

Krasilnikov, P. V., and Tabor, J. A. (2003). Perspectives on utilitarian ethnopedology. *Geoderma* **111**, 197–215.

Kulmatiski, A., and Beard, K. H. (2004). Reducing sampler error in soil research. *Soil Biol. Biochem.* **36**, 383–385.

Kumar, K., and Goh, K. M. (2000). Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. *Adv. Agron.* **68**, 197–319.

Lal, R. (1986). Conversion of tropical rainforest: Agronomic potential and ecological consequences. *Adv. Agron.* **39**, 173–264.

Lal, R. (1997). Degradation and resilience of soils. *In* "Philosophical Transactions of the Royal Society of London: Series B: Biological Sciences" (D. J. Greenland, P. J. Gregory, and P. Nye, Eds.), Vol. 352, pp. 997–1008.

Landon, J. R. (Ed.) (1991). "Booker Tropical Soil Manual." Longman, Harlow.

Lapenis, A. G., Torn, M. S., Harden, J. W., Hollocker, K., Babikov, B. V., Timofeev, A. I., Hornberger, M. I., and Nattis, R. (2000). Scientists unearth clues to soil contamination by comparing old and new soil samples. *EOS–Transactions American Geophysical Union* **81**.

Laryea, K. B., Anders, M. M., and Pathak, P. (1995). Long-term experiments on Alfisols and Vertisols in the semiarid tropics. *In* "Soil management - Experimental Basis for Sustainability and Environmental Quality" (R. Lal and B. A. Stewart, Eds.), pp. 267–292. CRC Press, Boca Raton.

Lehmann, J., Lilienfein, J., Rebel, K., Lima, S. D., and Wilcke, W. (2004). Subsoil retention of organic and inorganic nitrogen in a Brazilian savanna Oxisol. *Soil Use Manage.* **20**, 163–172.

Lima, H. N., Schaefer, C. E. R., Mello, J. W. V., Gilkes, R. J., and Ker, J. C. (2002). Pedogenesis and pre-Colombian land use of "Terra Preta Anthrosols" ("Indian black earth") of Western Amazonia. *Geoderma* **110**, 1–17.

Lipiec, J., and Stepniewski, W. (1995). Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil Tillage Res.* **35**, 37–52.

Logan, T. J. (1990). Chemical degradation of soil. *Adv. Soil Sci.* **11**, 187–221.

Masilaca, A. S., Prasad, R. A., and Morrison, R. J. (1985). The impact of sugarcane cultivation on three Oxisols from Vanua Levu, Fiji. *Trop. Agr.* **63**, 325–330.

McBratney, A. B. (1998). Some considerations on methods for spatially aggregating and disaggregating soil information. *Nutr. Cycl. Agroecosys.* **50**, 51–62.

McBratney, A. B., Minasny, B., Cattle, S. R., and Vervoort, R. W. (2002). From pedotransfer functions to soil inference systems. *Geoderma* **109**, 41–73.

McBratney, A. B., Odeh, I. O. A., Bishop, T. F. A., Dunbar, M. S., and Shatar, T. M. (2000). An overview of pedometric techniques for use in soil survey. *Geoderma* **97**, 293–327.

McLaughin, M. J., Reuter, D. J., and Rayment, G. E. (1999). Soil testing - principles and concepts. *In* "Soil Analysis: An Interpretation Manual" (K. I. Peverill, L. A. Sparrow, and D. J. Reuter, Eds.), pp. 1–21. CSIRO Publishing, Collingwood, Victoria.

Molloy, M. G., and Lockman, R. B. (1979). Soil analysis as affected by drying temperatures. *Commun. Soil Sci. Plan.* **10**, 545–550.

Mortimore, M., and Harris, F. (2005). Do small farmers' achievements contradict to nutrient depletion scenarios for Africa? *Land Use Policy* **22**, 43–56.

Motavalli, P. P., Lory, J. A., Nathan, M. V., and Fulcher, C. (2002). Increased access to soil testing databases through the World Wide Web: Opportunities and issues. *Commun. Soil Sci. Plan.* **33**, 1157–1171.

Muchena, F. N., Onduru, D. D., Gachini, G. N., and de Jager, A. (2005). Turning the tides of soil degradation in Africa: Capturing the reality and exploring opportunities. *Land Use Policy* **22**, 23–31.

Nandwa, S. M., and Bekunda, M. A. (1998). Research on nutrient flows and balances in East and Southern Africa: State-of-the-art. *Agr. Ecosys. Environ.* **71**, 5–18.

Neeteson, J. J., Schroder, J. J., and Ten Berge, H. F. M. (2002). A multi-scale system approach to nutrient management research in the Netherlands. *Neth. J. Agr. Sci.* **50**, 141–151.

Niemeijer, D., and Mazzucato, V. (2002). Soil degradation in the West African Sahel: How serious is it? *Environment* **44**, 22–31.

Nye, P. H., and Greenland, D. J. (1960). "The Soil Under Shifting Cultivation." Commonwealth Bureau of Soils, Harpenden.

Oenema, O., and Heinen, M. (1999). Uncertainties in nutrient budgets due to biases and errors. *In* "Nutrient Disequilibria in Agroecosystems: Concepts and Case Studies" (E. M. A. Smaling, O. Oenema, and L. O. Fresco, Eds.), pp. 75–97. CABI Publishing, Wallingford.

Oldeman, L. R., Hakkeling, R. T. A., and Sombroek, W. G. (1991). "World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note," 2nd revised ed. ISRIC, Wageningen.

Pachepsky, Y., and Rawls, W. J. (2005). "Developments of Pedotransfer Functions in Soil Hydrology. Developments in Soil Science 30." Elsevier, Amsterdam.

Pape, J. C. (1970). Plaggen soils in the Netherlands. *Geoderma* **4**, 229–255.

Parker, G. G. (1983). Throughfall and stemflow in the forest nutrient cycle. *Adv. Ecol. Res.* **13**, 57–133.

Payne, G. G., and Rechcigl, J. E. (1989). Influence of various drying techniques on the extractability of plant nutrients from selected Florida soils. *Soil Sci.* **148**, 275–283.

Peters, J. B. (2000). Gambian soil fertility trends, 1991–1998. *Commun. Soil Sci. Plan.* **31**, 2201–2210.

Pickett, S. T. A. (1991). Long-term studies: Past experience and recommendations for the future. *In* "Long-Term Ecological Research: An International Perspective. SCOPE 47" (P. G. Risser, Ed.), pp. 71–88. John Wiley & Sons, Chichester.

Pierce, F. J., and Nowak, P. (1999). Aspects of precision agriculture. *Adv. Agron.* **67**, 1–85.

Pieri, C. (1989). "Fertilité des terres de savanes," Ministère de la Cooperation et CIRAD-IRAT, Paris.

Pieri, C. (1995). Long-term soil management experiments in semiarid Francophone Africa. *In* "Soil Management: Experimental Basis for Sustainability and Environmental Quality" (R. Lal and B. A. Stewart, Eds.), pp. 225–266. CRC Press, Boca Raton.

Poels, R. L. H. (1987). Soils, water and nutrients in a forest ecosystem in Suriname. (Doctoral thesis), Wageningen Agricultural University.

Poels, R. L. H. (1989). Nutrient input and output in undisturbed and silviculturally treated tropical rain forest in Suriname. *Neth. J. Agr. Sci.* **37**, 383–386.

Poszwa, A., Dambrine, E., Ferry, B., Pollier, B., and Loubet, M. (2002). Do deep tree roots provide nutrients to the tropical rainforest? *Biogeochemistry* **60**, 97–118.

Prasolova, N. V., Xu, Z. H., Saffigna, P. G., and Dieters, M. J. (2000). Spatial-temporal variability of soil moisture, nitrogen availability indices and other chemical properties in hoop pine (*Araucaria cunninghamii*) plantations of subtropical Australia. *Forest Ecol. Manage.* **136**, 1–10.

Probert, M. E. (Ed.) (1992). "A Search for Strategies for Sustainable Dryland Cropping in Semi-arid Eastern Kenya." ACIAR, Canberra.

Raun, W. R., and Johnson, G. V. (1999). Improving nitrogen use efficiency for cereal production. *Agron. J.* **91**, 357–363.

Rayment, G. E., and Higginson, F. R. (1992). "Australian Laboratory Handbook of Soil and Water Chemical Methods." Inkata Press, Melbourne-Sydney.

Rhodes, E. R. (1995). Nutrient depletion by food crops in Ghana and soil organic nitrogen management. *Agr. Syst.* **48**, 101–118.

Robert, P. C. (2002). Precision agriculture: A challenge for crop nutrition management. *Plant Soil* **247**, 143–149.

Robertson, G. P. (1982). Regional nitrogen budgets: Approaches and problems. *Plant Soil* **67**, 73–79.

Sanchez, P. A. (1976). "Properties and Management of Soils in the Tropics." John Wiley & Sons, New York.

Sanchez, P. A., Palm, C. A., Davey, C. B., Szott, L. T., and Russel, C. E. (1985). Tree crops as soil improvers in the humid tropics? *In* "Attributes of Trees as Crop Plants" (M. G. R. Cannell and J. E. Jackson, Eds.), pp. 79–124. Institute of Terrestrial Ecology, Huntingdon.

Sanchez, P. A., Villachica, J. H., and Bandy, D. E. (1983). Soil fertility dynamics after clearing a tropical rainforest in Peru. *Soil Sci. Soc. Am. J.* **47**, 1171–1178.

Sandor, J. A., and Eash, N. S. (1995). Ancient agricultural soils in the Andes of Southern Peru. *Soil Sci. Soc. Am. J.* **59**, 170–179.

Schuffelen, A. C. (1974). A few aspects of 50 years of soil chemistry. *Geoderma* **12**, 281–297.

Servenay, A., and Prat, C. (2003). Erosion extension of indurated volcanic soils of Mexico by aerial photographs and remote sensing analysis. *Geoderma* **117**, 367–375.

Sheldrick, W. F., Syers, J. K., and Lingard, J. (2002). A conceptual model for conducting nutrient audits at national, regional, and global scales. *Nutr. Cycl. Agroecosys.* **62**, 61–72.

Sheldrick, W. F., Syers, J. K., and Lingard, J. (2003). Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agr. Ecos. Env.* **94**, 341–354.

Shepherd, K. D., Ohlsson, E., Okalebo, J. R., and Ndufa, J. K. (1996). Potential impact of agroforestry on soil nutrient balances at the farm scale in the East African Highlands. *Fert. Res.* **44**, 87–99.

Shepherd, K. D., Palm, C. A., Gachengo, C. N., and Vanlauwe, B. (2003). Rapid characterization of organic resource quality for soil and livestock management in tropical agroecosystems using near-infrared spectroscopy. *Agron. J.* **95**, 1314–1322.

Shepherd, K. D., and Walsh, M. G. (2002). Development of reflectance spectral libraries for characterization of soil properties. *Soil Sci. Soc. Am. J.* **66**, 988–998.

Sillitoe, P. (1998). Knowing the land: Soil and land resource evaluation and indigenous knowledge. *Soil Use Manage.* **14**, 188–193.

Sillitoe, P., and Shiel, R. S. (1999). Soil fertility under shifting and semi-continuous cultivation in the Southern Highlands of Papua New Guinea. *Soil Use Manage.* **15**, 49–55.

Simonson, R. W. (1995). Airborne dust and its significance to soils. *Geoderma* **65**, 1–43.

Singh, B. R., and Goma, H. C. (1995). Long-term soil fertility management experiments in Eastern Africa. *In* "Soil Management - Experimental Basis for Sustainability and Environmental Quality" (R. Lal and B. A. Stewart, Eds.), pp. 347–382. CRC Press, Boca Raton.

Slattery, W. J., and Burnett, V. F. (1992). Changes in soil pH due to long term soil storage. *Aus. J. Soil Res.* **30**, 169–175.

Smaling, E. M. A. (1993). An agro-ecological framework for integrated nutrient management with special reference to Kenya. (Doctoral thesis), Agricultural University, Wageningen.

Smaling, E. M. A., Stoorvogel, J. J., and Windmeijer, P. N. (1993). Calculating soil nutrient balances in Africa at different scales. 2. District scale. *Fer. Res.* **35**, 237–250.

Smyth, A. J., and Dumanski, J. (1995). A framework for evaluating sustainable land management. *Can. J. Soil Sci.* **75**, 401–406.

Smyth, T. J., and Cassel, D. K. (1995). Synthesis of long-term soil management research on Ultisols and Oxisols in the Amazon. *In* "Soil Management - Experimental Basis for Sustainability and Environmental Quality" (R. Lal and B. A. Stewart, Eds.), pp. 13–60. CRC Press, Boca Raton.

Soane, B. D. (1990). The role of organic matter in soil compactibility: A review of some practical aspects. *Soil Tillage Res.* **16**, 179–201.

Sobulo, R. A., and Osiname, O. A. (1986). Soil properties and crop yields under continuous cultivation with different management systems. *In* "Land Clearing and Development in the Tropics" (R. Lal, P. A. Sanchez, and R. W. Cummings, Eds.), pp. 363–370. A. A. Balkema, Rotterdam.

Sparks, D. L. (Ed.) (1996). "Methods of Soil Analysis. Part 3: Chemical Methods." SSSA, Madison, WI.

Sparks, D. L. (2001). Elucidating the fundamental chemistry of soils: Past and recent achievements and future frontiers. *Geoderma* **100**, 303–319.

Sparks, D. L. (2003). "Environmental Soil Chemistry," 2nd ed. Academic Press, Amsterdam.

Sposito, G., and Zabel, A. (2003). The assessment of soil quality. *Geoderma* **114**, 143–144.

Steiner, R. A., and Herdt, R. W. (Eds.) (1993). "A Global Directory of Long-Term Agronomic Experiments. Vol. 1: Non-European Experiments." Rockefeller Foundation, New York.

Stoorvogel, J. J., Janssen, B. H., and van Breemen, N. (1997). The nutrient budgets of a watershed and its forest ecosystems in the Taï National Park in Côte d'Ivoire. *Biogeochemistry* **37**, 159–172.

Stoorvogel, J. J., and Smaling, E. M. A. (1990). "Assessment of Soil Nutrient Decline in Sub-Saharan Africa, 1983–2000," Rep. No. Report no. 28. Winand Staring Centre-DLO, Wageningen.

Stoorvogel, J. J., and Smaling, E. M. A. (1998). Research on soil fertility decline in tropical environments: Integration of spatial scales. *Nutr. Cycl. Agroecosys.* **50**, 151–158.

Sumner, M. E., and Yamada, T. (2002). Farming with acidity. *Commun. Soil Sci. Plan.* **33**, 2467–2496.

Suprayogo, D., Van Noordwijk, M., Hairiah, K., and Cadisch, G. (2002). The inherent 'safety-net' of an Acrisol: Measuring and modelling retarded leaching of mineral nitrogen. *Eur. J. Soil Sci.* **53**, 185–194.

Tan, K. H. (1996). "Soil Sampling, Preparation, and Analysis." Marcel Dekker, New York.

Taylor, H. M., Upchurch, D. R., Brown, J. M., and Rogers, H. H. (1991). Some methods of root investigations. *In* "Plant Roots and their Environment" (B. L. McMichael and H. Persson, Eds.), pp. 553–564. Elsevier Science Publishers, Amsterdam.

Tinker, P. B. (1960). Soil heterogeneity and sampling procedures under oil palms. *J. West African Ins. Oil Palm Res.* **III**, 9–15.

Van den Bosch, H., De Jager, A., and Vlaming, J. (1998). Monitoring nutrient flows and economic performance in African farming systems (NUTMON) - II. Tool development. *Agr. Ecosyst. Environ.* **71**, 49–62.

van der Pol, F., and Traore, B. (1993). Soil nutrient depletion by agricultural production in southern Mali. *Fert. Res.* **36**, 79–90.

van Noordwijk, M. (1999). Nutrient cycling in ecosystems versus nutrient budgets of agricultural systems. *In* "Nutrient Disequilibria in Agroecosystems: Concepts and Case Studies" (E. M. A. Smaling, O. Oenema, and L. O. Fresco, Eds.), pp. 1–26. CABI Publishing, Wallingford.

van Noordwijk, M., Floris, J., and de Jager, A. (1985). Sampling schemes for estimating root density distribution in cropped fields. *Neth. J. Agr. Sci.* **33**, 241–262.

Van Ranst, E., Verloo, M., Demeyer, A., and Pauwels, J. M. (1999). "Manual for the Soil Chemistry and Fertility Laboratory." University of Gent, Gent.

van Reeuwijk, L. P. (1998). "Guidelines for Quality Management in Soil and Plant Laboratories." FAO/ISRIC, Rome/Wageningen.

Walley, F., Fu, G. M., van Groenigen, J. W., and van Kessel, C. (2001). Short-range spatial variability of nitrogen fixation by field-grown chickpea. *Soil Sci. Soc. Am. J.* **65**, 1717–1722.

Warkentin, B. P. (1999). The return of the "other" soil scientists. *Can. J. Soil Sci.* **79**, 1–4.

WinklerPrins, A. M. G. A., and Sandor, J. A. (2003). Local soil knowledge: Insights, applications, and challenges: Preface. *Geoderma* **111**, 165–170.

Woomer, P. L., Martin, A., Albrecht, A., Resck, D. V. S., and Scharpenseel, H. W. (1994). The importance and management of soil organic matter in the tropics. *In* "The Biological Management of Tropical Soil Fertility" (P. L. Woomer and M. J. Swift, Eds.), pp. 47–80. John Wiley & Sons, Chichester.

Wortmann, C. S., and Kaizzi, C. K. (1998). Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agr. Ecosyst. Env.* **71**, 115–129.

Yaalon, D. H. (1971). Soil-forming processes in time and space. *In* "Paleopedology: Origin, Nature and Dating of Paleosols" (D. H. Yaalon, Ed.), pp. 29–39. Israel Universities Press, Jerusalem.