Soil Fertility Decline: Definitions and Assessment

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INTRODUCTION

In permanent agricultural systems, soil fertility is maintained through applications of manure, other organic materials, inorganic fertilizers, lime, the inclusion of legumes in the cropping systems, or a combination of these. In many parts of the world the availability, use, and profitability of inorganic fertilizers have been low whereas there has been an intensification of land-use and an expansion of crop cultivation onto marginal soils. As a result, soil fertility has declined and it is perceived to be widespread, particularly in sub-Saharan Africa.[1–3] Soil fertility decline is considered as an important cause for low productivity of many soils.[4,5] It has not received the same amount of research attention as soil erosion; possibly as soil fertility decline is less visible and less spectacular, and more difficult to assess.

Assessing soil fertility decline is difficult because most soil chemical properties either change very slowly or have large seasonal fluctuations; in both cases, it requires long-term research commitment. There are several other confounding factors that make assessment of soil fertility decline complicated (e.g., spatial and temporal variation, soil analytical methods), and, for those reasons, other techniques have been used to estimate the rates and changes in soil fertility decline. The methods to assess soil fertility decline are described in this entry.

DEFINITIONS

Growing agricultural crops implies that nutrients (N, P, K, etc.) are removed from the soil through the agricultural produce (food, fibre, wood) and crop residues. Nutrient removal may result in a decline of the soil fertility if replenishment with inorganic or organic nutrient inputs is inadequate. Soil fertility is defined as "the quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops."[6]

Although it omits the importance of soil physical and biological conditions for crop productivity, it is a useful simplification. A decline in soil fertility implies a decline in the quality of the soil, and soil fertility decline is defined as "the decline in chemical soil fertility, or a decrease in the levels of soil organic matter, pH, cation exchange capacity (CEC), and plant nutrients."

Soil fertility decline thus includes

1. Nutrient depletion or nutrient decline (larger removal than addition of nutrients).
2. Nutrient mining (large removal of nutrients and no inputs).
3. Acidification (decline in pH and/or an increase in exchangeable Al).
4. The loss of organic matter.
5. An increase in toxic elements (e.g., Al, Mn).

ASSESSMENT OF SOIL FERTILITY DECLINE

Different data types are used to assess soil fertility changes: i) expert knowledge; ii) monitoring of soil chemical properties over time or at different sites; and iii) nutrient balances. Some of these data can be relatively easily collected, whereas some other data require long-term commitment and involve high cost. Each data type has specific advantages and disadvantages, and the type of data collected is determined by the research plan, the financial conditions, and objectives of the study (Table 1).

Expert Knowledge

Farmers and other users of the land have expert knowledge about their soils; this is mostly empirical knowledge, which is not soil process or data oriented, but yield or management oriented.[7] Yield decline as observed by a farmer could, however, 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. It is difficult to distinguish soil fertility decline from other factors, and farmers' knowledge on soil fertility decline must be substantiated by other types of data, e.g., crop yield, weather conditions or pests, and disease information. Farmers' knowledge can be instrumental in selection of sampling sites or for additional information and various examples in the literature exist where such information was used to investigate long-term changes in soil fertility.[8,9] Another form of expert knowledge is

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Table 1 Data types in soil fertility decline studies and their advantages and disadvantages

Data type	Short description	Advantages	Disadvantages
Expert knowledge	Combination of field observations with general knowledge	Easy to obtain, rapid assessment, useful for small-scale studies	Subjective, not quantitative
Measured values Type I Chronosequential	Monitoring soil properties over time	Accurate, hard data, using existing data	Slow, expensive, contamination of monitoring sites, spatial and temporal variability, sample storage
Measured values Type II Biosequential	Comparing soil properties under different land-use	Easy to obtain, rapid, relatively hard	Soils at sampling sites may differ, unknown land-use history of sites, spatial and temporal variability
Nutrient balances and budgets	Combination of existing data with pedotransfer functions or models	Using existing data, fairly rapid, indicative, appealing outcome	Not very hard, require computer power

(From Ref.[4].)

that of soil scientists and agronomists who can make some estimation on the soil fertility status and its changes based on vegetation or crop growth. As with farmers' knowledge, such information is important but not very quantitative.

MEASURED CHANGE IN SOIL CHEMICAL PROPERTIES

Two different approaches have been used to monitor soil chemical properties. First, soil dynamics can be monitored over time at the same site, which is called chronosequential sampling[10] or Type I data.[11] Type I data show changes in a soil chemical property under a particular type of land-use over time. Usually the original level is taken as the reference level to investigate the trend in such changes. 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. 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.[12] Type I data are also useful to assess the sustainability of land management practices in the tropics,[13] but limited data sets exist as they require long-term research commitment and detailed recordings of soil management and crop husbandry practises.[14]

In the second approach, soils under adjacent different land-use systems are sampled at the same time and compared. This is called biosequential sampling,[10] Type II data,[11] "sampling from paired sites" in the soil science literature from Australia,[15,16] the "space-for-time" method,[17] and the "inferential method."[18] The underlying assumption is that the soils of the cultivated and uncultivated land are the same soil series, but that differences in soil properties can be attributed to the differences in land-use. Obviously, this is not always the case and the uncultivated land may have been of inferior quality and therefore not planted. Also, spatial variability may be confounded with changes over time when for example tree crops of different age are sampled at the same time, and soil properties are often confounded with genetic improvement and silvicultural practices.[11] Other confounding factors are differences in clay content, soil depth, or unknown history of land-use, and these largely affect the usefulness of Type II data for the assessment of soil fertility decline. In ecology, Type II data studies have often proved to be misleading as functional parameters like nutrient availability and plant-animal interactions have been conspicuously underrepresented.[17] When carefully taken, however, biosequential soil samples can provide useful information, and this sampling strategy has been followed in a considerable number of studies.[14]

Monitoring of soil chemical properties gives information on how soils respond to agricultural activities and whether soil fertility decline takes place. Spatial and temporal variation requires a cautious selection of sampling sites, an appropriate number of replicated observations, and a careful interpretation of the results. Provided these are met, it may be difficult to extrapolate the information or to derive maps of the patterns observed in single pedons. Coupling the soil information to soil maps in a geographical information system (GIS) provides opportunities to map soil fertility decline in different areas. A large amount of data of sufficient quality is needed before such maps can be derived, and there are few examples where measured soil fertility decline was coupled to a GIS.[19] More studies exist in which the nutrient balance has been used to map soil fertility decline.

Nutrient Budgets and Balances

A third way of studying soil fertility decline embraces a semiquantitative approach using partial nutrient balances and budgets. Such studies operate at a much coarser (smaller) scale viz. national or supranational scale, and existing soil data are combined with pedotransfer functions (regression analysis between some soil or other parameters) into a GIS to estimate the decline in soil fertility at a given location.[20] This is essentially a mechanistic modeling approach in which expert knowledge is also important. It is generally perceived that such studies are not to replace soil-monitoring efforts but must be seen as the best possible way of getting the most out of available data.[14] The outcome of such studies provides qualitative, comparative, and spatial information on the decline in soil fertility.

Nutrient balances provide a convenient and biologically meaningful context within which to organize what is known about a system's biogeochemical cycles, put nutrient pools and fluxes into perspective, and can lead to considerable insight into processes that regulate nutrient cycling. Nutrient balances help to guide system management decisions and direct the course of future research.[21] The use of nutrient balances has been encouraged through a systems approach to both improve food crop production and maintain the soil resource base.[22]

CONCLUSIONS

Evaluating soil fertility decline can be done with different types of data. There are data from measured soil chemical properties, and such data can be from the same plot that is permanently cultivated (Type I data), or from plots under different land-use (Type II data). Soil fertility decline can also be assessed in a more semiquantitative way using nutrient balances. Each data type has its merits and drawbacks, and data are either quickly collected and indicative for what is going on, or the collection is more tedious which usually implies that the data are harder and more meaningful. Boundary conditions need to be properly set and the study must indicate whether soil fertility decline is assessed for a pedon, watershed, region, country, etc. At the watershed level, soil fertility may decline in one pedon but it may increase in a lower pedon, which illustrates the need for the delineation of spatial boundaries. Soil fertility decline studies must also have temporal boundaries and in general long-term observations yield better results.

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 a sufficient amount of subsamples and samples before rigid conclusions can be drawn. Soil fertility decline studies are largely dependent on soil chemical analysis, which include 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. The choice of the analytical technique in relation to the soil property or soil type is another potential source of errors.

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