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SOIL FERTILITY DECLINE ON AGRICULTURAL PLANTATIONS IN THE TROPICS

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ABSTRACT

Maintaining the soil chemical fertility is a key prerequisite to sustain crop productivity in the tropics. Several studies perceive that soil fertility decline is widely spread in tropical regions and that it is caused by inadequate nutrient replenishment and high losses as compared to natural ecosystems. Although this has been recognised for some decades, there is a need for hard data on soil changes to improve our understanding of agricultural systems and to design sustainable cropping systems. Most studies on soil fertility decline focussed on subsistence farmers and used nutrient balances to investigate agricultural sustainability. In this paper changes in soil chemical properties under different land-use system in the humid and sub-humid tropics are discussed with special attention to agricultural and forestry plantations. There were clear differences in the rate of soil fertility decline between land-use systems. Annual cropping systems and sugar cane showed the largest decline in soil fertility. Soil fertility decline on perennial crop plantations (sisal, cocoa, rubber, oilpalm) was lower, whereas soil changes on forest plantations were variable. Soil organic C declined on average in all land-use systems. The decline was largest in annual cropping systems and lowest in soils under perennial crops. Differences are related to soil management systems (level of nutrient inputs) and crop characteristics (trees vs. annual crops). As plantation agriculture is a major contributor to the income of many tropical countries and provides hundreds of thousands of people with labour and income, it is crucial that the soil resource base of agricultural plantations is sustained and the judicious use of inorganic fertilisers is indispensable.

Key words: plantation agriculture, soil fertility, tropics, inorganic fertilizers

INTRODUCTION

Currently, more than 95% of the human population increase is in the tropics, which puts existing agricultural systems under stress. In order to produce sufficient food and to curb land degradation, permanent and productive cropping systems need to be developed. The sustainability of permanent cropping systems is largely affected by the judicious management of the soil chemical fertility. This has been recognised for many decades, but there is a need for hard data on soil changes and nutrient management strategies in order to improve our understanding of agricultural systems and to design sustainable cropping systems in the tropics.

So far the discussion on soil productivity decline, nutrient mining and sustainable land management in the tropical regions has focussed on low-external input agriculture by subsistence farmers (Henao and Baanante, 1999; Pieri, 1989; Scoones and Toulmin, 1999; Smaling et al., 1999). This paper has its main focus on agricultural plantations, which have been largely neglected in the discussion on soil fertility decline and sustainable land management. Another major difference with the existing studies is that soil fertility decline is assessed using soil chemical data whereas other studies have used nutrient balances as the main tool to evaluate the sustainability of the systems (Hartemink, 2003).

The rationale for the focus on plantation agriculture is that it is an important form of land-use in the tropics and in many countries the area under plantation crops has expanded rapidly in the past decades. For example, in Indonesia the area under oilpalm expanded from 133,000 in 1970 to almost 1.8 million ha by the mid-1990s (Fairhurst, 1996). In Malaysia the extent of oil palm increased from about 150,000 ha in the early 1970s to over 3 million ha at the end of 1998. Plantation agriculture is contributing to the macro-economies in many tropical countries and provides much employment. Even in middle-income countries such as Malaysia total export earnings from oil palm plantations are 6% of the Gross National Product (Jalani, 1998). In Ivory Coast a group of plantation crops produce 22% of Gross National Product (Tiffen and Mortimore, 1988). As yields are usually higher on plantations than on smallholder farms, they may contribute proportionally more to GNP than the area they occupy, for example in Kenya tea plantations comprise 35% of the area under tea but they produce more than 60% of the total output (Tiffen and Mortimore, 1988).

Plantation crops are sometimes referred to as non-CGIAR crops (Smith, 2000). Despite the importance of plantation agriculture, long-term effects of plantation cropping on the soil have received little research attention. No systematic effort has been undertaken to prove that plantation agriculture is a more sustainable form of land-use than arable cropping. However, it has been long assumed that a perennial plant cover protects the soil better than an annual crop (Jacks and Whyte, 1939), and it has also been stated that land degradation under perennial crops is usually less than in arable farming under similar conditions (Hartemink, 2005; Ruthenberg, 1972).

The most important plantation crops are cocoa, coffee, tea, coconut, bananas, rubber, oil palm, jute, sisal and hemp (Burger, 1994). Other important plantation crops are sugar cane, tobacco, cinchona and pine apple. Oil palm is currently the most valuable plantation economy of the tropical world (Henderson and Osborne, 2000). The world plantation belt runs from Central and South America across the equatorial regions of Africa to Asia, to the Far East and Queensland in Australia.

The exact extent of plantations in the tropics is not known, but several reports have indicated that the area under plantation agriculture has increased in the past decades. Estimates from the 1970s showed that about 4% of the farming areas in the tropics are plantations (Sanchez, 1976). Based on the cultivated area, the plantation area in the mid 1970s was about 20 million ha. Nair (1984) estimated that perennial plantation crops in 1984 occupied about 8% of the total arable area in the tropics, which suggests an increase in area under plantations. Global statistics on the area under perennial cropping can be obtained from FAO databases but no distinction is made between smallholders and plantations (Hartemink, 2003).

Large plantation areas occur in Malaysia where the extent of oil palm increased from about 150,000 ha in the early 1970s to 2.0 million ha in 1990 (Hardter et al., 1997) to 2.6 million ha in 1997 (Jalani, 1998) and over 3 million ha at the end of 1998. The increase occurred at the expense of the rain forest, and rubber and cocoa (Pushparajah, 1998). The area under cocoa in Malaysia grew from 10,000 to 307,000 ha between 1970 and 1986 (Webster and Watson, 1988), but cocoa areas have declined to about 100,000 ha in 1998 because of labour shortages. It has been estimated that at least 0.8 million ha new oil palm plantings in Malaysia involved clearance of forest (PORIM, 1994).

The Malaysian government is actively promoting the cultivation of tree crops with a view to compensate for the loss of tree cover because of forest felling and to generate income for both the smallholder and plantation section. Another country where tree crops are actively promoted is Côte d'Ivoire. Cocoa production in Côte d'Ivoire increased from 150 Mg in the 1960s to over 1,100 Mg in the mid-1990s, which reflect a large increase in the area under cocoa that occurred largely at the expense of the rainforest. In Côte d'Ivoire cocoa is mainly cultivated by smallholders (Hartemink, 2005).

An important plantation crop of which the area has been substantially increased is sugar cane. In the 1960s, sugar production in the world was about 64 million Mg, of which half was produced in developing countries (FAO, 1996). By the mid 1990s, production had increased to 119 million Mg, of which 40 million Mg was produced in Asia and the Pacific (Hartemink and Wood, 1998). Between the mid-1960s and 1990s the largest expansion of sugar production occurred in India (from 3 to 15 million Mg) and Brazil (from 5 to 10 million Mg).

Part of the increase in sugar production has resulted from improved agronomic practices, but in many countries, increased production has resulted from a larger area under sugar cane. In Cuba and Barbados there has, however, been a decline in production in the past decades (Anderson et al., 1995).

In Papua New Guinea, where sugar cane is indigenous, commercial sugar cane only started in 1979 (Hartemink, 1998). Also the area under other plantation crops has much expanded in Papua New Guinea and more than 80,000 ha has been planted with oil palm since the mid-1960s. Overall, plantation crops cover less than 4% of the total land under agriculture in Papua New Guinea (Hartemink and Bourke, 2000).

Very few plantation crops have been as drastically reduced as the sisal in East Africa, especially in Tanzania. In the 1960s, sisal production in Tanzania equalled 234,000 Mg or nearly one-third of the world's annual sisal fibre production, but in the mid-1980s, Tanzania's sisal production had declined to about 30,000 Mg of fibre per year. In the Tanga Region, there were more than 70 large sisal plantations in the 1960s, but in the late 1980s less than 20 were fully operational (Hartemink, 1997).

In this paper soil fertility decline on agricultural plantations is reviewed using soil chemical data. Data from different sites under different land use systems are compared but also data are presented that monitored soil chemical properties over time. Five contrasting land use systems are compared in the humid and subhumid tropics: (i) annual crops, (ii) perennial crops, (iii) forest plantations, (iv) sugar cane plantations, and (v) sisal plantations.

DATA SOURCES AND ANALYSIS

There are few soil fertility studies involving long-term (>10 years) measurements in soil chemical fertility in the same field. Most studies measured changes over shorter periods and were focused on the effects of organic and inorganic nutrient inputs on soil properties and crop production. These studies often included a control treatment in which no nutrient inputs were made. They are considered here as baseline data showing what happens to the soil chemical fertility if no organic and inorganic fertilisers are used. As a considerable number of farmers in the tropics use little or no nutrient inputs, particularly in sub-Saharan Africa, such data are useful and could be treated as point of departure for subsequent studies on integrated nutrient management. The data also provide evidence for the widespread notion that soil fertility is declining under permanent cropping in the tropics. Few studies have been conducted with the sole aim to investigate changes in soil fertility under permanent cropping.

Studies from the humid and subhumid tropical regions in Africa, Asia, and Central America are reviewed. Occasionally data from tropical Australia and China, and from New Zealand are included, for example when they were of high quality and to supplement data for some soil orders and cropping systems. Such data are also included to enhance the understanding between soil change and soil management under the given set of agro-ecological conditions.

In this paper only data from upland, well-drained soils are included. The difference between sampling times should have been at least two years for both Type I and Type II data. Soil classification of the experimental site had to be provided in the papers. For convenience, all data in this paper are presented by the soil orders of Soil Taxonomy. Only studies were selected in which replicated data are given.

The data are grouped based on the mode of collection (Type I and Type II). Problems with Type II data arise when (i) no soil classification is given, (ii) soils under cultivation differ from uncultivated soils, (iii) the period of cultivation is unknown, (iv) the land-use history of the cultivated soils is unknown i.e. whether inorganic fertilisers were used. Studies in which one or more of these factors were uncertain are not included in this paper or discussed separately.

In summary, the principal selection criteria for data to be included were: subsistence farmer or experimental plots which were unfertilised and permanently cultivated with annual crops in the humid or subhumid tropics, replicated data, soil classification provided, and the period of observation had to exceed two years.

A wide range of analytical procedures is available to measure soil chemical properties. Soil chemical data presented throughout this paper were restricted to certain methods in order to make comparison between sites, crops and soils possible; these methods were:

- Soil pH usually measured in a soil-water suspension in the ratio 1:2.5 or 1:5. If the pH was determined in 1 *M* KCl as is sometimes done in strongly acid soils to measure the zero point of charge, or in NaF (in allophane-rich soils) the data were not used. If the pH was determined in 0.01 *M* $CaCl_2$ (common in Australia), this has been indicated and the data have been included.
- Soil organic C is mostly determined by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley & Black) or dry combustion, and total N by Kjeldahl (concentrated H_2SO_4) or dry combustion. Although both methods have their drawbacks, they are very widely used which makes exchange and comparison of soil C and N data possible. As will be shown later, total soil organic C is not a very sensitive parameter for short-term comparisons.
- Various methods exist for the determination of available P. The most common methods are Bray I and II, which uses NH_4F and HCl as extractant, Olsen (uses $NaHCO_3$ extractant), Truog - extraction by H_2SO_4 and $(NH_4)_2SO_4$ and Mehlich, which uses H_2SO_4 and HCl as extractant.
- Exchangeable cations Ca, Mg, K, Na and CEC, percolation by 1 *M* NH_4OAc followed by spectrophotometry (K, Na), AAS (Ca, Mg) and titration (CEC).

All units for soil fertility properties are standardised, as follows: organic matter (in %) has been multiplied by 5.8 to obtain organic C in g kg^{-1}; organic C and total N in % has been multiplied by 10 to obtain C and N in g kg^{-1}; exchangeable cations in ppm or mg kg^{-1} have been multiplied with 0.0499 (Ca), 0.0822 (Mg), and 0.0255 (K) to obtain levels in $mmol_c$ kg^{-1} soil; exchangeable cations (Ca, Mg, K) in me 100 g^{-1} have been multiplied by 10 to obtain levels in $mmol_c$ kg^{-1} soil.

For convenience, all soil chemical data were entered in Excel spreadsheets for storage and in order to facilitate calculations on the data. For each soil chemical property (χ) measured over a given time span (t), the following was 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, and this value is reported in this paper.

RESULTS

Rates of change as calculated for individual soil properties were also calculated for each of the five land-use systems (annual crops, perennial crops, forest plantations, sisal and sugar cane) - Fig. 1. The largest rates of change in soil chemical properties were found in soils under annual crops, and much of the data from the annual cropping systems were short-term (< 10 years). Rates of change under sugar cane were also fairly large followed by the rates of change in soils under sisal. The rates of change under perennial cropping were much lower, but in soils of forest plantations the rates were variable and in various studies, positive rates of change were found indicating an increase in soil chemical fertility.

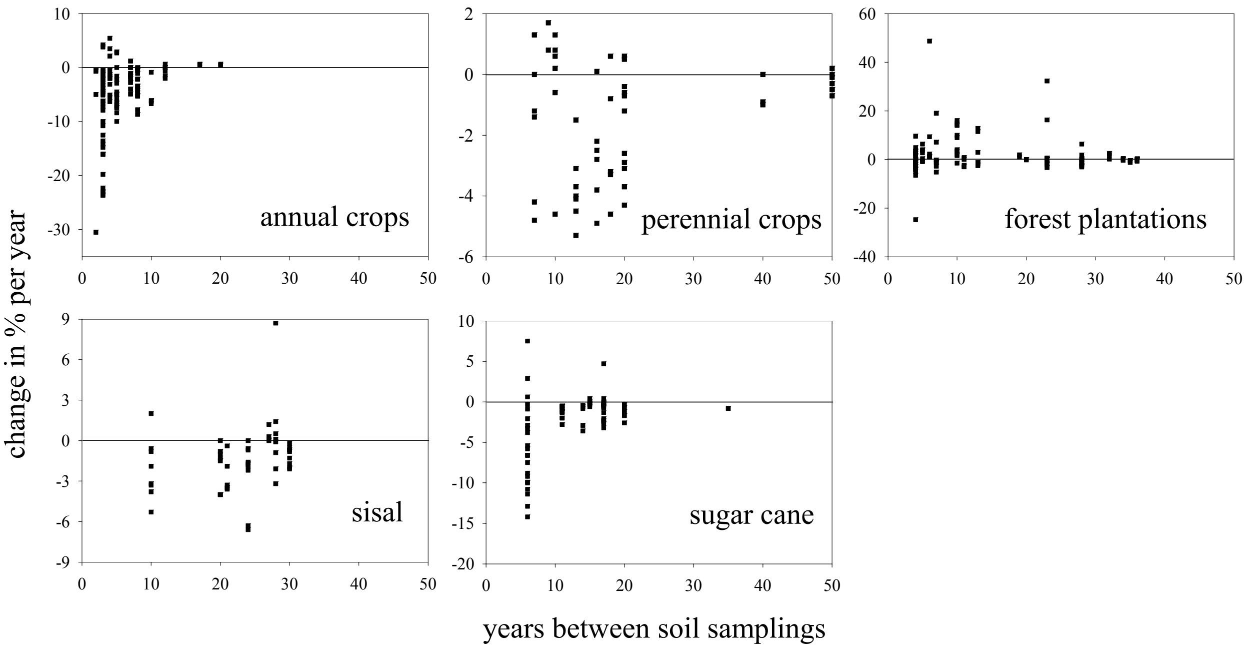

Fig. 1 Changes in topsoil (average 0.16 m depth) chemical properties (pH, organic C, total N, available P, CEC and exchangeable Ca, Mg and K) for different land-use systems related to period of observation. Note that scales of y-axis differ. After Hartemink (2003)

For each land-use system, the average rate of change was calculated per soil chemical property (Table 1). Although there were differences in the period of observation, rates of change were highest in soils under annual crops, followed by sugar cane. Rates of change in soils under sisal and perennial crops were about similar, and the rates were positive for most soil chemical properties under forest plantations.

Table 1 Mean change in topsoil chemical properties for different land-use systems, in percentage per year (± 1 SD). After Hartemink (2003)

		Woody plantation crops		Herbaceous plantation crops	
	Annual crops	Perennial crops	Forest plantations	Sisal	Sugar cane
pH	–1 ±2	<–0.5 ±1	<+0.5 ±1	–1 ±1	–1 ±1
Organic C	–5 ±6	–1 ±2	–1 ±5	–1 ±1	–2 ±2
Total N	–5 ±7	–1 ±3	+2 ±3	–2 ±1	–4 ±4
Available P	–4 ±8	–1 ±2	+2 ±5	–2 ±2	–1 ±3
CEC	–6 ±4	–3 ±2	+8 ±16	–1 ±1	–1 ±2
Exchangeable Ca	–7 ±4	–3 ±2	+5 ±14	–2 ±2	–5 ±6
Exchangeable Mg	–5 ±7	–1 ±3	+1 ±6	–1 ±4	–2 ±6
Exchangeable K	–7 ±8	–3 ±2	+3 ±7	–2 ±2	–3 ±4

Soil organic C declined on average in all land-use systems, but rates were found to be higher under annual crops and sugar cane. Also rates of change in soil N were high under annual crops. Rates of change in exchangeable cations were particularly high under sugar cane, which follows the general soil acidification trend. Part of the variation in the data is explained by the fact that these are the mean data from different soils

DISCUSSION AND CONCLUSIONS

This study in two important ways from earlier studies on soil fertility decline: (i) the assessment of soil fertility decline is based on soil chemical data, and (ii) it focuses on plantation crops (Hartemink, 2003). A quantitative approach has been taken and the data were used to calculate rates of change in soil chemical properties and to compare annual and various perennial cropping systems.

There are differences between land-use systems in the rate of soil fertility decline, which is related to crop characteristics and land management aspects. Annual cropping systems showed the largest rate of decline in soil fertility followed by the rates in soils under sugar cane. Rates of change in perennial cropping systems, including sisal, were lower than the rates under annual crops or sugar cane. Under forest plantations, rates of change were variable and in a number of studies the soil chemical fertility increase with time.

Changes in soil chemical properties under permanent cropping are reported from various parts of the tropics and under different land-use systems. There were differences between the land-use systems but the data presented in this paper confirmed the results from other studies on soil fertility decline and nutrient mining in the tropics (e.g. Smaling et al., 1999). The decline in soil fertility is caused by the inadequate use of inorganic fertilisers and other nutrient inputs, and the increased loss of nutrients by erosion, leaching and gaseous losses as compared to natural ecosystems. Soil fertility decline should be a major concern because of inadequate inorganic fertiliser, lime and manure applications, and the need to maintain and increase crop yields to feed the ever-growing population (Lal, 2001).

In some studies, the pattern in soil fertility decline was ambiguous. The absence of soil fertility decline under permanent cropping without nutrient replenishment is extremely implausible and the result might be due to errors in the sampling system employed or in the soil analytical procedures. It implies that methodologies for its assessment have not been used with rigour, but this can be partly understood as the systems under study - like all terrestrial ecosystems - are intractably complicated. Although the complexity is no excuse for a deficiency in scientific rigour, it may be an important factor explaining some of the variation and aberrant results reported in this paper (Hartemink, 2003).

Soil organic C declined on average in all land-use systems. The decline was largest in annual cropping systems and lowest in soils under perennial crops. Also the pH showed the largest decline under annual crops followed by the pH decline in soils under sugar cane cultivation. Although it is generally perceived that soil fertility decline is a problem in annual cropping systems of subsistence farmers, this paper has provided firm evidence that soil fertility decline also takes place on agricultural plantations.

Sustainability implies a steady state with a certain degree of natural variation. It is clear that many of the annual cropping systems in which soil fertility declined, are not sustainable from a soil chemical fertility point of view. As rates of change in soil fertility of annual cropping systems were on average much higher, it could be concluded these are less sustainable systems than cropping systems with perennials. Quantification of soil fertility changes as well as its impact on crop productivity is important for determination of the long-term sustainability of the plantation industry. This study has shown that soil chemical data can be used. The study confirms that soil fertility decline occurs in many land-use systems in the tropics and it is likely that the decline in soil fertility under annual cropping systems is contributing to the stagnation in the growth of food production experienced in some parts of the world, as in sub-Saharan Africa.

This study has shown that soil fertility decline can be serious under plantation cropping, which will sooner or later affect production and thus reduce the export and income of a country. Plantation agriculture is a major contributor to the income of many countries in the tropics and provides hundreds of thousands of people with labour and income. Sustaining and improving the production capacity of agricultural plantations is therefore important, and a decline in soil fertility should be avoided.

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