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Soil nutrient depletion by agricultural production in Southern Mali

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Abstract

The degree of soil mining by agricultural production in Southern Mali is assessed by calculating nutrient balances: differences between the amount of plant nutrients exported from the cultivated fields, and those added to the fields. Export processes include extraction by crops, losses due to leaching, to erosion, and to volatilization and denitrification. Inputs include applications of fertilizer and manure, restitution of crop residues, nitrogen fixation, atmospheric deposition of nutrients in rain and dust, and enrichment by weathering of soil minerals. Nutrient balances are calculated for N, P, K, Ca, and Mg. Both pessimistic and optimistic estimates are given.

The resulting figures indicate, even when the most optimistic estimates are used, large deficits for nitrogen, potassium and magnesium. For the region as a whole, the calculated deficits are −25 kg N/ha, −20 kg K/ha, and −5 kg Mg/ha. Further, acidification is to be expected, in particular in areas where cotton is grown. The deficits are caused by traditional cereal crops, but also by cotton and especially by groundnut. The latter two crops are fertilized, but insufficiently. It is important to note, that the negative figures are not automatic recommendations for application of a specific amount of additional fertilizer. For phosphorus and calcium the balance of the region as a whole appears to be about in equilibrium, but locally large variations may occur.

Erosion and denitrification are important causes of nutrient loss, accounting respectively for 17 and 22% of total nitrogen exports. Atmospheric deposition and weathering of minerals in the soil are still important nutrient inputs that contribute as much as nutrients as organic and mineral fertilizer combined. Nutrient depletion is very large in comparison to the amount of fertilizer applied. Drastic options, such as doubling the application of fertilizer or manure, or halving erosion losses, even if feasible, would still not be enough to make up for the calculated deficits.

The annual value of withdrawn nutrients, if related to prices of fertilizers, varies between 10,000 and 15,000 FCFA/ha (40–60 US $/ha). Since the estimated average gross margin from farming in this area is 34,000 FCFA/ha (123 US $/ha), soil mining appears to provide an amount equal to 40% of farmers' total income from agricultural activities.

Introduction

Agriculture in sub-Saharan Africa is in crisis: Its share in agricultural export is declining and in spite of increasing food imports, food shortages, and even famine are the rule, rather than the exeption. Statistics indicate stagnating production per hectare, which, in combination with rapid population growth, results in decreasing production per capita. As a consequence rural incomes are falling.

The relation between stagnating agricultural production, low rural income and ecological degradation has often been emphasized. Land degradation is associated with poverty, both as a cause, through falling production levels and as a consequence, as farmers lack the capital to invest in land to maintain its fertility, and have no energy for land conservation measures. The relations are, however, complex and varied. There is for instance some evidence that better financial incentives alone do not necessarily stimulate sustained production by more and better use of inputs [20]. Obviously, combatting land degradation requires parallel measures in many other areas such as land use, land tenure, risk spreading, extension, education and population control.

Efficient allocation of means and efforts to sustain agricultural production and prevent land degradation requires insight in the relative importance of the underlying processes. One of these processes is the depletion of the soil's nutrient reserves. It is known that West African farmers are depleting their soils in order to provide for their subsistence. Traditionally the absence of fertilization was compensated through long fallow periods, in which nutrient reserves were restored. With growing population pressure and expanding farm sizes, this recovery period is being lost. More or less imperceptibly farming passes into mining. This holds for both "traditional", cereal-based, cropping systems and for systems including more recently introduced cash crops. Mining by traditional cereal crops has been described for example for millet farmers on the Mossi plateau in Burkina Faso [5], whereas an example of mining by a cash crop of is described for the introduction of coton in Chad [10]. Although in a recent review of the French research on soil fertility in West Africa, Pieri qualifies the West African soils as "soils of good hope", he emphasizes that, in the present situation, depletion occurs under most of the common cropping systems, as a consequence of both insufficient fertilizer application and high nutrient losses [19].

In this study declining soil fertility is described in terms of nutrient depletion, as a logical consequence of current agricultural practices.

Nutrient requirements; the cost of sustainable production

Guaranteeing maintenance of soil fertility is governed to a large extent by the balances of the chemical elements that serve as plant nutrients. If export and losses of a nutrient exceed inputs by i.a. fertilization and weathering of soil minerals over a longer period of time, the resulting negative balance represents a process of soil mining. The degree of soil mining can be established through quantification of the nutrient balances.

Nutrient balances under prevailing cropping systems in West Africa, have been presented by various authors [1, 3, 4, 8, 13, 18, 24, 27]. Other authors present data on various processes of import and export [12, 17, 22, 23]. In the present study, nutrient balances have been calculated for a specific region, with all its different cropping systems. Data from the literature cited above are applied to the crops grown in the study area, and combined with locally collected production statistics. A comparable approach has been followed by Stoorvogel and Smaling for nutrient balances of all countries of Sub-Saharan Africa [26], and by van Duivenbooden for a region in central Mali [9].

Nutrients withdrawn from the soil store, can be valued on the basis of current fertilizer prices, in a way comparable to Stocking's accounting of the cost of soil erosion [25]. Thus, taking into account the value of the net imported or exported nutrients, an element is provided for a sound economic evaluation of cropping systems. To enable sustainable agricultural production, the withdrawn nutrients should be restituted to the soil. Consequently, their market value constitutes part of the production costs of agricultural products. Relating that value to farmers' income from agricultural activities, allows estimation of the degree to which this income is derived from soil mining. Calculation of nutrient balances thus provides a number of indicators for the degree of sustainability of agricultural production systems.

The region of study

The study refers to cropping systems in Southern

Mali, a region in the West African Soudan zone, where traditionally sorghum and millet are main crops. Cotton has been introduced here 40 years ago, and is the most important cash crop at the moment. CMDT (Compagnie Malienne pour le Développement des Textiles), originally a cotton development agency, is now responsible for rural development in the region, providing all agricultural services. Its statistics on agricultural production and prices have been used in this study.

In the seventies, with the expansion of cotton in Southern Mali, fertilizer application per hectare increased. From 1982 onwards, as a result of the structural adjustment policy imposed by IMF, CMDT no longer was in a position to subsidize fertilizers. It has been calculated that, with rising fertilizer prices, it was more profitable for farmers, at least in the short term, to direct investments and efforts towards expansion of the cultivated area rather than towards increasing production per unit area [2]. This, in fact, corresponded with the actual developments in the region: The trend of increasing fertilization reversed, as fertilizer application per hectare of cotton rapidly decreased [14]. The increase in cotton production between 1982 and 1986 can be attributed for 81% to expansion of the cotton area, while only 19% is due to yield improvements of 1.6% annually [6, 7]. These developments increase risks of land degradation through nutrient depletion.

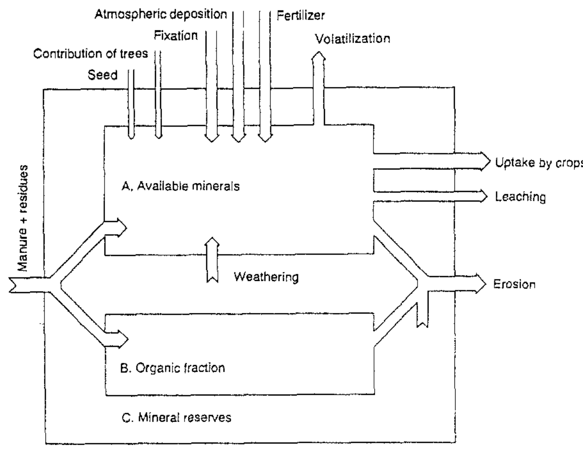
In this study the degree of soil mining actually taking place in the region is quantified. A more complete report on the study, with details all basic data used for the import and export processes has been published elsewhere [21].

Methodology

The net balance of nutrient fluxes

The approach followed for the calculation of nutrient balances has been described by Pieri and Frissel [19, 11]. The nutrient elements in the soil are classified in three pools:

Pool A: mineral elements available to plants
Pool B: elements associated with soil organic matter



Sources: Frissel, 1978; Pieri, 1989

Fig. 1. Nutrient fluxes in the soil.

Pool C: mineral reserves in the soil

The fluxes of elements in and out of the system, and between the pools are presented in Fig. 1.

To restrict the analysis to long term dynamics, elements in pool A and pool B are considered together as nutrients. The combined size of both pools determines to a large extent the fertility of a soil. Since we are interested in the overall balance, the internal flows between the available pool and the organic pool are not described. These fluxes constitute an annual cycle: mineralisation of organic nutrients just after the start of the rainy season, restitution of organic nutrients in the form of plant roots and litter during that season, and immobilization of nutrients at the end of the season. The cycle is of major importance for crop growth each year, but describes to a limited extent the long term developments in soil fertility. In the long run, over periods of 10–20 years, both pools are more or less in equilibrium: available nutrient depletion will be buffered by net mineralisation from organic matter, and vice versa. Thus, nutrient depletion is strongly associated with a gradual decline of the organic matter content in the soil. The quantity of nutrients being depleted each year will be used to estimate the rate of this decline.

On the other hand, elements in pool C, the mineral reserve, are not considered as nutrients. Although on a time scale relevant to soil formation processes an equilibrium may establish between mineral reserves and available and organic nutrients, under the influence of human activities the rates of change of these latter pools are too rapid to attain such a situation. Thus, elements are assumed to become available by transformation and dissolution of soil minerals at a constant rate: the rate of weathering. "Irreversible fixation" (which is in fact not irreversible), mainly of phosphorus and potassium, is the potentially opposite process.

The advantage of describing nutrient balances instead of total element balances lies in the possibility to account for nutrient inflow through weathering. Furthermore, an economic value can be assigned relatively easily to nutrients, whereas the mineral reserve has a very different value.

In the present approach, the following processes affect the nutrient pool:

Outputs of nutrients:
- Export in cropped products
- Losses by leaching
- Losses by erosion
- Losses by volatilization/denitrification
- Incorporation of phosphorus and potassium in the mineral reserve ("irreversible fixation")

Inputs of nutrients:
- Fertilizer application
- Organic manure application
- Restitution of crop residues
- Symbiotic nitrogen fixation
- Asymbiotic nitrogen fixation
- Recycling of leached nutrients and biological fixation by trees left growing in the fields
- Atmospheric deposition by rain and dust
- Transformation and dissolution of soil minerals
- Import with seed

The difference between outputs and inputs represents the net nutrient balance, the main subject of this study.

Acidification

Besides nutrient depletion, also acidification of soils occurs under increasingly intensive cultivation. This can be corrected for by liming, and thus acidification is regarded in this study as resulting from a negative "lime balance". Soils acidify by leaching of potassium, calcium and magnesium. The loss of these elements is part of the nutrient balance. But in addition, acidification also occurs after application of ammonium fertilizer or urea, as a result of the nitrification reactions. In our calculations on acidification, we have assumed that each kg of fertilizer N needs 1.75 kg of lime ($CaCO_3$) for neutralization [16]. That yields the amount of lime that should have been applied in combination with fertilizer N, to guarantee sustainable production, without acidification of the soil.

Economic evaluation of nutrient balances

Nutrients have been defined as elements available for crops, so they can be valued at the market price of fertilizers. This may seem a rough simplification of reality, but at present no other replacement for depleted nutrients is available at the market, because most of the organic manure is applied already. In addition, the production cost of nutrients in manure are not much lower than the prices per kg fertilizer nutrient [15]. Combining for each element the net nutrient balance per hectare with fertilizer prices per kg of nutrient, the market value of a nutrient deficit or surplus is obtained.

For assessing the possibilities for farmers in correcting a nutrient deficit, the absolute value of the deficit has also been related to farmers' income from agricultural activities.

Reliability margins and factors of uncertainty

The basic data for nutrient inputs and outputs have been selected from literature and from production statistics. Data from literature pertain to various sites in Western Africa, but are not necessarily representative for the CMDT area in Southern Mali. Taking into account the variation in rainfall, soil properties, etc., some "intelligent guessing" had to be applied. From the data a "most probable value" for the study region was selected, and a range representing the 95% probability level. If to all literature data the same statistical weight is given, the "most probable value" is the arithmetic mean, and the range corresponds to twice the standard deviation of the mean value ($\pm 2s/\sqrt{n}$, where n is the number of data, and s their standard deviation). In reality however, the variability in soil properties and rainfall, and the fact that not all literature data are based on the same number of experiments, made a subjective estimate of reliability ranges more appropriate than a purely statistical procedure.

Three net nutrient balance values have been calculated. The first one is based on the use of only "most probable" values. That value, in our opinion best reflects the actual nutrient balance of the region. The second value, labelled "optimistic", is based on the combination of low estimates for the outputs and high estimates for the inputs. The third value, the "pessimistic" one, is based on high estimates for outputs and low estimates for inputs.

To examine which parameters introduce most of the uncertainty in the overall nutrient balance, a sensitivity analysis has been carried out, calculating the range in net balance values, resulting from uncertainty in each parameter, setting all other parameters at their most probable values. An estimate of the relative contribution (C) of each parameter to the uncertainty in the overall nutrient balance is presented in Fig. 2, calculated according to

$$C_p = \Delta_p^2 / \sum_p \Delta_p^2 \times 100\%$$

where Δ_p stands for the range in net nutrient balance values caused by uncertainty in parameter p, calculated while all other parameters are at their most probable value.

If the accuracy of the nutrient balance calculations should be improved, more reliable data are needed, especially on

- losses by erosion;
- nutrient contents of crop products and crop residues;
- atmospheric deposition by rain and dust;
- nutrient input by weathering, particularly for the phosphorus, calcium and magnesium balances;
- the fate of crop residues, particularly for the potassium balance.

These conclusions are summarized in Table 1.

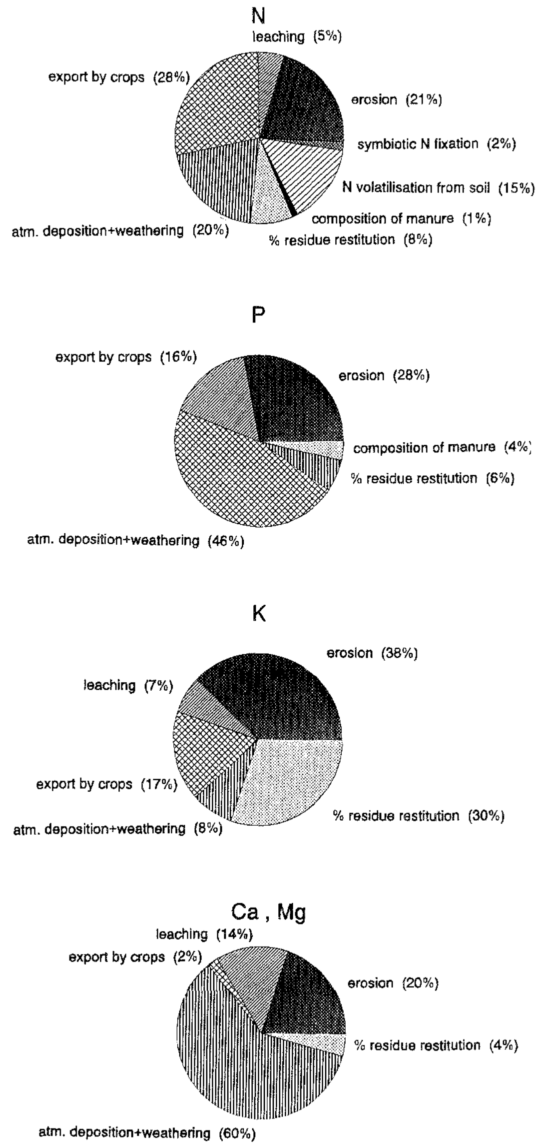


Fig. 2. Composition of the margins in the nutrient balance.

Nutrient Balances

The use of nutrient balances: a critical evaluation

The method of nutrient balance calculations needs critical considerations a priori. In the study area, most nutrient balances are negative, implying a net depletion of nutrients from the soil. But the magnitude of this depletion should not be considered as a recommended dose for additional fertilizer. Firstly, because higher fer-

Table 1. Important processes on which information is needed to improve the accuracy of nutrient balance calculations

	N	P	K	Ca	Mg
Total range in kg/ha: (Average CMDT area)	26	3.4	23	20	10
Contribution of process:					
Erosion	+	+	++	+	+
Crop composition	+	±	±		
% residue restitution			++		
Volatilization	±				
Input by rain, dust	±	+		++	
Input by weathering	±	+		±	++

± contributes 10–20% to the total range of the balance;
+ contributes 20–30% to the total range of the balance;
++ contributes more than 30% to the total range of the balance.

tilizer doses have consequences for the rates of the processes underlying the final nutrient balance. For example, if higher yields result from an additional dose, crop nutrient uptake is higher. Higher doses also entail higher leaching and volatilization losses. Thus the estimates of various inputs and outputs no longer hold. Secondly, such recommendations would be erroneous and unfeasible. Application of e.g. double doses of fertilizer on local millet or sorghum varieties will in many cases only result in increased losses. To solve the problem, cropping systems should be developped that respond efficiently to increased fertilization, minimize losses, and thus can become sustainable. Though nutrient balances may constitute an important diagnostic tool, they cannot be translated directly into practical solutions. The major impact of the calculation of nutrient balances is that the consequences of farming for soil fertility are described in a consistent and transparant manner.

Results of calculations

For the three elements N, P, and K, the net balances under the main crops in Southern Mali are presented in Fig. 3.

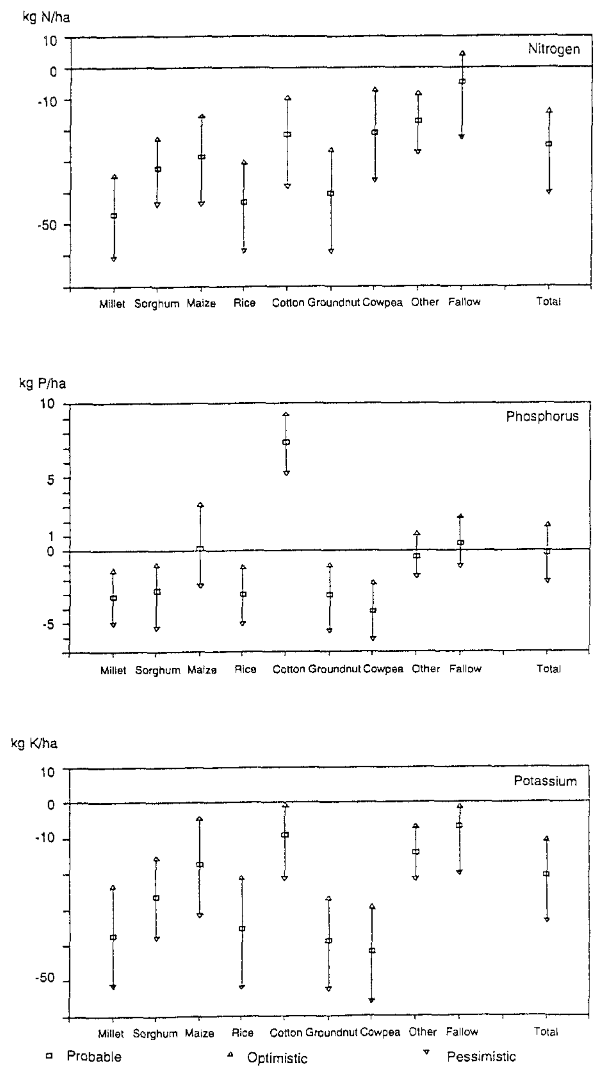


Fig. 3. Nutrient balances in southern Mali.

Nitrogen

The total nitrogen balance of the region is negative, even under the optimistic view. The most probable value is an annual loss of about 25 kg/ha from the soil nitrogen reserve. The reliability interval is situated between 14 and 40 kg/ha. The relative nitrogen deficiency, i.e. the part of the total output that is accounted for by soil depletion, is high (47%) see Fig. 4. The deficit of 25 kg/ha is also large compared to the average fertilizer use of only 10 kg N/ha in the

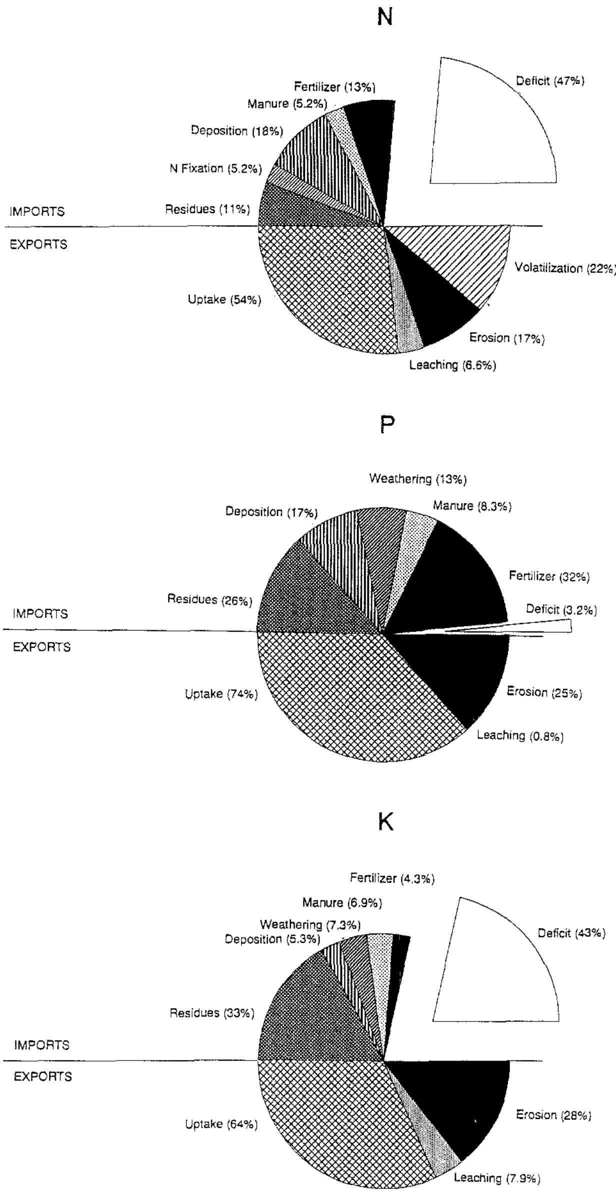


Fig. 4. Composition of nutrient balances.

region (7 and 3 kg/ha for mineral fertilizer and organic manure respectivily). This implies that a solution cannot be provided through the use of fertilizers alone.

At a normal C/N ratio of the soil organic matter of about 12, the loss of 25 kg N/ha implies an annual decomposition of about 600 kg organic matter, equivalent to a decrease in soil organic matter content of 0.15 g/kg soil. Non depleted soils in the region, in the first years of cultivation after a fallow period, have an avarage organic matter content of about 1%. Starting from this value it will take on average 30 years to reach the critical level of about 0.6%, below which soil structure is damaged and fast erosion occurs, degrading the soil irreversibly (Malcoiffe, IER-N'Tarla, private communication; [19]).

The negative balance is mainly due to the traditional unfertilized cereal crops millet (−47 kg/ha) and sorghum (−32 kg/ha). But also the N balance of cotton (−21 kg/ha) and maize (−29 kg/ha) is negative. This argues against the common idea that cotton and maize fertilization support the production of the entire crop rotation cotton/maize/sorghum.

Under the present exploitation levels also fallow land, mostly short-term fallow, has a slightly negative nitrogen balance (−5 kg/ha, range +4 to −23 kg/ha). This is in agreement with observations that the restorative capacity of short term fallow is virtually zero.

Phosphorus

For phosphorus the situation is less dramatic. The region as a whole is broadly in equilibrium (−0.2 kg/ha ± 2). The fertilizer application to cotton compensates for the export by unfertilized cereals. Locally, particularly in the drier areas with millet, cowpea and groundnut production, the net balance may be about −3 kg P/ha. Also phosphorus depletion implies a net decomposition of organic matter. A very rough estimate may be given for the period of time this depletion could continue before arriving at the previously mentioned critical level of 0.6%. Assuming a C/P ratio of 100 in soil organic matter and an additional mineral P buffer of 30% of the organic phosphorus, per ha about 450 kg organic matter should be decomposed annually to provide for the phosphorus. With this rate it will take 40 years until the critical level is reached. But P-fertility levels decrease faster, so that production levels will decline earlier.

Potassium

The potassium balance resembles that of nitrogen: even under the most optimistic view it is negative. Annually about 20 kg K/ha (range 10 to 33) is extracted from the soil reserve, representing 43% of the total uptake. The deficit of 20 kg/ha is very large compared to the average application of respectively 2 and 3 kg K/ha through mineral fertilizer and manure. Again this argues against solutions through fertilization alone.

The soil reserve for a depth of 30 to 60 cm is estimated at about 400–800 kg/ha (2 × exchangeable K of 0.15 meq/100 g soil; Oliver, CIRAD, private communication; [19]), and as this reserve is not tied up with organic matter, it can be used probably more completely without negatively affecting the soil structure, but leading to declining yields. After 20 to 40 years of cultivation the potassium reserve of the soil will be completely exhausted.

As for nitrogen, the major cause of soil depletion are the non-fertilized cereal crops, i.e. millet and sorghum, but K fertilization of maize and cotton is also insufficient to maintain the soil reserve.

Calcium and Magnesium

The calcium and magnesium balances depend to a large extent on the assumed contributions from atmospheric deposition and weathering, which are difficult to quantify because of the scarcity of available data.

The most probable value for the net calcium balance is calculated at +3 kg Ca/ha (range 12 to −8). Compared to the total output of 25 kg/ha this surplus is small, so the calcium balance can be considered more or less in equilibrium. For magnesium a net negative value is found (−5 kg Mg/ha, range 0 to −10), which represents 38% of the total output.

As the use of Ca and Mg fertilizers is limited, net balances are more negative for more intensive crops; the calcium balance is positive for extensive millet and sorghum production: +5 kg/ha for millet and sorghum, and negative for maize (−8 kg/ha) and cotton(−2 kg/ha). A similar trend is found for magnesium. Due to increased erosion under groundnut, serious calcium and magnesium depletion may occur under this crop. Under fallow the net balances are positive, because of the high contribution of atmospheric deposition and weathering, hence short term fallowing results in regeneration with respect to calcium and magnesium.

Acidification

Application of 7 kg N/ha on average, would require 12 kg lime/ha (range 9–16 kg lime/ha) to avoid acidification, none of which is given.

In Table 2 the balances for the entire CMDT area in Southern Mali are summarized.

Impact of Technical Options

A question is how the current nutrient deficits compare to the effects of technical measures that can be taken to prevent depletion. In this context one should keep in mind that nutrient balances represent the situation of agriculture under current management practices. The rates of the underlying processes may change when technical measures are taken. If fertilizer is applied, higher yields may be associated with higher nutrient uptake, while concurrently the better vegetative cover may reduce losses by erosion and leaching. Hence only a rough estimate is given of the extent to which various options would contribute to bridging the two most important nutrient gaps, those of nitrogen and potassium.

The possible positive effects on the N and K balances of four options are illustrated in Fig. 5: (i) reduction of erosion losses by 50%; (ii) increased crop residue restitution by 50%; (iii) doubled application of organic manure; (iv) doubled application of mineral fertilizer.

Even though the interventions have been given a drastic character, none of those alone seriously affects the nutrient deficit. Even a combination of all four interventions will not completely prevent soil depletion.

Table 2. Calculated nutrient balances per hectare for Southern Mali, 1988–89

Balance in kg/ha	N	P	K	Ca	Mg	Lime
Probable value:	−25	0	−20	+ 3	− 5	−12
Optimistic:	−14	+2	−10	+12	0	− 9
Pessimistic:	−40	−2	−33	− 8	−10	−16

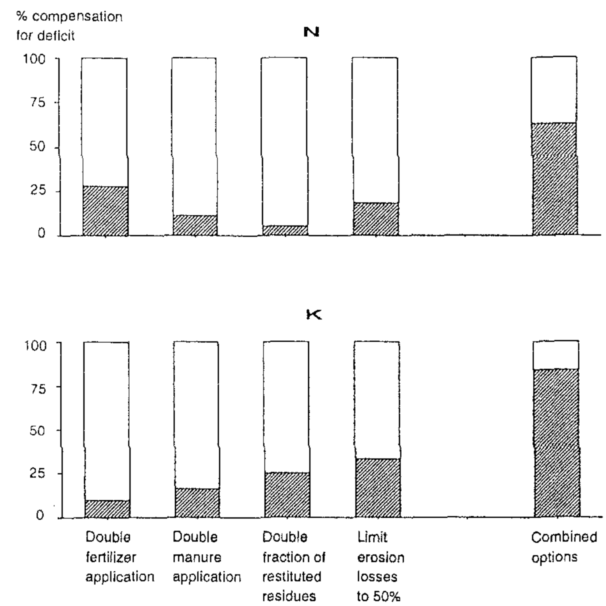


Fig. 5. Effects of measures on nitrogen and potassium deficits.

Economic Evaluation

The economic value of nutrient deficits and surpluses has been calculated on the basis of prices which farmers had to pay for fertilizers (financial prices) in 1989. Recent price reductions in Mali changed the picture to some extent (Table 3).

Because of the uncertainty in calcium and magnesium balances, these elements have not been included, so the "nutrient depletion market value" has been derived from deficits and surpluses of N, P, K, and lime.

In line with the preceding physical considerations, the economic evaluation shows a considerable contribution of soil nutrient depletion to farmer's income. Average nutrient deficit per hectare values around FCFA 15,000 in 1989 and FCFA 11,000 in 1992 (US $39/ha). Compared to income from agricultural activities this represents a substantial proportion. Evaluating all harvested products, including cereals, at 1989 market prices, the average gross margin from agricultural activities in the study region amounts to FCFA 34,200/ha (US $134/ha). Thus in 1989, soil nutrient depletion represented as much as 44% of the average farmer's income. In 1992, even with the recent price reductions, depletion valued still one third of the average farmer's income.

As the maintenance of soil fertility constitutes a basic condition for sustainable agriculture, we may conclude that at maximum only 50 to 70% of the farmer's income is sustainable. For the rest of his income, the farmer is taking a loan on the future production capacity of the soil.

The market value of losses, due to erosion, leaching and volatilization/denitrification, is high (FCFA 17,900, US $70/ha), both with respect to the deficits and the farmers' income. Improving sustainability must partly be realized in limiting these losses. Another option is in increasing investments in application of fertilizer and manure. Compared to the value of the current nutrient depletion, average depenses for fertilizers are low (FCFA 4,500, US $17.5/ha) and represent only 11% of the gross income from agricultural activities. In a situation of transition from fallow-based systems to permanent cultiva-

Table 3. Economic evaluation of nutrient depletion in southern Mali

	kg/ha 1989	FCFA/ha 1989	FCFA/ha 1992	US $/ha 1992
Balance N	−25	− 7875	− 5425	−20
Balance P	0	0	0	0
Balance K	−20	− 6500	− 4740	−17
Balance lime	−12	− 720	− 720	− 3
Total market value of deficit		−15095	−10885	−39
Gross margin on agricultural activities		34200	34200	123
Nutrient depletion on gross margin		44%	32%	
Sustainable fraction of gross margin		56%	68%	
Investment in fertilizer		4483 (=11% of gross income)		
Market value of losses		17899		

tion, more efforts will be needed to maintain the fertility of the soils.

Conclusions

To understand soil degradation, quantitative knowledge on depletion of plant nutrients from soils is required, as nutrient depletion is one of underlying causes of soil degradation. In this study, nutrient depletion is estimated from the difference between plant-nutrients imported and exported from the cultivated area in the entire region of Southern Mali.

The results of the study show that reliability margins in the nutrient balances are considerable, due to uncertainty in the quantification of processes of import and export of nutrients. Differences between "optimistic" and "pessimistic" estimates are of the same order of magnitude as the balance values. Losses due to erosion are an important source of uncertainty for all elements, and the uncertainty on nutrient inputs by atmospheric deposition (rain and dust) and weathering of soil minerals is also high. For nitrogen, gaseous losses and uptake by the various crops are not known very accurately, while for potassium the fraction of crop residues returned to the soil is a source of uncertainty. However, even though the margins are wide, the calculations allow a number of clear conclusions.

In the first place, large deficits exist for nitrogen, potassium and magnesium, even when the most optimistic estimates are used. These deficits mainly originate from cultivation of the traditional cereal crops, but also from that of cotton and especially groundnut, for both of which exports exceed inputs from external sources. Soil acidification as a result of urea and ammonium application is to be expected under cotton.

For phosphorus and calcium the balance of the region as a whole appears to be about in equilibrium, but locally large variations may occur for phosphorus, since fertilization of cotton in the Southern part of the region, compensates for the negative balances in the Northern part, where the importance of cotton is less.

Erosion and volatilization/denitrification are important causes of nutrient losses. Leaching losses are relatively low, but comprise readily available soluble components. Atmospheric deposition and weathering of soil minerals are important nutrient sources that contribute as much to N, P and K inputs as organic and mineral fertilizer combined.

The nutrient deficits are very large in comparison to the current levels of fertilizer application. Drastic measures, such as doubling fertilizer or manure application rates, or reducing erosion losses by half, would not be sufficient to reverse the current negative trend.

If total soil nutrient depletion is economically valued at prices farmers pay for fertilizers, a value of depletion per hectare of cultivated land is obtained that may serve as an indicator for sustainability of the current farming systems. The absolute market value, if related to farmers' income, provides an impression on the potential of a system to be made sustainable. If the market value of depletion is small with respect to the income, farmers can be expected, or encouraged, to depense part of it to guarantee their future income. But where extra depenses for sustainable production are high with respect to the farmer income, this would marginalize the income from their labour, and thus the farmers interest.

For the study area, taking into account price fluctuations and uncertainty in basic data, nutrient depletion represents on average 25–50% of the farmer's gross margin from agricultural activities. There is, especially in view of the low investments in soil fertility maintenance, no reason to be optimistic on the sustainability of farming in the region. The results from this study clearly indicate that current farming systems are not sustainable in terms of nutrient elements, and that it will not be easy to find a solution to this problem.

In order to sustain productivity, policy makers should reckon with at least a doubling of the actual investments in the maintenance of soil fertility. It follows that a larger part of African national budgets should be reserved for creating an environment that enables higher investment in nutrients. This should be reached by promoting nutrient application and nutrient saving measures. The incentives needed could apply to specific fertilizers (eg to balance the existing preference for N-fertilizer), to erosion control measures, but also to nutrient saving cropping systems, such as those including tree-crops. The incentives may relate to subsidies, to price setting, but also to restrictions and to respectation of rules. They should allow the rural society to pass on to permanent cultivation systems without deteriorating irreversibly the productive capacity of the land.

Acknowledgements

Quantifying nutrient balances has not been easy, as it had to be based on estimates of rates of processes, scarce or contradictory data. The estimates were made in cooperation with many scientists, whose experience in this way is incorporated in the present study.

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