INPUT AND OUTPUT OF MAJOR NUTRIENTS UNDER MONOCROPPING SISAL IN TANZANIA

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ABSTRACT

A semiquantitative nutrient balance is presented for a field monocropped with sisal on Ferralsols in Tanzania. Input of nutrients included wet deposition, non-symbiotic nitrogen fixation and nutrients added with planting material. Nutrient output consisted of the harvested product. The average annual shortfall between 1966 to 1990 was 12 kg N ha^{-1}, 2·8 kg P ha^{-1}, 38 kg K ha^{-1}, 44 kg Ca ha^{-1} and 19 kg Mg ha^{-1}. The nutrient balance was compared to changes in topsoil (0–20 cm) nutrient contents of the sisal field during the same period. Average annual decrease in soil nutrient contents was: 104 kg N ha^{-1}, 1·8 kg P ha^{-1}, 11 kg K ha^{-1}, 29 kg Ca ha^{-1} and 10 kg Mg ha^{-1}. Much more nitrogen was lost from the topsoil than can be explained by the nutrient balance, indicating significant losses. Changes in soil phosphorus content are almost explained by the nutrient balance. More exchangeable cations were removed with the yield than were lost from the topsoil, which may imply that cations are extracted from the subsoil. Both the nutrient balance and the changes in soil nutrient contents showed that monocropping sisal is mining nutrients. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

A nutrient balance (or budget) is a useful tool in research and extension studies, and may provide insight into the sustainability of an agroecosystem from a nutrient perspective. Frequently, the balances are used to plan nutrient management or to estimate an unknown output of a system. Nutrient balances have been calculated at various scales for subSaharan Africa (e.g. Stoorvogel and Smaling, 1990; Van der Pol and Traore, 1993). Stoorvogel and Smaling (1990) considered five input and five output records for the nutrient balance. In their study nutrient input included mineral fertilizers, animal manure, wet and dry deposition, biological nitrogen fixation and sedimentation, whereas nutrient output included harvested crop parts, crop residues, leaching, denitrification and water erosion. The authors showed that there is a negative nutrient balance for many crops in large parts of subSaharan Africa.

Nutrient balances have also been calculated for a number of plantation crops, although the data are scanty and research methodologies differ. They include cocoa (Boyer, 1973; Fassbender, *et al*., 1991; Hartemink, 1993), oilpalm (Roth, *et al*., 1986), rubber (Shorrocks, 1965; Watson, 1989), and tea (Bonheure and Willson, 1992). In most of these studies the nutrient balance consists of the difference between nutrient inputs with rainfall and fertilizer, and nutrient outputs with the harvested yield.

In the present paper, a semiquantitative nutrient balance is presented for sisal (*Agave sisalana*) in Tanzania. Sisal has been an important export earner for Tanzania and currently large rehabilitation programmes are being undertaken to revive its production. Previous studies have indicated that nutrient depletion occurs under monocropping sisal (Kimaro, *et al*., 1994; Hartemink and Bridges, 1995; Hartemink, 1997). This paper analyses the nutrient depletion semiquantitatively by calculating the nutrient balance of a

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field monocropped with sisal between 1966 and 1990. The balance is compared to changes in soil nutrient content of the same field over the same period. For the balance calculations, the methodology of Stoorvogel and Smaling (1990) was used with a few modifications. The research was conducted *on plantation* in the northeastern part of Tanzania.

MATERIALS AND METHODS

The Site

The research took place on a sisal plantation in Tanga Region (4°55′ *S*, 39°20′ *E*). Within the plantation, a sisal field was selected on an elongated ridge at an altitude of 180 m a.s.l. At the site, the soils were very deep (>4 m), uniform and highly weathered. They were classified as Rhodic Ferralsols (FAO-Unesco) or very fine, isohyperthermic, Rhodic Haplustox (Soil Taxonomy). The natural forest at the site was cleared in 1956 and the field was planted for the first time with sisal (*Agave sisalana*) in 1957. After the sisal had poled, the land was cleared and replanted with sisal (*Agave sisalana*) in 1966. In 1976, a third crop was planted which was harvested up to the late 1980s. The planted crop in 1976 was Hybrid 11648, which is a long-fibre agave hybrid. In this paper both *Agave sialana* and Hybrid 1648 will be referred to as sisal. From 1966 to 1990, sisal yield (Mg ha^{-1} $year^{-1}$) and rainfall (mm d^{-1}) was recorded. The field had never been fertilized or manured.

In 1966, a composite topsoil sample was taken from the field by workers of the Sisal Research Station Mlingano before the second planting. The sample was taken from ca. 0·5 ha and consisted of 15 subsamples (J.F. Osborne, personal communication). In the same field, a new composite topsoil sample was taken in 1990. Soil analytical methods for the 1966 and 1990 samples were: pH water (1 : 2·5, w/v); organic carbon (Walkley-Black); total nitrogen (Kjeldahl); available phosphorus (Bray I); exchangeable cations and CEC (1 M NH_4OAc at pH 7). The methods are described in detail in Page, *et al.* (1982).

Ring samples (100 mL) were taken in soil pits in 1990 for the determination of the bulk density (ρ_D). Topsoil bulk density was 1·31 Mg m^{-3} (mean of three replicates) and this value was used to calculate soil nutrient contents in kg ha^{-1}. The measured bulk densities of 1990 were also used for the 1996 soil analytical data. As the soils in 1966 were already ten years under cultivation, it is assumed that their bulk densities had not significantly changed between 1966 and 1990.

Nutrient Input

The following nutrient inputs were included in the balance: wet deposition, non-symbiotic nitrogen fixation and nutrients added with the planting material.

Nutrients in the wet deposition (IN_{RAIN}) were calculated with the regression equation of Stoorvogel and Smaling (1990). The equation uses the square root of the total annual rainfall multiplied with a factor (0·14 for N; 0·023 for P; 0·092 for K). At the research site, annual rainfall varied from 599 to 1669 mm between 1966 and 1990. Nitrogen deposited with the rainfall hence varied from 3·4–5·8 kg ha^{-1} $year^{-1}$ (mean 4·6 kg N ha^{-1} $year^{-1}$), phosphorus deposits ranged from 0·6–0·9 kg ha^{-1} $year^{-1}$ (mean 0·8 kg P ha^{-1} $year^{-1}$), and potassium deposition was on average 3·0 kg ha^{-1} $year^{-1}$ (range 2·3–3·8 kg ha^{-1} $year^{-1}$). These values fairly well correspond with the scarce literature on NPK contents in wet deposition (e.g. Parker, 1983; Poels, 1987).

No equation could be found which links annual rainfall with calcium or magnesium deposition. As the site is about 60 km from the coast of the Indian Ocean and the rainwater is mainly derived from sea evaporation, a relatively high calcium and magnesium concentration may be expected. Parker (1983) gives average values for calcium and magnesium in the rainwater as 0·82 and 0·40 mg L^{-1} respectively, which is equivalent to 0·82 kg Ca ha^{-1} and 0·40 kg Mg ha^{-1} per 100 mm of rain. At the research site, the average calcium and magnesium input with rainfall was estimated to be 8·5 kg Ca ha^{-1} $year^{-1}$ and 4·2 kg Mg ha^{-1} $year^{-1}$.

Annual input of calcium and magnesium in Ghana (rainfall: 1850 mm $year^{-1}$) was 12·8 kg Ca ha^{-1} and 11·3 kg Mg ha^{-1} (Nye, 1961). Bruijnzeel (1990) compiled data from various sources and gives for Venezuela (rainfall: 1500 mm $year^{-1}$) 5·6 kg Ca ha^{-1} $year^{-1}$ and 5·2 kg Mg ha^{-1} $year^{-1}$. The calcium and magnesium deposition calculated with the rainwater concentrations given by Parker (1983) correspond reasonably well with these figures.

A small source of nitrogen input occurs with non-symbiotic fixation (IN_{NNF}). It occurs in most soils but its contribution to the nitrogen balance is difficult to quantify (Giller and Wilson, 1991). Stoorvogel and Smaling (1990) used an equation in which non-symbiotic nitrogen fixation was considered rainfall-dependent: $A = 2 + (P - 1350) \times 0{\cdot}005$ in which A is the kg N ha^{-1} year^{-1} and P is mm year^{-1}. For the sisal field, non-symbiotic fixation hence ranged from 0 to 3·6 kg N ha^{-1} year^{-1} (mean $<$0·5 kg N ha^{-1} year^{-1}).

An important source of nutrient inputs for a sisal field is the planting material (IN_{PLANT}). Input of nutrients with seeds or planting material are, however, rarely included in nutrient balances. For sisal, such inclusion is required as at the beginning of a cycle thousands of small sisal plants (ca. 2 kg each) are brought to the field. These plants are raised in nurseries at a density of 80 000 ha^{-1}. Nutrient removal from such nurseries is 257 kg nitrogen, 78 kg phosphorus, 283 kg potassium 699 kg calcium and 102 kg magnesium per hectare (Osborne, 1967). At the research site, plant densities of field sisal were 5000 ha^{-1}. Input of nutrients with the planting material in 1966 and 1976 was hence calculated as 5000/80 000 multiplied by the nutrient removal of sisal nurseries.

Nutrient Output

The only output of nutrients which could be quantified was the removal with the harvested products (OUT_{YIELD}). Crop residues were not removed from the field and are therefore not included in the balance. It has frequently been observed that erosion is negligible on Ferralsols under sisal cultivation in Tanga Region when there is a grass cover, and this has also been reported by Ngatunga, *et al.* (1984). Moreover, sisal is a perennial crop with a grass cover between the rows which gives better soil protection than annual crops (Ahn, 1977). Losses of nutrients by erosion are therefore considered negligible.

Yield data were multiplied by nutrient removal data (kg ha^{-1}) to arrive at kg nutrient per Mg fibre ha^{-1}. Nutrient removal data were taken from Osborne (1967) who conducted research on leaf analysis and nutrient removal in Mlingano in the 1960s. For *Agave sisalana*, Osborne (1967) found a removal per Mg fibre of: 27 kg N ha^{-1}, 7 kg P ha^{-1}, 69 kg K ha^{-1}, 70 kg Ca ha^{-1} and 34 kg Mg ha^{-1}. Nutrient removal for sisal Hybrid 11648 was estimated to be: 26 kg N ha^{-1}, 3·5 kg P ha^{-1}, 44 kg K ha^{-1}, 82 kg Ca ha^{-1} and 31 kg Mg ha^{-1} per Mg of fibre. For the nutrient balance, the *Agave sialana* removal data were multiplied with the yields from 1966–76 ($OUT_{YIELD1966–76}$) and the sisal Hybrid 11648 data for the yields from 1976–90 ($OUT_{YIELD1976–90}$).

RESULTS

The Nutrient Balance

Differences between nutrient input with rainfall, non-symbiotic nitrogen fixation and planting material, and output by the harvested product (yield), were calculated for the five major nutrients. In the absence of fertilizers and manure the balance is negative for each nutrient (Table I).

Table I. Nutrient balance of a sisal field during the period 1966–90 (kg ha^{-1})

	Nutrient				
	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
IN_{RAIN} 1966–90	115	19	75	213	105
IN_{NNF} 1966–90	19	0	0	0	0
IN_{PLANT} 1966 + 1976	32	10	35	87	13
OUT_{YIELD} 1966–76	271	70	692	702	341
OUT_{YIELD} 1976–90	221	30	375	698	264
$\sum IN_{1966-90} - \sum OUT_{1966-90}$	−326	−71	−957	−1100	−487

Total input of nitrogen during the period 1966–90 was 166 kg N ha^{-1} of which the major part was added with the rainfall. Output of nitrogen with the harvested product was about three times larger than the sum of inputs, and the total differences between 1966 and 1990 was 326 kg N ha^{-1}. Little phosphorus is deposited with the rainfall (<1 kg P ha^{-1} $year^{-1}$), but the output of phosphorus is also moderate (100 kg P ha^{-1} in 25 years). The total difference is 71 kg ha^{-1}. Although considerable amounts of cations are deposited in the rainfall and supplied with the planting material, there is a large shortfall for each of the three cations. The removal of potassium with the yield is tenfold greater than the sum of inputs. For calcium and magnesium, the nutrient removal with the yield is about five times larger than the sum of inputs.

Soil Nutrient Contents

Soil chemical properties of the sisal field in 1966 and 1990 are given in Table II. The data show that the chemical fertility has declined during this period and confirm other observations in similar soil types.

Topsoil nutrient contents were calculated from the 1966 and 1990 soil analytical data. The content of each of the five nutrients had been seriously reduced during this period (Table III).

Table II. Soil chemical properties (0–20 cm) of a sisal field sampled in 1966 and in 1990

	1966	1990
pH (H_2O) 1:2·5	5·5	5·0
Organic C (g kg^{-1})	25	15
Total N (g kg^{-1})	2·2	1·2
Available P (Bray I) (mg kg^{-1})	20	3
CEC (NH_4OAc pH 7) ($mmol_c$ kg^{-1})	75	62
Exchangeable Ca ($mmol_c$ kg^{-1})	19	6
Exchangeable Mg ($mmol_c$ kg^{-1})	11	3
Exchangeable K ($mmol_c$ kg^{-1})	3·6	0·8
Base saturation (%)	45	16

Table III. Soil nutrient content of a sisal field sampled in 1966 and in 1990 (kg ha^{-1} for 0–20 cm)

	Nutrient				
	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
$SOIL_{1966}$	5764	52	369	996	355
$SOIL_{1990}$	3144	8	82	271	97
$SOIL_{1990}$–$SOIL_{1966}$	−2620	−44	−287	−725	−258

The largest decrease was found in the soil nitrogen content and 2620 kg ha^{-1} had disappeared from the soil. The relative largest decrease was found in the soil phosphorus content and only 8 kg P ha^{-1} was available in the topsoils in 1990. Potassium, calcium and magnesium contents in 1990 were less than 30 per cent of their 1966 contents.

Nutrient Balance vs. Soil Nutrient Contents

The nutrient balance was compared with the difference in soil nutrient contents between 1966 and 1990 on a yearly base (Table IV).

More nitrogen had disappeared from the topsoil than was calculated from the nutrient balance. Differences in topsoil phosphorus content were slightly lower than was calculated from the nutrient balance. The annual decrease in exchangeable cations of the topsoil was considerably lower than the shortfall based

Table IV. Nutrient balance and differences in soil nutrient contents between 1966 and 1990 (kg ha^{-1} year^{-1})

	Nutrient				
	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
$(\sum IN_{1966-90} - \sum OUT_{1966-90})/25$	−13	−2·8	−38	−44	−19
$(SOIL_{1990} - SOIL_{1966})/25$	−104	−1·8	−11	−29	−10

on the nutrient balance. Noticeably more potassium had disappeared when calculated with the nutrient balance than was lost from the topsoil.

DISCUSSION

Both the nutrient balance and the difference in soil nutrient contents showed a serious shortfall for each nutrient. The absolute largest decrease was found in the soil nitrogen content. Much more nitrogen was lost from the topsoil than was calculated from the nitrogen balance. It may be caused by an underestimation of nitrogen input from atmospheric deposition but it is more likely that there have been considerable losses through leaching and/or denitrification. The mean annual losses can be estimated as the net difference in soil nitrogen content *minus* the difference between nitrogen input and output, as follows:

$$[\text{net annual loss} = (SOIL_{1990} - SOIL_{1966})/25 - (\Sigma IN_{1966\text{–}90} - \Sigma OUT_{1966\text{–}90})/25]$$

which becomes:

$$[-104 - -13 = -91 \text{ kg N ha}^{-1} \text{ year}^{-1}]$$

These mean annual losses are high, particularly when taking into account that the data are from unfertilized conditions. Nitrogen losses may have increased when the process of soil fertility decline had proceeded and other nutrients (e.g. potassium, calcium) were limiting sisal growth. It may have been lost from the topsoil through leaching, which could occur during April and May when the rainfall surplus is on average about 75 mm. There may have been leaching losses at the time of land preparation when there is no uptake (Sanchez, *et al*., 1983), and such losses can be very high if land preparation takes place at the beginning of the rainy season when mineralisation is enhanced (Cahn, *et al*., 1993). The leached nitrate from the topsoil is apparently not retrieved by the sisal roots and recycled to the topsoil as occurs under some other perennials (Seyfried and Rao, 1991). Indeed, most sisal plants concentrate their roots in the upper 30 cm and have very few roots at depth.

Differences in topsoil phosphorus contents were only slightly lower than was calculated from the nutrient balance. It suggests that the nutrient balance explains most of the changes measured in soil available phosphorus. Absolute levels of available phosphorus had decreased through the combination of increasing acidity as a result of the large cation removal, and the decrease in soil organic matter which supplies most of the phosphorus when mineralizing.

The annual decrease in cation content of the topsoil was lower than was calculated from the nutrient balance. Part of the difference may be explained by the weathering of soil particles releasing cations and thus affecting the exchangeable cation levels. However, this soil was highly weathered so it is expected that such a contribution is only very small. It is more likely that the subsoil was an important source of cations despite the shallow root systems of the sisal. Another explanation may be that the inputs of cations with the rainfall is underestimated explaining the large shortfall in the nutrient balance as compared to the differences in soil cation contents.

The study has shown that a simple nutrient balance can only partly explain changes that take place in soil nutrient contents over a prolonged period.

CONCLUSIONS

The nutrient balance under monocropping sisal in the absence of fertilizers or manure is negative for each nutrient. As the soil nutrient pool has to offset the negative balance, it implies that the system is mining soil nutrients and not sustainable.

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