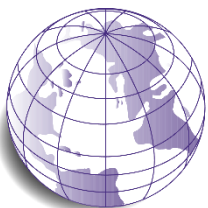


Beyond N and P: Toward a Land Resource Ecology Perspective and Impactful Fertilizer Interventions in Sub-Saharan Africa



Roelf L. Voortman and Prem S. Bindraban



VFRC



Centre for World Food Studies
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VFRC Report 2015/1

Washington, D.C. USA

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Citation:

R. Voortman and P.S. Bindraban, 2015.

Beyond N and P: Toward a Land Resource Ecology Perspective and Impactful Fertilizer Interventions in Sub-Saharan Africa. VFRC Report 2015/1. Virtual Fertilizer Research Center, Washington, D.C. 49 pp.; 15 tables; 17 figs.; 2 text boxes; 67 ref.



Virtual Fertilizer Research Center

Contents

1	Introduction	1
2	Land resource ecology in the Miombo biome on basement complex in Central-South Africa	3
2.1	Sources of spatial variability of soils	4
2.2	Soil chemical data of Miombo and a comparison with Brazilian Cerrado soils.....	4
2.3	Key soil chemistry variables associated with the spatial variability of soils: the case of Angonia District, Mozambique	9
2.4	Verification with Miombo Soil Chemistry Elsewhere.....	20
3	Nutrient omission trials in relation to soil chemistry in the Miombo biome of Malawi.....	23
3.1	Nutrient omission trials	23
3.2	The liming trial.....	31
3.3	Further data exploration: control yields and soil chemistry	32
3.4	The Malawi demonstration trials	35
4	Micronutrient trials in the Miombo of Zimbabwe.....	37
5	Brazilian fertilizer technology experiences of relevance for sub-Saharan Africa	39
6	Conclusions	42
7	References	45

Table 1.	A comparison of average soil chemical properties of Miombo woodlands in Zambia and Zimbabwe	6
Table 2.	Topsoil properties of various forms of Cerrado and forest in Brazil.....	8
Table 3.	Available Cu, Zn and Fe in the topsoil of Miombo soils in Angonia district, Mozambique, compared with various forms of Cerrado, Brazil (values in ppm; topsoil 0-20 cm)	9
Table 4.	Cultivation density as a function of N, P and K levels from the topsoil, subsoil and deeper subsoil (Initially tested with a full quadratic equation) and in combination with soil texture, TEB, BS and pH.	12
Table 5.	Cultivation density as a function of individual elements and their ratio's (with and without subsoil N).....	14
Table 6.	Binary logistic regression: Nguni versus true Miombo woodland	15
Table 7.	Binary logistic regression: Nguni versus Miombo bushlands.....	17
Table 8.	Properties of Miombo versus Nguni vegetation.....	20
Table 9.	Soil chemical properties of Miombo soils in Zambia, Malawi and Zimbabwe.....	22
Table 10.	Measured and calculated soil chemical properties of topsoils for eight observations ordered in ascending control yields.	27


Table 11.	The P rate (kg P ha ⁻¹), control yield (kg ha ⁻¹), Malawi Standard yield (MS; kg ha ⁻¹), the difference between the MS and control yields (ΔY -MS; kg ha ⁻¹), the difference per kg nutrient applied (ΔY -MS/kg), the 'All' yield (All; kg ha ⁻¹), the difference between the 'All' and control yields (ΔY -All; kg ha ⁻¹) and the difference per kg nutrient applied (ΔY -All/kg). Only in observation 3 the 'All' treatment contained lime.	28
Table 12.	Yield changes due to the omission of part or the entire dose of individual nutrients compared to the 'All' treatment (kg ha ⁻¹).....	28
Table 13.	Demonstration plot maize yields and additive yield increases by fertilizer technology applied for different land types characterized by their vegetation (based on 79 demonstration plots).....	35
Table 14.	Crop yields on various sites at Henderson Research Station, Zimbabwe, in NPK trials and with micronutrients added.....	38
Table Intermezzo 1.	Indicative summary of principal plant nutrient interactions	26
Figure 1.	The spatial distribution of Miombo woodland formations (green) (red rectangle is the location the Angonia district).	3
Figure 2.	Sharp soil boundary due to differences in the mineralogy of parent rock, as evident in track at the foreground with reddish brown fertile soil with remnants of tall grasses (burned at end of dry season) and in the background pale sandy soil of low fertility with Miombo woodland vegetation, Angonia district, Mozambique	5
Figure 3.	Sharp soil boundary due to differences in the mineralogy of parent rock; in the middle a tilted structural ridge with on the left a red soil with modest levels of organic matter (Ferric Luvisol) and on the right a brown soil very high in organic matter (Luvic Phaeozem), Angonia district, Mozambique	5
Figure 4.	Subsoil TEB (cmol kg ⁻¹) as a function of mean annual rainfall (mm) for Miombo woodlands in the Angonia district (Mozambique)	7
Figure 5.	Compilation of photographs of nine map sheets of the land unit map of Angonia district, Mozambique	10
Figure 6.	Typical Miombo woodland (uncultivated) on shallowish and sandy soil	19
Figure 7.	Typical Nguni land: Cultivated land showing tall grasses and 'chocolate brown' soils with the small Angoni breed cattle stubble grazing	19
Figure 8.	The liming experiment result for the Malawi standard and the missing nutrient trial at the Bembeke station.....	31
Figure 9.	Control yields (kg ha ⁻¹) related to soil available P level (ppm); observation numbers in brackets	32
Figure 10.	Control yields (kg ha ⁻¹) related to soil K level (cmol kg ⁻¹); observation numbers in brackets	33

Figure 11.	Control yields (kg ha ⁻¹) related to soil TEB (cmol kg ⁻¹); observation numbers in brackets	34
Figure 12.	Control yields (kg ha ⁻¹) related to soil Mg/K ratio; observation numbers in brackets	35
Figure 13.	Maize yield response to S-Zn-B as a function of yield response to P.....	36
Figure 14.	Comparison of the effects of broadcast and incorporated dolomitic lime (0 and 6 t/ha) and gypsum (0 and 6 t/ha) on soil pH down the profile of a dark yellow alic Oxisol of medium texture 27 months after application (no estimates of error were presented)	40
Figure 15.	Effect of applications of single superphosphate (SSP; OSP in the legend) and triple superphosphate (TSP) at rates of 873 kg P/ha on Al saturation down the profile of a Brazilian Oxisol.	41
Figure 16.	Effect of exchangeable Mg/Ca ratio for various combinations of dolomitic lime and phosphogypsum at different rates on the relative increase in cane yield over the control in two experiments.....	42
Figure Intermezzo 1.	Mulders nutrient interaction chart.....	25

List of Acronyms and Abbreviations

Al	Aluminum
B	Boron
B. Tobacco	Burley Tobacco
BNF	Biological Nitrogen Fixation
BS	Base Saturation
C	Organic Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
Cu	Copper
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária
ESP	Exchangeable Sodium Percentage
Fe	Iron
G	Gypsum
K	Potassium
L	Lime
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Ni	Nickel
OLS	Ordinary Least Squares
OSP	Ordinary Superphosphate (= SSP)
P	Phosphorus
S	Sulfur
SOW-VU	Stichting Onderzoek Wereldvoedselvoorziening (Centre for World Food Studies)
SSP	Single Superphosphate
TEB	Total Exchangeable Bases
TSP	Triple Superphosphate
VFRC	Virtual Fertilizer Research Center
Zn	Zinc



 Widespread soil Zinc deficiency

 Medium soil Zinc deficiency

Source: Alloway. 2008. Zinc in soils and crop nutrition.

1 Introduction

Crop plants need essential nutrients in certain amounts and proportions taken up from the soil to grow and ultimately to produce their economic yield. If these requirements are not fulfilled, growth and yield will be poor. The required amounts may be present in the soil but not readily available in sufficient quantities for the crop. Under these conditions, plants may satisfy their needs for instance through nutrient acquisition mechanisms such as root exudation, whereby nutrients in the soil are made more soluble. Nutrient shortages can also be overcome through mutualistic nutrient acquisition mechanisms with soil biota: mycorrhiza, for instance, can make nutrients available in exchange for plant assimilates. Despite these and various other nutrient acquisition strategies, one or more nutrients may still be insufficiently present in the soil. In such cases, appropriate fertilizer application is likely to generate a substantial yield increase.

Impactful fertilizer interventions are those that achieve substantial yield improvement at low doses. Theoretical considerations suggest that such interventions would have to consist of only the most limiting nutrients at low doses to avoid decreasing marginal returns. Low-dose fertilizer technologies have the added advantage of being more affordable for poor farmers. Additional benefits of such technologies include improved food quality due to higher densities of the most limiting nutrients in the food. This combination of characteristics is particularly important for sub-Saharan Africa, the main scope of this paper.

Sub-Saharan Africa presents a peculiar situation when compared to agriculture practiced in other tropical areas. For instance, ample use is made of inorganic fertilizers in South America and India, even under smallholder conditions. In Africa, however, the use of such fertilizers currently is still very limited. Production increases have mainly been obtained by area expansion and also by yield increases to a modest extent, supposedly through better crop and land husbandry practices. In the past, soil fertility was restored through the application of fallow periods, which, due to population pressure became increasingly shorter, result in lower soil fertility levels. Consequently, new land must be taken into use, which is likely to be more marginal in terms of nutrient deficiencies and other characteristics like low or variable rainfall. This situation urgently calls for increasing fertilizer use in Africa to boost yield levels on current agricultural lands.

It is, however, evident from agronomic research that past experiences with fertilizers in Africa are not very promising. It has long been known that nutrients other than nitrogen (N) and phosphorus (P) can be the most limiting ones in tropical soils including in Sub-Saharan Africa (e.g., Rodel and Hopley, 1973; Sillanpää, 1982; Kang and Osiname, 1985; Davies, 1997; Singh, 2009), which is entirely in accordance with theoretical expectation. Nevertheless, most of the fertilizer research conducted in Africa has concentrated on N and P fertilizers, the two plant nutrients that were instrumental in achieving a Green Revolution in Asia. In Africa, though, application of these two nutrients may sometimes result in sizeable yield increases. More frequently, fertilizer impacts are modest, and yields may even decrease. Other research shows reasonable yield increases at low levels of application up to about 40 kg of N or P per hectare, with steady or declining yields at higher application levels. Voortman (2010) hypothesizes on these findings that in Africa nutrients other than N or P are likely the most limiting nutrients, or do become so at low doses of N and P. Supporting evidence for the proposition that other essential plant nutrients might be deficient is derived from medical research showing that half of the global deaths due to zinc deficiency in under-5 children, or about 400,000 per year, occur in sub-Saharan Africa (Caulfield et al., 2006). The high death toll in children in sub-Saharan Africa is presumably related to the monotonous diets of locally produced zinc-deficient crops. The emanating message would be to consider a broader spectrum of essential plant nutrients than N and P alone in the research agenda, to address soil nutrient deficiencies in sub-Saharan Africa.

The variability of crop yield response to N and P fertilizers, from positive to negative, also suggests that soils and, consequently, native soil fertility vary considerably in space. This is also evident from the results of control experiments, where no fertilizer is applied. For instance, Hikwa et al. (1998) present data from Zimbabwe and show that, within small areas, velvet bean biomass under unfertilized conditions varies from 317 kg ha⁻¹ to 7240 kg ha⁻¹. The same research also shows the large variability of yield response to P fertilizer, and this variability is also unrelated to control yield levels. Similar conclusions can be drawn from fertilizer trials with N and P in Kenya (Smaling and Janssen, 1993). Impactful fertilizer interventions will therefore have to be site-specific with respect to nutrient dose and composition. This paper will, therefore, consider the factors governing the ecological diversity of African soils and its spatial patterns in terms of the native soil chemical conditions. Matching site-specific soil chemical conditions with fine-tuned fertilizer technologies, yet to be developed, seems a viable way to achieve the sizeable crop yield increments that are urgently required in sub-Saharan Africa.

Against this background, the Virtual Fertilizer Research Centre (VFRC) has indicated its interest to verify whether the use of essential nutrients beyond N and P – specifically Ca, K, Mg, S and micronutrients (B, Cu, Fe, Mn, Mo, Ni and Zn) – possibly provide for the urgently needed impactful fertilizer interventions. If this were the case, it could lead to the development of a new generation of effective fertilizer technologies. It appears, however, that the data available are too sparse to warrant deep statistical analysis on the combined impacts of various nutrients under the prevailing soil and climatic conditions. We, therefore, limit ourselves to capitalizing on the data sets available in a selected number of case studies, each with data limitations of its own regarding coverage and size. The case studies considered are data-rich in terms of agro-ecology and soil chemistry, and it appears that, together, they provide a consistent (albeit incomplete) picture of nutrient deficiencies beyond N and P. They further suggest more general conclusions about the key factors that govern the spatial variability of soils and that need to be addressed in the development of a new generation of fertilizer technologies.

This paper concentrates on the Miombo woodland biome that covers large parts of Central-South Africa. First, we present data on a land use and land resource ecology study from Mozambique and discuss soil fertility of Miombo in general as well the key soil chemistry factors that govern the spatial distribution of ecosystems (and land use) and their functioning (Section 2). The data of this case study consist of the commonly analyzed soil chemical properties, including Ca, Mg and K, and also the micronutrients Cu, Fe and Zn. Section 3 reports on agronomic research conducted in Miombo in Malawi, and Section 4 presents the results of micronutrient trials in the Miombo of Zimbabwe. In both cases, the objective is to verify if the earlier identified key factors are also important in terms of crop yield. The trials in Malawi include experiments with lime, S, B and Zn and also provide information on soil content of Cu, Fe and Mn. The Zimbabwe case deals with the yield impact of B, Zn and dolomitic lime if added to NPK applications. Finally, we review the successes in advancing agricultural productivity in Brazil on soils deriving from parent rock material similar to those on which most of the African agriculture takes place (Section 5) and discuss the research agenda for plant nutrients beyond N, P and K and how this was brought into practice. We propose a similar research approach for sub-Saharan Africa to identify key nutrient deficiencies and to develop appropriate fertilizer technologies. Section 6 concludes.

2 Land resource ecology in the Miombo biome on basement complex in Central-South Africa

Miombo woodland vegetation is dominated by two tree genera: *Brachystegia* and *Julbernardia* (Fabaceae, Subfamily Caesalpinioideae). It covers large parts of Tanzania, Malawi, Zambia, Zimbabwe, Mozambique and Angola (Fig. 1). The Miombo biome was only sparsely populated until about four decades ago, which is generally attributed to prevailing low soil fertility (Frost, 1996; Desanker et al., 1997). Dispersed, densely cultivated pockets occurred within the Miombo range but always on different soils that also support non-Miombo vegetation types. Currently, though, large parts of the Miombo have and are being taken into use due to population pressure. This situation calls for the development of fertilizer technologies that are appropriate for the Miombo soils.

The two genera that dominate Miombo together comprise about 40 species. Consequently, these make up a variety of woodland types, the species composition of which varies with the factors of soil formation: the mineralogy of parent rock, climate, soil age, relief and organisms. Yet because of the dominance of two genera only, Miombo soils may have certain similarities that are relevant for the development of impactful fertilizer technologies. Therefore, in this section we summarize soil fertility data as observed in the Miombo biome with the objective to identify the key soil chemical properties that are relevant for the development of such fertilizer technologies.

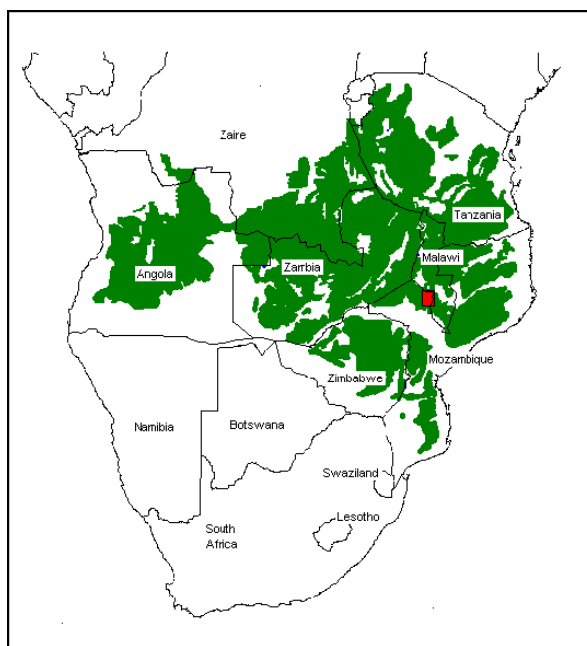


Figure 1. The spatial distribution of Miombo woodland formations (green) (red rectangle is the location the Angonia district).

First, we discuss and illustrate the sources of soil spatial variability in these woodlands (Section 2.1). Then, based on mean data from various countries, it will be verified if the soils under Miombo share common soil chemical properties and assess if these confirm that soil fertility is low. In order to obtain a proper perspective on the soil fertility status in this part of Africa, the soil chemical data will be compared with those obtained in the Brazilian Cerrados. The soils supporting Cerrado vegetation initially were thought to be of too low fertility for agricultural use but have been largely

reclaimed by now with adapted fertilizer technologies (Section 2.2). Next, the findings of a land use and land resource ecology study in the Angonia district in Mozambique will be summarized. This district is located in the Miombo range (Fig. 1) and is largely covered by Miombo woodland, which was not cultivated four decades ago. But the district also has sizeable tracts of land with deviating soils and vegetation, and these types of land are preferred for cultivation. This section reports on what soil chemical properties were found to be the key factors governing the ecological diversity of these African soils and their spatial patterns (Section 2.3). In Section 2.4, individual observations with detailed soil chemical properties in the Miombo of Zambia, Malawi and Zimbabwe will be used to verify whether these share the same key ecological factors (Section 2.4). This being the case could then lead to guiding principles for the development of appropriate fertilizer technologies for the entire Miombo biome.

2.1 Sources of spatial variability of soils

The two principle factors of soil formation that cause spatial variability in soils are parent material and climate. With respect to the latter, in the entire Miombo range the Length of the Growing Period (LGP, calculated with a water balance model) varies from 90 days in Southern Zambia to 240 days in Shaba, Congo (Fischer et al., 2000), for example. In Northern Angola and the Zambezia province of Mozambique, Miombo even extends into the 270-300 LGP zone. These large variations in climate are likely to find reflection in soil chemical properties and species composition of the woodlands. However, the observed large variation in climatic conditions rule out the possibility that particular climatic circumstances are the common denominator for the occurrence of Miombo woodland. With respect to parent material, albeit with minor exceptions in Southern Mozambique and Western Zambia, the Miombo woodlands are underlain by Precambrian Basement Complex (Bederke and Wunderlich, 1968). However, this geological formation is merely a classification based on the era in which it was formed and does not include a definition in terms of lithology/mineralogy, which at local levels is the most fundamental factor of soil formation, certainly where soil chemistry is concerned. The Basement parent material has in common, though, that it consists of crystalline rock. Due to its formation history, the lithology/mineralogy of this geological formation can show large variations, sometimes even at very local scales (Figures 2 and 3). Because of such abrupt geological boundaries, unlike climate, variations in parent material can result in an entirely different assembly of soil chemical properties in very short distances (Voortman et al., 2000). Consequently, soil nutrient deficiencies may be very different as well, thus calling for locally adapted fertilizer technologies.

2.2 Soil chemical data of Miombo and a comparison with Brazilian Cerrado soils

In this section, we depart from general notions on soil fertility in the Miombo biome and then provide actual data obtained from various locations in the Miombo range. What follows is a comparison with soil fertility levels data for various Cerrado formations. Lastly, the soil micronutrient content of Miombo and Cerrado are also compared.

The most recent reviews of Miombo generally emphasize its low soil fertility, typically being acid, low in P and N, low levels of Total Exchangeable Bases (TEB) and P-sorbing properties (Frost, 1996; Desanker et al., 1997). However, such generalizations on tropical soil properties have been seriously contested (Eswaran et al., 1992; Sanchez and Logan, 1992) and, as will be shown, these generalizations are not consistently supported by the three available data sets (Table 1).



Figure 2. Sharp soil boundary due to differences in the mineralogy of parent rock, as evident in track at the foreground with reddish brown fertile soil with remnants of tall grasses (burned at end of dry season) and in the background pale sandy soil of low fertility with Miombo woodland vegetation, Angonia district, Mozambique

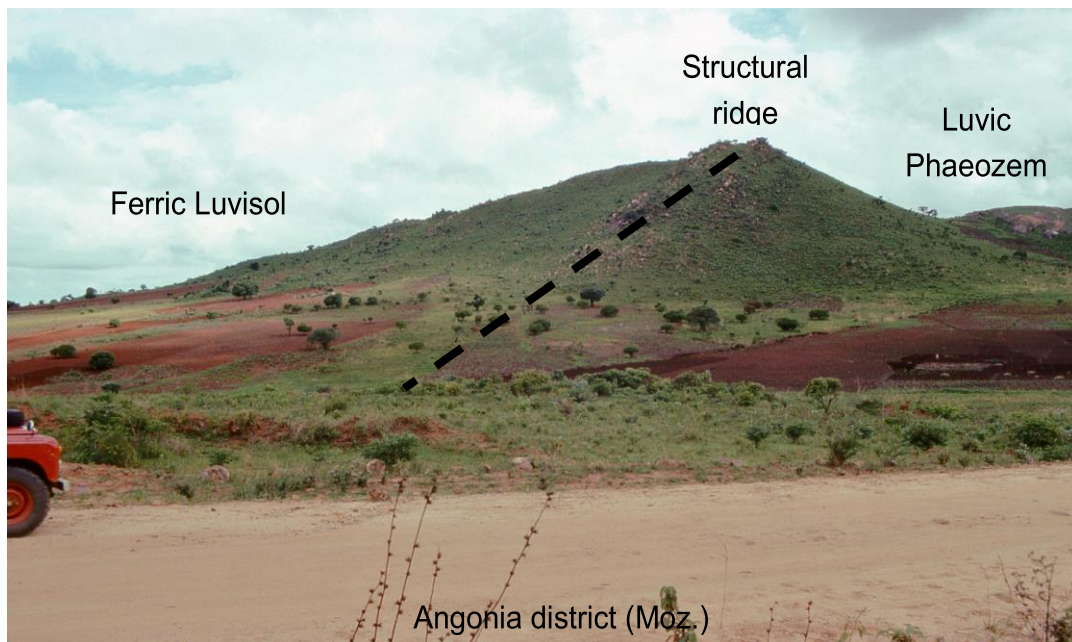


Figure 3. Sharp soil boundary due to differences in the mineralogy of parent rock; in the middle a tilted structural ridge with on the left a red soil with modest levels of organic matter (Ferric Luvisol) and on the right a brown soil very high in organic matter (Luvic Phaeozem), Angonia district, Mozambique

Table 1. A comparison of average soil chemical properties of Miombo woodlands in Zambia and Zimbabwe

(Frost, 1996; 34-84 observations depending on variable and depth of sample [34 for subsoil P and 84 for topsoil Ca, Mg and K]), the Angonia district in Mozambique (Voortman and Spiers, 1986; 32 complete observations for upland Miombo from a total of 145) and Dedza Hills in Malawi (Wendt and Rijpma, 1997; 8 topsoil observations). The range of the observed values is given in brackets.

Location		Zambia & Zimbabwe	Zambia & Zimbabwe	Angonia Mozambique	Angonia Mozambique	Dedza Hills Malawi
Depth		0-0.2 m	0.2-0.5 m	0-0.2 m	0.2-0.5 m	0-0.2 m
Variable	Dimension					
Org. C	%	1.40 (0.3-3.8)	0.58 (0.3-1.3)	1.32 (0.36-2.47)	0.44 (0.08-1.44)	1.44 (1.0-2.16)
N	%	0.10 (0.02-0.62)	0.04 (0.0-0.13)	0.11 (0.03-0.21)	0.04 (0.01-0.12)	N.A.
P-avail.	ppm	13.40 (0.0-54.0)	7.00 (0.0-25.0)	30.64 (0.05-89.0)	22.64 (0.0-192.0)	53.43 (15-105)
pH	-	5.60 (4.2-6.9)	5.30 (4.2-6.9)	5.90 (4.9-6.3)	5.88 (4.5-6.6)	5.36 (4.5-5.6)
Ca	cmol kg ⁻¹	2.72 (0.0-15.0)	1.74 (0.05-11.8)	3.52 (0.05-10.6)	2.97 (0.05-9.0)	2.92 (0.80-4.27)
Mg	cmol kg ⁻¹	1.46 (0.0-8.4)	1.35 (0.0-16.3)	1.98 (0.05-6.4)	2.26 (0.05-16.2)	1.00 (0.38-2.39)
K	cmol kg ⁻¹	0.32 (0.0-2.3)	0.20 (0.02-0.63)	0.59 (0.32-1.02)	0.52 (0.18-0.84)	0.45 (0.14-0.70)
Na	cmol kg ⁻¹	0.06 (0.0-0.48)	0.05 (0.01-0.20)	0.06 (0.03-0.16)	0.06 (0.03-0.12)	N.A.
TEB	cmol kg ⁻¹	4.74 (0.35-20.8)	3.43 (0.10-27.0)	6.14 (0.73-14.7)	5.81 (0.46-19.6)	4.37 (2.19-6.08)
BS	%	57.60 (3.0-100)	46.40 (3.4-100)	76.35 (20.9-91.0)	74.79 (13.7-94.2)	93.35 (60.8-100)

TEB: Total Exchangeable Bases (sum of Ca, Mg, K and Na); BS: Base Saturation; N.A.: Not Available.

Average topsoil organic carbon and N levels are indeed particularly low in Miombo and remarkably similar in all three data sets. The levels of these variables also decrease rapidly below the shallow topsoil. The mean pH values of the three data sets are also similar and indicate that Miombo soils are not excessively acidic. From this, it can be inferred that they do not share high aluminum toxicity levels, while high sorption properties are equally unlikely. The average available P levels under Miombo in Zambia and Zimbabwe are substantially lower than in Angonia, but these values are not particularly low by themselves, using the criteria presented in Landon (1991; Table 7.16), with even higher P levels in Malawi. Hence, Miombo soils also do not have systematically low levels of soil phosphorus in common. This point is further corroborated by data from Malawi that is largely covered by Miombo (Wild and Grandvaux Barbosa, 1967), where the average available P level for 395 soil samples taken throughout the country was 35 ppm (Wendt and Rijpma, 1997).

Total Exchangeable Bases (TEB) is also not low on average. In Angonia, the topsoil levels are well above the lower limit of medium (TEB = 5; Source: Ministère de la Coopération, 1980). Miombo soils in Zambia and Zimbabwe appear to be lower in Base Saturation and TEB, if compared with Angonia, while in Malawi TEB is lower, but base saturation is higher. A possible reason for the lower base saturation and TEB in Zambia and Zimbabwe is that a considerable portion of the observations derives from higher rainfall conditions in combination with flatter topography (i.e., old-age surfaces) in Northern Zambia. But also under these conditions, by themselves the average TEB values approximate the lower limit of medium levels (5 cmol kg⁻¹) and are certainly not very low (<2 cmol kg⁻¹; Source: Ministère de la Coopération, 1980). Therefore, in combination with the observations from Angonia, it must be concluded that Miombo soils do not share a low level of exchangeable bases (TEB). From the mean values, it is further evident that the Mg content is generally high, relative to exchangeable Ca, and that subsoil K is rather low, relative to Mg. This observation may be taken as a first indication that Miombo has relative high Mg in common, a possible cause of Ca and K deficiency (see Text Box 2). In any case, the above generalizations about the low soil fertility in the Miombo are not supported by the average data.

If we look at the spread in the data, it is obvious that the variation in the soil chemical properties in Miombo is large. N and P can be very low but also high; in the case of P, it could even be excessively present (a value of 13 for available P is considered adequate and >25 as being rich in P [Landon 1991; Table 7.18]). The range of pH values is not very large, but due to its logarithmic scale, the difference between the higher and lower values may be highly relevant for plant growth and agriculture. The basic cation levels (Ca, Mg and K) in Miombo, just like N and P, vary from not measurable to very high levels, which are also obviously reflected in the broad range of TEB levels. Part of this variation can be attributed to differences in mean annual rainfall (Figure 4)¹. Furthermore, it can be observed that in both datasets where subsoil data are available, subsoil Mg can have values that are higher than the highest subsoil Ca level. Moreover, the highest Mg level is 20 or more times the highest level of K. Both observations are a further signal that unbalanced cation ratios indeed may be at play in the Miombo biome (Boyer, 1978; Ministère de la Coopération, 1980; see also Text Box 2). This possibility will be verified later in this paper with complete data from individual observations.

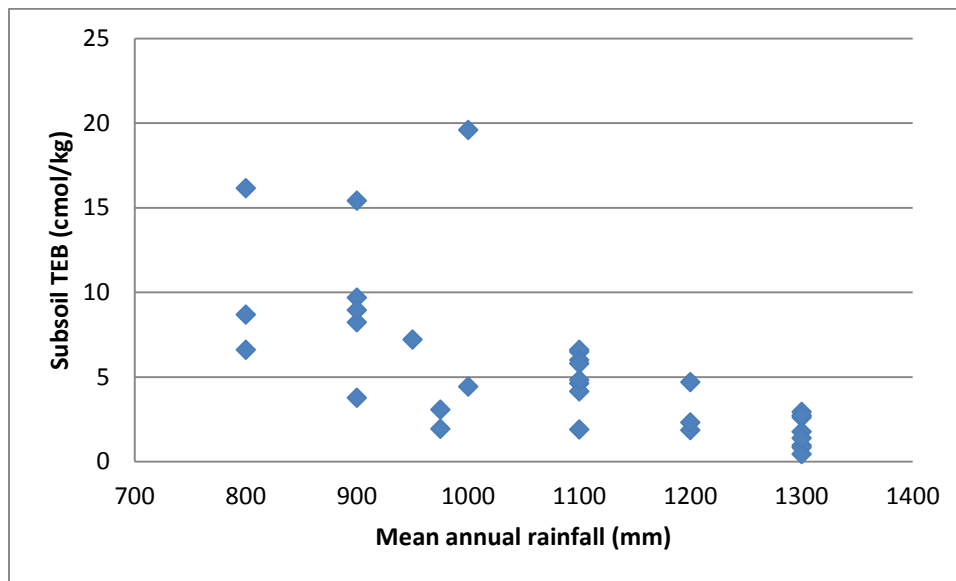


Figure 4. Subsoil TEB (cmol kg^{-1}) as a function of mean annual rainfall (mm) for Miombo woodlands in the Angonia district (Mozambique)

To put Miombo soil fertility in proper perspective, Table 2 provides average topsoil values for a large sample of various forms of Cerrado vegetation in Brazil. These data show that, compared to the Cerrado, the Miombo soils are of rather high fertility. Cerrado appears to have similar organic carbon content, but pH and base saturation are lower. Moreover, Cerrado soils are practically devoid of P and basic cations on average. As is commonly the case, other data sources confirm that Cerrado subsoil chemistry values are even substantially lower than those of the Cerrado topsoils. (e.g., Amorim and Batalha, 2006).

¹ Lower rainfall in Angonia coincides with lower altitudes and rainshadow areas (Voortman and Spiers, 1986; Volume 5: 'Climate, agro-climatic zones and agro-climatic suitability'. At lower altitudes soils are also of younger age, because of headward incision of streams due to natural (geologic) erosion. Soils of younger age generally are less leached and contain more weatherable minerals.

Table 2. Topsoil properties of various forms of Cerrado and forest in Brazil

(Source: Lopes and Cox, 1977)

Cerrado type		Campo limpo	Campo cerrado	Cerrado	Cerradão	Forest
n		64	148	245	45	16
Variable	Dimension					
Org. C*	%	1.3	1.4	1.4	1.4	1.8
P-available	ppm	0.5	0.5	0.9	2.1	1.4
pH	-	4.87	4.94	5.00	5.14	5.28
Ca	cmol kg ⁻¹	0.20	0.33	0.45	0.69	1.50
Mg	cmol kg ⁻¹	0.06	0.13	0.21	0.38	0.55
K	cmol kg ⁻¹	0.08	0.10	0.11	0.13	0.17
Al	cmol kg ⁻¹	0.74	0.63	0.66	0.61	0.78
TEB	cmol kg ⁻¹	0.34	0.56	0.72	1.30	2.22
BS	%	34.0	42.0	46.0	56.0	60.0

*The original table indicates Organic Matter (%) but in the references it seems that reference is made to a method to determine Organic Carbon (%). The figure has been corrected on the basis of OC being about 58% of OM)

Text Box 1. Vegetation structure of Cerrado as an indicator for soil chemistry

The data presented in Table 2 illustrate how vegetation (density of woody species in this case) can be used as an indicator for soil chemical properties. Cerrado generally consists of contorted trees, but the tree density may vary. From Campo limpo to Cerradão, there is a gradient from no tree species at all to a rather dense cover of trees and shrubs. This gradient is correlated with a steady increase in available P, pH and TEB. But also the nature of the cation exchange complex changes. For instance, the ratio of Mg/K gradually changes from less than 1 in campo limpo to about 3 in Cerradão. The ratio of Ca/Mg also increases but less systematically so. Table 3 further shows that along the gradient Cu and Zn increase gradually while Fe decreases. Thus, along this vegetation gradient, almost all soil chemistry values change in their level.

Micronutrients

Table 3 shows the micronutrient topsoil values for Angonia and the various Cerrado formations. For Cu, the mean values for Cerradão are similar to the Miombo of Angonia, while in the more open vegetation types Cu is substantially lower and decreases with decreasing woody vegetation. The soil Zn content of all Cerrado types stands at about 50 percent of the Miombo soils. Fe is systematically much higher in Cerrado, and soil Fe content decreases among the Cerrado types with increasing cover of woody plants.

In summary, it is commonly suggested in the literature that Miombo soils have low fertility in common. Yet more detailed inspection of actual soil data shows this proves to be the case only for organic carbon and nitrogen levels, which also appear to be concentrated in a shallow topsoil. Low soil fertility is not supported by the average data on pH, TEB, BS and the absolute level of individual plant nutrients present in the soil, including P and micronutrients. Miombo soil fertility is even high if compared to Brazilian Cerrado. Nevertheless, the spread in the soil chemical properties is large to the extent that some Miombo soils are very poor indeed. On the other hand, a portion of Miombo soils can be

considered rich. Based on the evidence provided, while excluding the very poor Miombo soils, the observed soil nutrient levels suggest that it may be expected that crops planted in most of the Miombo will be responsive to fertilizer applications, provided that composition and dose are finely tuned to the site-specific soil chemical properties. In short, the question is not if fertilizers will produce substantial yield improvement but which nutrient deficiencies need to be addressed with fertilizers.

Table 3. Available Cu, Zn and Fe in the topsoil of Miombo soils in Angonia district, Mozambique, compared with various forms of Cerrado, Brazil (values in ppm; topsoil 0-20 cm)

(Sources: Voortman and Spiers, unpublished data, and Lopes and Cox, 1977)

	Variable	n	Mean (ppm)	Range
Miombo (Ang)	Cu	32	1.17	(0.08-4.20)
Miombo (Ang)	Zn	32	1.05	(0.40-2.40)
Miombo (Ang)	Fe	32	2.67	(0.90-7.40)
Campo limpo	Cu	64	0.60	(N.A.)
Campo limpo	Zn	64	0.58	(N.A.)
Campo limpo	Fe	64	35.7	(N.A.)
Campo sujo	Cu	148	0.79	(N.A.)
Campo sujo	Zn	148	0.61	(N.A.)
Campo sujo	Fe	148	33.9	(N.A.)
Cerrado	Cu	245	0.94	(N.A.)
Cerrado	Zn	245	0.66	(N.A.)
Cerrado	Fe	245	33.0	(N.A.)
Cerradão	Cu	45	1.32	(N.A.)
Cerradão	Zn	45	0.67	(N.A.)
Cerradão	Fe	45	27.1	(N.A.)
Forest	Cu	16	0.95	(N.A.)
Forest	Zn	16	1.11	(N.A.)
Forest	Fe	16	37.2	(N.A.)

2.3 Key soil chemistry variables associated with the spatial variability of soils: the case of Angonia District, Mozambique

In the previous section, it was established that low soil fertility can occur in Miombo, but it certainly is not a common property. In the present section we, therefore, identify the key ecological factors, notably soil chemistry, that govern the diversity and spatial distribution of ecosystems in the Miombo biome (Voortman and Spiers, 2010 a/b). These studies are based on the findings of a landscape-ecological survey conducted in the Angonia district in Mozambique (Voortman and Spiers, 1986) that, to a large extent, is covered with Miombo woodland. The location of the study area is shown in Figure 1. The district is underlain by tilted Precambrian Basement Complex rock with different kinds of mineralogy in short distances. Apart from that, there is also a large variation in altitude (700-1600 m), rainfall (900- mm to 1400+ mm) and growing season length (150- days to 210+ days). Hence, the district is ideally suited for research on environmental variation. The landscape-ecological survey resulted in a map of land units, each of which was

defined, according to the concept of land² (Voortman, 1985), in terms of the factors of soil formation: climate, the lithology of parent rock, geomorphology/relief, soils and vegetation/land use. In total, 613 observations were made, of which 145 detailed soil profile descriptions from soil pits with each horizon sampled for textural and chemical analysis. At these sites complete vegetation relevés (i.e., a landscape sampling method for natural vegetation) were also made in terms of species composition, cover/abundance of each species as well as vegetation structure (physiognomy). The landscape-ecological survey has resulted in a map at scale 1:50,000 with about 140 individual land units (soil/vegetation types), grouped in 40 landscapes, and comprising different combinations of land units (Figure 5). To avoid influences of soil drainage class and to emphasize the impact of soil chemical properties in the following, only soils with a drainage class better than imperfect were used, thus resulting in about 121 observations.



Figure 5. *Compilation of photographs of nine map sheets of the land unit map of Angonia district, Mozambique*

Nguni land in brown colors and Miombo woodland in green and yellow colors. The black line separates the geological formation called Tete-Chipata Belt, West Gondwana, with more felsic parent materials in the West and South and the formation of the Angonia group, East Gondwana, with more mafic parent material in the North-East with higher spatial variability (area size about 100 km North-South and 60 km East-West).

Most of the district is covered with Miombo woodlands that were generally uncultivated (32 observations). But, other land types with different soils/vegetation also do occur and are related to presence of different types of soil parent material. An example of this is the so-called Nguni vegetation, physiognomically a wooded grassland with a dense and tall grass-layer. As far as woody species are concerned, it entirely lacks the typical Miombo species and is characterized by the genera such as *Acacia*, *Pterocarpus*, *Combretum*, *Pericopsis*, *Erythrina*, *Ficus*, *Albizzia* and

² "A tract of land is defined geographically as a specific area of the earth's surface: its characteristics embrace all reasonably stable, or predictably cyclic attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and underlying rocks, the topography, the hydrology, the plant and animal populations and the result of past and present human activity to the extent that these attributes exert a significant influence on present and future uses of the land by man" (adapted from Vink, 1975; Brinkman and Smyth, 1973; and Christian and Stewart in Rey et al., 1968).

Piliostigma, with a large part of the observed species being nodulating legumes. This type of land was highly preferred for cultivation (44 observations). Another 45 observations include various soil/vegetation types such as montane grasslands, leached poor soils in high-rainfall zones and grasslands on mafic parent materials. All these were not cultivated. With respect to these rather clear-cut soil preferences where cultivation is concerned, it has been observed that much local knowledge on soils exists in sub-Saharan Africa. Apparently, such tacit knowledge has been transmitted from one generation to the next. Indeed, it has been argued that no African community would have survived for long if site selection for cultivation would take place in a haphazard manner (Allen, 1965). Systems of local knowledge on land quality are obviously not based on knowledge of soil chemical properties but rather on properties that are observable at the surface, notably vegetation (in fact, using the basic axiom of landscape ecology on bio-indication). Both local ecological knowledge and the possible use of vegetation as an indicator for site conditions can be instrumental for the development of appropriate fertilizers and their dissemination. Therefore, we have used the soil profile chemical data in combination with vegetation/land use data to identify the following:

- Which soil chemical variables explain the degree to which the land units have been taken into use for cultivation (percentage of land cultivated)?
- Which soil chemical properties explain the occurrence of different vegetation types?

The method used to explain cultivation density is Ordinary Least Squares regression (OLS, normal and step-wise). First, an attempt was made to find an explanation on the basis of conventional soil fertility characteristics, including N, P and K. The data used derive from three soil depths (topsoil, subsoil and deeper subsoils). With respect to the essential plant nutrients N, P and K, the departure was a full quadratic formulation including their square values and multiplications for each combination. Next, we consider a broader spectrum of nutrients, including nutrient ratios that represent antagonistic mechanisms where nutrient uptake by plants is concerned. The results for N, P and K and commonly used soil fertility indicators are presented in Table 4.

Cultivation density can be explained by a linear formulation of topsoil N and P only (Table 4, Equation 1). Cultivation density increases as soil N increases. It unexpectedly decreases with increasing levels of P, and overall explanatory power is low (adjusted $R^2 = 0.28$ only). The same formulation was tested for the subsoil and deeper subsoil. For the subsoil, only N is significant and a linear relationship explains 54 percent of the differences in cultivation density (Table 4, Equation 2). For the deeper subsoil, it is again only N in a linear specification that is significant with an adjusted R^2 of 0.55. A possible explanation for the higher diagnostic value of subsoil N, rather than topsoil N, is that in all ecosystems organic matter and N accumulate in the topsoil but that the depth to which accumulation takes place is substantially different in preferred and avoided soils. The use of topsoil values only, when characterizing and comparing soils, may thus conceal important differences between soils. Another problem of the high explanatory power of subsoil N is that N does not commonly occur in soil parent material and, therefore, is the most endogenous of all soil chemical properties, a potential cause for circular reasoning. Therefore, we purposely also exclude N from the equations in the following to identify the possible underlying and deeper causes of high N accumulation.

Table 4. Cultivation density as a function of N, P and K levels from the topsoil, subsoil and deeper subsoil (Initially tested with a full quadratic equation) and in combination with soil texture, TEb, BS and pH.

The dependent variable cultivation density is a field-based estimate with classes of 0, 30, 50, 80 and 100 percent. Soil depth 10 cm refers to 0-20 cm, 30 cm to 20-50 cm, 70 cm to 50-90 cm (Source: Voortman and Spiers, 2010a)

Equation	1	2	3	4	5	6	7	8	9
Soil depth	10 cm	30 cm	70 cm	10 cm	10 cm	10 cm	30 cm	30 cm	30 cm
Intercept	-0.14	-1.43	-1.33	-6.63	-2.32	2.40	-12.29	-7.41	-12.93
p	0.8804	0.0025	0.0099	0.0002	0.0238	0.2482	0.0006	0.1102	0.0053
N	29.93	59.04	120.76	16.75			48.33		
p	<.0001	<.0001	<.0001	0.0056			<.0001		
P-available	-0.037			-0.041	-0.037	-0.050		-0.022	-0.024
p	0.0097			0.0038	0.0048	0.0005		0.0485	0.0396
Clay				0.080	0.077				
p				0.0038	0.0025				
BS				0.083		0.10			
p				0.0003		<.0001			
TEB					0.67			0.36	
p					<.0001			0.0006	
Sand						-0.095	-0.038	-0.087	-0.099
p						<.0001	0.0246	<.0001	<.0001
pH							2.69	2.70	4.12
p							<.0001	0.0021	<.0001
K							-4.54	-6.36	-6.27
p							0.0015	0.0003	0.0007
Adj. R ²	0.28	0.54	0.55	0.38	0.41	0.34	0.62	0.42	0.36
n	121	119	103	121	121	121	119	119	119

We proceed our study on the relationship between cultivation density and soil chemistry by considering other commonly used indicators of soil fertility and land suitability, such as soil texture, pH, base saturation (BS) and total exchangeable bases (TEB). Regressions for the topsoil (Table 4: Equations 4-6) show that, of the macronutrients, again only topsoil N and P are significant and that various expressions for texture and the exchange complex (BS and TEB) considerably improve explanatory power (as compared to Equation 1). In all three equations, response to P remains consistently negative, but for all other variables the response conforms to expectations: positive for clay content, BS and TEB and negative for sand content. Equation 5, in which N is excluded, is more parsimonious than equation 4, in which N has been maintained. It has the highest explanatory power of the topsoil equations ($R^2=0.41$). Apparently, TEB alone discriminates better between cultivation densities than the combination of topsoil N and BS. It might be argued that apparently TEB stands in for Organic Matter (and consequently N) based on the common assumption that both are closely related. Regression analysis indeed confirms the positive relationship between TEB and OM content, but OM levels explain only 30 percent of the variation in TEB ($P <.0001$; not shown). Another common assumption is also not confirmed by equation 5, being that TEB would be closely related to the soil clay content: both in combination explain cultivation density with high significance levels. Indeed, topsoil TEB proved to be entirely unrelated to clay content ($P = 0.9237$; not shown). It might further be argued that TEB possibly stands in for BS because there is obviously some relationship, merely by definition. However, maintaining P and texture and substitution of BS for TEB produces substantial loss of explanatory power (Table 4: Equation 6). These results cast some doubt on commonly made assumptions on the relationships between soil chemical properties, which may not be as universally valid as sometimes expected. It has thus been convincingly shown that TEB has an explanatory power in its own right. At this point, we tentatively conclude that the relative independence of TEB from clay content and organic matter levels is possibly related to parent material characteristics. In any case, the findings indicate that TEB is an important discriminator between cultivated and avoided land types.

The subsoil equations (Table 4: Equations 7-9) show that, with N maintained, only rather modest improvement of explanatory power can be realized (compared to Equation 2). Without N, the R^2 values drop considerably, but the best performing equation again includes both texture and TEB with high significance levels. The positive signs of TEB and pH are as expected, and so is the negative sign for sand content. The negative relationship between cultivation density and soil P levels is further confirmed by the subsoil values. Non-linear specifications and combinations of topsoil and subsoil properties have also been tested, but these did not improve on the explanation of cultivation density.

We conclude that the soil fertility indicators used here (TEB, pH, BS) in addition to soil macronutrient levels provide for modest increases of explanatory power only. Without the endogenous N, such soil fertility indicators explain about 40 percent of the differences in cultivation density. When using these indicators, the positive correlation of N and the negative correlation of P with cultivation density are confirmed, and the latter also appears to apply for the subsoil. The above findings may be interesting in their own right in that they confirm earlier findings (Voortman and Brouwer, 2003; Voortman et al., 2004). Apparently, macronutrients and other commonly used indicators of soil fertility only tell part of the story of African land and production ecology. Moreover, the equations obtained are not very meaningful for the practical purpose of developing effective fertilizer technologies, except for the role of N and P – firstly because soil texture is difficult to change and secondly because pH, BS and TEB cannot be readily linked to deficiencies of individual plant nutrients.

The results obtained while using a broader spectrum of nutrients, including nutrient ratios, are shown in Table 5. While excluding the equations that include N, it appears that cultivated soils in the topsoil are associated with low P and high Ca, but Ca can also become too high (Ca^2), low Fe or low Fe/Zn and low Exchangeable Sodium Percentage (ESP). The subsoil properties of cultivated soils are high in the ratio $(Ca+Mg)/K$ in combination with high Ca and low K, or high in the ratio $(Ca+Mg)/K$, in combination with high Ca and Cu, and low Mg/K. The cultivated subsoils further have a low P/Fe ratio. Equation 7 also shows that cultivated soils are low in P and Mg/K (as reflected in the multiplication; $P \cdot Mg/K$), but if the P level is somewhat high, it may still be cultivated if the Mg/K ratio is sufficiently low. Similarly, a somewhat lower $(Ca+Mg)/K$ ratio in cultivated land may be compensated for, if the level of Cu is sufficiently high. Thus, it appears that P, the basic cations and micronutrients and their interrelations as expressed in ratios, which are known to represent nutrient antagonisms, explain land use better than the commonly used soil fertility indicators. Yet the explanatory powers (R^2) are still not high, supposedly due to the heterogeneity of the group of uncultivated land. Nevertheless, these findings allow interpretation in terms of individual plant nutrients that are deficient or in excess in cultivated and unused land with possible direct implications for fertilizer technologies that obviously require testing. Next, we will seek to improve on performance by analyzing two more homogeneous vegetation types.

Table 5. Cultivation density as a function of individual elements and their ratio's (with and without subsoil N)

(Source: Voortman and Spiers, 2010a)

Equation	1	2	3	4	5	6	7
Intercept	-0.80	-0.43	2.62	0.97	3.51	2.85	-0.31
p	0.3256	0.5316	0.0152	0.2567	<.0001	0.0006	0.7690
N (30)	44.79	46.74					
p	<.0001	<.0001					
(Ca+Mg)/K (30)	0.066	0.071		0.18	0.27	0.28	
p	0.0020	0.0011		0.0005	<.0001	<.0001	
Fe (10)	-0.66		-0.83	-0.82			-0.70
p	0.0014		0.0001	0.0002			0.0020
Zn (10)	1.06						
p	0.0516						
Fe/Zn (10)		-0.37			-0.50		
p		0.0054			0.0023		
Ca (30)			0.53				
p			0.0074				
K (30)			-4.49				
p			0.0027				
Ca (10)			0.48	0.48			1.81
p			0.0177	0.0099			<.0001
Cu (30)			0.63	0.73			
p			0.0304	0.0080			
Mg/K (30)				-0.27	-0.40	-0.42	
p				0.0132	0.0005	0.0003	
ESP (10)					-0.55	-0.74	
p					0.0600	0.0128	
P/Fe (30)					-0.024		
p					0.0545		
P-available (10)						-0.035	
p						0.0078	
P x Mg/K (10)							-0.005
p							0.0428
Ca² (10)							-0.12
p							0.0114
(Ca+Mg)/K x Cu (30)							0.036
p							<.0001
Adj. R ²	0.62	0.61	0.52	0.52	0.43	0.40	0.53
n	118	118	118	118	118	118	118

Table 6. Binary logistic regression: Nguni versus true Miombo woodland

(Source: Voortman and Spiers, 2010a)

Equation Nr.	1	2	3	4	5	6
Intercept	-12.59	-16.80	-18.58	-15.23	6.13	6.68
p	0.0870	0.0090	0.0159	0.0114	0.0002	0.0001
N (30)	229.7					
p	0.0837					
e ^β	>999					
P-available(10)		-0.11		-0.05		-0.06
P		0.0044		0.1234		0.0006
e ^β		0.89		0.96		0.97
K (10)		27.43	14.32	14.84		
P		0.0085	0.0342	0.267		
e ^β		>999	>999	>999		
(Ca+Mg)/K (30)		0.32				
p		0.0035				
e ^β		1.38				
Clay (10)			0.036	0.23		
p			0.0300	0.0230		
e ^β			1.43	1.25		
Ca (30)			1.01	0.67		
p			0.0420	0.0766		
e ^β			2.74	1.95		
ESP (10)					-2.78	-2.45
P					0.0186	0.0134
e ^β					0.062	0.087
Fe/Cu (10)			-1.14			
p			0.0393			
e ^β			0.32			
P/Cu (10)					-0.11	
p					0.0009	
e ^β					0.90	
Zn/Cu (10)						-1.22
p						0.0323
e ^β						0.29
LR, p	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Score, p	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Wald, p	0.0837	0.0267	0.1217	0.0331	0.0012	0.0018
R ²	0.95	0.86	0.87	0.85	0.78	0.72
Conc. %	99.6	98.4	98.4	98.2	95.1	93.7
H&L, p	0.9980	0.9500	0.5594	0.9935	0.2194	0.1001
Hit ratio	96.8	91.8	93.4	90.3	91.8	90.0
Sensitivity	97.7	95.2	95.2	93.0	95.2	93.0
Specificity	94.7	84.2	89.5	84.2	84.2	82.4

A basic axiom of landscape ecology is that vegetation species composition is an indicator for environmental conditions, including its soil chemical properties. A study on the relationship between different vegetation types and soil chemical properties can, therefore, serve the objective to identify which soil chemical properties are the key factors governing

the ecological diversity of soils and its spatial patterns. For this purpose, we exclude the 45 observations in miscellaneous land types and concentrate on Miombo and Nguni vegetation that can easily be distinguished in the field. There is only minor overlap between these two types: Nguni with some Miombo species present at low cover/abundance ratings (seven observations) and Miombo with some Nguni species (three observations). The limited number of observations of these intermediate vegetation types does not allow meaningful statistical analysis. Hence, we concentrated on pure Nguni (44 observations) and pure Miombo (32 observations). The Miombo was sub-divided into two groups that occur in spatially distinct areas as related to geological formation. Miombo with true woodland stature (20 observations) occur in the western and southern part of the district (see Figure 5), coinciding with Tete-Chipata Belt, West Gondwana, with more felsic parent materials (Westerhof et al., 2008; ING, 1987). The other group of Miombo consists of bushlands and shrublands (12 observations). These occur in association with cultivated land and were used for fuel, which in an undisturbed state could once have been woodlands. The latter group is located in the geological formation called the Angonia group, East Gondwana, with more mafic parent material (Westerhof et al., 2008; ING, 1987). The chemical properties of both Miombo groups were analyzed in relation to the Nguni data. Binary logistic regression was applied to these pairs of vegetation classes. The program searches for the most significant soil chemistry variables that explain the different vegetation types. The performance of the obtained equation can be judged on an R^2 and the hit ratio, being the percentage of the observations that are properly classified, while using the soil chemical properties identified. The results obtained for the binary logistic regression for pure Nguni and true Miombo woodland are presented in Table 6. The comparison and classification of the two vegetation types perform well, with R^2 s of about 0.85 and hit ratios above 90 percent. From Table 6, it is clear that the types of variables that discriminate best between the two vegetation types are similar to those that explained cultivation density. The results for pure Nguni and the Miombo bushland types are presented in Table 7. As might have been expected, due to greater similarity of parent material, R^2 s at around 40 are rather modest. The hit ratio, at around 85, seems fine but is misleading. It mainly derives from the good classification of the Nguni observations (sensitivity), while the portion of Miombo bushlands that is properly classified is well below 50 percent (specificity). These modest results may be due to the large difference in the number of observations between the two land types, but the main difference between the two types is possibly related to plant nutrients that have not been analyzed. This calls for further research. In any case, the type of variables involved is again of a similar nature.

These examples and other analyses reported in Voortman and Spiers (2010a) suggest that a consistent set of soil chemical variables explains both the differences in cultivation density and the differences between soil/vegetation types. This set of soil chemistry variables, as identified in the case study, can be summarized as follows:

- individual cations, their sum and their ratios:
Ca, Mg, K, TEB, $(Ca+Mg)/K$, Ca/Mg, Mg/K, ESP (Exchangeable Sodium Percentage)
- individual micronutrients and their ratios:
Cu, Fe, Zn, Fe/Zn, Fe/Cu, Zn/Cu
- phosphorus levels and ratios of P with micronutrients:
P, P/Fe, P/Cu, P/Zn
- interactions of cation ratios with P and micronutrients:
 $P*(Mg/K)$, $((Ca+Mg)/K)*Cu$

Table 7. Binary logistic regression: Nguni versus Miombo bushlands*(Source: Voortman and Spiers, 2010a)*

Equation Nr.	1	2	3	4	5
Intercept	-3.32	-1.97	-1.92	-3.82	-0.41
p	0.0231	0.3078	0.2503	0.0467	0.7576
N (30)	53.54				
p	0.0022				
e ^β	>999				
TEB (10)		0.93			
p		0.0156			
e ^β		2.54			
Mg (30)		-1.31	-1.18		
p		0.0126	0.224		
e ^β		0.27	0.31		
Ca (10)			1.51		
P			0.0077		
e ^β			4.55		
Ca/Mg (10)				2.87	
p				0.0116	
e ^β				17.68	
Ca/Mg (30)					1.46
p					0.0257
e ^β					4.29
Zn/Cu (30)					-1.91
p					0.0987
e ^β					0.15
LR, p	<.0001	0.0014	0.0002	0.0002	0.0031
Score, p	<.0001	0.0021	0.0009	0.0013	0.0093
Wald, p	0.0022	0.0295	0.0220	0.0116	0.0440
R ²	0.56	0.39	0.49	0.40	0.35
Conc. %	90.5	82.8	87.8	86.9	83.7
H&L, p	0.9048	0.6658	0.2298	0.8302	0.5916
Hit ratio	86.0	86.3	86.0	84.0	84.3
Sensitivity	92.9	95.3	95.2	95.2	97.7
Specificity	50.0	37.5	37.5	25.0	12.5

We now translate the findings into possible nutrient deficiencies and research agenda for the three land types considered: the land preferred for cultivation, true Miombo woodland and the Miombo bushlands. The analysis revealed that the land types preferred for cultivation are those that are low in topsoil and subsoil P as well as in subsoil K. It is very likely that P fertilizer is effective here, and small doses of K are worth trying. These lands also have heavier textured topsoils and a higher topsoil and subsoil TEB. Topsoil Cu and Fe also added to the explanation, with Cu being higher and Fe being lower, hence their ratio being higher. In these cultivated lands, topsoil and subsoil Ca and the subsoil (Ca+Mg)/K ratio were higher, while the Mg/K ratio is lower, suggesting that intricacies at the exchange complex have an important impact on the decision to select land. The same types of soil chemical properties also determine

the spatial distribution of different vegetation types and govern the ecological diversity of these African soils and its spatial patterns.

With respect to the true Miombo woodlands, the binary logistic regression indicates that the soil P level is generally high. However, the spread is large, and very low levels occur as well (Table 1). Further research is required to locate and identify the environmental conditions (geology, climate) from which such differences derive. The regressions in combination with the mean data (not shown) further suggest that N and Cu may be deficient in large parts of this type of Miombo, while the Ca/Mg and (Ca+Mg)/K ratios are unbalanced due to low Ca. The results for the Miombo bushlands on the Angonia group formation show that P levels are higher than in Nguni, but P application is still worth trying. Other likely deficiencies refer to N, Cu and Ca but are possibly less severe than in the true woodlands on the Tete-Chipata Belt. However, here the Ca requirement does not only derive from low Ca levels but also from high Mg levels in part of the observations. Because of that, K application is also likely to benefit crop yield. Thus, based on the results of the binary logistic regressions and the mean values of soil chemical properties, a well-targeted agronomic research agenda has been developed for each of the three land types considered here as follows (Voortman and Spiers, 2010a):

- Nguni land: no N, P, small doses of K and possibly Fe and Zn
- Miombo woodland: no P, N, Ca at non-liming rates, Cu and possibly Zn
- Miombo bushland: N, P, Ca at non liming rates, K, Cu and possibly Zn

In summary, Figures 6 and 7 illustrate the different types of ecosystems that can occur on both sides of a sharp soil boundary, as shown in Figure 2. The Miombo was not used for cultivation but does serve as a source of fuel. Pole wood, fiber, honey and mushrooms (mycorrhizae) are collected as well. Figure 7 shows the cultivation steppe of Nguni vegetation. The grasses are taller than humans, and the land is fully cultivated with scattered mango and acacia trees in the field. Our analyses have shown that among the key soil chemistry factors that govern the diversity and spatial distribution of natural vegetation type and land-use density, the properties of the exchange complex and micronutrients figure prominently. Nutrient ratios, reflecting well-known antagonisms where nutrient uptake is concerned, have shown to provide higher explanatory power than the absolute levels of individual nutrients present in the soil. Table 8 summarizes the findings in terms of soil chemical properties. In addition, particularities of mechanisms of indirect nutrient acquisition are presented, as well as the prevalence of functional groups of termites. The indirect nutrient acquisition strategies – referring to the prevalent type of mycorrhizae and presence of nodulating legumes that can fix nitrogen (BNF) – can be derived from the species composition of the vegetation. The presence/absence of termites with different feeding habits is based on field observations. Table 8 indicates that the soil chemical properties identified as making the difference between Miombo and Nguni land are rather fundamental ones and find expression even in the type of mycorrhizae, presence of BNF and termite feeding strategies. The observed differences in soil chemistry thus appear to be related to entirely different ecosystems and ecosystem functioning.



Figure 6. *Typical Miombo woodland (uncultivated) on shallowish and sandy soil
Picture taken in the early wet season (Photography: R.L. Voortman)*



Figure 7. *Typical Nguni land: Cultivated land showing tall grasses and 'chocolate brown' soils with the small Angoni breed cattle stubble grazing
Picture taken during the dry season (Photography: R.L. Voortman).*

Table 8. *Properties of Miombo versus Nguni vegetation*

(Source: Voortman and Spiers, 2010b)

Miombo vegetation (not taken into cultivation)	Nguni vegetation (taken into cultivation)
Low N, high P	High N, Low P
P-induced micronutrient deficiencies likely	P-induced micronutrient deficiencies unlikely
Medium TEB	High TEB
Low Ca/Mg, high Mg/K	High Ca, high Ca/Mg, lower Mg/K
Ecto-Mycorrhizae	VA-Mycorrhizae
Macrotermes mound-building termites	Soil-feeding termites
No nodulating legumes	Dominantly nodulating legumes (BNF)

2.4 Verification with Miombo Soil Chemistry Elsewhere

Data on soil chemistry of Miombo that enable to calculate the cation ratios of individual soil observations are hard to find. Frost (1996, Table 2.3) published the top- and subsoil chemical properties of 14 individual soil observations in Miombo in Zambia, Malawi and Zimbabwe, and these have been used to verify whether the key soil chemistry variables identified in Angonia apply elsewhere in the Miombo biome as well. The characterization was, however, limited to soil P levels and the exchange complex, since micronutrient data are unavailable in the Frost data. For all 14 observations, the cation ratios for Ca/Mg, Mg/K and (Ca+Mg)/K have been calculated, and the data are presented in Table 9. From the outset it must be observed that the data for Chitedze in Malawi are unlikely to refer to Miombo soils. Firstly, at Chitedze, rather than Miombo, the dominant vegetation consists of Nguni (Wild and Grandvaux Barbosa, 1967). Second, the description as given in Young (1976) refers to dark reddish brown ferruginous soils that are high in organic matter even after many years of permanent cultivation. The Kasungu observation in Malawi is also suspect because of the presence of both Miombo and Nguni vegetation in the area.

With respect to the cation ratios the data will be classified according to the criteria developed in Text Box 2. In addition, Total Exchangeable Bases (TEB) and soil P levels will be used. TEB is considered, because at the same cation ratio the absolute values of the individual cations may vary from low to high. Schuffelen (1940) illustrates that the optimal band-width of cation ratios depends on soil acidity and TEB, whereby in acid/low TEB soils the optimum is more narrowly defined. Therefore, a very low TEB has been used as an additional classification criterion: $\leq 2 \text{ cmol kg}^{-1}$ (Ministère de la Coopération, 1980). Because of the findings in the Angonia study, it is also important to identify the soils that can be considered high in P. However, it is difficult to use a single criterion due to the five different analytical methods used (and in one observation, the method was not given). Based on various sources, an arbitrary limit was established: P is high if $\geq 10 \text{ ppm}$ (various tables in Landon, 1991). These criteria have been applied to the subsoil chemical properties in view of its earlier observed higher diagnostic properties if compared to topsoil values.

The results of the classification are marked in color in Table 9. Excluding the Chitedze observation for reasons given above, it appears that most observations have a very low TEB, despite earlier conclusions that a low TEB is not a systematic characteristic of Miombo. This phenomenon arises from the fact that all Zambian sites are located in the humid north and that four of the observations in Zimbabwe derive from granitic sandy soils. Hence, the low TEB in these cases is fully in accordance with expectations based on the likely effect of the factors of soil formation. Virtually all observations have unbalanced cation ratios to a varying degree.

Text Box 2: Balanced and unbalanced cation ratios

The basic cations Ca, Mg and K are antagonists where uptake by plants is concerned. It implies that, if the level of one of them (e.g., Mg) is high relative to the others (Ca and K), the uptake of Ca and Mg is hampered (e.g., de Wit, 1963; Boyer, 1972). On the other hand, it also implies that the quantities of these cations, as present in the soil, can be in balance such that adequate amounts of all of them can be taken up by the plant. The existence of such antagonisms were already established at the end of the 19th century by Loew (1892). The balance or unbalance between the basic cations can be suitably expressed by their dimensionless ratio, based on the level of individual nutrients as measured in cmol kg⁻¹.

Boyer (1978) summarizes much of the work done on these basic cations in the African French-speaking territories. According to Boyer (1978), for many plants the optimum Ca/Mg ratio is between 2 and 10; the optimum Mg/K ratio is between 3 and 4; the optimum (Ca+Mg)/K ratio is between 15 and 30. Other evidence suggests the optimum Ca/Mg ratio to be between 2.5 and 5 (Sumner, 2012). Hence, a provisional working hypothesis may be that a Ca:Mg:K ratio of 9:3:1 is optimal. These optimum values obviously vary with crop species, soil texture, the absolute levels present in the soil and the entire stoichiometrical conditions of the soil. The optimality of these ratios clearly needs further research.

To describe the data in Section 2.4 and compare them with the previous results of statistical analysis, we need a kind of decision tree on the basis of which a variable can be scored as having a high or low value. Based on Boyer (1978), Ministère de la Cooperation (1980), Voortman (1985), Landon (1991) and Sumner (2012), a provisional rating scheme was made as follows:

	Ca/Mg	Mg/K	(Ca+Mg)/K
Very unbalanced low	≤ 1	≤ 1	≤ 5
Unbalanced low	1.1-2	1.12	5.1- 15
Balanced	2.1-5.9	2.1-5.9	15-30
Unbalanced high	≥ 6	≥ 6	≥ 30

Clearly this classification is provisional and requires further elaboration. Yet despite the shortcomings, it provides a consistent tool to describe and compare the data.

Two observations have only one unbalanced ratio, both consisting of (Ca+Mg)/K. Six observations combine two unbalanced ratios and five observations reveal even three unbalanced ratios. Although the data on soil P are hard to interpret due to the different analytical methods used, the data show that unbalanced cation ratios can occur in combination with high P levels, but not systematically so. This recalculation of actual soil chemical data from elsewhere in the Miombo biome thus shows a remarkable resemblance in terms of the combination of P and the characteristics of the exchange complex with the set of variables that characterizes Miombo in Angonia.

Table 9. Soil chemical properties of Miombo soils in Zambia, Malawi and Zimbabwe

(Source: Frost, 1996, Table 2.2) Low TEB marked in red, low Ca/Mg and low Mg/K marked in orange, high Mg/K marked in bleu, low (Ca+Mg)/K marked in light purple, high (Ca+Mg)/K marked in deep purple, high P marked in yellow.

Obs.	Locality	Parent rock	Depth (cm)	pH (*)	C (%)	N (%)	Ca cmol kg ⁻¹	Mg cmol kg ⁻¹	K cmol kg ⁻¹	TEB cmol kg ⁻¹	Ca/Mg	Mg/K	Ca+Mg)/K	P ppm (**)
ZAMBIA														
1	Kasama	granite	0-10	4.9a	1.09	-	1.32	0.57	0.10	1.99	2.3	5.7	18.9	27 a
			10-20	4.5	0.53	-	0.47	0.29	0.04	0.80	1.6	7.3	19.0	18
2	Kasama	granite	0-10	4.8a	1.20	0.130	1.64	1.23	0.20	3.07	1.3	6.2	14.4	6 f
			10-20	4.5	0.74	0.090	0.57	0.22	0.15	0.94	2.6	1.5	5.3	2
3	Luapula	Precambrian sediments	0-15 40-50	4.2c 4.3	0.89 0.30	0.051 0.028	0.16 0.24	0.12 0.11	0.08 0.05	0.36 0.40	1.3 2.2	1.5 2.2	3.5 7.0	<1 b
4	Chingola	Basement complex	0-10 10-45	5.4c 5.2	1.90 0.52	0.091 0.029	0.70 0.05	0.55 0.11	0.47 0.36	1.72 0.52	1.3 0.5	1.2 0.3	2.7 0.4	-
5	Ndola	Basement complex	0-15 15-30	5.2b 5.0	0.86 0.43	0.068 0.035	0.15 0.07	0.24 0.12	0.11 0.06	0.50 0.25	0.6 0.6	2.2 2.0	3.5 3.2	4 c
6	Kapiri-Mposhi	quartz-rich gneiss	0-14 14-23	5.8a 6.1	1.20 0.50	0.080 0.030	2.90 2.20	1.00 0.80	0.60 0.50	4.50 3.50	2.9 2.8	1.7 1.6	6.5 6.0	44 a 32
MALAWI														
7	Kasungu	biotite gneiss	0-15 15-30	6.1b 5.8	1.89 0.67	0.120 0.042	9.79 5.99	4.21 3.44	0.78 0.72	14.78 10.15	2.3 1.7	5.4 4.8	17.9 13.1	11 b <1
8	Chitedze	gneiss	0-13 13-30	6.0b 5.7	1.30 0.70	0.100 0.070	15.30 6.30	1.50 1.40	1.20 0.50	18.00 8.20	10.2 4.5	1.3 2.8	14.0 15.4	25 e 14
ZIMBABWE														
9	Banket	epidiorite	0-15 23-45	4.8a 4.8	- -	0.100 -	11.53 11.61	3.45 3.75	0.36 0.18	15.34 15.54	3.3 3.1	9.6 20.8	41.6 85.3	9 b 5
10	Banket	dacite	0-10 20-35	5.2a 4.5	- -	0.072 -	2.43 1.22	1.43 2.35	0.32 0.20	4.18 3.77	1.7 0.5	4.5 11.8	12.1 17.9	3 b <1
11	Banket	granite	0-15 30-45	5.4a 5.3	- -	0.050 -	2.11 0.83	0.33 0.31	0.14 0.10	2.58 1.24	6.4 2.7	2.4 3.1	17.4 11.4	16 b 2
12	Harare	granite	0-8 ?-43	6.5b 5.7	1.02 0.18	0.068 0.016	2.20 0.25	0.90 0.20	0.28 0.14	3.38 0.59	2.4 1.3	3.2 1.4	11.1 3.2	45 d 20
13	Marondera	granite	0-11 11-30	4.6a 4.2	1.18 0.84	0.081 0.056	1.10 0.30	0.70 0.30	0.20 0.20	2.00 0.80	1.6 1.0	3.5 1.5	9.0 3.0	- -
14	Marondera	granite	0-9 17-50	6.6b 5.8	1.55 0.41	0.066 0.015	1.26 0.44	0.36 0.22	0.12 0.21	1.74 0.87	3.5 2.0	3.0 1.0	13.5 3.1	16 a 4
* a=pH(CaCl2); b= pH(H2O); c = not stated.														
** a = Bray I; b = anion exchange resin; c = Truog; d = NaOH; e = NH4F; f = not stated.														
- = not measured														

In summary, Miombo comprises many vegetation types differing in structure and species composition but have in common the genera of the dominant tree species belonging to the *Ceasalpinioideae*. The chemistry of the soils of this assembly of vegetation types cannot simply be captured under one linear denominator such as pH, TEB, BS and phosphorus levels or a combination of these. Soils of Miombo appear to share low endogenous N levels that rapidly decrease with soil depth. Other soil chemistry variables are not consistently low and even high compared to the Cerrado in Brazil. What Miombo soils have in common is an unbalanced stoichiometry either deriving from unbalanced cation ratios or from high P-induced micronutrient deficiencies or both.

3 Nutrient omission trials in relation to soil chemistry in the Miombo biome of Malawi

In this section, we will verify whether the key soil chemistry variables that govern the diversity, spatial distribution and functioning of ecosystems in Angonia (Section 2.3) are also related to crop yields. Results of dedicated nutrient omission trials with maize conducted in the Dedza hills area in Malawi, located just across the border with the Angonia district (Wendt and Rijpma, 1997) will be used for this purpose. According to Wild and Grandvaux Barbosa (1967) and our own field observations, the area is indeed covered with Miombo vegetation. However, one of the trial sites, the Bembeke research station, is located at a higher altitude and is classified as a montane grassland ecosystem (Wild and Grandvaux Barbosa, 1967). These trials included the application of N, P, K, lime (Ca and Mg), S, B and Zn. The chemical properties of the topsoil were also reported for these plant nutrients. Therefore, yield response can be related to soil chemical conditions. Soil Cu, Fe and Mn levels were also determined, but these nutrients were not applied in the trials.

First, we report on the nutrient omission trials proper (Section 3.1) and assess the impact of omitting N, P, K, S, B and Zn in relation to soil chemical properties. Then, a liming trial conducted within these research activities will be reported upon (Section 3.2). In Section 3.3, we continue with some data exploration on the yields obtained in the zero fertilizer control trials in relation to native soil chemical properties. Section 3.4 presents the results from demonstration trials that were linked to these experiments, using the same plant nutrients but having more observations and covering a larger geographical area.

3.1 Nutrient omission trials

Experimental methods

The reported research departed from the observation that there was generally low response to N and P when the recommended fertilizer type and dose was applied: 96 kg N, 18 kg P and 40 kg P₂O₅; 18 P and 16 N as DAP; and 80 kg N as urea topdressing (in the following called the Malawi Standard). In fact, varietal trials at Bembeke research station (located in Dedza hills) were abandoned in 1989-90 due to poor yields even with 120 kg N and 26 kg P (58 kg P₂O₅) and adequate rainfall, thus suggesting deficiencies of nutrients other than N and P (Wendt and Rijpma, 1997). In the 1990-91 growing season, the nutrient omission trials were conducted at five sites, including Bembeke research station and four randomly selected farmer sites. The "All" treatment included 120 kg N, 100 kg K, 40 kg S, 5 kg Zn and 1 kg B. The P application was variable depending on soil conditions (P sorption isotherms). In these trials, the nutrients were omitted one by one from the composite fertilizer package. In addition, the experiments included All minus 30 N (90 kg N) and All minus half of the P-dose treatments. Further treatments included the Malawi Standard and a zero control with no fertilizer application at all. A liming experiment was added when Al +H approached 40 percent of the effective CEC (Bembeke only), with 2015 kg of an even mixture of calcitic and dolomitic lime. The trials were conducted in a randomized complete block design with three replicates. Unfortunately, only average values were reported.

In the 1991-92 season, trials were conducted at three farmer sites also in the Dedza Hills region. However, the set-up of the trials was different in terms of the nutrients applied and their doses. Soil tests had indicated that P, K and lime were not necessary. Based on the experience of the previous year, the doses of N and S in the All-treatment were decreased to 92 and 25 kg ha⁻¹, respectively, and the doses of Zn and B were increased to 15 and 3 kg ha⁻¹, respectively.

Data

Table 10 presents the chemical soil properties of the research sites and the calculated TEB and nutrient ratios on this basis. Table 11 presents the maize yields obtained in the control, the Malawi Standard and the “All” treatments, and also the differences between the two as well as the change in yield in terms of kilogram (kg) of grain per kg of nutrient applied. The reported yield change per kg of nutrient applied refers to the pure nutrient (e.g., to P and not to P₂O₅). Table 12 reports the data of the nutrient omission experiments proper. It is important to note that in Observation 3, the “All” treatment included lime. The issue of lime application will be addressed separately later in this paper. Furthermore, it is relevant to note that Table 11, and also Table 12, include data for 1991/92 when the experiments and doses applied were changed.

Results nutrient omission trials

While discussing the results of these nutrient omission trials, frequent reference will be made to nutrient antagonisms and synergisms. These mechanisms imply that the possibility for a plant to take up a particular plant nutrient is not only determined by the absolute level of that nutrient in the soil but also by the levels of other plant nutrients (soil stoichiometry). These issues will first be introduced in the following intermezzo.

Intermezzo

Crop yields under conditions of native soil fertility depend on the entire soil stoichiometry of soils (i.e., the absolute levels of each nutrient as well as the proportions between the individual nutrients). The uptake of an individual nutrient is not only determined by its own level present in the soil but also by the level of particular other nutrients. Application of nutrients to the soil by means of fertilizers alters the stoichiometry of soils and may affect the uptake of nutrients that are not applied. Conversely, fertilizer efficiencies may be influenced by the native soil chemical constellation. These nutrient interactions can have an antagonistic and synergistic nature. A relationship is antagonistic when a nutrient at relative high supply suppresses the uptake of another that is in relative short supply. In case of synergisms, one nutrient stimulates the uptake of another. Four types of such relationship can occur:

- Uni-directional antagonisms
- Uni-directional synergisms
- Mutual antagonisms
- Mutual synergisms

These relationships and the nutrients involved are presented in Figure Intermezzo-1 in the so-called Mulders chart that was developed for fruit crops on sedimentary soils in the Netherlands (Mulder, 1953). Although, on theoretical grounds, it may be suspected that these nutrient relationships have universal applicability, a cautionary remark is in place here. This example must be considered as a first approximation only, as many different versions can be found on the Internet. It may further be suspected that, say, for tropical field crops on tropical soils, some of these nutrient interactions are less or more strongly expressed. It must be further observed that these nutrient interaction mechanisms have met with little research attention, and there may still be considerable knowledge gaps (see also Text Box 2).

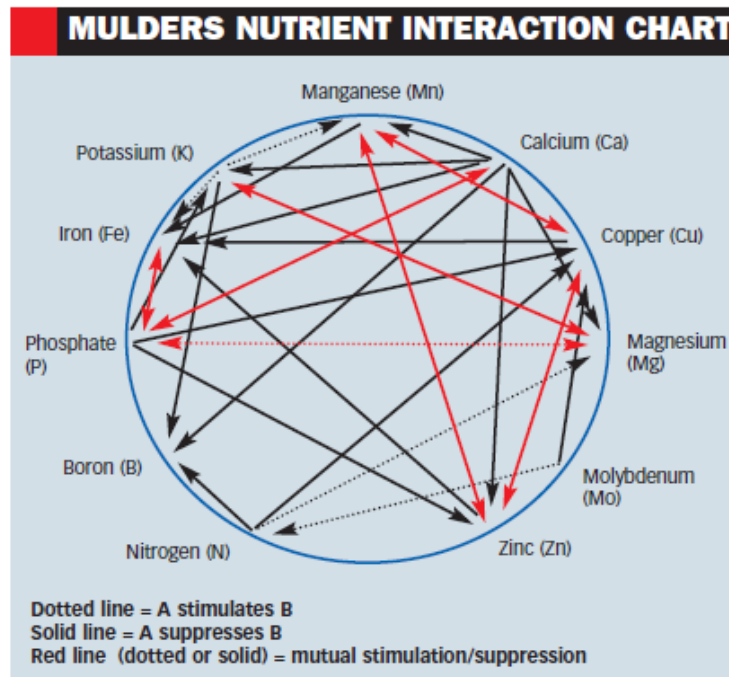


Figure Intermezzo 1. *Mulders nutrient interaction chart*

Source: Balancing crops nutrition will see growers get more from less, FarmBusiness, March 5, 2010

Discrepancies in current knowledge is evident if we compare the nutrient relationships in the above Mulders chart with those presented in Table Intermezzo 1. This table is presented in a handbook on tropical soils and is based on various sources, including handbooks on micronutrients. Furthermore, one may observe the frequency of nutrient combinations that indicate “insufficient data or effects too variable to summarize simply.”

Because antagonisms/synergisms will play a central role in what follows, here we elaborate a small but telling example. Yates (1964) observed in parts of sugarcane trials in Australia an “abnormal response” to P application. At low N application, the response to high P application levels varied from a slight yield decrease to a slight yield increase. However, at high N applications, a high application rate of P caused a systematic and greater yield decrease. These phenomena were observed only in part of the observations, and these were characterized by high native P (mean 128 ppm) in combination with the lowest Ca/Mg ratio (<3). The phenomena observed at low N application levels can be explained as follows. Phosphorus is an antagonist for Ca and a synergist for Mg (Table Intermezzo 1). The application of P causes the plant to experience a worsening (lower) Ca/Mg ratio. The systematic and larger yield decrease at high N application levels is likely due to the stimulating effect that N has on P (Table Intermezzo 1). N is also synergistic with Ca, but any effect on the Ca/Mg ratio is likely to be balanced by the fact that N is also synergistic with Mg (Table Intermezzo 1). Obviously, dedicated research would be required to unravel which mechanisms can suitably further explain the empirical observations. In any case, this example shows that the matter at hand is certainly not uni-variate and linear, but rather of a more complex multi-variate non-linear nature.

Table Intermezzo 1. Indicative summary of principal plant nutrient interactions

A= Antagonism; E = enhancing effect (synergism); - = insufficient data or effects too variable to summarize simply. Source: Landon, 1991; based on Davies, 1980; Kumar et al., 1981; Olsen, 1972; Lucas and Knezek, 1972; Russell, 1973; Richards, 1954; Wright, 1976; Phosyn Chemicals Ltd., 1980 and Samuels, 1982.

Acting Element ↓	Element affected												
	B	Ca	Cu	Fe	K	Mg	Mn	Mo	N	Na	P	S	Zn
B	/	-	-	-	-	-	-	-	-	-	A	-	-
Ca	A	/	-	A	A	A	A	-	-	A	A	-	A
Cu	-	E	/	A	-	-	A	A	-	-	A	-	A
Fe	-	-	A	/	A	-	A	-	-	-	A	-	-
K	A	A	-	E	/	A	E	A	A	A	-	-	-
Mg	-	A	A	A	A	/	A	E	-	A	E	E	A
Mn	-	-	-	A	-	-	/	A	-	-	-	-	-
Mo	-	-	A	A	-	-	A	/	-	-	-	A	-
N	A	E	A	-	A	E	-	E	/	-	E	-	A
Na	-	A	-	-	A	A	-	-	-	/	A	-	A
P	-	A	A	A	A	E	A	E	A	-	/	E	A
S	-	-	-	-	-	-	-	A	-	-	E	/	-
Zn	-	-	A	A	-	A	A	-	-	-	A	A	/

Because of the complex issues at hand as described in the intermezzo, the observations will be discussed one by one. Observation 1 has the lowest control yield, and yields for the Malawi Standard and the “All” treatment are among lowest as well. These low yields and yield responses coincide with the lowest levels of organic carbon, TEB and the Mg/K and (Ca+Mg)/K ratios. Although absolute K levels, compared to the other observations, is not high, the ratio is very unbalanced, with Mg even lower than K. P is the second highest of the eight observations, and because Zn is among the lowest, the P/Zn ratio is highest of all, and both the Zn/Cu and Zn/Fe ratios are also among the lowest values. Nevertheless, withholding P gives a yield decrease of 750 kg, supposedly because P is antagonistic with K, while at the same time it enhances the activity of Mg (synergism). Together, this may cause the very low Mg/K and (Ca+Mg)/K ratios to be less detrimental to crop yield. That Mg/K is very unbalanced is evident from the yield increase of 550 kg when K is withheld. The yield decrease due to withdrawal of S (570 kg) coincides with the lowest soil S values. Omission of Zn causes a yield loss of 750 kg that can be explained by the imbalances with P, Cu and Fe. Removing B (1 kg) from the fertilizer has the largest yield effect (1140 kg,) likely due to the high relative K, which is antagonistic with B.

With 960 kg, Observation 2 has the second lowest control yield, but in this case response to the Malawi Standard and the “All” treatment is among the highest levels. The TEB is on the low side, and the Mg/K and (Ca+Mg)/K ratios are again unbalanced but less than the previous observation. The yield loss when P is omitted may derive from the mechanisms as described for Observation 1 (the P-Mg synergism) but also directly because Cu is high and P/Cu is low. Otherwise, as far as the available data are concerned, the values are not particularly aberrant (as is also evident from the high yield in the “All” treatment), and the withdrawal of all individual nutrients applied in the “All” treatment caused a yield decrease at this site. There are still possibly other essential plant nutrients that are present in deficient or toxic levels.

Table 10. Measured and calculated soil chemical properties of topsoils for eight observations ordered in ascending control yields.

Salient soil chemical properties discussed in the text are marked with a color, which is different for each observation and which is repeated for other salient features in Tables 11 and 12. For observations 6-7, it has also been marked what they have in common.

Obs. No.		1	2	3	4	5	6	7	8
Year		1990-91	1990-91	1990-91	1990-91	1990-91	1991-92	1991-92	1991-92
pH		5.1	5.4	4.5	5.3	5.3	5.3	5.5	5.6
Org. C	%	1	1.46	2.08	1.63	2.16	1.33	1.34	1.19
Ca	cmol kg	0.8	2.87	1.53	4.27	3.68	2.99	3.48	2.34
Mg	cmol kg	0.38	0.84	0.52	0.53	0.58	2.39	1.19	1.08
K	cmol kg	0.41	0.48	0.14	0.24	0.22	0.7	0.54	0.55
Al+H	cmol kg	0.13	0.02	1.41	0.18	0.65	0.58	0	0.63
Zn	ppm	0.54	1.15	0.42	1.41	0.96	1.96	1.54	1.09
Cu	ppm	1.69	2.3	3.07	2	1.46	1.17	1.18	1.41
Mn	ppm	12.9	16	18.8	6.8	9.2	nd	nd	nd
Fe	ppm	10.4	12.5	13.8	14.7	14	nd	nd	nd
B	ppm	0.23	0.28	0.25	0.23	0.24	0.22	0.32	0.24
P-Bray-1	ppm	65	47	15	105	50	39	46	22
S	ppm	3.3	5.7	3.7	6.3	3.8	5.1	5.5	6.6
BS	%	92.44	99.52	60.83	96.55	87.33	91.29	100.00	86.30
Calculated	properties								
TEB	cmol kg	1.59	4.19	2.19	5.04	4.48	6.08	5.21	3.97
Ca/Mg		2.11	3.42	2.94	8.06	6.34	1.25	2.92	2.17
Mg/K		0.93	1.75	3.71	2.21	2.64	3.41	2.20	1.96
(Ca+Mg)/K		2.88	7.73	14.64	20.00	19.36	7.69	8.65	6.22
P/Zn		120.37	40.87	35.71	74.47	52.08	19.90	29.87	20.18
P/Cu		38.46	20.43	4.89	52.50	34.25	33.33	38.98	15.60
P/Fe		6.25	3.76	1.09	7.14	3.57	na	na	na
Zn/Cu		0.32	0.50	0.14	0.71	0.66	1.68	1.31	0.77
Zn/Fe		0.05	0.09	0.03	0.10	0.07	na	na	na
Fe/Cu		6.15	5.43	4.50	7.35	9.59	na	na	na
<ul style="list-style-type: none"> • Observation 3 refers to the Bembeke research station 									

Observation 3 refers to the Bembeke station and is the most acidic soil (pH and BS), in combination with the one but lowest TEB. Based on these criteria, this site could be considered the poorest of the eight. Yet control yields are high, and organic carbon levels rank second in the data set. These phenomena, on the one hand, coincide with well-balanced cation ratios. On the other hand, part of the explanation of high organic carbon levels may be related to the cool temperatures at this higher elevation and the soil acidity, both retarding the decay of organic matter. Application of the

Table 11. The P rate (kg P ha⁻¹), control yield (kg ha⁻¹), Malawi Standard yield (MS; kg ha⁻¹), the difference between the MS and control yields (ΔY -MS; kg ha⁻¹), the difference per kg nutrient applied (ΔY -MS/kg), the 'All' yield (All; kg ha⁻¹), the difference between the 'All' and control yields (ΔY -All; kg ha⁻¹) and the difference per kg nutrient applied (ΔY -All/kg). Only in observation 3 the 'All' treatment contained lime.

Obs.	Year	P rate	Control	MS	ΔY -MS	ΔY -MS/kg	All	ΔY -All	ΔY -All/kg
1	1990-91	47	380	1560	1180	10	3110	2730	9
2	1990-91	50	960	3500	2540	22	5960	5000	16
3	1990-91	125	1550	1470	-80	-1	5140	3590	9
4	1990-91	22	1740	4320	2580	23	7240	5500	19
5	1990-91	59	3170	3750	580	5	5180	2010	6
6	1991-92	0	2420	3760	1340	12	4640	2220	16
7	1991-92	0	2860	4150	1290	11	4450	1590	12
8	1991-92	0	3150	3150	2190	19	7330	4180	31
	Average		2029	3208	1453	13	5381	3353	15

Table 12. Yield changes due to the omission of part or the entire dose of individual nutrients compared to the 'All' treatment (kg ha⁻¹)

The bottom line gives the average yield change due to omission of N, P and K for the observations excluding the Bembeke station.

Obs.	Year	P rate	All	All-30N	All-P	All-1/2P	All-K	All-S	All-Zn	All-B
1	1990-91	47	3110	-150	-750	-160	550	-570	-750	-1140
2	1990-91	50	5960	-90	-1030	60	-160	-1300	-360	-440
3	1990-91	125	5140	-1880	-2360	-290	-2720	-260	-3230	-690
4	1990-91	22	7240	100	220	-490	20	-1230	-2090	-3940
5	1990-91	59	5180	60	-280	-70	300	-200	-120	70
6	1991-92	0	4640					-1650	-250	1450
7	1991-92	0	4450					-30	880	1200
8	1991-92	0	7330					-970	-480	-1220
	Average		5381	-392	-840	-190	-402	-776	-800	-589
	Average	Bemb.		-20	-460	-165	178			

Malawi Standard (only N and P) results in a slightly lower yield, but high yields are obtained with the "All" treatment (including lime). This site combines the highest values for Cu and the lowest for P and Zn. Hence, with Cu being antagonistic to P and Zn, the uptake of P and Zn may be impeded by Cu. Provided that the other nutrients (S, Zn and B) are applied, the withdrawal of all three macronutrients (N, P and K) results in large yield decreases. Within this data set, the largest yield decrease to omission of P is obtained at this site, which is likely to be due to the low native soil P level in combination with the high Cu level. In case of K, it must be observed that the "All" treatment contained large doses of lime (Ca, Mg) and that, consequently, the balanced cation ratios were disturbed in favor of Ca and Mg, resulting in higher Mg/K and (Ca+Mg)/K ratios, which were possibly balanced again by K application, hence the large yield decrease (2720 kg) upon omission of K. The largest yield decrease, though, is observed for Zn: each kg of Zn withdrawn results in 646 kg less for the yield. Here again, the lime applied may play a role, as both Ca and Mg are

antagonistic to Zn, while liming also generally reduces Zn availability due to the increase in soil pH (pH is 4.5). The considerable yield decrease due to omission of B is likely the result of the other applied nutrients, since both Ca and K are antagonistic with B (see intermezzo).

For Observation 4, the control yield (1740 kg) is modest, but response to the Malawi Standard and the "All" treatment is very positive within this data set at about 20 kg of maize per kg nutrient applied. Data-wise, there are some peculiarities for this site, though. It appears that omission of 50 percent of the (lowest) P dose gives a yield reduction of 490 kg, while applying no P at all gives a yield increase of 220 kg. Furthermore, withdrawing 30 kg N gives 100 kg higher maize yield. At the same time, the Malawi Standard that consists of N and P only produces yield increases of about 150 percent. In any case, the P level at 105 ppm is highest of all observations, and P deficiency is unlikely. Moreover, the yield of the "All" treatment is far higher than the Malawi Standard. Furthermore, it is clear that B, Zn and S are the most significant deficiencies, in that order. This soil combines the highest P level and the second highest P/Zn ratio with the highest Ca/Mg ratio. Ca is antagonistic with B and Zn, and also P with Zn. Therefore, large yield decreases appear when either B or Zn is omitted: 3940 kg of maize per kg of B and 418 kg maize for 1 kg of Zn. The more modest response to withdrawal of S cannot be readily explained but may be due to a limitation on the synergistic effect that Mg normally has on S because of the rather low Mg/K ratio.

The highest control yield in the 1990-91 season was Observation 5 at 3170 kg and both, the Malawi Standard and the "All" treatment, are very inefficient at 5 and 6 kg maize per kg nutrient, respectively. Both cation ratios are more favorable than Observation 4, and P levels are also more than 50 percent less, coinciding with the highest organic carbon level. The properties of this soil tend not to reveal aberrant features. The copper level is low, but P/Cu and Zn/Cu are not high. S and B are also on the low side. The omission trials, however, confirm that none of the withdrawals has a large yield impact. At the same time, neither the control nor the "All" treatment yield are particularly high, thus suggesting that other essential plant nutrients may be the most limiting. The high Fe/Cu ratio indeed suggests that possibly Cu is deficient.

The observations of the 1991-92 season (6, 7 and 8) collectively have some properties in common that make them different from the previous five observations. Excepting the Bembeke station, all three have the lowest soil P and Cu content, while Zn is invariably on the high side; consequently, P/Zn is low and Zn/Cu is high. Absolute K and Mg are both invariably high, but the other basic cation Ca varies. Yet they differ also in many other aspects. Of these three observations, Observation 6 has the lowest control yield, which coincides with the highest TEB and by far the highest absolute Mg levels that are not checked by the low Ca levels (an unbalanced low Ca/Mg ratio), and Mg is antagonistic with Cu and Zn. At the same time, the Zn level is highest of all, resulting in the lowest P/Zn ratio and the highest Zn/Cu ratio. The highest control yields are obtained when the Zn/Cu ratio and P are lowest (observation 8). Control yields increase with decreasing Zn/Cu ratio.

For all three observations, the negative responses when S is withheld can be partly explained on the basis of the Zn-S antagonism, while these three observations are particularly high in Zn, a possible cause of S deficiency. However, although the greatest yield decrease occurs when the Zn/S is highest, the relationship is not systematically maintained for the two other observations. Yet the magnitude of the yield decreases (due to withdrawal of S) varies systematically with the value of the Ca/Mg ratio, being higher when this ratio is low. A possible explanation is that, since the sulfur was applied as gypsum, this effect can be ascribed to the Ca that gypsum contains. In any case, seven out of eight trials indicate S deficiency. Yet the yield response to S in this trial is much less than obtained elsewhere in Malawi at much lower application rates: 80-160 kg of maize/kg S at application rates of 5-10 kg S per ha (Weil and Mughogho, 2000).

Unexpectedly, observation 6 gives a yield decrease, albeit very small, when Zn is omitted despite the low P/Zn and high Zn/Cu ratios. This is likely due to the severe check on Zn uptake exerted by the very high absolute Mg level in combination with the very low Ca/Mg ratio. In Observation 7, absolute Mg is still high but is kept in balance by Ca. Yet within the entire dataset, P/Zn is still low and Zn/Cu is still high. Withholding Zn then gives a yield increase by alleviating these antagonisms. The yield decrease due to Zn for observation 8 is likely to derive from the lower Zn/Cu ratio.

With respect to B, we observe that its withdrawal causes large yield increases in Observations 6 and 7 and a large yield decrease in 8. These magnitudes decrease with decreasing Zn and increasing Cu level and consequently with decreasing Zn/Cu, but also with decreasing TEB and Mg/K ratio. These phenomena are difficult to explain, given the uncertainties surrounding the possible antagonisms and synergisms in which B is possibly involved. As earlier observed, more work needs to be done on the intricacies of soil B in relation to other soil chemical properties.

In summary, N, P and K are most commonly applied as fertilizer. However, excluding the Bembeke station (last row of Table 12), because of possible confounding effect of lime application (antagonistic with P and K), it appears that withdrawal of N, P and K has little or very modest yield impacts only, provided that S, Zn and B are applied. On average, withdrawal of 100 kg K has even a positive yield effect (Table 12). A reduction of 30 kg of the N rate and halving the P rate provides for yield reductions that are practically negligible. When the entire P rate is withheld, on average there is a modest yield decrease, but this average derives from rather large yield decreases in Observations 1 and 2 only, while the yield changes are again negligible in Observations 4 and 5. Observations 1 and 2 are those with the lowest Mg/K ratios, the impacts of which have been explained earlier (the P-Mg synergism) in relation to P. In combination, these observations suggest that the doses of N, P and K could be substantially reduced to avoid the phenomenon of decreasing marginal returns. With respect to S, Zn and B, one can observe that omission of at least one of these nutrients causes substantial yield decrease of more than 1 ton/ha⁻¹, with the exception of Observations 5 and 7. Given the relative small doses applied in case of these nutrients, they are more efficient than N, P and K in raising yields on a kg grain per kg nutrient basis, certainly where Zn and B are concerned.

It further appeared that the impact of omission of nutrients did not depend on the levels of the same nutrient present in the soil but also on cation ratios, the ratios of P with micronutrients and the ratios between micronutrients. Such ratios, in combination with the absolute level of individual nutrients, considered together with nutrient antagonisms and synergisms as operating mechanisms, provided a suitable framework to interpret the effect of nutrient emissions and to explain fertilizer efficiencies. As such, these findings confirm that the key factors (in terms of soil chemical properties) that govern the ecological diversity of African soils and its spatial patterns, as identified in Section 2, are also involved where crop yields and yield response to fertilizer is concerned.

The attempt to explain maize yields and changes of yields due to nutrient omissions has also shown that it is plausible that the key variables identified in the previous section for natural systems and land use preferences can be meaningfully related to crop performance. It is suspected that relating variation in crop yields to native soil chemistry and fertilizer applied can be still further improved if a number of conditions are taken care of in future research:

- Sampling and chemical analysis of subsoils, since nutrients tend to accumulate in topsoils and thus tend to homogenize soil properties and their effect between essentially different sites.
- Soil analysis of all essential plant nutrients.
- Experiments with all essential plant nutrients.
- Based on similar interpretations as above identify hypotheses on nutrient deficiencies, their causes and possible remediation, so as to identify a well-targeted research agenda aiming at impactful nutrient compositions and doses in fertilizer technologies.

A basic precondition is that knowledge on the existence of antagonisms and synergisms is further developed and synthesized into a coherent framework of soil stoichiometric conditions. Particular emphasis is required for quantitative relationships between plant nutrients and their yield effect in dependence of soil texture and crop species, for instance.

3.2 The liming trial

Liming is common practice in tropical agriculture where acid soils are concerned. However, as also evident from the data presented in Section 3.2, Miombo soils are usually not very acidic. In the present experiment, only in the case of the Bembeke station (non-Miombo) was it deemed necessary to test the potential effects of lime application. The results including the lime treatments of 2015 kg of an even mixture of calcitic and dolomitic lime are depicted in Figure 8. Adding lime to the Malawi Standard reduces yields by about 50 percent. This phenomenon may be explained by the fact that Ca is antagonistic to both B and Zn but also more generally because micronutrients become less available when the pH increases (pH before liming was 4.5). The “All” treatment, where B and Zn were simultaneously applied with lime, results in a yield increase of almost 250 percent, compared to the control. Yet withholding the lime from the “All” treatment reduced yields by about 1 ton, or 20 percent. Consequently, every kg of lime led to the production of an additional 0.5 kg of maize. This relatively low response to large applications of lime may also be caused by the resulting imbalance of the cations (Ca, Mg and K). In any case, liming appears not to be effective if only N and P are applied, supposedly because of micronutrient deficiencies. Hence, a broader spectrum of nutrients, particularly including micronutrients, is required for lime to become more effective. However, this one-year experiment does not allow concluding on the long-term yield effects due to the residual effect of lime application.

In summary, liming at high rates can give unexpected effects on maize yields on some African soils. Because of the large volumes involved and the transportation problems in SSA, it is possibly better to first verify what yield increases can be obtained with micronutrients. However, calcitic lime, dolomitic lime and also gypsum can be used at non-liming rates in order to correct unbalanced cation ratios. Moreover, an essential precondition before applying these materials is their chemical analysis for the content of micronutrients and toxic substances (e.g., U, Cd).

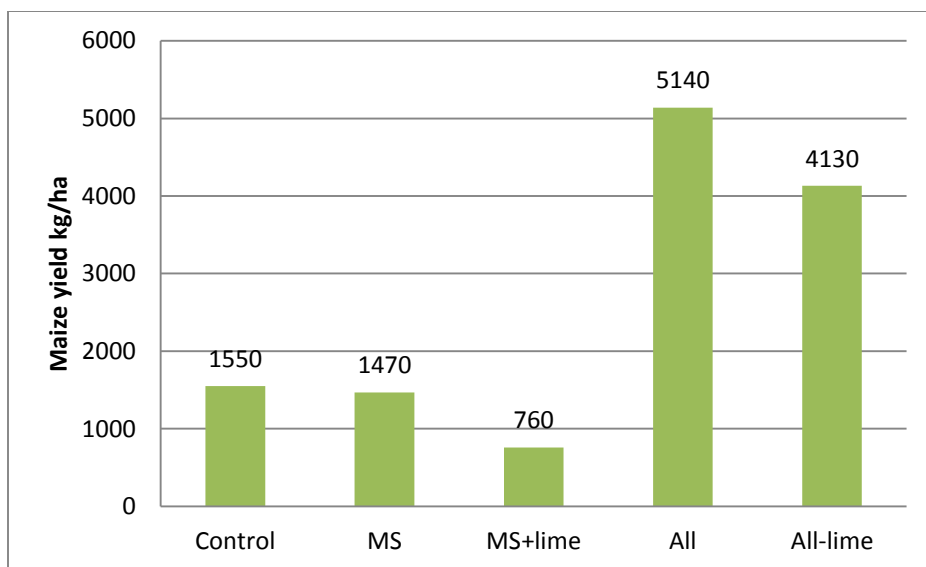


Figure 8. The liming experiment result for the Malawi standard and the missing nutrient trial at the Bembeke station

3.3 Further data exploration: control yields and soil chemistry

Obviously, the number of observations in this study (Wendt and Rijpma, 1997) is too limited to do serious data exploration with appropriate statistical tools. Therefore, we are limited to readily observable general trends in combination with exception reporting. This has limitations, but it can be shown that it is probable that the earlier identified key ecological factors related to land use density and the distribution of vegetation types also affect crop performance and yields. For this purpose, the control yields (where no fertilizer was applied) will be used. With respect to individual nutrients and their ratios in a one-dimensional space, the expectation is that somewhere in the range of values an optimal level will exist where yields are high and with lower yield levels in suboptimal ranges at lower and higher values of the variable concerned. This may be apparent only when the range of values is sufficiently large. Yet the relations are expected to be multidimensional; the likely causes for substantial deviations will be discussed.

Plotting maize yield against soil P levels does not produce a straightforward relationship (Figure 9). The exceptionally low yield obtained where P is 47 ppm coincides with an unbalanced low Mg/K ratio in combination with low ratios of P with Zn, Cu and Fe (possible P deficiency). In case of the even lower yield at higher P (65 ppm), the Ca/Mg ratio is low, and both the Mg/K ratio and the (Ca+Mg)/K ratio are very unbalanced and lowest of all observations. At the same time, Zn is low and the P/Zn ratio is highest of all. Apparently, medium to high soil P levels do not always result in high crop yield since high P can be overruled by low cation ratios or by P-induced micronutrient deficiency. Both observations at 50 and 105 ppm P are similar in that they combine a high TEB and a high Ca/Mg ratio (above 6), but yields at the highest P level (105) are only just over 50 percent, of the yield obtained at the medium P level (50). High P levels by themselves in otherwise similar soils thus sort a negative yield impact, which in this case is likely to derive from P-induced micronutrient deficiencies: high P/Zn, P/Cu and P/Fe ratios. The small yield dip at 39 ppm soil P coincides with the highest Zn/Cu ratio, which may point toward a possible Zn-induced Cu deficiency (see Table 10).

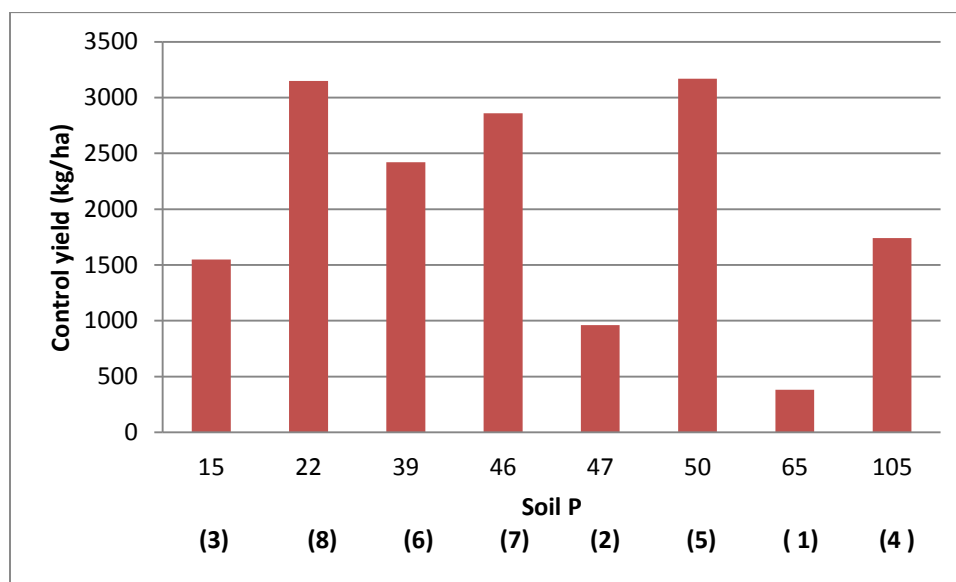


Figure 9. Control yields (kg ha^{-1}) related to soil available P level (ppm); observation numbers in brackets

In case of K, the relation between soil K level and control yield is also not as would be expected (Figure 10). Instead, the pattern is the opposite of the expectation with the lowest yields at medium K levels. The yield dip where K is $0.24 \text{ cmol kg}^{-1}$ is again the observation with the highest P level with associated characteristics, as described in the previous paragraph (Observation 4). The lowest control yield at K is 0.41 is again the observation where both the Mg/K ratio and the (Ca+Mg)/K ratio are very unbalanced, while the P/Zn ratio is highest of all (Observation 1). The observation at

K is 0.48, referring to the situation where Mg/K is low in combination with low ratios of P with Zn, Cu and Fe (Observation 2). Since the K levels are medium in the two latter cases, these findings suggest that cation ratios impact more on yield than the absolute K levels. Both soils may be Mg-deficient.

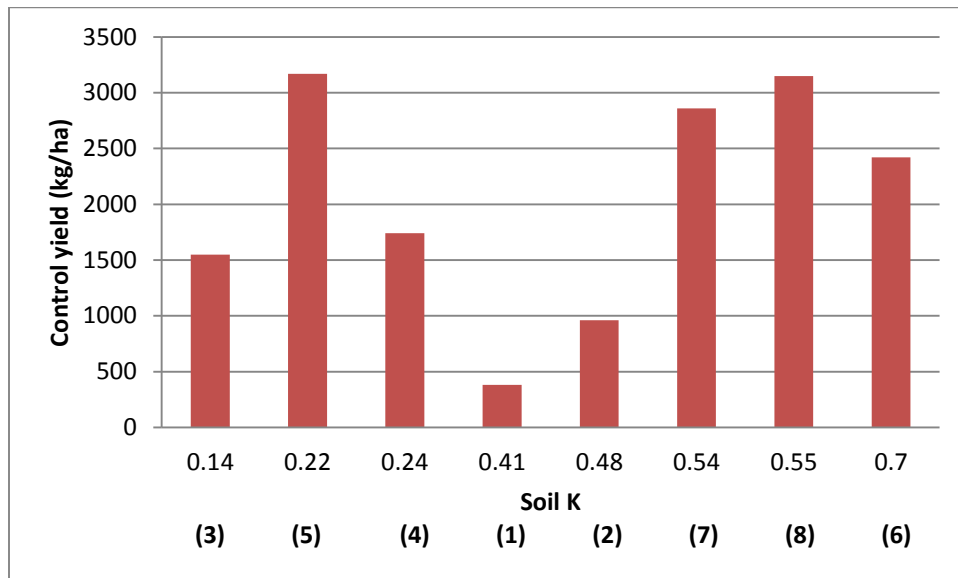


Figure 10. Control yields (kg ha⁻¹) related to soil K level (cmol kg⁻¹); observation numbers in brackets

The plot of control yields against soil TEB (Figure 11) produces a fair pattern that allows sensible interpretation. At TEB 1.59, the TEB is obviously lowest of all and has the earlier observed associated properties of Observation 1. At 2.19, TEB is still on the low side, but both cation ratios are balanced and P is the lowest of all observations. Despite the TEB still being low in absolute terms, these soil conditions give more than three times higher yield, compared to the soil with TEB 1.59. At 3.97, TEB has almost doubled compared to the previous observation and occurs in combination with cation ratios that are on the low side (but not severely unbalanced) and the second lowest P level (P/Zn and P/Cu are both low), resulting in high control yields. At TEB is 4.19 (observation 2) the low yield coincides with a low Mg/K ratio in combination with low ratios of P with Zn, Cu and Fe. Where the TEB is 4.48, the cation ratios are balanced resulting again in high yields. The lower yields at TEB is 5.04 coincide again with the highest P level (Observation 4). Control yields are again high when the TEB is 5.21, which occurs in combination with balanced cation ratios. The yield decrease toward TEB as 6.08 coincides with an unbalanced low Ca/Mg ratio.

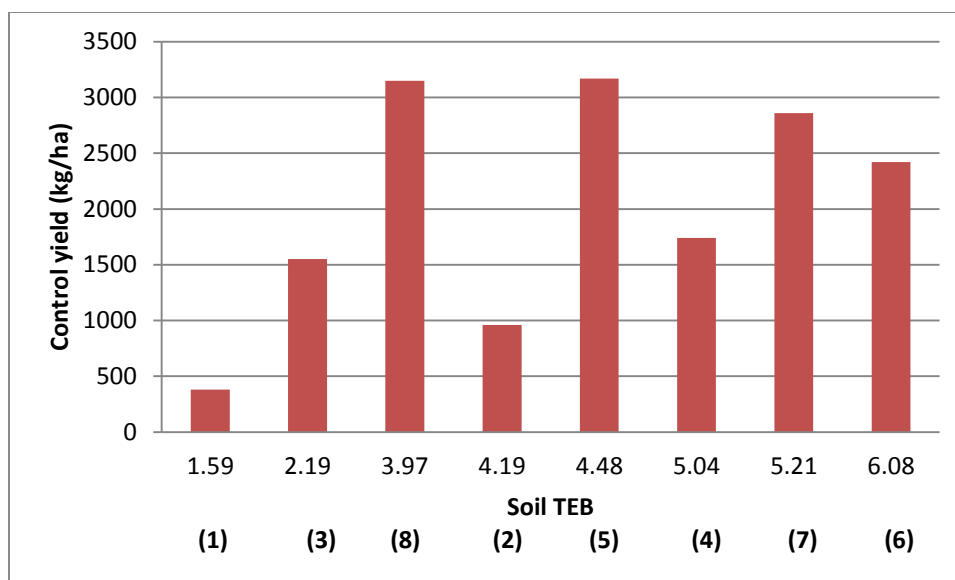


Figure 11. Control yields (kg ha⁻¹) related to soil TEB (cmol kg⁻¹); observation numbers in brackets

Figure 12 shows that at low soil Mg/K ratios, control yields rapidly increase with an increasing Mg/K ratio – also at the higher tail end of Mg/K yields decrease, but in a more gradual manner. In the medium range yields are high with the exception of the second observation with a soil Mg/K ratio of 2.2. This is again the observation with the highest P level and high ratios of P with Zn, Cu and Fe. The low yields when Mg/K is low possibly point toward Mg deficiency, while the decreases when Mg/K becomes higher (from 2.6 to 3.7) are likely to reflect K deficiency.

In summary, due to data limitations only general trends could be established, and exceptions to such trends were identified while seeking an explanation for such deviations. It proved that control yields can best be explained from the interface between TEB, cation ratios, micronutrient ratios and ratios between P and micronutrients, whereby high P generally had a negative yield impact. It is precisely this interface that has been identified earlier as constituting the key ecological factors in the Angonia study. Thus, these also have an impact on crop yield where no fertilizer is used. Hence, these key factors and nutrient ratios, which reflect antagonisms where nutrient uptake by plants is concerned, need to be addressed when developing impactful new fertilizer technologies.

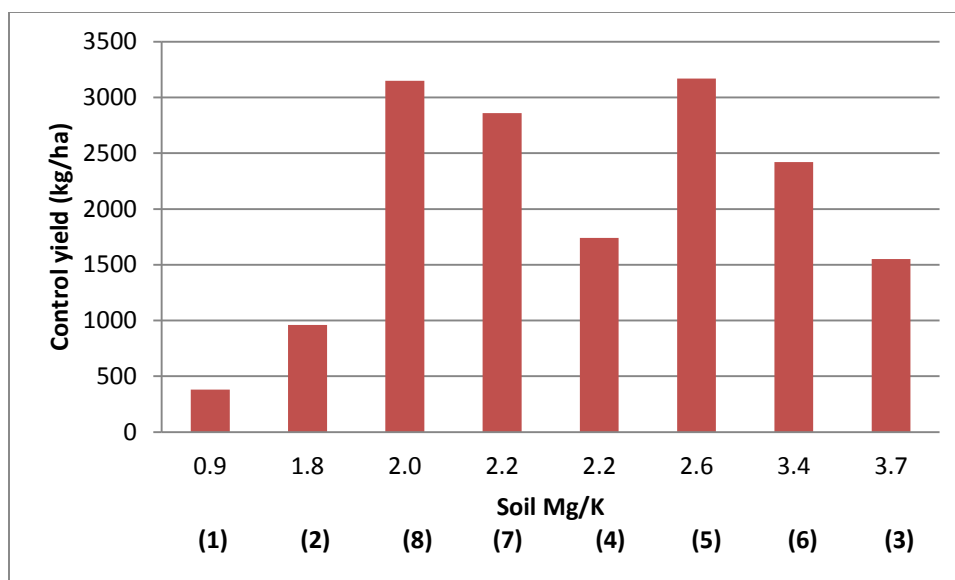


Figure 12. Control yields (kg ha^{-1}) related to soil Mg/K ratio; observation numbers in brackets

3.4 The Malawi demonstration trials

During 1992-93 growing season, 79 demonstration plots were successfully implemented in the Dedza Hills and Thiwi-Lifidzi areas, based on findings from the missing nutrient trials. Dedza Hills mainly supports various forms of Miombo woodland, while Thiwi-Lifidzi is located on an extension of the preferred lands in the Angonia district. The latter area is covered with what has been called Nguni vegetation. The presence of these different vegetation types is confirmed by the vegetation map of Wild and Grandvaux Barbosa (1967). The differences are also evident from the soil chemical data presented by Wendt and Rijpma (1997) and confirm the findings of Voortman and Spiers (2010a) that Miombo soils are higher in P and have a lower TEB with a higher Mg saturation relative to Ca. They do not differ much in absolute Zn, Cu and B content, but S appears to be higher in Miombo. These demonstration plots consisted of a zero control and three treatments as follows: 96 N, 96N +18P and 96N +18P+S-Zn-B (20 kg S as gypsum, 5 kg Zn as ZnO, 2 kg Zn-EDTA and 0.5 kg B as sodium borate). Being demonstration plots, they are not true experiments in the sense that each nutrient is applied individually and in various combinations. Yet it is possible to assess the additive effects from the control to N only and the additions of P followed by applications of S, Zn and B. This proves to be very informative. The results of the control and the response to the treatments are presented in Table 13.

Table 13. Demonstration plot maize yields and additive yield increases by fertilizer technology applied for different land types characterized by their vegetation (based on 79 demonstration plots)

Vegetation	Zero control	96 N	96 N +18 P	96N + 18P + S-Zn-B	Response N	Response P	Response S-Zn-B
Nguni	1750	2830	4130	4520	1080	1290	390
Miombo	1130	2380	2900	4060	1250	520	1160

The control yield in Nguni is higher than in Miombo. Response to N is somewhat greater in Miombo, as expected on the basis of the evidence presented earlier for Angonia.

Response to P in Nguni is about 2.5 times the response to P in Miombo, but conversely the response to S-Zn-B in Miombo is three times greater than in Nguni.

The obtained results have been regressed by the average values of Extension Planning Areas (EPA), where a near perfect relation was obtained as follows:

$$\text{Response to S-Zn-B} = -0.88 * (\text{response to P}) + 1540 \quad (R^2 = 0.83)$$

Based on a reconstruction of the data points of Wendt and Rijpma (1997) this relationship is depicted in Figure 13.

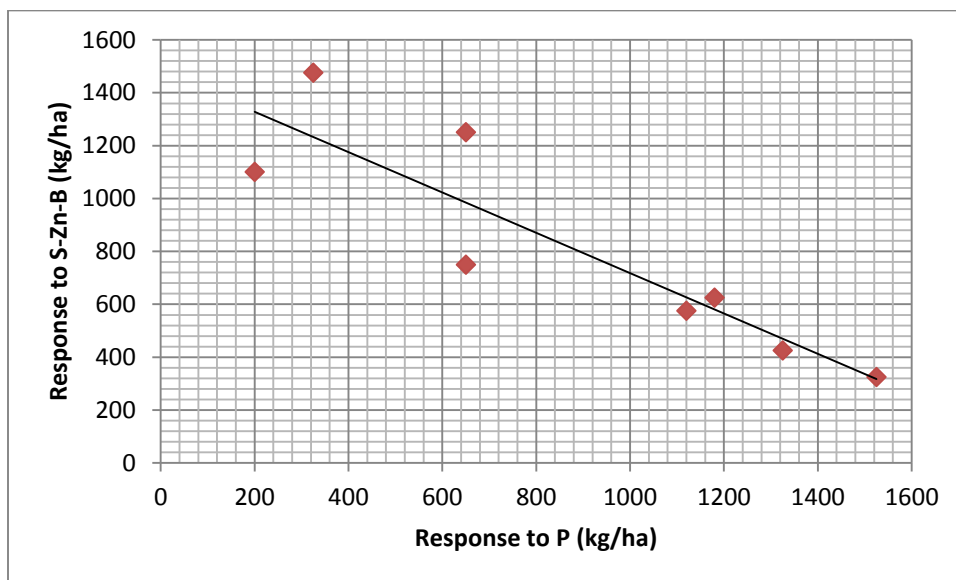


Figure 13. Maize yield response to S-Zn-B as a function of yield response to P

The eight data points are means obtained at individual Extension Planning Areas (EPAs)

In this case, we cannot separate the yield effects of S, Zn and B individually, but a positive response to Zn and B can be explained from high P levels and the higher relative K levels (lower (Ca+Mg)/K ratio) in Miombo soils. Since P is antagonistic with Zn and K with B, the application of Zn and B relieves the antagonism that is occurring in the soil. Whether the positive response to S-Zn-B in Miombo at least in part derives from S is uncertain from the data, since S levels in Miombo are higher than in Nguni. Potentially, since S was applied as gypsum, a positive yield effect from the Ca it contains may also be expected. Although we cannot assess the yield impact of individual nutrients from the results of these demonstration plots, the evidence clearly shows that the most productive fertilizer technology varies with the soil/vegetation type. One additional kg of P produces 72 and 29 kg of maize in Nguni and Miombo, respectively. One additional kg of a mixture of S, Zn and B achieves 14 and 42 kg more maize in Nguni and Miombo, respectively. These results could have been even better, giving more pronounced differences, if aggregation had been done on the basis of vegetation/soil type rather than the administrative EPAs. Additional research into fine-tuned site-specific fertilizer technologies is likely to improve further on the efficiencies already obtained.

To conclude this section, the reported research provides food for thought and certainly gives a first impression of the complexity of yield response to fertilizer. First of all, it appears that yield response to an applied nutrient does not necessarily correspond to its level in the soil. In addition to that, yield response to fertilizer is also influenced by nutrient

interactions in the soil and, therefore, the total soil stoichiometry has to be considered and interpreted. We have tried to do so based on the findings and insights obtained from the land resource ecology perspective in the Angonia district. Although there is no proof, it seems plausible by means of inference that the same variables are also at play where crop yield response to fertilizer is concerned. Apart from that, it has been shown that certainly for P and K, large-dose applications need to be de-emphasized and, further, that significant yield increases can be obtained from micronutrient application but not systematically so. The crux in this respect is the total soil stoichiometry and interactions among nutrients, whereby cation ratios play a prominent role.

4 Micronutrient trials in the Miombo of Zimbabwe

Another location in the Miombo biome where micronutrient trials were conducted is the Henderson Research station, located in the Miombo heartland of Zimbabwe. During the 1960s, research was conducted with the objective to develop agricultural technologies suitable partly for subsistence and partly for commercial production in what were then called tribal trust lands (Rodel and Hopley, 1973). The authors claim that the soils are representative for those used by the local population. The study has some shortcomings. First of all, the journal in which it was published had an extension focus, because of which the experiments were not perfectly documented. For instance, soil samples were taken, analyzed and used for determining the fertilizer dose. However, the analytical results were not provided, and for part of the experiments, it is only indicated as “adequately fertilized” (which means high doses). A second shortcoming is that the research was of an incremental nature. It appeared that fertilizer applications of N, P and K aiming for high theoretically calculated yield levels did not achieve these. Hence, the experiment had to be continuously adapted. At some point, it was observed that the maize plants showed Zn- and B-deficiency symptoms. These nutrients were applied in the following years and partly to other crops as well. Despite the shortcomings, the results are telling with respect to what type of fertilizer technologies are appropriate in the Miombo environment.

In the early years of the experiment, high production targets were pursued with large doses of fertilizer. For instance, in the case of maize the aim was 75 bags (or 6825 kg), which could be achieved, according to theoretical calculations, with 90 kg N, 45 kg P₂O₅ and 45 kg K₂O. However, the yields obtained, without additional manure application, were mostly below 40 bags and at some locations even well below 30 bags (Table 14). The farm average was as low as 24 bags. These results suggested that other plant nutrients were possibly limiting. Searching for apparent crop nutrient deficiency symptoms suggested B and Zn deficiency in maize and Mg in cotton. Subsequently, 22 kg of Zn sulfate and 11 kg of borate were added to the NPK package previously used. The result, at about 80 bags of maize, was slightly above the targeted level (see green marked results in Table 14).

Even if we do not know the soil chemical properties, what yields were aimed for in the case of groundnut and Burley tobacco, and what quantities and types of fertilizer in each case were considered “adequate,” the results for the other crops are equally revealing that micronutrients are indispensable for good yields in this environment. Moreover, the cotton experiment that included dolomitic lime, but at quantities much lower than normal liming rates, suggests that management of Ca and Mg levels – and consequently Ca/Mg ratios – may prove to be a useful strategy to increase crop yields in the Miombo biome.

An interesting question deriving from these experiments is what would have happened if they had abstained from applying P and K, since P is antagonistic with Zn and K with B. In any case, the findings confirm that, just like in Malawi, large crop yield increases can be obtained with small amounts of micronutrients in this type of environment.

Table 14. Crop yields on various sites at Henderson Research Station, Zimbabwe, in NPK trials and with micronutrients added

	Crop	Aim	N	P ₂ O ₅	K ₂ O	Manure	Zn sulf.	Borate	Dol. Lime	Yield	Obs.
			(kg)	(kg)	(kg)	(tons)	(kg)	(kg)	(kg)		
Site 1	Maize	75 b.	yes	yes	yes	3.5	0	0	0	30 b.	1
Site 2	Maize	75 b.	90	45	45	0	0	0	0	36.6 b.	
Site 2	Maize	75 b.	90	45	45	0	0	0	0	31.6 b.	3
Site 2	Maize	75 b.	90	45	45	4	0	0	0	39.5 b.	
Site 2	Maize	75 b.	90	45	45	8	0	0	0	49.2 b.	
Site 3	Maize	75 b.	90	45	45	0	0	0	0	21 b.	
Site 3	Maize	75 b.	90	45	45	8	0	0	0	26 b.	
?	Maize	75 b.	90	45	45	0	22	11	0	76 b.	2
?	Maize	75 b.	90	45	45	8?	22	11	0	83 b.	2
Site 4	Maize	75 b.	90	45	45	0	0	0	0	46 b.	
Site 4	Maize	75 b.	90	45	45	0	22	11	0	57.7 b.	
Farm average	Maize	75 b.	90	45	45	0	0	0	0	24 b.	
Farm average	Maize	75 b.	90	45	45	0	22	11	0	64 b.	
?	Cotton	2250 kg	yes	yes	yes	?	0	0	0	550 kg	1, 2
?	Cotton	2250 kg	yes	yes	yes	?	0	11	225	2830 kg	1, 2
Site 4	Cotton	2250 kg	yes	yes	yes	0	0	0	0	353 kg	1
Site 4	Cotton	2250 kg	yes	yes	yes	0	0	11	?	1244 kg	1
?	Groundnut	?	?	yes	yes	?	0	0	0	820 kg	1, 2
?	Groundnut	?	?	yes	yes	?	0	11	0	3270 kg	1, 2
Site 4	Groundnut	?	?	yes	yes	0	0	0	0	908 kg	1
Site 4	Groundnut	?	?	yes	yes	0	0	11	0	1738 kg	1
Site 4	B.Tobacco	?	yes	yes	yes	0	0	0	0	810 kg	1
Site 4	B.Tobacco	?	yes	yes	yes	0	0	11	0	1491 kg	1

b = 1 bag is 91 kg

1 = 'adequately fertilized'

2 = supposedly site 1

3 = stover ploughed in

5 Brazilian fertilizer technology experiences of relevance for sub-Saharan Africa

South America is geologically more varied than Africa, not in the least because of the uplift of the Andes in association with volcanism and subsequent erosion. Nevertheless, just like Africa, the Guyanas and Brazil are also largely underlain by Precambrian Basement Complex (Bederke and Wunderlich, 1968). In fact, before continental drift took place, Brazil and the Guyanas were even contiguous with Africa. Excluding the humid Amazonian basin, in Brazil the range in length of growing period is also similar to the savannah zone of Africa, where most of its agriculture takes place. Because of the similarity of conditions, and because of the successful development of the Brazilian agricultural sector, we concentrate here on Brazil. However, for many reasons, conditions with respect to fertilizer use are very different in Brazil as compared to Africa. Brazil has a large agricultural research system (EMBRAPA), its own fertilizer industry that supplies part of the requirements, and better-developed infrastructure and transportation, resulting in relatively cheap fertilizers. Therefore, in Brazil the use of large doses of fertilizers on very poor soils can still be economical in large-scale mechanized enterprises, albeit with modest crop yields. This is not the most obvious development pathway for Africa. Increasing crop yields and food production is more likely to rely on smallholder development, gradually increasing in scale and mechanization. Fortunately, this is also a viable option because, as elaborated in this report, most African soils have a higher inherent soil fertility than the Brazilian Cerrados, for example. Therefore, fine-tuned and site-specific fertilizer technologies at modest doses are likely to achieve substantial yield improvement in Africa. Because of that, we will not discuss here the Brazilian high-dose interventions, but rather the type of interventions that have proven to be successful and the type of research that has resulted in increased yields.

Obviously in Brazil, N, P and also K use is widespread, but the successful technologies cover a broader spectrum of fertilizer technologies. Research also frequently tests the yield effects of lime (Ca + micronutrients), dolomitic lime (Ca, Mg + micronutrients) and gypsum (Ca, S, micronutrients). Their application in large doses has been instrumental for the development of the Cerrados. It is the first necessary step to develop an acceptable soil fertility. Remarkably, the possibility that these technologies can be useful seems to be forgotten in Africa, even though the main impetus for the Brazilian research on the subject consists of earlier research in South Africa (Sumner, 2012). In any case, in Section 2.2 it was shown that soils in Africa are not as acidic and poor as the Cerrados, and it appeared that at Bembeke station liming with large doses together with N and P can only be detrimental to yield – large doses, therefore, do not seem required. On the other hand, the example of cotton in Zimbabwe suggests that application of lime at modest non-liming rates can be beneficial. In such cases, the lime merely serves to correct Ca and/or Mg deficiencies and influences the soil cation ratios. Also, in the case of gypsum, there is hardly any research conducted in Africa. In Brazil, gypsum is a valued soil conditioner: it corrects Al acidity without raising the pH, thus maintaining the availability of most micronutrients (see Figure 14). Gypsum further increases TEB and corrects low Ca/Mg ratios but also increases depth of rooting and improves water infiltration (Rocha, 2007: quoted in Sumner, 2012; Dontsova and Norton, 2002). The increased rooting depth with gypsum application derives from the fact that gypsum penetrates deeper in the subsoil, compared to lime.

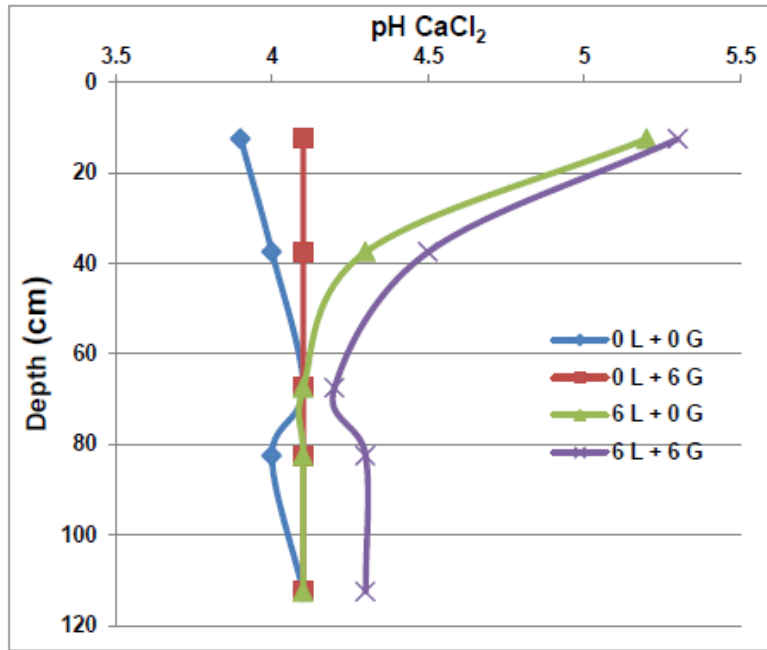


Figure 14. Comparison of the effects of broadcast and incorporated dolomitic lime (0 and 6 t/ha) and gypsum (0 and 6 t/ha) on soil pH down the profile of a dark yellow alic Oxisol of medium texture 27 months after application (no estimates of error were presented)

Source: Sumner, 2012; based on data from Morelli et al., 1992).

Similar effects were obtained by using Single Superphosphate (SSP) rather than Triple Superphosphate (TSP), because SSP contains gypsum (Ritchey et al., 1980; Figure 15). SSP is, therefore, not discarded in Brazil (a new SSP factory was recently started in the Cerrados); while in African agronomic research, it is hardly being used anymore. One of the possible reasons for this is that African countries apparently prefer to import fertilizer with a high nutrient content in order to ease transportation inefficiencies (Chianu et al., 2012). However, in the case of SSP and TSP, this applies if one restricts oneself to P content only and if the gypsum content of SSP (Ca, S) is discarded as being useless. In Brazil, due attention is also given to the micronutrient content in phosphate fertilizers that may differ dramatically even within one and the same type, say SSP (Carvalho et al., 2012; Gabe and Rodella, 1999). Furthermore, because liming at the high Brazilian doses may not be required in Africa, rather than using calcitic and dolomitic lime to correct Ca and Mg deficiency, respectively, possibly Ca- and Mg-sulfate is more indicated for African conditions.

Yet another particularity of Brazilian research and farming practice is that specific attention is given to cation ratios and their correction toward optimal levels. Figure 16 is illustrative in this respect. It shows that high yield increases are only obtained within a certain range of the Mg/Ca ratio. But it also shows that within that range, high yield increases are not always guaranteed. Such phenomena were also observed in the earlier described nutrient omission trials in Malawi and are an unavoidable implication of the multi-dimensional space that soil fertility is: the cation ratios may be right, but another variable can be within a suboptimal range.

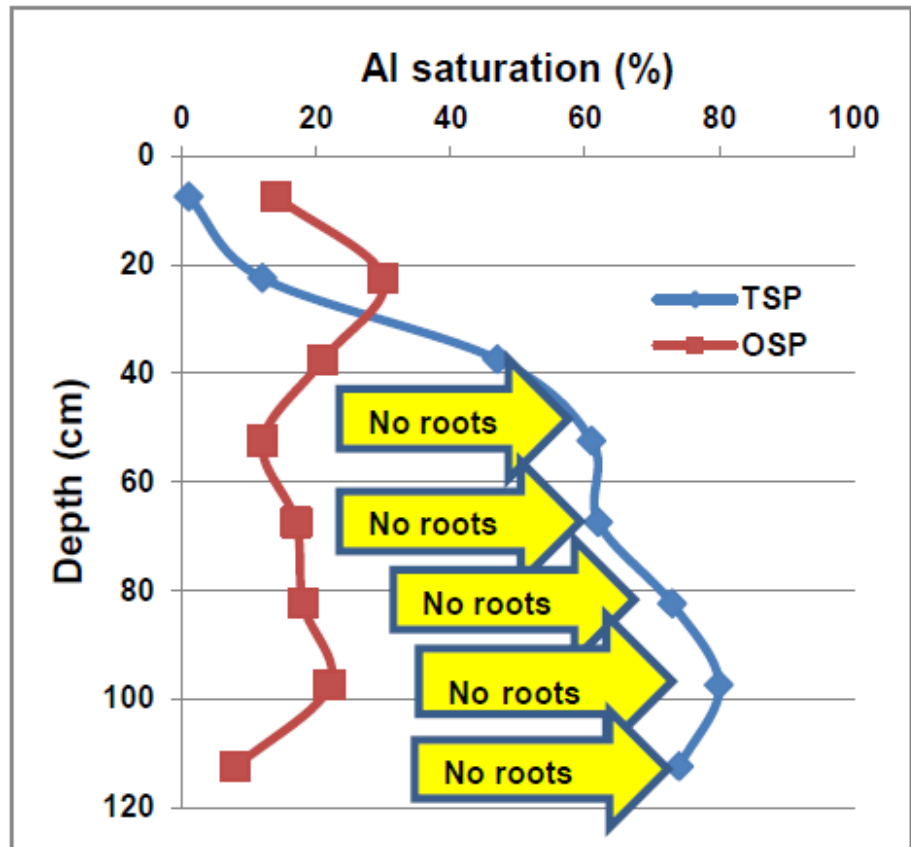


Figure 15. Effect of applications of single superphosphate (SSP; OSP in the legend) and triple superphosphate (TSP) at rates of 873 kg P/ha on Al saturation down the profile of a Brazilian Oxisol.

In the case of TSP application, only topsoil Al saturation is low and below 40 cm depth high Al saturation precludes root development. In the case of SSP that contains gypsum Al saturation is cured to much greater depth and roots were present (Ritchey et al., 1980; Source: Sumner, 2012)

A final specificity of Brazilian research and farming practice is the ample attention to micronutrient deficiencies as well as toxicities. Resende (2003) reviews history and current practice of micronutrient deficiencies and use in the Cerrados and shows a mixed picture of possible situations. Micronutrient deficiencies do frequently occur but obviously vary with soil type (soil parent material). Sometimes deficiencies refer to a single nutrient, but it also occurs that a broader spectrum of micronutrients is required to achieve acceptable yield levels (see also Yamada, 2004). Moreover, overt deficiencies on the same soil can vary strongly with the crop species grown. However, at the same time, micronutrient deficiencies are also not the rule in the Cerrados and it can occur that there is no response to micronutrient application. On the other hand, even toxic effects have been observed as well. This obviously is inherent in the nature of soil fertility and agrees with theoretical expectation. It is further worthwhile to observe that Brazil avails of a massive amount of literature on micronutrients in agriculture, certainly for developing countries, and yet it is recommended to conduct more systematic research in order to come to grips with these micronutrients (Resende, 2003). Current knowledge on micronutrient deficiencies in Brazil is well-illustrated in existing extension material where deficiency symptoms are shown in colored photographs (e.g., Malavolta et al., 1993; 'Be the doctor of your coffee plantation').

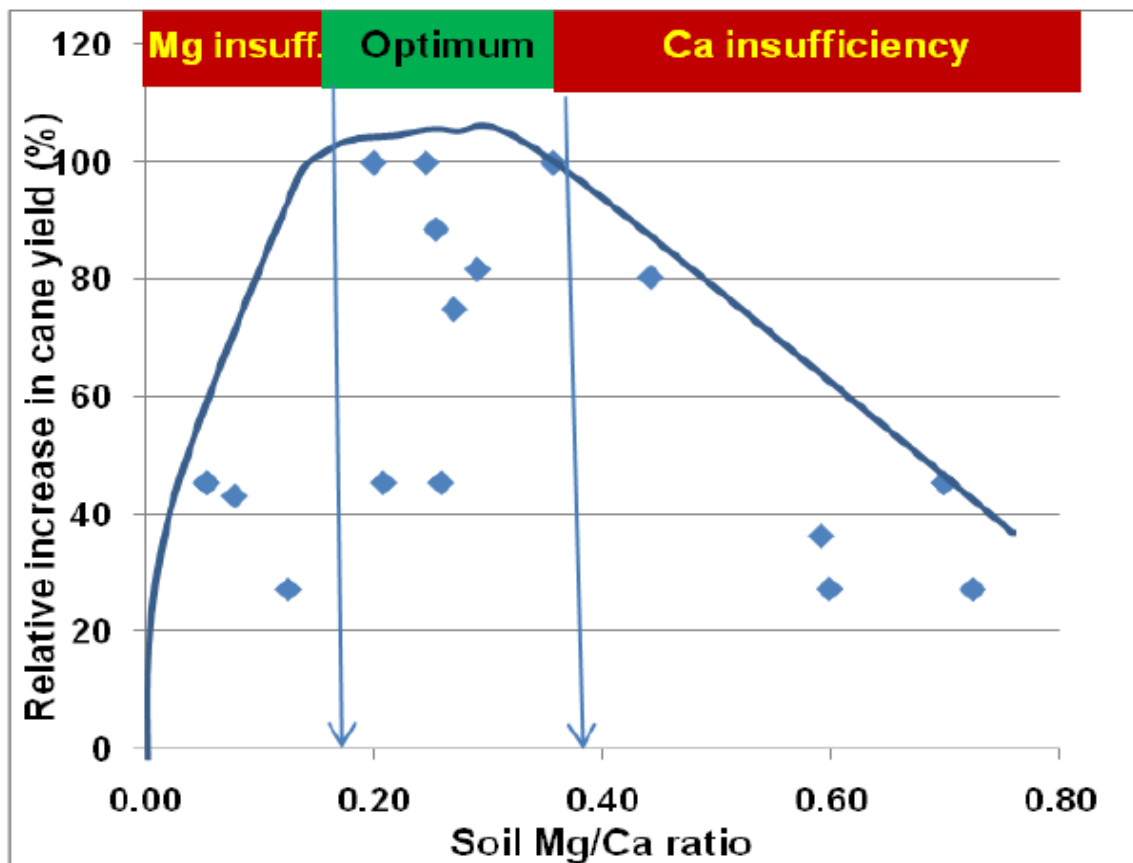


Figure 16. Effect of exchangeable Mg/Ca ratio for various combinations of dolomitic lime and phosphogypsum at different rates on the relative increase in cane yield over the control in two experiments

(Source: Sumner [2012], plotted from the data of Lorenzetti et al., 1992 and Demattê, 2011)

In summary, it appears that the key soil chemical properties governing the diversity and spatial distribution of ecosystems, as well as ecosystem functioning in sub-Saharan Africa are routinely addressed in Brazilian agronomic research and agricultural practice. This confirms that also in Brazil they are considered as key factors to develop agriculture. Compared with sub-Saharan Africa, large parts of the cultivated areas of Brazil have a similar type of soil parent rock and climate is also not essentially different and yet Brazilian agriculture is well developed. The progress in agriculture is achieved by taking a broad spectrum of essential plant nutrients into consideration, including Ca, Mg and micronutrients. Furthermore accounting for cation ratios is common practice in Brazil. It is remarkable that the example of Brazil is not followed elsewhere in developing countries such as sub-Saharan Africa. Possibly one of the reasons is merely a language barrier, because most of the Brazilian literature is in Portuguese.

6 Conclusions

Climate usually does not vary in short distances, and, therefore, soil parent material is the principle determinant of the local spatial variability of upland soils. The mineralogy of different soil parent materials is likely to be reflected in the chemical properties of the soil. Both propositions have been confirmed in this paper for the Miombo biome agro-ecosystem. Further, in most parent materials N is practically absent and the N levels in the soil derive mainly from

ecosystem functioning and, therefore, soil N levels are a highly endogenous ecosystem property. Local differences in soil N levels must therefore have deeper causes that are related to the mineralogy of parent rock and, consequently, to the other soil chemical properties. In fact, from the outset, one must suspect that differences in the mineralogy of parent rock can be reflected in the levels of all essential plant nutrients and involve the entire soil stoichiometry: not only the absolute levels of the nutrients, but also their proportions relative to each other. The latter is important, because, as has been shown at various occasions in this paper, the presence of particular ecosystems, crop yields and yield response to fertilizer, commonly do not reflect the absolute levels of nutrients in the soil. Such phenomena derive from the fact that the uptake possibilities of plants of a particular nutrient are influenced by the levels of other nutrients present in the soil. Such influences may be antagonistic as well as synergistic and may be mutual, but not necessarily so. These theoretical considerations have been the cornerstone for the approaches reported in this paper.

Also on theoretical grounds, it cannot be expected that N and P are the only limiting nutrients for high crop yields. Indeed, any of the essential plant nutrients may be the most limiting, even if required in very small amount by plants. Yet recommended fertilizer technologies and agronomic experiments in sub-Saharan Africa are mostly limited to N and P only. Yield response to these nutrients varies, but is often modest only and quite frequently even negative. The latter suggests that an antagonism with another more limiting nutrient is strengthened. Such phenomena call for more attention to a broader spectrum of essential nutrients. The over-emphasis on N and P has clearly come to the fore in this paper. In the Angonia district the people purposely select soils that are low in P in combination with high N, while high-P soils are avoided for cultivation. The underlying mechanism is suspected to be P-induced micronutrient deficiencies when P is high. The diversity and spatial distribution of different ecosystems could also not adequately be explained on the basis of N and P only. In the Malawi missing nutrient trials, in 4 out of 5 cases, 30kg of N and all P could be withheld without a sizeable effect on maize yield (provided that S, B and Zn were applied). Here, control yields were also poorly related to soil P levels. Hence, in both cases there is more to land resource ecology, crop yield and yield response to fertilizer than N and P.

In the land resource ecology study of the Angonia district, it was established that rather than N and P, an entirely different set of soil chemistry variables govern the spatial distribution of land use as well as the ecological diversity of soils and its spatial patterns. These key variables can be expressed as cations, their sum, their ratios and also micronutrients, micronutrient ratios, P and ratios of P with micronutrients, where high P stands for poor soils, because of the impact such conditions have on the uptake of other nutrients. The nutrient ratios involved all consist of antagonisms where nutrient uptake is concerned. In the Malawi study only general trends could be established, while seeking a satisfactory explanation for deviations. It proved that control yields also can be best explained from the interface between TEB, cation ratios, micronutrient ratios and ratios between P and micronutrients, whereby high P again generally had a negative yield impact. Such findings were confirmed by the nutrient omission trials. The importance of micronutrients in agriculture is further confirmed by both the Malawi and Zimbabwe studies, which show that, in case of deficiency, very large yield increases can be obtained with minimal amounts of fertilizer. As such the findings of the case studies used provide converging evidence of a natural order in which cation ratios and micronutrient and nutrient interactions in general play an important role.

With respect to fertilizer technologies the findings, first of all, call for interventions that remediate unbalanced cation ratios (by using Ca, Mg and K). Next to improving nutrient availability and crop yield, the improvement of these ratios is likely to facilitate the build-up of organic matter content, thus enhancing soil structure and water infiltration and, consequently, reducing soil erodibility. Balancing cation ratios has the additional advantage that it reduces the antagonistic impact that Ca, Mg and K can have on micronutrient availability. Other fertilizer technologies required are those that can address S and micronutrient deficiencies. Essentially, beyond N and P, more research is required that considers the entire spectrum of essential plant nutrients. Remarkably, what has been observed here from the few available data sets and experiments in Africa, is common knowledge in Brazil. And, this country has developed its

agriculture tremendously. Although N, P and K are often applied in Brazil, micronutrient deficiencies are routinely checked for, and if established are addressed. It has also been shown that in Brazil the impact of cation ratios on crop yield is a point of concern and subject of research. Calcitic lime, dolomitic lime and gypsum are frequently applied, certainly on poor and acid soils such as the Cerrados. This report has shown that it is very plausible that such inputs may be useful to improve crop yields in sub-Saharan Africa. In the Miombo biome, depending on the sources of imbalance between the cations, these can also be remedied with the mentioned source materials as well as other Ca, Mg and K containing salts. However, the application of limes and gypsum in Africa is unlikely to require the amounts of conventional liming rates, because most soils are not acidic to the extent to require an increase of pH. Lime and gypsum application are merely required to balance the cation ratios. Gypsum has the advantages over limes that it does not raise the pH of the soil and, consequently, micronutrient availability is not reduced in truly acid soils. Moreover, it penetrates deeper in the soil profile, improves subsoil structure and rooting conditions, and it enhances water infiltration as well. In short, essentially what we propose here for the Miombo biome of Africa is a low-dose version of Brazilian practice, while considering all essential plant nutrients. More generally, explicit consideration of the spatial diversity of soils in combination with agronomic research that assesses yield effects of all essential plant nutrients is a likely key to impactful fertilizer interventions elsewhere in sub-Saharan Africa as well.

Lastly, the Brazilian experiences also reveal the important limitation that, depending on the source, liming materials and gypsum (and also P containing conventional fertilizer) may contain undesirable or even hazardous impurities (e.g., Gabe and Rodella, 1999). Levels of Fe are often high and frequently also Mn, and both may already be high in tropical soils. A further major concern is for instance the content of U, Ra, Ba, Cd and Pb and the possibilities for their accumulation in the soil and entering the food chain as well as surface waters. Removing undesirable impurities from these materials is a major challenge in the development of innovative fertilizer technologies.

7 References

- Allan, W., 1965.
The African Husbandman. Oliver & Boyd, London, 483 p.
- Alloway, B.J., 2008.
Zinc in soils and crop nutrition. IZA and IFA, Brussels and Paris.
- Amorim, P.K., and M.A. Batalha, 2006.
Soil characteristics of a hyper seasonal Cerrado compared to a seasonal Cerrado and a floodplain grassland: implications for plant community structure. *Brazilian Journal of Biology* 66 (2B):661-670.
- Bederke, E., and H.G. Wunderlich, 1968.
Atlas zur Geologie. Meyers grosser physischer Weltatlas, Band 2. Bibliographisches Institut, Mannheim.
- Boyer, J., 1978.
Le Calcium et le Magnésium dans les sols des régions tropicales humides et sub-humides. Initiations-Documentations Techniques No. 35, ORSTOM, Paris.
- Boyer, J., 1972.
Soil Potassium. In: *Soils of the humid tropics*, pp. 102-135. National Academy of Sciences, Washington.
- Brinkman, R., and A.J. Smith (eds).
Land evaluation for rural purposes. Publication 17. ILRI, Wageningen.
- Carvalho, V.G.B., C.W. Araújo do Nascimento and C.M. Biondi, 2012.
Potencial de fertilizantes e corretivos no aporte de micronutrientes ao solo (Potential of fertilizers and lime as micronutrient suppliers to soil). *Revista Brasileira de Ciências de Solo* 36:931-938.
- Caulfield, L.E., S.A. Richard, J.A. Rivera, P. Musgrove and R.E. Black, 2006.
Stunting, wasting and micronutrient deficiency disorders. In: D.T. Jamison, J.G. Breman, A.R. Measham et al. (eds), *Disease Control Priorities in Developing Countries* (Ch 28), pp. 551-67, Oxford Press and World Bank.
- Chianu, J.N., J.N. Chianu and F. Mairura, 2012.
Mineral fertilizers in the farming systems of sub-Saharan Africa. A Review. *Agronomy for Sustainable Development* 32:545-566.
- Christian, C.S., and G.A. Stewart, 1968.
Methodology of integrated surveys. In *UNESCO: Aerial surveys and integrated studies*. Proceedings of the Toulouse conference. Natural resources research VI, UNESCO, Paris.
- Davies, B.E. (ed.), 1980.
Applied trace elements. Wiley, Chichester, 482 p.
- Davies, B.E., 1997.
Deficiencies and toxicities of trace elements and micronutrients in tropical soils: Limitations of knowledge and future research needs. *Environmental Toxicology and Chemistry* 16:75-83.
- Demattê, S.L.I., 2011.
Ação do gesso e do calcário na relação cálcio:magnésio do solo e na produtividade da cana-de-açúcar (The impact of gypsum and lime on the Ca/Mg ratio of the soil and on the productivity of sugarcane). *Informações Agronômicas* 136:11-16.
- Desanker, P.V., P.G.H. Frost, C.O. Frost, C.O. Justice and R.J. Scholes, 1997.
The Miombo network: Framework for a terrestrial transect study of land-use and land-cover change in the Miombo ecosystems of Central Africa. IGBP report 41. The International Geosphere-Biosphere Programme, Stockholm, Sweden.
- Dontsova, K.M., and L.D. Norton, 2002.
Clay dispersion, infiltration, and erosion as influenced by exchangeable Ca and Mg. *Soil Science* 167:184-193.

- Eswaran, H., F.H. Beinroth, J. Kimble and T. Cook, 1992.
Soil diversity in the tropics: Implications for agricultural development. In: R. Lal and P.A. Sanchez (eds), *Myths and Science of Soils in the Tropics*, pp. 1-16. SSSA Special Publication No. 29. SSSA, Madison.
- Fischer, G., H. van Velthuizen and F.O. Nachtergaele, 2000.
Global Agro-Ecological Zones Assessment: Methodology and Results. IIASA Interim report 00-064. IIASA, Laxenburg, Austria and FAO, Rome.
- Frost, P., 1996.
The ecology of Miombo woodlands. In: B. Campbell (ed.), *The Miombo in transition: Woodlands and welfare in Africa*, pp. 11-58. CIFOR, Bogor, Indonesia.
- Gabe, U., and A.A. Rodella, 1999.
Trace elements in Brazilian agricultural limestones and mineral fertilizers. *Communications in Soil Science and Plant Analysis* 30:605-620.
- Hikwa, D., M. Murata, F. Tagwira, C. Chiduzo, H. Murwira, L. Muza and S.R. Waddington, 1998.
Performance of green manure legumes on exhausted soils in northern Zimbabwe: A Soil Fertility Network trial. In: S.R. Waddington, H. Murwira, J.D.T. Kumwenda, D. Hikwa and F. Tagwira (eds), *Soil fertility research for maize-based farming systems in Malawi and Zimbabwe*. Proceedings of the Soil Fertility Network results and planning workshop, 7-11 July 1997, Mutare, Zimbabwe. Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe.
- ING, 1987.
Carta Geológica, escala 1:1,000,000. Instituto Nacional de Geologia, Maputo.
- Kang, B.T., and O.A. Osiname, 1985.
Micronutrient problems in tropical Africa. *Fertilizer Research* 7:131-150.
- Kumar, V., B.K. Bhatia and U.C. Shukla, 1981.
Magnesium and zinc relationship in relation to dry matter yield and the concentration and uptake of nutrients in wheat. *Soil Science* 131:151-155.
- Olsen, S.R., 1972.
Micronutrient interactions. In: J.J. Mortvedt et al. (eds), *Micronutrients in Agriculture*, pp. 243-264. Soil Science Society of America, Madison, Wisconsin.
- Kopittke, P.M., and N.W. Menzies, 2007.
A review of the use of the basic cation saturation ratio and the "ideal" soil. *Soil Science Society of America Journal* 71:259-265.
- Landon, J.R. (ed.), 1991.
Booker tropical soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman, Harlow.
- Loew, O., 1892.
Ueber die physiologischen Functionen der Calcium- und Magnesiumsalze im Pflanzenorganismus. Flora oder Allgemeine botanische Zeitung, M.r. 50. Jahrgang oder der ganzen Reihe 75. Jahrgang. Marburg.
- Lopes, A.S., and F.R. Cox, 1977.
Cerrado vegetation in Brazil: An edaphic gradient. *Agronomy Journal* 69:828-831.
- Lorenzetti, J.M., J.C. Rodrigues, S.H. Morales and S.L.I. Demattê, 1992.
Uso de calcário e gesso em soqueiras de cana-de-açúcar (The use of lime and gypsum in sugarcane ratoon crops). *Revista da Sociedade dos Técnicos Açúcareiros e Alcooleiros do Brasil* 16:14-18.
- Lucas, R.E., and B.D. Knezek, 1972.
Climatic and soil conditions promoting micronutrient deficiencies in plants. In: J.J. Mortvedt et al. (eds), *Micronutrients in Agriculture*, pp. 265-288. Soil Science Society of America, Madison, Wisconsin.

- Malavolta, E., D.R. Fernandez and J.P. Romero, 1993.
Seja o doutor do seu cafezal (Be the doctor of your coffee plantation). Encarte técnico, Informações Agrônômicas No. 64, Campinas.
- Morelli, J.L., A.E. Dalben, J.O.C. Almeida and S.L.I. Demattê, 1992.
 Calcário e gesso na produtividade da cana-de-açúcar e nas características químicas de um Latossolo de textura média álico (Lime and phosphogypsum effects on the productivity of sugarcane and on the chemical properties of a medium textured alic Latosol). *Revista Brasileira de Ciência do Solo* 16:187-194.
- Ministère de la Coopération, 1980.
Mémento de l'agronome. Collection techniques rurales en Afrique. Ministère de la Coopération, Paris.
- Mulder, D. 1953.
Voedingsziekten bij fruitgewassen (Nutritional diseases in fruit crops). Staatsdrukkerij- en uitgeverijbedrijf, 's-Gravenhage.
- Olsen, S.R. 1972.
 Micronutrient interaction. In: J.J. Mortvedt et al. (eds), *Micronutrients in Agriculture*, pp. 243-264. Soil Science Society of America, Madison, Wisconsin.
- Phosyn Chemicals Ltd., 1980.
The important role of trace elements in plant nutrition. Phosyn Chemicals Ltd., Pocklington, York.
- Resende, Á.V. de, 2003.
Aducação com micronutrientes no Cerrado (Fertilizing with Micronutrients in the Cerrado). Documento 80, Embrapa, Ministério da Agricultura, Pecuária e Abastecimento, Planaltina, DF.
- Richards, L.A. (ed.), 1954.
Diagnosis and improvement of saline and alkali soils. Handbook 60, USDA, Washington D.C.
- Ritchey, K.D., D.M.G. Souza, E. Lobato and O. Correa, 1980.
 Calcium leaching to increase rooting depth in a Brazilian Savannah Oxisol. *Agronomy Journal* 72:41-44.
- Rocha, A.T. da, 2007.
Gesso mineral na melhoria do ambiente radicular da cana-de-açúcar e implicações na produtividade agrícola e industrial (Mined gypsum in amelioration of sugarcane root environment and agricultural and industrial productivity implications). DSc Thesis, Federal Rural University of Pernambuco, Recife, Brazil.
- Rodel, M.G.W., and J.D.H. Hopley, 1973.
 Investigations into systems of farming suitable for tribal trust land. *Rhodesia Agricultural Journal* 70:1-18.
- Russel, E.W., 1973.
Soil conditions and plant growth (10th edition). Longman, London.
- Samuels, G., 1982.
 A matter of balance. *Sugar Journal* 45:33-37.
- Sanchez, P.A., and T.J. Logan, 1992.
 Myths and science about chemistry and fertility of soils in the tropics. In: R. Lal and P.A. Sanchez (eds), *Myths and Science of Soils in the Tropics*, pp. 33-46. SSSA Special Publication No. 29. SSSA, Madison.
- Schuffelen, A.C., 1940.
 Is de plantengroei afhankelijk van de ionenverhouding in den grond ? II. De ionenverhouding in den grond en de rentabiliteit der meststoffen (Is plant growth depending on the ionic balance in the soil? II. The ionic balance in the soil and the profitability of fertilizers). *Landbouwkundig Tijdschrift* 52:845-868.
- Sillanpää, M., 1982.
Micronutrients and the nutrient status of soils: A global study. FAO Soils Bulletin 48. FAO, Rome.
- Singh, M.V., 2009.
 Micronutrient nutritional problems in soils of India and improvement for human and animal health. *Indian Journal of Fertilizers* 4:11-16, 19-26, 56.

- Smaling, E.M.A., and B.H. Janssen, 1993.
Calibrating QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* 59:21-44.
- Sumner, M.E., 2012.
Review of Brazilian research on subsoil acidity. *Proceedings of the South African Sugar Technology Association* 85:67-79.
- Vink, A.P.A., 1975.
Land use in advancing agriculture. Advanced series in agricultural sciences 1. Springer Verlag, Berlin.
- Voortman, R.L., 2012.
Micronutrients in agriculture and the world food system – Future scarcity and implications. In: H.A. Udo de Haes et al., *Schaarste van micronutriënten in bodem, voedsel en minerale voorraden; urgentie en opties voor beleid.* Platform Landbouw, Innovatie & Samenleving.
- Voortman, R.L., 2010.
Explorations into African land resource ecology; On the chemistry between soils, plants and fertilizers. Gildeprint Drukkerijen, Enschede, 263 p. Online available at: dare.uvu.vu.nl/bitstream/1871/15943/1/dissertation.pdf.
- Voortman, R.L., 1985.
Guidelines on land evaluation for rainfed agriculture in Mozambique (Basement Complex). Série Terra e Água, Comunicação no. 30, INIA, Maputo.
- Voortman, R.L., B.G.J.S. Sonneveld and M.A. Keyzer, 2000.
African land ecology: Opportunities and constraints for agricultural development. CID working paper No. 37, Centre for International Development, Harvard University, Cambridge, MA. (a revised and abbreviated version is published in *Ambio* 32: 367-373 [2003]).
- Voortman, R.L., and B. Spiers, 2010a.
The use of local knowledge and bio-indication for the development of effective fertilizer technologies: The case of Angonia district, Mozambique. Chapter 6 in R.L. Voortman, 2010.
- Voortman, R.L., and B. Spiers, 2010b.
Key ecological factors and unifying principles in land resource ecology: Generalizations from the case of Angonia. Chapter 7 in R.L. Voortman, 2010.
- Voortman, R.L., and B. Spiers, 1986.
Angonia, Landscape ecological survey and land evaluation for rural development planning, Angonia district, Tete province. *Série Terra e Água, Comunicação* 33, Vol. 1-7. INIA, Maputo and FAO, Rome.
- Weil, R.R., and S.P. Mughogho, 2000.
Sulfur nutrition of Maize in four regions of Malawi. *Agronomy Journal* 92: 649-656.
- Wendt, J.W., and J. Rijpma, 1997.
Sulphur, zinc, and boron deficiencies in the Dedza Hills and Thiwi-Lifidzi regions in Malawi. *Tropical Agriculture* 74:81-89.
- Westerhof, A B.P., M.I. Lehtonen, H. Mäkitie, T. Manninen, Y. Pekkala, B. Gustafsson and A. Tahon, 2008.
The Tete-Chipata Belt: A new multiple terrane element from western Mozambique and southern Zambia. Geological Survey of Finland, Special Paper 48, 145-166.
- Wild, H., and L.A. Grandvaux Barbosa, 1967.
Flora Zambesiaca Supplement: Vegetation Map of the Flora Zambesiaca Area. Collins, Salisbury.
- Wit, C.T. de, W. Dijkshoorn and J.C. Noggle, 1963.
Ionic balance and growth of plants. Landbouwk. Onderz. Nr. 69.15. Pudoc, Wageningen.
- Wright, M.J., 1976.
Plant adaptation to mineral stress in problem soils. Special Publication, Cornell University Agronomic Experimental station, Ithaca, New York.

Yamada, T., 2004.

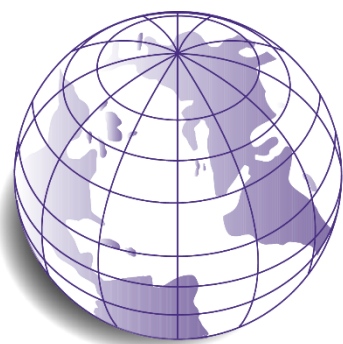
Deficiências de micronutrientes, ocorrência, detecção e correção; o sucesso da experiência brasileira (Micronutrient deficiencies, presence, detection and correction; the success of the Brazilian experience). Encarte dos informações agronômicas No 105. 12 p.

Yates, R.A., 1964.

Yield depression due to phosphate fertilizer in sugarcane. *Australian Journal of Agricultural Research* 15:537-547.

Young, A., 1976.

Tropical Soils and Soil Survey. Cambridge University Press, Cambridge.



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