Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna

M.C.S. Wopereis *, A. Tamélokpo, K. Ezui, D. Gnakkénou, B. Fofana, H. Breman

An International Center for Soil Fertility and Agricultural Development (IFDC) – Africa Division, BP 4483, Lomé, Togo

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Abstract

Maize grain yield and response to N (0, 50, and 100 kg ha$^{-1}$) and P fertilization (0, 15, and 30 kg ha$^{-1}$) were determined for fields differing in history of organic inputs of four farmers in the Sudan savanna zone of northern Togo over a period of 3 years. Each farmer selected a field that had benefited from long-term organic inputs close to his family homestead (‘infield’) and another field receiving considerably less or no organic inputs (‘outfield’). Soil organic C content was 13.4 g kg$^{-1}$ for infields and 6.3 g kg$^{-1}$ for outfields. Maize yields on infields were consistently 1.0–1.5 t ha$^{-1}$ higher than on outfields with and without fertilizer. N was the major limiting yield nutrient in this study. Phosphorus had only a minor, and in most cases, non-significant effect. Average recovery fractions of applied N fertilizer (RFN) were significantly ($p = 0.01$) higher on infields compared to outfields over 3 years (0.41 kg kg$^{-1}$ versus 0.33 kg kg$^{-1}$). However, the agronomic efficiency of applied N (AEN) was similar over three years (19.0 kg grain kg$^{-1}$ N). The greatest differences between outfields and infields were observed in 2001, due to low and erratic rainfall. In that year, gains of infields over outfields were highly significant in terms of maize yield (from 0.8 to 2.0 t ha$^{-1}$), RFN (from 0.21 to 0.33 kg kg$^{-1}$), and AEN (from 9.4 to 14.4 kg grain kg$^{-1}$ N). Highest N recovery rates were consistently obtained on infields using 50 kg N and 15 kg P ha$^{-1}$. Results indicate that judicious use of mineral fertilizer (i.e., taking into account the indigenous soil nutrient supplying capacity and targeting yield levels below 80% of climate-determined yield) should be promoted on relatively fertile infields rather than on poorer outfields. This strategy would lead to reduced production risk in years with low rainfall, higher fertilizer recovery, and increased productivity.

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Keywords: Maize; Nitrogen use efficiency; Fertilizer; Organic inputs; Indigenous nutrient supply

1. Introduction

Soils are critical to agriculture in sub-Saharan Africa, and therefore to food security and livelihoods. Over the last decade there has been growing concern about declining fertility of soils and, consequently, the sustainability of land use. Many studies (Stoorvogel and Smaling, 1990; Oldeman et al., 1991; Henao and Baanante, 1999) suggest that soils are rapidly degrading in large parts of sub-Saharan Africa. Soil nutrient depletion is the result of increasing pressure on agricultural land, resulting in higher nutrient outflows that are not compensated. External inputs are required to ensure that intensive systems become sustainable. However, these are often not within reach of smallholder farmers because of poor road and market infrastructure, lack of timely access to credit and inputs at reasonable costs, lack of timely information, and ineffective extension systems. Vanlauwe et al. (2002) give the example of maize in certain areas of Benin where the reduction of fallow from 6 to 2 years resulted in a yield decline from 3 to about 0.7 t ha$^{-1}$.

While recognizing the importance of the national-level studies and analyses cited above, it is crucial to underscore that there is a large spatial heterogeneity in terms of changes in soil fertility in Africa (e.g., Scoones and Toulmin, 1999). Soil fertility varies in the landscape due to natural processes such as wind erosion and dust deposition, erosion and sedimentation of soil particles with moving water, and due to human interventions such as fertilization, burning vegetation, grazing

Abbreviations: RFN, recovery fraction of applied fertilizer N; AEN, agronomic efficiency of applied fertilizer N; IEN, internal efficiency of N; INS, indigenous soil N supply; IPS, indigenous soil P supply; IKS, indigenous soil K supply

* Corresponding author. Fax: +228 2217817.
E-mail address: marcowopereis@yahoo.com (M.C.S. Wopereis).

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livestock, etc. Soil fertility is also strongly related to parent rock and topography. Human settlements may also generate gradients in soil fertility. Decline in soil fertility may be counteracted by farmers through reallocation and intensified use of organic material (De Ridder et al., 2004). Prudencio (1983) described the concentric rings of varying soil fertility status that are often said to be typical of West Africa. In this model, soil fertility and soil fertility management strategies vary with increasing distance from a village or town. In the first ring directly around the village, organic amendments such as household waste are used to increase soil fertility, offering good growing conditions for nutrient-demanding crops like maize. In the second ring, use of organic resources declines and some use of mineral fertilizer might be observed. In the third outer ring, soil fertility is maintained through fallowing. Grazing cattle may actually mine nutrients from these areas and bring these to the first ring if cattle are kept overnight at the homestead. Farmers’ labor input usually decreases going from the first ring (‘infields’) to the third ring (‘outfields’). Such differences in soil fertility are usually especially pronounced for phosphorus (P) compared to potassium (K) and nitrogen (N) because this nutrient is less mobile and better retained in the soil (Penning de Vries and Djitéye, 1982).

It should be noted that such ring patterns often disappear if population density exceeds a certain threshold level (Defoer et al., 2000). In such situations, unfertilized outfields of farmer A may be found next to fertilized infields of farmer B. Instead of neat rings, one would then observe a patchwork of areas of diverse soil fertility status. There may be considerable within-field variability due to termite hills, sandy patches, abandoned kraal sites, etc. De Ridder et al. (2004) distinguished between ‘passive’ concentration of manure and nutrients around villages and wells related to livestock movement and ‘active’ concentration of organic inputs by farmers to reach production goals.

Soil fertility management can be strongly related to the degree of access to resources (e.g., land, carts, cattle, labor, and cash). Land tenure is a very important issue. Farmers who do not own the land they cultivate may well be hesitant to invest in soil fertility because the pay-off is not always directly visible. Access to resources often differs among household members; e.g., women may have only limited access to certain resources.

Field use history, distance to compound, farmer wealth, and other factors may, therefore, create ‘islands of soil fertility’ (Sanchez and Jama, 2002). The existence of man-made differences in soil fertility in farmers’ fields calls for different mineral fertilizer strategies. One hypothesis would be that outfields would require more mineral fertilizer because they have poorer soil fertility. However, it is also possible that the poverty of these soils, especially their low organic matter status, reduces the effect of fertilizers because of higher leaching rates or because other factors limit growth, such as drought or nutrient limitations not addressed by the fertilizers applied. If indeed, fertilizers are used more efficiently on infields, farmers would be advised to apply these on infields rather than outfields, especially in case of limited accessibility, as hypothesized by Breman and Sissoko (1998).

To test these hypotheses, experiments were carried out in Northern Togo from 1999 to 2002. In these experiments the effects of different doses of N and P were compared for infields and outfields. Because it is assumed that K is not a limiting factor on these soils, K was not taken into account. To evaluate the results, yields and nutrient uptake were measured and nutrient use efficiencies were determined.

2. Materials and methods

2.1. Description of experimental sites

The field experiments were conducted in collaboration with four farmers from two villages in northern Togo, between the town of Mango (10°21’N, 0°28’E) and the village of Koukombo (10°16’N, 0°22’E) during the growing season (June–August) in three consecutive years, i.e., 1999–2001. These farmers were selected because they possessed both infields and outfields in the same village on a similar soil type. The annual weather is tropical with mono-modal rainfall (about 800–1000 mm per year).

Each of the four farmers selected one infield and one outfield that were not too far apart (ranging from 100 to 500 m) and were sited on the same soil type (ferric Luvisols; FAO-Unesco, 1973); their main difference was organic input history. On infields, farmers had applied organic inputs prior to the installation of the field experiments for a period of at least 10 years. On outfields, no organic inputs had been applied during the same period. Pressure on land in northern Togo is high, ranging from 50 to 200 inhabitants km⁻² and patterns of soil fertility around villages do not correspond to the Prudencio (1983) model of concentric rings with fertility gradually declining with distance from the village. Unfertilized fields of farmer A may be found next to fertilized fields of farmer B, forming a patchwork of areas of varying soil fertility described by Defoer et al. (2000).

2.2. Experimental set-up

The experimental set-up was a randomized complete block design with three replicates and nine treatments for both infields and outfields. Plot size was 6 m × 6 m. Factors were urea-N application at 0, 50, and 100 kg N ha⁻¹; applied in two equal splits at 15 days after sowing (DAS) and 45 DAS, and P-application (as triple superphosphate, TSP) at 0, 15, and 30 kg P ha⁻¹, applied at 15 DAS. This yielded a total of nine treatments, T1–T9:

- **T1**: 0 kg N ha⁻¹, 0 kg P ha⁻¹;
- **T2**: 50 kg N ha⁻¹, 0 kg P ha⁻¹;
- **T3**: 100 kg N ha⁻¹, 0 kg P ha⁻¹;
- **T4**: 0 kg N ha⁻¹, 15 kg P ha⁻¹;
- **T5**: 50 kg N ha⁻¹, 15 kg P ha⁻¹;
- **T6**: 100 kg N ha⁻¹, 15 kg P ha⁻¹;
- **T7**: 0 kg N ha⁻¹, 30 kg P ha⁻¹;
- **T8**: 50 kg N ha⁻¹, 30 kg P ha⁻¹;
- **T9**: 100 kg N ha⁻¹, 30 kg P ha⁻¹;
All plots received a yearly basal application of 100 kg K ha\(^{-1}\) as potassium sulphate (42% K, 19% S) to avoid that K or S would limit crop growth, applied in two equal splits at 15 DAS and 45 DAS, although K and S are not usually limiting maize growth on these soils. Fertilizers were applied in bands at about 5–10 cm distance from a maize row, at 5 cm depth and immediately covered with soil material using hand hoes.

The trial was started in 1999 and repeated in 2000 and 2001 with the same farmers and on the same fields. Best planting dates for maize in northern Togo are in June. Maize (Ikenne 81-49-SR) was planted between 19 June and 3 July. Of planting dates for maize in northern Togo are in June. Maize (Ikenne 81-49-SR) was planted between 19 June and 3 July. Treatment 1, 2, and 3, respectively, had 100 kg N ha\(^{-1}\); 50 kg N ha\(^{-1}\); and 0 kg N ha\(^{-1}\). Treatment 4, 5, and 6, respectively, had 100 kg P ha\(^{-1}\); 50 kg P ha\(^{-1}\); and 0 kg P ha\(^{-1}\). Treatment 7, 8, and 9, respectively, had 100 kg K ha\(^{-1}\); 50 kg K ha\(^{-1}\); and 0 kg K ha\(^{-1}\).

2.3. Plant and soil sampling and analyses

Maize plants were harvested from a 20 m\(^2\) area. Grain and stover samples were oven-dried at 60°C, weighed, ground to pass 0.5 mm, and then analyzed for total N. Dry matter production and grain yield are expressed on a dry-weight basis. Soils were sampled prior to land preparation to a depth of 0.2 m, air-dried, and then passed through a 2-mm sieve, prior analysis. Organic carbon, total N (H\(_2\)O), P-Olsen, exchangeable K, and CEC. Plant N uptake was determined in 1999, 2000, and 2001 from the concentrations in grain and straw, grain yield at 3% moisture content, and straw yield. All analyses were conducted using standard methodologies in the ICRISAT laboratory in Niamey, Niger; plant tissue N analysis was done using the micro-Kjeldahl method.

The aboveground maize N uptake in the subplots with an application of 30 kg P ha\(^{-1}\) but without N application was used as a proxy for the indigenous N supply of the soil (INS). Similarly, the indigenous P supply of the soil (IPS) was calculated for subplots without P application and an application of 100 kg N ha\(^{-1}\). The agronomic efficiency of applied fertilizer N (AEN) was calculated as yield gain from N application divided by fertilizer N applied, at constant P rates. The recovery fraction of applied fertilizer N (RFN) was based upon the difference in aboveground maize N uptake at harvest between plots, with and without N application, at constant P rates. Internal efficiency of nitrogen (IEN) was calculated as grain yield divided by total N uptake by the maize crop at harvest. Average IEN over all years, treatments, and replications was estimated through regression analysis, plotting all data on N uptake versus maize grain yield for both outfields and infields.

2.4. Weather data and data interpretation

Data on daily minimum and maximum air temperatures and solar radiation were obtained from a weather station located near the experimental sites (maximum distance about 3 km). These data were used as an input for the CERES–Maize model (Jones et al., 1998) to estimate potential maize yields without water and nutrient limitations, nor interference of other growth reducing factors. The model was recently validated for maize growing conditions in Togo (Dzotsi et al., 2003). Simulated yields are yield ceilings for the growth environment. Insufficient data on soil hydraulic properties were available to simulate water-limited yields with the CERES model. Data on daily rainfall were collected using rainfall gauges next to the experimental sites. Total effective rainfall and rainfall distribution were used to interpret experimental results. Statistical analyses were conducted using Statistica software.

3. Results and discussion

3.1. Soil data

We observed large differences in soil characteristics of infields and outfields, although such fields were located at relatively short distances and on similar soil types. Results of the soil analyses indicate statistically significant differences between outfields and infields for all soil parameters analyzed except for exchangeable Ca (Table 1). Organic carbon (C-org) of infields was 13.4 g kg\(^{-1}\), and of outfields, 6.3 g kg\(^{-1}\). Struif Bontkes et al. (2003) reported C-org values ranging from 4.5 to 19 g kg\(^{-1}\) for various experimental sites in Togo. The C-org values reported here are also within the range (3.8–16.4 g kg\(^{-1}\) reported by Murwira et al. (2002) for trial sites in East Africa receiving less than

Table 1

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Infield</th>
<th>Outfield</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH, H(_2)O</td>
<td>7.68</td>
<td>6.43</td>
<td>0.013</td>
</tr>
<tr>
<td>pH, KCl</td>
<td>6.90</td>
<td>5.98</td>
<td>0.026</td>
</tr>
<tr>
<td>H(^+) (cmol kg(^{-1}))</td>
<td>0.07</td>
<td>0.02</td>
<td>0.017</td>
</tr>
<tr>
<td>Na(^+) (cmol kg(^{-1}))</td>
<td>0.09</td>
<td>0.048</td>
<td>0.0027</td>
</tr>
<tr>
<td>K(^+) (cmol kg(^{-1}))</td>
<td>1.70</td>
<td>0.25</td>
<td>0.0334</td>
</tr>
<tr>
<td>Ca(^{2+}) (cmol kg(^{-1}))</td>
<td>2.90</td>
<td>3.51</td>
<td>0.0078</td>
</tr>
<tr>
<td>Mg(^{2+}) (cmol kg(^{-1}))</td>
<td>1.12</td>
<td>0.56</td>
<td>0.032</td>
</tr>
<tr>
<td>CEC (cmol kg(^{-1}))</td>
<td>6.95</td>
<td>3.10</td>
<td>0.0038</td>
</tr>
<tr>
<td>C-org (g kg(^{-1}))</td>
<td>13.4</td>
<td>6.3</td>
<td>0.044</td>
</tr>
<tr>
<td>N tot (mg kg(^{-1}))</td>
<td>968</td>
<td>511</td>
<td>0.021</td>
</tr>
<tr>
<td>P-Olsen (mg kg(^{-1}))</td>
<td>48</td>
<td>1.15</td>
<td>0.015</td>
</tr>
</tbody>
</table>
900–1800 mm rainfall per year. They are, however, still relatively high in comparison with the values of 7.9 and 4.6 g kg\(^{-1}\) found by Breman (2002) as average values for infields and outfields from 5 different West African sources. Total N (N-tot) level for infields was about 1 g kg\(^{-1}\), compared to about 0.5 g kg\(^{-1}\) for outfields. These data too are somewhat higher than the average values of 0.75 and 0.47 g kg\(^{-1}\) found by Breman (2002). Struif Bontkes et al. (2003) reported a range in N-tot of 0.6–1.6 g kg\(^{-1}\) for various experimental sites in Togo. Differences in plant-available P between outfields (1.2 mg kg\(^{-1}\)) and infields (48 mg kg\(^{-1}\)) were large; these differences were probably amplified by the method used (P-Olsen) and the substantially higher pH of infields compared to outfields. The average values obtained by Breman (2002) were 6 mg kg\(^{-1}\) (outfields) and 50 mg kg\(^{-1}\) (infields) at almost equal pH values. Iwuafor et al. (2002) reported P-Olsen levels ranging from 5.1 to 13.3 mg kg\(^{-1}\) for four sites in West Africa, with

### Table 2
Grain yield, N recovery (RFN) and agronomic efficiency of N (AEN) in maize for infields and outfields in northern Togo in 1999, 2000, and 2001

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Grain yield (t ha(^{-1}))</th>
<th>p</th>
<th>RFN (kg kg(^{-1}))</th>
<th>p</th>
<th>AEN (kg grain kg(^{-1}))</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Outfields</td>
<td>Infields</td>
<td>Outfields</td>
<td>Infields</td>
<td>Outfields</td>
<td>Infields</td>
</tr>
<tr>
<td>1999</td>
<td>All</td>
<td>1.84 (1.25)</td>
<td>3.16 (1.46)</td>
<td>0.000009</td>
<td>0.33 (0.25)</td>
<td>0.41 (0.38)</td>
<td>0.0098</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>0.88 (0.63)</td>
<td>2.10 (1.14)</td>
<td>0.0001</td>
<td>0.31 (0.23)</td>
<td>0.35 (0.48)</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>1.80 (1.08)</td>
<td>3.03 (1.22)</td>
<td>0.0001</td>
<td>0.26 (0.19)</td>
<td>0.43 (0.22)</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>0.97 (0.70)</td>
<td>2.03 (1.22)</td>
<td>0.0001</td>
<td>0.38 (0.30)</td>
<td>0.61 (0.38)</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.69 (1.33)</td>
<td>4.07 (1.34)</td>
<td>0.0002</td>
<td>0.31 (0.18)</td>
<td>0.45 (0.27)</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>1.00 (0.81)</td>
<td>2.56 (1.41)</td>
<td>0.0001</td>
<td>0.39 (0.36)</td>
<td>0.27 (0.53)</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.07 (1.04)</td>
<td>3.29 (1.25)</td>
<td>0.0001</td>
<td>0.35 (0.25)</td>
<td>0.35 (0.24)</td>
<td>0.87</td>
</tr>
<tr>
<td>2000</td>
<td>All</td>
<td>2.45 (1.06)</td>
<td>3.48 (1.24)</td>
<td>0.000009</td>
<td>0.35 (0.25)</td>
<td>0.52 (0.38)</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>1.22 (0.51)</td>
<td>2.21 (0.73)</td>
<td>0.001</td>
<td>0.36 (0.22)</td>
<td>0.58 (0.49)</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.48 (0.58)</td>
<td>3.55 (0.88)</td>
<td>0.002</td>
<td>0.31 (0.19)</td>
<td>0.44 (0.15)</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>3.05 (0.72)</td>
<td>4.38 (0.63)</td>
<td>0.00023</td>
<td>0.37 (0.34)</td>
<td>0.78 (0.38)</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>3.51 (0.73)</td>
<td>4.52 (0.80)</td>
<td>0.004</td>
<td>0.33 (0.18)</td>
<td>0.52 (0.24)</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>1.37 (0.70)</td>
<td>2.54 (1.08)</td>
<td>0.005</td>
<td>0.40 (0.36)</td>
<td>0.32 (0.55)</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.74 (0.64)</td>
<td>3.67 (1.13)</td>
<td>0.02</td>
<td>0.35 (0.18)</td>
<td>0.47 (0.16)</td>
<td>0.13</td>
</tr>
<tr>
<td>2001</td>
<td>All</td>
<td>2.30 (1.25)</td>
<td>4.06 (1.35)</td>
<td>0.00009</td>
<td>0.42 (0.28)</td>
<td>0.40 (0.44)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>1.14 (0.62)</td>
<td>2.92 (1.33)</td>
<td>0.0005</td>
<td>0.40 (0.21)</td>
<td>0.28 (0.52)</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.24 (1.03)</td>
<td>3.59 (1.26)</td>
<td>0.009</td>
<td>0.32 (0.20)</td>
<td>0.53 (0.26)</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>1.19 (0.55)</td>
<td>2.88 (1.42)</td>
<td>0.002</td>
<td>0.49 (0.34)</td>
<td>0.58 (0.43)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>2.87 (1.02)</td>
<td>4.35 (0.89)</td>
<td>0.001</td>
<td>0.36 (0.18)</td>
<td>0.45 (0.35)</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>3.31 (1.10)</td>
<td>5.09 (0.96)</td>
<td>0.0005</td>
<td>0.43 (0.19)</td>
<td>0.35 (0.31)</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>3.50 (0.89)</td>
<td>5.03 (0.76)</td>
<td>0.0003</td>
<td>0.43 (0.19)</td>
<td>0.35 (0.31)</td>
<td>0.43</td>
</tr>
</tbody>
</table>

RFN was calculated as the difference in above-ground maize N uptake at harvest between plots, with and without N application, divided by fertilizer N applied, at constant P rates. AEN was calculated as yield gain from N application over the zero N treatment divided by fertilizer N applied, at constant P rates. Standard deviations are indicated in brackets. N and P treatment levels in kg ha\(^{-1}\).
pH (H₂O) ranging from 6 to 6.7. Exchangeable K in infields was much higher than in outfields (1.70 cmol kg⁻¹ versus 0.25 cmol kg⁻¹). Murwira et al. (2002) reported a range of 0.02–0.56 cmol kg⁻¹ for exchangeable K. Similar levels (0.02–0.40 cmol kg⁻¹) were reported by Struif Bontkes et al. (2003). K-levels were, therefore, very high in the fields used in this study, especially in the infields. CEC values of infields were about twice those of outfields, and typical for relatively sandy soils. Exchangeable Ca and Mg levels were on the high side in both outfields and infields compared to data presented by Murwira et al. (2002).

3.2. Observed and simulated maize yields

Potential maize yields, simulated with the CERES model, ranged from 4.6 t ha⁻¹ for late sowing in July 2001 to 6.5 t ha⁻¹ for sowing on 29 June in 2000. Maize yields on outfields ranged from 0 to 5.2 t ha⁻¹ with an average of 1.8 t ha⁻¹ and on infields from 0.15 to 6.5 t ha⁻¹, with an average of 3.2 t ha⁻¹ (Table 2). The higher yield levels obtained on infields in 1999 and 2000 at 100 kg N ha⁻¹ were close to the maximum yield potential as estimated by the CERES model (Table 2). Maize yields were consistently higher on infields compared to outfields (p = 0.000009 for all 3 years, and for each year individually). Maize yields were comparable in 1999 (2.4 t ha⁻¹ on outfields and 3.5 t ha⁻¹ on infields) and 2000 (2.3 t ha⁻¹ on outfields and 4.1 t ha⁻¹ on infields), but 2001 resulted in relatively low maize yields, i.e., on average 0.8 t ha⁻¹ on outfields and 2.0 t ha⁻¹ on infields.

Cumulative rainfall over the growing period from sowing to physiological maturity (as simulated with the CERES model) was on average 773 mm in 1999, 447 mm in 2000 and 440 mm in 2001. Rainfall in 1999 and 2000 was relatively well distributed. In 2001, sowing was late and about 80% of rainfall fell in the period from sowing to 40 days after sowing. Maize plants experienced virtually no rainfall around and after flowering, explaining the low yields obtained in that year (Fig. 1).

3.3. Response to N and P fertilizer

Response to 50 and 100 kg ha⁻¹ of fertilizer N was highly significant for all years, and for each year individually (p < 0.001). This was true for all fields taken together and for outfields and infields individually. However, response to 15 or 30 kg ha⁻¹ of fertilizer P was not significant, i.e., not on outfields and also not on infields. N was, therefore, clearly the limiting factor for yield on both types of fields and in all years. Drought further limited yields in 2001. Average partial factor productivity of N (kg grain per kg N applied) over all treatments and three years was about 40–60 kg grain (kg N applied)⁻¹ on infields and about 20–40 kg grain (kg N applied)⁻¹ on outfields. On infields, average yield gains obtained from applying 50 kg N ha⁻¹ and from a further increase to 100 kg N ha⁻¹ were in the order of 0.7–1.0 t ha⁻¹. Best yield levels were still well below simulated potential levels, and farmer yield data were, therefore, still clearly on the linear part of the response curve to fertilizer N. This was less obvious for outfields; in this case yield response to an additional 50 kg N ha⁻¹ from 50 to 100 kg N ha⁻¹ was less pronounced, indicating that other factors were limiting or reducing crop growth.

3.4. Recovery of fertilizer applied N (RFN)

RFN ranged for infields from −1.13 to 1.66 kg kg⁻¹ (total of 216 cases) and for outfields from −0.52 to 1.34 kg kg⁻¹ (total of 216 cases). Both negative RFN values and RFN values >1 can be due to experimental error, INS variability or to differences in growing conditions, e.g., due to presence of termite hills. For the infields, the number of
cases with RFN < 0 kg kg\(^{-1}\) was 27 and the number of cases with RFN > 1.0 kg kg\(^{-1}\) was 11, with 9 between 1.0 and 1.5 kg kg\(^{-1}\) and 2 between 1.5 and 2 kg kg\(^{-1}\). For outfields, the number of cases with RFN < 0 kg kg\(^{-1}\) was 12 and the number of cases with RFN > 1.0 kg kg\(^{-1}\) was 4, all below 1.5 kg kg\(^{-1}\).

Average RFN over all 3 years was significantly (\(p = 0.01\)) higher on infields (0.41 kg kg\(^{-1}\)) compared to outfields (0.33 kg kg\(^{-1}\)). Such recoveries are impressive. In comparison, Cassman et al. (2002) cited in Dobermann and Cassman (2002) reported that on average only 37% of applied fertilizer-N is taken up by maize in intensive maize systems in the USA. Highest RFN was consistently obtained on infields with an application of 50 kg N and 15 kg P ha\(^{-1}\). Highest RFN on outfields was obtained with an application of 50 kg N and 30 kg P ha\(^{-1}\). Differences in RFN between infields and outfields were especially pronounced in 1999 and 2001, with lowest RFN values obtained in 2001 on outfields. Applying N fertilizer on infields resulted, therefore, in a better N uptake by the maize crop in 2 out of 3 years compared to outfields, especially in the case of drought (year 2001). This may be due to better water retention in infields compared to outfields, as a result of reduced evaporation because of household waste and crop residues covering the soil surface, and better infiltration capacity. The higher organic matter status may also have contributed to greater inherent water holding capacity, but this effect is estimated to be rather small (De Ridder and Van Keulen, 1990).

3.5. Indigenous soil N and P supply (INS and IPS)

Given the very limited response to P fertilizer, INS was calculated using N uptake measured for all zero-N treatments, i.e., for applications of 0, 15, and 30 kg P ha\(^{-1}\).

1. Average INS for infields was 45 kg ha\(^{-1}\), ranging from 3 to 127 kg ha\(^{-1}\), with 95% of the 108 cases between 0 and 100 kg ha\(^{-1}\). Average INS for outfields was 18 kg ha\(^{-1}\), ranging from 1 to 75 kg ha\(^{-1}\), with 95% of the 108 cases between 0 and 40 kg ha\(^{-1}\). The INS of infields was, therefore, more than twice as high as the INS of the outfields, corresponding to the differences in org-C and total N contents in the soil.

For IPS, only the fields where 100 kg N ha\(^{-1}\) was applied were taken into account. Average IPS for infields was 31 kg P ha\(^{-1}\), ranging from 9 to 49 kg ha\(^{-1}\), with about 83% of the 36 cases between 0 and 45 kg ha\(^{-1}\). Average IPS for outfields was 12 kg P ha\(^{-1}\), ranging from 1 to 32 kg ha\(^{-1}\), with 83% of the 36 cases between 0 and 20 kg ha\(^{-1}\).

As reported above, the organic carbon content of infields was more than twice as high as outfields. This resulted in a doubling of INS for infields compared to outfields. The average INS obtained in this study (18 kg N ha\(^{-1}\)) for the outfields corresponds well with the INS reported by Breman and De Ridder (1991) of 15–20 kg N ha\(^{-1}\), which they presented as ‘natural N availability’ in the Sudan savannah. Average organic carbon and N concentrations in outfields presented by Breman (2002) are, however, still about 50% lower than those reported here. The IPS of infields was almost three times as high as that of outfields, illustrating the immobile nature of P and that farmers’ strategy to enrich fields near their homestead was very effective. These differences in indigenous soil fertility led, on average, to yield gaps between infields and outfields of between 1 and 2 t ha\(^{-1}\). Despite these differences in indigenous soil fertility, response to N and P fertilizer was strikingly similar, with a marked response to N, but virtually no response to P. Although K was not a treatment factor, soil K data indicated that K is not a concern in the short to medium term, especially for infields.

3.6. Internal efficiency of N

Fig. 2 depicts N uptake versus maize yield as determined for all experimental fields in 1999, 2000, and 2001. No clear trend is visible distinguishing infields from outfields, other than that outfields resulted in less N uptake and lower yields. The envelope lines drawn in Fig. 1 give a first idea of maximum dilution to reach a target yield (upper line) and maximum accumulation of N (lower line) in maize for the Sudan savanna agro-ecological zone in West Africa. Similar results were obtained for maize in the north-central USA (Dobermann and Cassman, 2002), albeit over a much larger range of N uptake and grain yield. The slope of the regression line forced through zero indicated an average IEN of 49 kg grain (kg N uptake)\(^{-1}\).

3.7. Agronomic efficiency of N

The agronomic efficiency of N (AEN) for infields ranged from −47 kg grain (kg N applied)\(^{-1}\) to 74 kg grain (kg N applied)\(^{-1}\) with an average of 19.0 kg grain (kg N applied)\(^{-1}\). AEN of outfields varied from −29 kg grain (kg N applied)\(^{-1}\) to 78 kg grain (kg N applied)\(^{-1}\), with an average of 18.7 kg grain (kg N applied)\(^{-1}\).

![Fig. 2](image-url)
For the infields, the number of cases with AEN < 0 kg kg⁻¹ was 23 and 88% of the 216 cases was below 40 kg grain (kg N applied)⁻¹. For outfields, the number of cases with AEN < 0 kg grain (kg N applied)⁻¹ was 10 and 92% of the 216 cases was below 40 kg grain (kg N applied)⁻¹. The AEN was, therefore, similar on both infields and outfields for the complete dataset over three years. However, great differences were observed in 2001, with an average AEN of 9.4 kg grain kg⁻¹ N on outfields and an average AEN of 14.4 kg grain kg⁻¹ N on infields. This effect is again possibly due to better water retention in infields, and such fields were, therefore, better equipped to face the long drought spell around and after flowering in that year.

3.8. Consequences for fertilizer management

Farmers in northern Togo have limited means and cannot afford to apply fertilizer on all their fields in sufficient quantities. Our results suggest that they would be better off giving priority to infields because the recovery of mineral fertilizer N was higher on such fields compared to outfields in 2 out of 3 years. This result is somewhat counterintuitive because it is usually thought that fertilization should focus on the poorer outfields. However, yield levels obtained on infields without fertilization were far off potential yield levels, and large yield gains were obtained with mineral fertilizer, even with N application levels of up to 100 kg N ha⁻¹. In general, yield response to N uptake is linear up to about 80% of potential yield, determined by climate (temperature and solar radiation), if no other factors are limiting or reducing growth. With June sowing potential, yield was estimated at about 6–6.5 t ha⁻¹ in this environment using the CERES model, and farmers should, therefore, target yields of no more than about 5 t ha⁻¹, to avoid obtaining diminishing returns on N fertilizer. Such yields were indeed obtained in our trials in 2000 with an application of 100 kg N ha⁻¹ (Table 2).

Vanlauwe et al. (2001) distinguished direct and indirect interactions between fertilizer N and organic matter. Direct interactions are the result of the capture of fertilizer N in the soil by the soil microbial biomass, which may improve the synchrony between supply and demand of N by the crop and reduce N losses to the environment. Indirect interactions refer to organic matter related improvements in general growth conditions, and therefore improved N uptake. Our results seem to indicate that improved recovery of fertilizer N on infields compared to outfields was mostly related to the indirect effect of improved soil water retention (probably reduced evaporation and enhanced infiltration), thereby improving general crop growth conditions. This was observed in 2001 when an extensive drought period hit the crop 40 days after sowing. The relatively good results obtained on infields in 2001, when a dry spell hit the crop, indicate that a fertilizer strategy that would give priority to infields rather than outfields would also lead to less risk and higher productivity in case of drought.

Infields receive large quantities of household waste and ashes, likely to be rich in K; dust deposition will also contribute K to the system (Haefele, 2001). Moreover, exchangeable K levels were extremely high (Table 1). Not applying K in mineral fertilizer form seems, therefore, not a real concern in these fields. Not applying P may seem more risky, and if high yields are targeted, some P may become beneficial in the long run. However, P reserves in the infields seem to be more than adequate. In conclusion, a slow P and K mining strategy on infields seems more adequate than a soil P and K maintenance strategy. This basically implies recommending farmers to apply only urea on infields, rather than the current recommendation of 3 bags of urea and 3 bags of composite NPK fertilizer per hectare regardless of the type of field.

Monitoring INS, IPS, and IKS every 5–10 years with nutrient-omission plots in farmers’ fields proposed by Dobermann et al. (2003) could serve to readjust this nutrient management strategy, i.e., focusing on infields and mineral fertilizer N doses of 50–100 kg N ha⁻¹. The results obtained here must now be used to optimize fertilizer allocation strategies at farm level as proposed by Giller et al. (2006).

4. Conclusions

Results indicate that judicious use of mineral fertilizer (i.e., taking into account the indigenous soil nutrient supplying capacity and targeting yield levels below 80% of climate-determined yield) should be promoted on relatively fertile infields rather than on poorer outfields. This strategy would lead to reduced production risk in years with low rainfall, higher fertilizer recovery, and increased productivity. N was the major limiting yield nutrient in this study. Phosphorus had only a minor, and in most cases, non-significant effect.

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References


