Effects of soil amendments and drought on Zinc husbandry and grain quality in Sahelian sorghum

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I dedicate this thesis to:
my late father, Traore Ardiouma
my son Traore Zié Alassane Frabrice

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Chapter 1

General introduction

1. General introduction

1.1 Justification

Crop performance in the Sahel is limited by both water and nutrient availability (Stroosnijder and Rheenen, 2001). The region is characterized by erratic climatic conditions. Total annual rainfall is decreasing with a poor distribution (Zougmoré, 2003). Frequent droughts and inappropriate use of natural resources have destroyed the vegetative cover which has exposed the soils to wind and water erosion. As a consequence, soils are strongly weathered and leached and often overlie ironstone hardpans which even feature at the surface in some places (Ouedraogo, 2004). Soils are fragile and mostly of low to moderate inherent fertility (Mando, 1997; Bationo et al., 1998; Zougmoré, 2003; Ouedraogo, 2004). The shifting cultivation system used by farmers in the past to replenish soil fertility was abandoned because of rapid population growth. Continuous and intensive cropping without restoration of the soil fertility has depleted the nutrient base of most soils (INERA, 2003). Nitrogen and phosphorus are the plant nutrients most limiting crop production in the Sahel (Hien, 1995; Compaore et al., 2001; Ouedraogo, 2004). For many cropping systems in the region, nutrient balances are negative (Bationo et al., 1998).

Soil organic matter (SOM) content is low (<1%) and determines largely the cation exchange capacity (Ouedraogo, 2004), hence the stocking and buffering capacity of soils for nutrients. Maintaining adequate SOM level in the soil is a challenge for sustainable crop production in semi arid Africa.

After the recurrent droughts of the 1980s and 1990s, farmers in parts of the Sahel have adopted soil and water conservation (SWC) techniques (stone lines, planting pits, half moons, mulching, etc.) to restore the productivity of degraded lands (Reij et al., 1996). The use of SWC techniques has improved both water and nutrient availability and thousands of hectares of degraded land have been brought back to productivity. Adoption of SWC techniques was accompanied by systematic adoption of organic soil amendments (OAs) (Reij et al., 1996). Farmers whose cattle used to be herded by herders now keep their animals at the homestead in order to benefit from manure production. Numerous studies (Roose et al., 1993; Kaboré et al., 1994; Zougmoré, 1995; Reij et al., 1996; Maatman et al., 1998; Ambouta et al., 1999; Zougmoré et al., 1999) were carried out on SWC techniques and OAs with the objective to improve land productivity and cereals yield in the Sahel. So far the emphasis has been on increasing productivity of the land, with a major effort placed on staple foods.

Sorghum (*Sorghum bicolor* (L.) Moench) is the main crop grown in the Sahel because of it adaptation to erratic climatic conditions and to low soil fertility conditions. In Burkina Faso, the sorghum production area is 1.3 million ha with a total production of 1.2 million tons (Ministère de l'Agriculture, 2000). It represents the first cereal of the country and the total production was increased with about 70% from 1984 to 1998 (Daho, 2004). The entire production is exclusively destined to household consumption. Farmers in Burkina Faso use about 35 sorghum varieties (traditional and improved). Breeders select for varieties with high yield, resistance to *Striga*, with good grain properties for making the local porridge (Tô) and drought tolerance (Pinkert, 2004).

Despite impressive increases in agricultural production in some countries, malnutrition persists in developing countries. This is not only due to low energy and protein intake but also to chronic micronutrient deficiencies. The latter is caused by the fact that in developing countries the population consumes diets mainly consisting of cereals and legume seeds (Bouis et al., 2000). These plant foods have high concentrations of anti nutritional compounds (phytates, polyphenol) which reduce the bio-availability of micronutrients for human metabolism (Cakmak et al., 1999; Bouis, 1999; Frossard et al., 2000). These deficiencies – particularly of vitamin A, iron and zinc – are believed to cause or contribute to more than 50% of child mortality. They also lead to impaired mental and physical development and decreased work output, and they contribute to morbidity from infections. Where poverty alleviation is impossible in the short term, improved micronutrient concentration or rather mass fraction in staple foods and/or improved availability of micronutrients from staple foods would already significantly contribute to an improvement in public health. This can be achieved through among others agricultural practices (Bouis et al., 2000).

OAs as advocated for soil and water conservation reasons can also change the micronutrients availability in the soil. OAs not only increase soil organic matter content acting as a source of nutrients (Bationo et al., 1998) but also improve soil chemistry (pH, redox-potential) and enhance biological activity thus improving micronutrient availability. In addition, improved soil physical properties (porosity, structure, water holding capacity) can increase micronutrient availability (Shelton, 1991; Kitt et al., 1997; Ouedraogo et al., 2000). Many studies (Grusak et al., 1999; Buekert et al., 1998; Rengel et al., 1999; Rupa et al., 2003) have concluded that OAs either applied alone or combined with inorganic fertilizers can improve micronutrient mass fractions (MFs) in cereal grains. Analysis of the use of different OAs has mainly focused on their ecological and economical sustainability, so on yield levels and input costs in terms of labour and money. Micronutrient availability and uptake by cereals and the effects of changed soil chemical properties thereon have so far received little attention. The exact release pattern of micronutrients from OAs, nor the temporal pattern of changes in soil chemical conditions have been studied. Given the erratic rainfall, the impact of OAs on micronutrient MFs in cereal grains needs to be considered in conjunction with the effect of drought spells. Furthermore, it can be expected that effective improvement of micronutrient uptake by cereals is related to the phenology of the crop. High phosphorus levels can affect soil properties which in turn may influence the Zn availability to plants and the levels of phytates in the seed. Changes in chemical properties brought about by phosphate additions, can alter the equilibrium of Zn in the soil, leading to a redistribution of Zn in different soil fractions. Numerous studies on P and Zn interactions have been conducted but have shown conflicting results (Rupa et al., 2003). These issues will be central points in the current thesis with a special emphasis on Zn and P.

1.2 The study area

1.2.1 Climate and weather

On-farm experiments were carried out in farmers' fields in the villages of Somyaga and Gourcy in northern Burkina Faso (13°06'-14°26' latitude North, 1°43'-2°55 longitude West) (Figure 1.1), in the soudano-sahelian zone, an area where SWC techniques have been adopted. Annual rainfall is between 400 and 700 mm with a cropping period of 4 months (June-September). The suitable period for sowing sorghum is June because then rainfall exceeds the evapotranspiration (Figure 1.2).

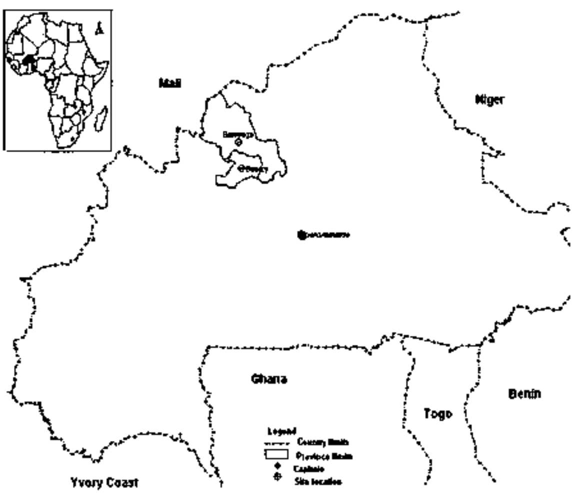

Figure 1.1 *Location of the study sites*

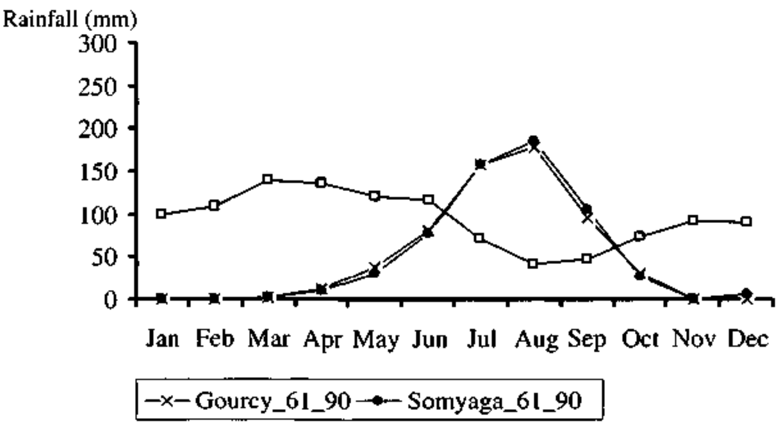

Figure 1.2 *Average monthly rainfall and evapotransration (□) (1961-1990 average) in Gourcy and Somyaga (Data from National Meteorological Station).*

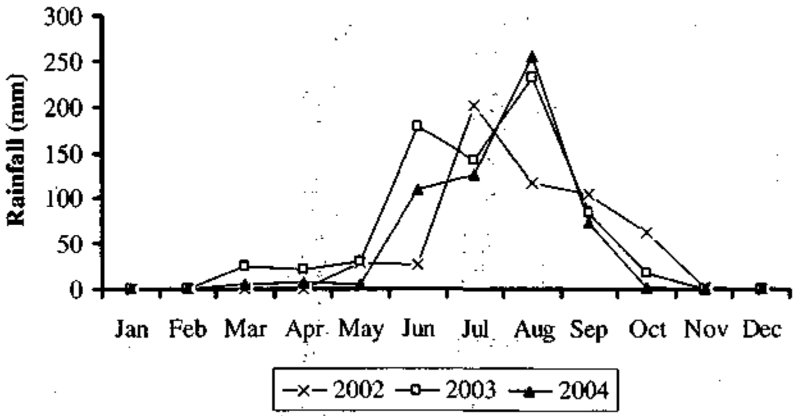

Figure 1.3 *Monthly rainfall in Somyaga in 2002, 2003 and 2004*

Rainfall distribution is very poor in the area with many drought spells during the cropping period. Rains have a high intensity causing damage to the soil structure (Nicou et al., 1990; Guillobez and Zougmoré, 1991) leading to high runoff and erosion. Rainfall distribution over the three cropping seasons during which experiments for this thesis were carried out shows an almost normal distribution in 2002. Rainfall distributions in 2003 and 2004 were comparable with in both years an early ending of the cropping season (Figure 1.3).

Average temperature is around 25 °C during the cold dry season (December - February) and 33 °C during the hot dry season (April - June). Temperatures are also very high during the growing season which reduces the efficiency of rainfall due to the high evapotranspiration. These high temperatures also speed up the microorganism activity leading to a high decomposition rate of the soil organic matter.

1.2.2 Soils

The main soil types present in northern Burkina are (FAO/UNESCO classification) luvisols and regosols (39%), Leptosols and Plintosols (26%), Gleysols (13%) and Vertisols and Cambisols (11%) (Mando, 2000). All these soils are characterized by their bad structural stability and low organic matter content (~0.75%) (Pieri, 1989). Heavy rainfall, wind and high temperatures created extensive physically degraded zones (crusted, compacted). Yearly soil losses due to erosion (water and wind) were estimated to be 0.5 t ha^{-1} under natural vegetation, 73 t ha^{-1} under sorghum and 25 t ha^{-1} on bare soils (Roose, 1981). The high population growth rate has increased the pressure on the natural resources. About 51% of the area is under cultivation and 46% is degraded and uncultivated. The cultivated land is intensively cropped without much fertilization. Various indigenous and improved soil and water conservation (SWC) techniques are being tested by farmers in order to stop land degradation. These techniques include: stone lines, mulching, planting pits, vegetative bands, half moons and earth bunds. These techniques are often more successful when they are combined. In most cases these soil and water techniques are also combined with organic amendments (Reij et al., 1996), implying that from zero fertilization farmers gradually convert to fertility management. The added fertility is largely or fully based on the use of organic soil amendments, including return of previously harvested material.

1.2.3 Crop production

Crop production is the main occupation in Burkina Faso (89 - 94% of the population) and it contributes to 37% of the gross domestic product (Zougmoré, 2003). The cropping system is an extensive system and the cultivated area is exclusively allocated to cereal production (millet, sorghum, maize). Crop production is rainfall dependent causing cereals production to be highly variable from year to year. This in its turn leads to a highly insecure food situation at household level in rural areas. Sorghum and millet are the most important crops and represent 90% of total production. The size of the farms varies from 2 to 6 ha and the fields are distributed all over the village territory. In order to increase the productivity of their land and reinforce the effect of SWC techniques, farmers have started to use different types of OAs. These include farmyard manure, compost, crop residues and household refuses. The most widely used in our study area are compost and farmyard manure (Chapter 2). Because of the harsh production conditions farmers are ready to try any technique that enables them to improve the productivity of their land or to make more land suitable for crop production.

1.3 Cultivation system

The cultivation system used in our field experiments was the planting pit system locally known as zaï. This zaï technique is the most widely adopted SWC measure in the Sahelian zone of Burkina Faso. The technique originated from the Dogon area in Mali and was improved in Northern Burkina by farmers after the drought during the 1980s and (re)introduced in Mali and Niger (Dakio, 2000). The fundamental reason for its success is the combination of soil fertility improvement with water conservation leading to an improved (and more secure) productivity, while inputs are all locally available. According to INERA (2003) the zaï technique allows a yield increase between 57% and 131%. The zaï technique is used by more than 80% of farmers in the semi arid zone of Burkina. Many research activities were initiated by the government, NGOs and farmers in order to improve the efficiency of the technique (Roose et al., 1993; Keni, 1999; Dakio, 2000).

Zaï is a planting pit with a diameter of 20–30 cm and a depth of 10–20 cm. Dimensions vary according to the type of soil. Pits are dug during the dry season from November until June. The number of zaï pits per ha varies from 12,000 to 25,000 (Reij et al., 1996). After digging the planting pits, farmers add organic matter to the pits which is covered again with a thin layer of soil. After the first rainfall seeds are planted in the middle of the pit. The average quantity of organic matter applied per pit is around 0.6 kg pit^{-1} (Some et al., 2000). The excavated earth is put down-slope which adds to the capacity of the pits to retain water. The pits concentrate rainfall and run-off and for that reason crops are less susceptible to dry periods within the rainy season. The planting pits combine three types of conservation practices on degraded crusted soils, i.e. water conservation, soil fertility enhancement and erosion protection. Zaï also concentrates manure (compost, animal manure and household waste) where plant roots are most abundant and is therefore a means of economizing on its use. This is particularly attractive to farmers with few livestock (Keni, 1999; Dakio, 2000). Using this zaï technique many hectares of degraded lands were brought back to productivity (Mando et al., 1996; Ouedraogo et al., 2000). The planting pit technique is suitable for the entire soudano-sahelian zone with annual rainfall between 500 and 700 mm. In areas with more rainfall there is a risk of flooding whereas in areas with less than 500 mm rainfall, the crops are often burned from too much concentration of OA. The major constraint for its large scale application is the availability of labour for pit preparation. In some areas the availability of organic resources is another limiting factor for zaï. Because of the wide-spread adoption of the technique almost all farmers in the study area are nowadays breeding livestock for manure production.

1.4 Theoretical background

1.4.1 Zn deficiency in humans in Burkina Faso

Little information is available on Zn and other micronutrients deficiency in humans in Burkina Faso. Nevertheless many diseases reported by the Ministry of Health in Burkina Faso are due to micronutrient deficiency. These diseases are more prevalent in infants, children and women of child bearing age. According to the Ministère de l'Agriculture (2000) more than 29% of children under five years in Burkina Faso are affected by growth retardation, 13% are stunted and 30% have inadequate weight. The sahelian zone is the most affected area with 31% of the total cases of growth retardation and 24% of cases of diarrhea (Ministère de l'Agriculture, 2000). Growth retardation is 1.5 times more important in rural areas than in towns. This study focuses on Zn, as next to being important in humans, Zn also plays an essential role in crops and has been reported potentially limiting crop performance (Frossard et al., 2000; Katyal, 2004).

1.4.2 Zn deficiency in the soil and plants

In the soil, Zn is found in many different forms that differ in plant availability. Zn can occur as (Erenoglu, 2002):

- complexed with both inorganic and organic ligands in the soil solution;
- adsorbed on the surface of soil aggregates and exchangeable;
- associated with organic matter;
- associated with oxides;
- fixed in primary minerals and secondary alumino silicate minerals.

Most of total soil Zn is in the unavailable form. Adsorption is a major contributing factor to a low concentration of Zn in solution in soils with low Zn availability. The major factors contributing to Zn adsorption are: mineral clays, hydrous oxides and organic matter (Erenoglu, 2002). Low Zn availability in the soil occurs under many different soils chemical and physical conditions (Chuan et al., 1996; Rengel et al., 1999; Arnold, 2000). Zn deficiency in the soil is high on alkaline soils (calcareous soils, sodic and saline soils, peat soils) with high available P. Zn deficiency is also found on intensively cropped, highly weathered and acid soils (Rengel et al., 1999). In the soil, Zn is considered deficient when Zn(EDTA) is below 1.5 mg kg^{-1} or Zn (0.1N HCl) is below 2.0 mg kg^{-1}. In the plant, the ranges of Zn deficiency in the whole shoot during vegetative growth are as follows (Dobermann and Fairhurst, 2000):

- < 10 mg kg^{-1} definite Zn deficiency;
- 10–15 mg kg^{-1} Zn deficiency very likely;
- 15–20 mg kg^{-1} Zn deficiency likely;
- >20 mg kg^{-1} Zn deficiency unlikely (sufficient).

In the seeds, Zn is considered poorly available when the molar ratio phytate: Zn is above 15 (Buerkert et al., 1998) or 20 (Cakmak et al., 1999). Phytate or phytic acid, myo-inositol 1,2,3,4,5,6-hexakis (dihydrogen phosphate), is the main phosphorus store in mature seeds. Phytic acid has a strong binding capacity, readily forming complexes with multivalent cations and proteins (Frossard et al., 2000). Over 85 percent of the total phosphorus in the whole grain is bound as phytate phosphorus. Most of the phytate-metal complexes are insoluble at physiological pH. A significant grain increase in ionizable iron and soluble Zn content may improve human Zn bio-available.

Low Zn availability is under some conditions effectively corrected by soil Zn application (Cakmak et al., 1999, Srivastava et al., 2000; Alam and Raza, 2001; Katyal, 2004). Because of its high water solubility, Zn sulphate is the most commonly used Zn fertilizer. Fertilizers that generate acidity (e.g., replace some urea with ammonium sulphate) and organic manure improve the availability of the micronutrient. In rice application of 5–10 kg Zn ha^{-1} as Zn sulphate, Zn oxide, or Zn chloride, incorporated in the soil before seeding or transplanting or applied to the nursery seedbed a few days before transplanting is already able to correct Zn deficiency (Dobermann and Fairhurst, 2000). The effect of Zn application can persist up to five years depending on the soil and cropping pattern. On alkaline soils with severe Zn deficiency, the residual effect of applied Zn is small, and therefore Zn must be applied to each crop. On most other soils, applications of Zn should be made every two to eight crops (Dobermann and Fairhurst, 2000). Zn deficiency is also tackled by growing Zn-efficient varieties that are tolerant of high HCO^{3-} and low plant-available Zn content (Dobermann and Fairhurst, 2000).

The challenge for the current thesis is to go beyond the effect of Zn application on grain yield. Our objective is to link the effect of Zn and P application on improving food quality and productivity since improving only food quality is not going to be enough of a selling point for a new technique as the influence on health is not to be seen immediately.

1.4.3 Soil organic and inorganic amendments: soil Zn availability and plant uptake

OAs have the potential to influence the availability of Zn by changing soil chemical properties. Soluble organics may raise the carrying capacity of the soil solution for Zn by the formation of soluble organo–metallic complexes (Almas and Singh, 2001). There are also indications that OAs change the distribution of Zn in the soil and an important part of Zn in the oxide form may move into the organic fraction making it available (Rupa et al., 2003). Furthermore, micro-organisms in OAs improve the Zn availability by synthesizing and releasing metal chelating compounds, called sideriphores, easily taken up by roots (Rengel et al., 1999). Many studies (Rengel et al., 1999; Grusak et al., 1999; Rupa et al., 2003) have reported that Zn use efficiency is increased when OAs are combined with inorganic Zn fertilizer. Srivastava et al. (2000) have obtained a higher rice grain Zn-MF when Zn fertilizer was combined with farmyard manure than when Zn fertilizer was applied alone. In conclusion, OAs have an important potential for Zn supply to the soil and the impact of OAs increases with the simultaneous application of inorganic Zn. However, the uptake distribution and remobilization of the micronutrients include processes that take place both in the soil and in the plant. In fact, plants suffering nutrient deficiency during reproductive development may rely totally on reserves within the roots, stem and leaves for nutrient content of seeds (Grusak et al., 1999). Therefore an adequate supply of micronutrients during that period will ensure a higher Zn-MF (Cakmak et al., 1999).

1.5 Thesis objectives and outline

This thesis analyses the Zn and P husbandry in the sorghum production systems of Burkina Faso by analyzing the effects of organic soil amendments and Zn and P fertilization on the availability of Zn and P in the soil, the uptake of these nutrients by the plant, the allocation of these nutrients to the harvestable plant parts (the grains), the accumulation of Zn, P and phytate in the grains and consequences of these processes for the quality of the grains for human consumption. The main objectives of the current study were to:

1. assess the effects of different OAs, as practised by farmers in the Sahelian zone of Burkina Faso, under erratic rainfall and poor soil fertility conditions on yield and Zn mass fraction (Zn-MF) of sorghum grain;
2. identify possible inorganic amendments (Zn and P) that can be used in combination with most promising OAs to increase both sorghum grain yield and its Zn-MF under prevailing environmental conditions.

At the same time we wanted to acquire understanding of:

3. Zn availability (in the soil) and uptake (in the plant) as influenced by type of OA and Zn and P fertilizers application;
4. the relation between amount and timing of amendments (organic and inorganic) on Zn-MF in sorghum grain;
5. the relation between drought stress and Zn-MF in sorghum grains;
6. the chances that modified OAs will be adopted by farmers.

The methodology adopted in order to reach the above objectives was a combination of field monitoring, on-farm experiments and on-station pot experiments in the greenhouse.

In the first year (2002) a number of "base-line" studies was carried out in order to further underline findings from the literature and to pinpoint the details of the field and pot experiments in the second and third year. The first baseline study was a farmers' survey in two Sahelian villages (Somyaga and Gourcy) to collect information on:

- farmer's perceptions of sorghum grain quality;
- farmer's perceptions of the effects of OAs on yield and grain quality;
- farmer's knowledge of the relation between sorghum grain quality and health of children and adults.

The survey was carried out in June 2002 and the results are summarized in Chapter 2. The second baseline study was a preliminary experiment on zaï pits differing in soil type and OA. This experiment (reported in Chapters 3, 4, 5 and 6) was initiated to provide information on:

- the quality of OAs that are being applied;
- changes in soil chemical characteristics;
- sorghum grain yield;
- plant Zn uptake and Zn MF;
- plant P uptake;
- levels of phytate in the grains;
- the grain phytate/Zn molar ratio.

The results have been used for the design of further field and pot experiments.

In the second year (2003), pot and field experiments were carried out. In the pot experiment, the effects of fertilization timing on Zn availability in the soil, Zn uptake by sorghum and Zn-MF in sorghum grain were tested. In the field experiment, the effect of management on Zn availability, on sorghum grain yield, on Zn uptake and Zn-MF was studied with one OA (compost) and one soil type (sandy).

In the third year (2004), field and pot experiments were set up to reinforce the findings from the 2002 and 2003 experiments. Differences were expected because of rainfall pattern differences and management differences between farmers. The field experiment was carried out to quantify sorghum yield and quality as influenced by organic and inorganic amendments and farmers' management. Treatments consisted of all combinations of two P fertilizer levels, two Zn fertilizer levels. These treatments were applied under two soil types (gravelly and sandy) and with one quantity of one OA (compost). The pot experiment was carried out to determine the effect of water stress on Zn availability, Zn uptake and Zn-MF as influenced by organic and inorganic amendments. The results from 2004 pot experiment are discussed in Chapter 7. The results of the field experiments in 2003 and 2004 are presented together with the results of the 2002 field experiment in Chapters 3-6.

Chapter 8 gives a synthesis of the main results of all experiments and an outlook on the development options that appear from these results.

The research described in this thesis was part of a larger research program described on pages 161 and 162 of this thesis (cf. Slingerland et al. 2006).

Chapter 2

Sorghum quality, organic matter amendments and health: farmers' perception in Burkina Faso, West Africa

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2. Sorghum quality, organic matter amendments and health: farmers' perception in Burkina Faso, West Africa

2.1 Introduction

About 2 billion people, mainly pregnant and lactating women and young children, suffer from iron or zinc deficiency. The supply of Fe and Zn falls short when consumed foods have low iron or zinc content and/or when absorption of iron or zinc from the food is low due to its complexation with the anti-nutritional factors phytic acid and polyphenols. Current interventions consist of dietary diversification, supplementation, fortification or bio-fortification. In the case of west-Africa these interventions have low chances of succeeding due to low purchasing power of households, lack of elementary logistics, lack of central processing of food and the high heterogeneity in production and consumption conditions. A food chain approach focusing on the staple crop Sorghum and including local practices is proposed as an alternative. The approach aims at elaborating a variety of technical interventions to increase the amount of bioavailable iron and zinc in sorghum and to improve iron and zinc intake by the vulnerable local groups. The approach allows to support informed decision-making concerning where to intervene for highest impact.

The approach is implemented through an interdisciplinary research program, "From natural resources to healthy people", funded by Wageningen University. This program links soil and plant sciences to food and nutrition sciences allowing to look beyond disciplinary boundaries. Synergy and trade-offs resulting from the integrated interdisciplinary approach show its added value compared to disciplinary approaches. At each level actors of change, be it producers, processors or consumers, are incorporated in technology development. Execution of the research is entirely done in West African villages assuring that ecological, cultural and socio-economic aspects are directly taken into account.

Agriculture is the main activity in Burkina Faso: more than 80% of the population is involved in farming. The agriculture is subsistence farming based on cereals (predominantly sorghum, millet and maize). Most (88%) of the total cultivated land is under cereals. However, crop performance is severely limited by water and nutrient availability (Stroosnijder and Van Rheenen, 2001). Continuous and intensive cropping of soils with inherent low mineral reserves such as Alfisols, Regosols and Luvisols without restoration of the soil fertility has depleted the nutrient reserves of most soils (Mando, 2000). The cropping land is very degraded and is characterised by a low organic matter content (less than 0.7%) and poor physical structure (Lompo *et al.*, 2000). The farmers have increasingly taken marginal land into cultivation, but this has resulted in degraded bare areas.

Since the early 1980s, traditional soil and water conservation (SWC) techniques have been rapidly adopted by farmers (planting pits or *zaï*, half moon, mulching, stone line etc.) and have improved both water and nutrient availability. With SWC techniques, runoff is slowed down; more water infiltrates the soil and crops are less susceptible to dry periods within the rainy season (Hien, 1995; INERA, 2001). In Burkina Faso, thousands of hectares of degraded land have been brought back to productivity using SWC techniques (Reij *et al.*, 1996).

The introduction of SWC in Burkina Faso has also been accompanied by the systematic adoption of compost pits (Reij *et al.*, 1996). Organic amendments play an important role in soil management in the tropics through their short-term effects on nutrient supply and long-term contribution to soil organic matter (SOM) formation (Palm *et al.*, 2001; Janssen, 2002). The maintenance and improvement of SOM is a key to soil fertility management across cropping systems and environments.

So far, development efforts have focused on land productivity, i.e. on yields. However, many essential nutrients such as Fe, Zn and Ca are often lacking in human diets, either due to insufficient intake or to poor absorption from food. In developing countries, deficiencies of Fe and Zn lead to much suffering and death, which has a negative impact on socio-economic development (Frossard *et al.*, 2000). Micronutrients deficiency in Burkina has been evaluated by the Ministere de l'Agriculture (2000). It reported that 29% of children under 5 have growth problem, 19% are emaciated and 30% are stunted. Furthermore, 70% of children under 5 and 40% of pregnant women are suffering from anaemia. These sicknesses are attributed to the diet pattern based on cereals, rich in phytic acid and fibers which decreases the bioavailability of micronutrients. Given this situation, the development of a nutritious and safe food source must be a central objective of any research strategy for food security and poverty alleviation in developing countries.

Fundamental to the development and improvement of technologies for managing soil fertility are farmers' knowledge and perception. Their knowledge, perceptions and attitudes are increasingly being seen as an important resource for understanding technologies and participating in their development. Farmers' points of view can also guide the scientific assessment and they will only invest in a technology if the benefits of improvement or maintenance for a given piece of land exceed the perceived costs that the individual has to bear.

This paper reports on a survey of Burkina Faso farmers' perceptions on organic amendments and the effect of such amendments on crop quality and human health. The objective of the survey was to monitor farmers' perceptions on cereal grain quality, the effects of organic amendments on cereal yield and grain quality and relation between food quality and health of children and adults. If these farmers are to participate fully in the implementation of an improved organic amendment strategy, their ideas on organic amendment must be taken into account when developing such a strategy.

2.2 Materials and methods

The survey was done in the villages of Somyaga and Gourcy in Northern Burkina Faso. These two villages were chosen because they were former soil and water conservation project (Conservation des eaux et des sols phase II, CES II) experimental sites and the farmers are used to participatory research tools. Here the annual rainfall is between 400 and 800 mm and there is a four-month cropping period (from June to September). The rainfall is very unevenly distributed in space and time, with many spells of drought during the cropping season and with very intense rain events that damage soil structure (Nicou *et al.*, 1990; Guillobez and Zougmoré, 1991). The average temperature is 25 °C during the cold season (December-February) and 33°C during the hot season (April-June). Two main soil types are encountered in the area: Luvisols and Regosols (Mando, 2000).

The main economic activity in the survey area is the integrated production of staple food and livestock. During the dry season, farmers engage in petty trade and in gardening around wells and barrages. The population pressure on the natural resources is very high and because of the shortage of fertile soils, the farmers have been farming marginal land, which has degenerated and become virtually unreclaimable.

Prior to the survey itself, a meeting was organized with all the farmers from the two villages to explain the objective of the survey. The following data were collected from the civil services:

- data on weather, crop production and livestock breeding (Direction Regionale de l'Agriculture, DRA; Direction Regionale des ressources animales, DRRA),
- statistics on population, livestock and infrastructures (schools, health centers, roads, etc.) (National Institute for Statistics and Demography, INSD),
- statistics on diseases and malnutrition (Direction Provinciale de la Sante, DPS),
- statistics on school attendance (Direction Provinciale de l'Enseignement de Base et de l'Alphabetisation, DPBA),
- data on environment (Direction Regionale des Eaux et Forets, DREF)

Fifty households were selected at random from the list delivered by the regional office for agriculture (DRA, Enquete permanente agricole). The household was chosen as the reference unit because it represents the basic socio-economic unit. Its members, who may be related, live together in the same house or compound, share their resources and satisfy together their need for food and other vital goods (Graaff *et al.*, 1999).

Two investigators with secondary school level and previous survey experience were hired and were trained one week on:

- how to organize the survey,
- how to carry out the survey in the field,
- how to fill the questionnaire.

After the investigators were trained the questionnaire was tested on farmers. This entailed using the draft questionnaire to interview four households with different socio-economic conditions. The questionnaire was then modified and tested again on four new households. Only then was the final version printed (see annex 1). The study protocol has been approved by the director of the 'Institut de l'Environnement et de Recherches Agricoles (INERA)' and informed consent was obtained from the farmers of Gourcy and Somyaga in Burkina Faso. The survey started on June 15 and ended on August 15. The survey was done in local language (Moore). Each investigator was assigned one village. Before starting the survey each investigator organized a meeting with the farmers and made a round trip program per week. Two households were interviewed per day (one in the morning and one in the afternoon). The interview was organized at home with all the members of the household (men, women, children, adults) present. Questions 34 and 35 were especially addressed to women. All the household heads were men because in our survey area the socio-cultural organization did not allow women to be a head of household. The investigators were supervised every week by two supervisors from INERA (Institut de l'Environnement et de Recherches Agricoles). Data from the survey were computed and analyzed with the statistic package WINSTAT 2.0.

2.3 Results and discussion

2.3.1 Organic matter production

The farmers in northern Burkina use different organic resources as organic soil amendments. These include compost, farmyard manure, and crop and household wastes. In our two survey villages the farmers indicated that the most important sources of organic matter in the area were compost and farmyard manure. However, some of them apply crop and household wastes directly to the fields. Which technique is used to apply the organic amendment depends on the available labour and material and also on the possibility of transporting the input to the field.

To reduce the problem of availability of materials (mainly water) and labour, most of the farmers usually produce the organic matter at home. Only 5% of farmers in Gourcy and 21% in Somyaga produce their compost in the field. When organic matter is produced at home, the major problem is transporting it to the field. Therefore, most (60%) of the farmers in both villages had bought or were negotiating the purchase of a cart. The cart has become one of the most important items of equipment in the area because it serves not only to transport organic matter from the home to the field, but also to transport harvested products, crop residues, fodder and organic matter from the field to the home.

The organic matter production technique preferred by all farmers (100% for both villages) is the compost pit. The reason for using the compost pit is the quality of the product. The heat in compost pits destroys weed seeds. The size of the pit depends on the capacity of the household. The method of filling the pit was very similar for all farmers. Figure 2.1 shows the arrangement of organic material described by the farmers. The objective of such arrangement is to produce good quality compost. The most important layer of the pit is at the bottom, where farmyard manure must predominate. Farmyard manure represents the most important ingredient for the compost. The farmers were very aware of the risk associated with applying the farmyard manure directly in the field. One of them when comparing the organic matter types said: *"The farmyard manure brings weeds in the field, while crop residues have low fertility. The best organic matter remains the compost"*. Another farmer said that crop production would not be possible in the area without animals which shows the importance of farmyard manure. Farmers whose cattle used to be herded by herders now keep their animals at the homestead.

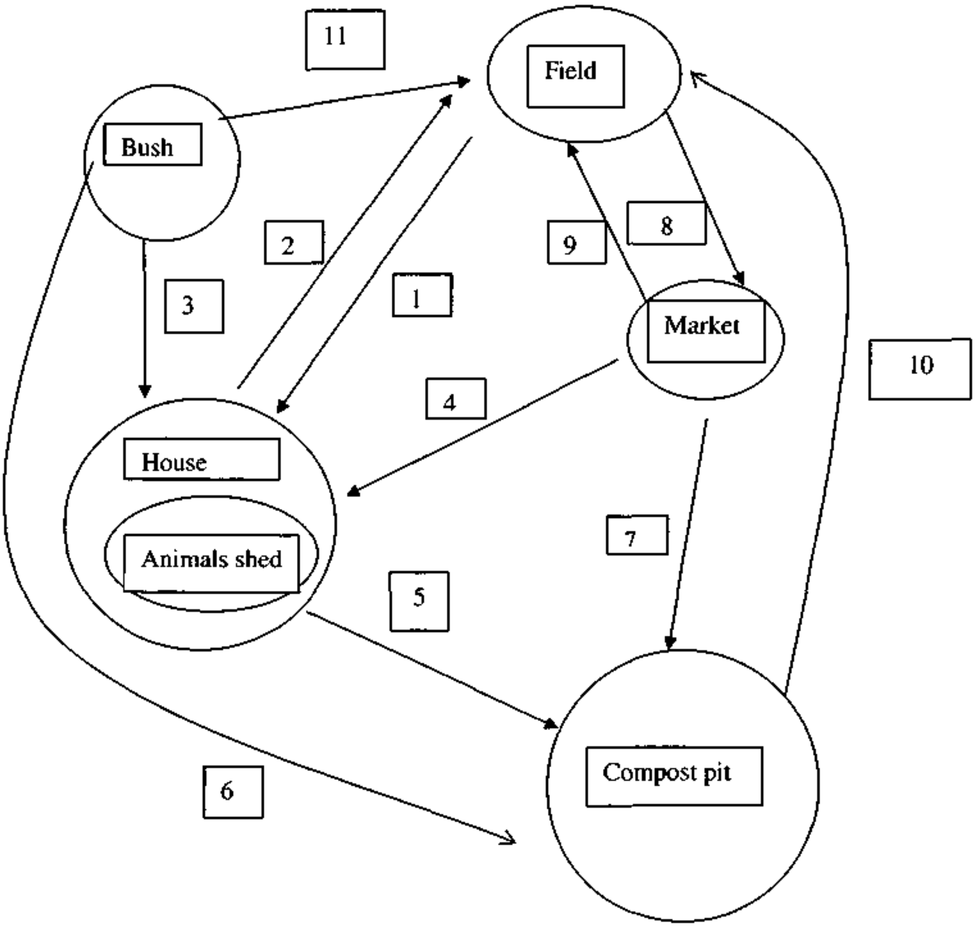

Figure 2.3 *Organic matter flow chart designed by farmers in Somyaga and Gourcy, 2002, Burkina Faso. 1 = crop residues, 2 = manure,household waste, 3 = fodder for animals, wood for fire, 4 = animal food from factories, manure, 5 =household waste, water for compost maturity, animal manure, ashes 6 = straw, clay, manure, 7 = local rock phosphate, manure, 8 = crop residues, 9 = manure, 10 = compost, 11 = grass for mulching*

During the dry season the livestock is fed with this fodder and the resulting manure is used as the first material in compost pits. The composting time and period varied between farmers and villages. For 57% of the farmers interviewed in Gourcy, compost production starts in January and ends at the beginning of the rainy season (May-June). For 42%, compost production starts at the beginning of the rainy season (May-June) and ends at the end of the rainy season (i.e. in September). On the other hand, in Somyaga, the composting period is not limited and farmers in that village produce compost year-round. These different approaches result in two products of different quality. Because of the shortage of water, the compost from

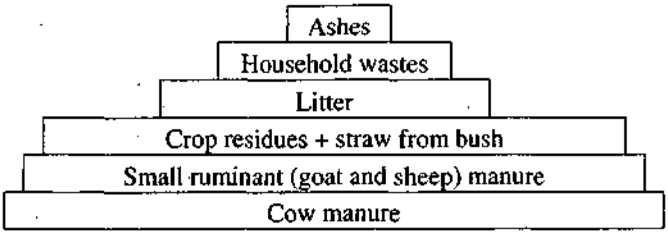

Figure 2.1 *Structure of a compost pit as described by farmers in Gourcy and Somyaga, northern Burkina Faso, 2002. The width of the rectangles represents the importance of each organic resource.*

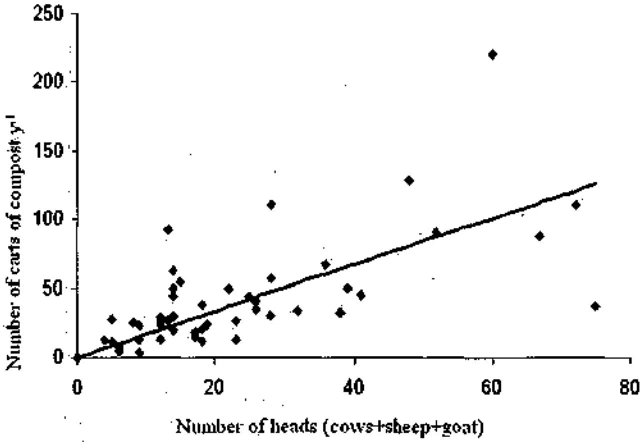

Figure 2.2 *Compost production as a function of the herd size. Regression equation $Y = 1.67X$; $R^2 = 0.41$*

The animals are not only kept only for meat and milk but also for farmyard manure production. The integration of livestock farming with crop production is becoming a necessity for crop production (Sawadogo *et al.*, 2001).

Figure 2.2 shows the correlation between the size of the livestock herd and total organic matter produced by households in each village. Figure 2.2 shows that compost production increases with total number of animals (cows, sheep and goats) in the household. However, when the number of animals becomes too high, the available labour limits the production of compost. This confirms the labour constraint to compost production that the farmers and others (Reij *et al.*, 1996; Keni, 1999) have indicated. Figure 2.3, based on information supplied by the farmers, shows the flow chart for all the organic matter sources entering the household. Human excrement is not used in the system, for cultural reasons. This means that human consumption of harvested products is a crucial sink of nutrients and organic matter. Figure 2.3 shows that livestock farming is closely integrated with cropping activities. The farmers interviewed stated that they had adopted the flow of organic matter since starting using SWC techniques. Increasingly, they harvest crop residues and natural fodder at the end of the growing season and store them at home in the house, or on racks, on trees, or in sheds.

the dry season is not completely decomposed and is of poorer quality compared to compost made in the wet season.

All the farmers in the two villages agree that the suitable period for the start of composting is the end of rainy season, when water and straw are still abundant. That period corresponds to the end of the harvest and so labour is available for digging the compost pit and transporting crop residues and manure.

The farmers carefully schedule organic matter application in the fields, to avoid losses. If the organic resource is applied too early, it is exposed to animals and wind and thus some will be lost. Organic matter is applied to the soil after the first rainfall.

When asked to compare organic materials, the farmers indicated that compost was a superior organic resource to farmyard manure, to crop residues and household wastes. The main reasons for this are compost's ability to conserve more water in the soil and its freedom from weed seeds. During droughts, crops on plots amended with compost suffer less. Often, organic matter application is associated with a soil and water conservation technique (stone bunds, half moon, *Zaï*, etc.).

The farmers' perception of the benefit of applying organic material to the soil is primarily that it supplies nutrients to the crop and so enhances crop production. Improving soil quality is only a secondary objective. For 92% of the farmers in Gourcy and 76% of the farmers in Somyaga the quantity of organic matter they produce is less than their actual needs. The production capacity is limited by water availability and also for many producers by a shortage of labour and a limited number of animals.

2.3.2 Organic matter use

Although the farmers prefer compost, farmyard manure may also be used directly as organic amendment in the field if the labour and material for compost production are not available. In Gourcy, about 28% of the farmers interviewed applied farmyard manure directly to their fields. In Somyaga, the percentage was much higher (60%). Household wastes are also used directly in the field (2% of farmers interviewed in Gourcy and 20% in Somyaga); farmers doing so have no livestock or only a few animals.

Using crop residues in the compost pit improves the quality of the compost and allows enough organic matter to be produced to cover needs. Crop residues left in the field will be destroyed during the dry season by grazing animals and bush fires.

The allocation of organic matter to fields is based on soil texture and the nature of the crop to be grown. On gravely soils on which the very demanding crops sorghum and maize are to be grown, compost is preferred. Some of the compost is also used for vegetable production in home gardens. Farmyard manure is applied on sandy and sandy loam soils, where the dominant crop is pearl millet. Farmers claimed that this distribution increases total production most and improves soil fertility best. They also think that such a distribution could help in reducing the effect of extreme weather. They are aware that using organic matter (compost or farmyard manure) improves soil water retention and thus can help to reduce the effect of drought.

The technique of organic application depends on the soil and water conservation technique being used. The farmers are increasingly using the traditional technique of *Zaï*: planting pits in which the organic matter is applied directly to the seedbed. The average rate of organic matter used in that system has been estimated to be 7.5 t ha^{-1} (Dakio, 2000) which is higher than the 5 t ha^{-1} recommended by the extension office.

The frequency of organic matter application is variable. For 60% of the farmers in Somyaga and 76% of the farmers in Gourcy, the organic matter is applied at two-year intervals. For 40% of the farmers in Somyaga and 24% of the farmers in Gourcy the organic matter is applied each year.

Since the total organic matter production is unable to supply all the fields, some fields are never fertilised by 65% of farmers in Somyaga and 21% of farmers in Gourcy. A few farmers buy or loan organic matter from acquaintances. Farmers with high income fertilise their fields with inorganic fertilisers. But the use of such fertiliser is very low (less than 10 kg ha^{-1}).

2.3.3 Food quality and human health

The majority of farmers in both villages indicated their food production was below their household's needs. Indeed, more than half of the households in the two villages have difficulty feeding their family during the entire rainy season. According to Africare (2000), (a project working on food security in northern Burkina), the food production of households will only cover the food need during seven months of the year. So, the first objective of farmers in adopting a technology is to increase the total crop production. Their motivation for using organic resources is primarily associated with that objective; the quality of the food is the second objective, and for that, the main criterion is flavour.

The farmers grew cereals (sorghum and millet) solely for home consumption; none of them sold cereals during the dry season. On the other hand, over half of them (52% for Gourcy and 80% for Somyaga) bought cereals during the year. The farmers did sell peanut and cowpea in local markets; these are the cash crops in the area. However, the proportion of land cropped with these crops was very limited, so the income from these sales was low.

The household meals are cereal-based and are mainly composed of cereal (sorghum or millet) porridge with meatless sauce and sometimes with fish. The number of meals per day was two for most of farmers (72% for Gourcy and 48% for Somyaga), with three meals per day for 52% of the farmers in Somyaga and 28% in Gourcy. The number of meals is associated with the level of self-sufficiency and habit. The farmers in Somyaga have been using SWC measures for a long time. They have a higher production capacity than the Gourcy farmers, who have only recently started using SWC techniques (Dakio, 2000). Because of the proximity of Ouahigouya (the most important town in the area) the farmers from Somyaga can sell their products (small ruminants, garden produce) more easily and at a higher price than farmers in the other rural zone. Their purchasing power is higher than that of farmers in Gourcy.

All the farmers associated organic matter with a good crop production and a good grain quality, especially when it is applied in the form of compost from the compost pits.

They evaluate the quality of the crop by the physical appearance of the grain and the quality of the food produced with it. For them, superior sorghum has large, well-coloured grains. The grain is also good when the porridge made from it is solid.

All the farmers in the two villages were aware of the quality of their organic matter and use this knowledge to allocate the material to the different fields or areas within the fields. They indicated, for example, that using farmyard manure for maize or sorghum production would result in small ears of poor quality grain. The farmers carefully balance the allocation of organic matter to fields to optimise food production and grain quality.

When asked about common diseases and their causes the farmers came up with the following classification:

- The first cause of sickness is food of bad quality or the over-consumption of food. The farmers ascribed malaria to the over-consumption of sugar or vegetable oil.
- The second cause of diseases is a change in the weather (cold season, hot season, dust).
- The last cause of sickness is the hygiene of households. When the home environment is dirty, children tend to have diarrhoea and stomach-ache.

Thus, according to the farmers the most important cause of sickness is food quality. They are sufficiently aware of the effect of food quality on their health status. The illnesses associated with poor-quality food are colic and diarrhoea; they occur throughout the year, i.e. are not associated with a specific period. When the farmers are sick they first try local or pharmaceutical remedies; if these fail, they go to a health centre.

Though the farmers did not establish a direct link between food quality and micronutrient deficiency, they indicated some illnesses corresponding to the effect of these deficiencies. They indicated, for example, fatigue in adults, stunted growth of children and the incapacity of many children to follow the regular school programme. The main health consequences of a deficiency in micronutrients (especially in Fe and Zn) indicated by many authors is the decrease in mental and psychomotor development in children. Micronutrient deficiency reduces growth and the immune system (Frossard *et al.*, 2000; West and Verhoef, 2002). In connection with this, farmers were asked about problems their children were having at school. In more than half of the households interviewed at least one child had been absent from school during the 2001 – 2002 school year. Data collected from the regional directorate for primary education and health confirmed this. Figure 2.4 shows that the schools most affected are in the rural area. The lowest percentage was found in Ouahigouya A, which corresponds to the large town of Ouahigouya.

When asked why their children had missed school, the first reason given by most farmers (53% in Gourcy and 80% in Somyaga) was the inability of the children to follow the regular school programme. For the farmers that inability has to do with deficient intelligence and lack of income, which means they cannot afford school books or coach the children at

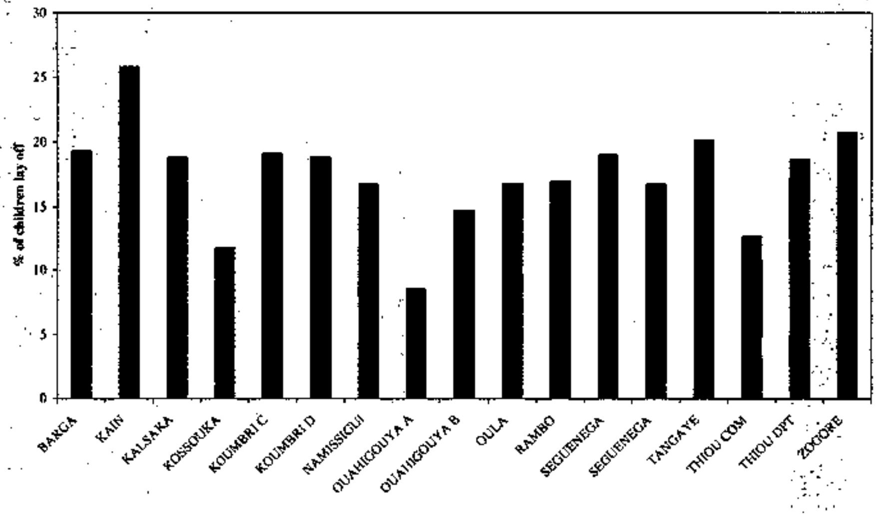

Figure 2.4 *Percentile of children lay-off from schools, Ouahigouya, Burkina Faso (2002)*

home. Other reasons for their children being not successful at school were their behaviour at school and frequent sickness.

From the farmers' responses it is clear that they are aware of some of the consequences of micronutrient deficiency. But they did not associate food quality with this. Micronutrient deficiency in the area is becoming a development problem and has been reported by many authors (Ministere de l'Agriculture, 2000; Africare, 2000; Direction Régionale des Etudes et de la Planification -Nord, 2001). Some surveys by the health office and Zandoma food security project (PSAZ), on malnutrition in northern Burkina Faso found that more than 25% of children under 10 years have a growth problem and 10% were presenting malnutrition symptoms. The fundamental conclusion of these surveys was that children attending hospitals for malnutrition problems live in villages. Thus, in the specific case of the survey on malnutrition, the results showed that 70% of nutrient-deficient children attending Ouahigouya hospital were from villages around Ouahigouya and only 30% of them were from the town of Ouahigouya.

As noted above, the only source of nutrients is the porridge from cereals (mostly sorghum). The farmers rarely eat animal products rich in micronutrients. The livestock is sold in the local market and the money is used to buy cereals during the growing season. A sustainable way to improve the micronutrient status of the population in the area is to improve the level of micronutrients in the cereals. The farmers are aware of the consequences of malnutrition and are determined to try or test any technique in order to improve their family's health and their knowledge, and to eat good food.

2.3.4 Validation of farmers' perception

During our survey, organic resources (compost and farmyard manure) were collected from the farmers and analysed for their nutrient content. Table 2.1 shows the nutrient contents for the two most important organic resources. The nutrient contents of these two organic resources differed; the results are similar to those found by others (Janssen, 1993; Hassen *et al.*, 1997; Gomez, 1998; Palm *et al.*, 2001; Lupwayi *et al.*, 2000). As Table 2.1 shows, total nitrogen content is higher for farmyard manure than for compost. The possible reason for this could be the important proportion of litter and moisture in farmyard manure. On the other hand, the C: N ratio is better for compost than for farmyard manure, which shows that compost is better for soil amendment. The decrease in organic carbon in compost is associated with the loss of CO_2 during the composting period (Janssen, 1993).

Table 2.1 *Nutrient content as a function of organic resource type, data averaged from 4 farmers in northern Burkina, 2002.*

	Compost	Manure
C-total (g kg^{-1})	77 (25.6)*	108 (1.5)
N-total (mg kg^{-1})	5 (1.4)	6 (0.9)
C:N	14 (1.6)	18 (2.4)
P-total (g kg^{-1})	1.6 (0.7)	1.3 (0.3)

* Values in brackets = standard deviation

One of the characteristics of the farmyard manure we collected was the important proportion of non-decomposed crop residues rich in lignin and other structural carbohydrates. Applying such material without additional inorganic fertiliser could create a nitrogen shortage at the beginning of the season (Janssen, 2002). The farmers had implied this by stating that farmyard manure has a lower fertilising capacity than compost. When asked to compare organic resources, all the farmers reported that the best one was compost. Farmyard manure came second, because of its lower fertilising capacity. The farmers had noticed that vegetative development in manured plots was poor. At the beginning of the growing season this is due to the nitrogen shortage created by micro organism activity. The mineralization process consumes nitrogen, creating a nitrogen shortage for plants (Delville, 1996). Using the farmyard manure directly in the field at the beginning of the growing season would only be effective if chemical nitrogen were applied at the same time, but this is beyond the means of our farmers. Therefore, the extension office recommends applying organic soil amendments at least one month before planting, so that the micro organisms' activities in the organic resource have finished before the crop is planted.

Table 2.2 *Zai pit nutrient content as a function of organic amendment and soil texture, data averaged from sixteen samples from Somyaga and Gourcy, 2002, Burkina Faso.*

	Gravely		Sandy	
	Compost	Manure	Compost	Manure
C-total (g kg^{-1})	9.78 (2.3)*	8.72 (3.9)	7.11 (1.7)	7.22 (2.1)
N-total (g kg^{-1})	0.63 (0.2)	0.62 (0.3)	0.50 (0.1)	0.52 (0.1)
P-total (g kg^{-1})	0.36 (0.1)	0.29 (0.1)	0.29 (0.1)	0.24 (0.1)
pH (H2O)	7.18 (0.4)	6.87 (0.4)	7.29 (0.5)	6.73 (0.5)
pH (KCl)	6.49 (0.6)	5.99 (0.4)	6.60 (0.6)	5.85 (0.5)

*Values in brackets = standard deviation

Many previous studies have reported that phosphorus is the most limiting nutrient in Sahelian soils, because of the continuous farming without replenishment of soil nutrients (Bado and Hien, 1998; Traore, 1998; Compaore *et al.*, 2001). According to Delville (1996) the regional balance for phosphorus is in general insufficient in a system without inorganic fertiliser (depletion rate of 5 to 20 kg ha^{-1} y^{-1}). In Burkina Faso, the average level of available phosphorus has been estimated to be 1.12 mg of P per kg of soil, i.e. below the quantity needed for plants to produce reasonably (Compaore *et al.*, 2001). As compost contains more phosphorus than does farmyard manure (Table 2.1), it is one of the most interesting organic amendments in the Sahel. The data in Table 2.2 confirm this: the compost-amended planting pits contained more P. Compost application increases the availability of soil phosphorus and as a result vegetative development and crop yield are improved. The results from experiments carried out in northern Burkina Faso by INERA (2001) on the effect of farmyard manure and compost on sorghum production have shown that compost has a greater effect than farmyard manure on sorghum grain and biomass production (Table 2.3).

Table 2.3 *Sorghum grain and straw yield as a function of organic resource type in planting pits (Zai) system. Data averaged from 3 repetitions, Ouahigouya, 1999, Burkina Faso.*

	Straw yield (kg ha^{-1})	Grain yield (kg ha^{-1})
Zai + compost	1637 a*	1042a
Zai + manure	1333 b	715b
Zaï only	88 c	00c

Means in the same column followed by the same letter are not significantly different (p< 5%). Source: INERA, 2001.

Table 2.3 shows that in the *Zaï* system, crop production is highly correlated with the quality of the organic resource used. It is higher in the case of composted pits than in the case of manured pits. These findings bear out the farmers' perception. One of the farmers explained that superior effect of compost by comparing the compost to "a food ready to eat" and the farmyard manure being "flour, needing processing" for the soil organisms.

In the application of organic resources, another important factor for good crop production is the amount applied. Figure 2.5 shows the relation between the quantity of organic material applied and the yield. The amount currently used by farmers (7.5 t ha^{-1}) gives reasonable grain yields given the level of the other inputs. Once the input of e.g. inorganic P and N is increased, optimal organic matter levels may rise (Wit, 1992). Figure 2.5 also shows that the differences in dose affect the harvest index.

With the full rate (7.5 t ha^{-1}) farmers will not be able to treat their entire area. Given the small effect of application rate on grain yield, using half the rate (3.75 kg ha^{-1}) will result in better resource use efficiency. However, farmers are unwilling to reduce the rate because they have not been informed of the beneficial effect of better resources allocation on total crop production. For the farmers, the amount of organic matter applied depends on the size of their planting pit: the larger the pit, the more organic matter is applied. Our findings suggest that more needs to be done in order to increase farmers' knowledge and improve the micronutrient status in cereal grain in the Sahel. The amount of organic resource needed to achieve good crop production should be determined in an experiment including treatments with increasing amounts of organic matter.

Since farmers have no knowledge about sorghum grain micronutrient content, it is essential to carry out a test on the impact of organic amendment on the level of micronutrients in sorghum grain. If needed, an inorganic source of these micronutrients should be combined with soil organic amendment.

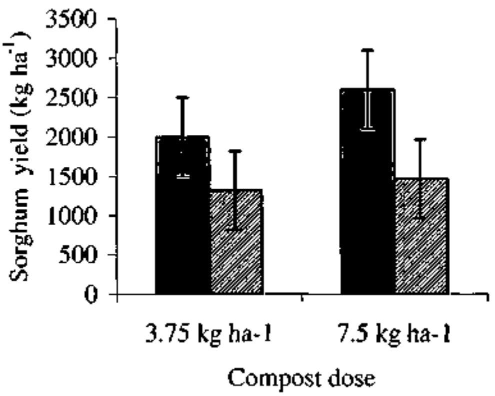

Figure 2.5 *Sorghum straw and grain yield as a function of organic matter dose. Average of 4 replications* ■ *straw yield,* □ *grain yield. Source, INERA, 2001.*

2.4 Conclusions

The survey showed that farmers have good knowledge about ongoing land degradation. They are also well aware of the necessity to restore the soil fertility in order to improve the total productivity of the land. Organic matter production is now completely integrated in their production system. The choice of organic matter to use and the allocation of organic resources in the field are associated with the system they apply and the crop they are producing and – to some extent – also with their strategy of avoiding setbacks from the weather. The production of organic resources (both in terms of amounts produced and techniques used) is a function of the availability of animals, labour, and equipment. When one of these elements is missing, the farmer applies a suboptimal system: for example, applying the farmyard manure directly without composting, or using household or crop residues as a soil organic amendment.

Our survey results also showed that farmers' practices and perceptions are well supported by scientific research. The success of the new organic matter systems can be attributed to the pro-active work of NGOs and national extension offices and also to the experience gained by farmers themselves during the many years of irregular rainfall. The regional office of agriculture should integrate farmers' knowledge on harvest quality and organic amendment allocation to better focus their intervention in order to cover both quantity and quality aspects.

The main objective of the farmers is still to meet their need for food. They also want to stay healthy. They do not know enough about the link between deficiencies in micronutrients and certain disorders, such as stunted growth, fatigue in adults and poor school performance of children. Yet these human problems have been reported to be important not only by the farmers themselves but also by some NGOs (e.g. Africare) and local administration (e.g. regional health service for northern Burkina). Farmers are very concerned about these health problems because they impede the socio-economic development of the villages and the regions. When children miss school, the application of new technologies becomes difficult. All the farmers expressed their willingness to participate in any experiment directed to improving the wellbeing of their families.

Chapter 3

Soil availability of Zn and P following the application of compost, manure and Zn and P fertilizers to acidic soils in the Sahel

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3. Soil availability of Zn and P following the application of compost, manure and Zn and P fertilizers to acidic soils in the Sahel

3.1 Introduction

Soils that contain insufficient levels of Zn are common throughout the world (Cakmak *et al.*, 1999; Katyal, 2004). As a result, Zn deficiency is a widespread problem in crops, especially in cereals. Zn is considered deficient in the soil when soil Zn EDTA is below 1.5 mg Zn kg^{-1} soil (Dobermann & Fairhurst, 2000). The importance of plant food as a source of Zn, particularly in the marginal diets of developing countries, is well established (Jonathan *et al.*, 1998). Improving Zn availability in soils may therefore potentially have both a positive effect on plant production and on quality of human nutrition.

For the West African Sahelian zone limited information is available on Zn availability. Continuous and intensive cropping without restoration of soil fertility has depleted the nutrient base of most soils (Bationo *et al.*, 1998). Furthermore, wind and water erosion have removed the nutrient-rich topsoil from the low-fertility agricultural soils thus causing a decline in the soil productivity (Zougmore, 2003). Since the early 1980s, improved soil and water conservation techniques adopted by farmers in the Sahelian zone of Burkina Faso have improved both water and nutrient availability in a careful balance. The adoption of these techniques was followed by an increase in the use of soil organic amendments (Reij *et al.*, 1996). The attention of scientists in the area over the past decades was mainly focused on the capacity of soils to release macronutrients especially N, P, and K. Analysis of soil organic amendments and soil and water conservation practices has mainly focused on their ecological and economical sustainability, so on yield levels, soil and water conservation effects and input costs in terms of labor and money.

It is accepted that soil organic amendments increase organic matter content, act as a source of micronutrients, change soil chemical properties (e.g. pH) and biological activities and improve soil physical properties (porosity, structure, water holding capacity) (Kitt *et al.*, 1997; Dougbeldji, 2002; Ouedraogo, 2004; Shelton, 1991). The changes in soil chemical and physical conditions following soil organic amendments potentially affect Zn availability (Marschner, 1995; Rengel *et al.*, 1999). Among all soil factors, soil pH is indicated to have the most important effect on Zn availability. In general, the lower the pH, the higher the Zn availability (Frossard *et al.*, 2000). Apart from soil pH, soil clay and organic matter content are also important for Zn availability (Erenoglu, 2002; Rupa *et al.*, 2003). Meers *et al.* (2002) have indicated that the negatively charged clay minerals increase the binding capacity of soils for Zn. The effect of organic amendments on micronutrients availability and, the amount of nutrients released from organic amendments is influenced by the quality of the parent materiel in the organic amendment (Gomez, 1998; Hassen *et al.*, 1997; Nicholson *et al.*, 1999). Zn availability is highly increased with the combined application of organic amendment and an inorganic source of Zn (Katyal, 2004; Rengel *et al.*, 1999; Rupa *et al.*, 2003).

Among all the macronutrients, phosphorus was indicated as the most limiting nutrient for crop production in the Sahel (Bado & Hien, 1998; Bationo *et al.*, 1998; Traore *et al.*, 2001 Compaore *et al.*, 2001). Using a source of P is then a key for sustainable crop production in the Sahel. But, there are indications that P application can interact with micronutrients especially Zn (Mengel & Kirkby, 1987; Marschner, 1995). The soils in the Sahelian zone are characterized by their large variability in chemical and physical conditions. In northern Burkina Faso, crop production takes mainly place on two soil textures: sandy soil and Gravely soil. These two soil textures have different soil chemical and physical characteristics which may generate different Zn availability after organic amendment application.

The objectives of the current study were to better understand: (1) Zn and P availability after soil organic amendments as practised by farmers in northern Burkina Faso, (2) the extent of increase in available P and Zn when organic amendments are combined with Zn and P fertilizers, (3) changes in Zn and P availability over the rainy seasons, and (4) the effect of organic amendment dose and timing of Zn and P fertilizer on Zn availability. We assume that soil organic amendments and Zn and P fertilizers change soil pH and soil total and available Zn and P. We hypothesize also that these effects can differ between soil and organic amendment type.

3.2 Materials and methods

3.2.1 Site description

On-farm experiments were carried in farmers' fields in northern Burkina Faso (13°06'-14°26' latitude North, 1°43'-2°55 longitude West), in the soudano-sahelian zone in 2002, 2003 and 2004. Annual rainfall is between 400 and 700 mm with a cropping season of 4 months (June-September). Two main soil types are present in the area: Luvisols and Regosols (Mando, 2000); both types have a poor structure and low nutrient and organic matter contents (Pieri, 1989).

3.2.2 Experiment design

The field experiments had a randomized block design; the size of each experimental unit was 25 m^2 (5 m × 5 m) and the distance between the plots was 1 m. Treatments in all 3 years included the four combinations of two levels of P fertilizer (no P or 86 kg P_2O_5 ha^{-1} as triple super phosphate, TSP, 43%) and two levels of Zn fertilizer (no Zn or 3.5 kg Zn ha^{-1} as $ZnSO_4$, 25%). The dose of P corresponded to the amount needed to correct soil P deficiency in the area (Compaore *et al.*, 2001).

In 2002, the four fertilizer treatments were combined in a 2 × 2 × 2 factorial set-up with two organic amendment types (compost, 15 t ha^{-1} and farmyard manure, 10 t ha^{-1}). These treatments were tested on both sandy and gravely Luvisols in fields of two farmers who cultivated both soil textures. The number of experimental units was 32.

In 2003, the four fertilizer treatments were tested on fields of a single farmer in eight blocks on a sandy Luvisol amended with 15 t ha^{-1} of compost. The number of experimental units was 32. In 2004, the four fertilizer treatments were tested again on both a sandy and Gravely Luvisol in four blocks per soil texture. The eight blocks were distributed over the fields of two farmers. Plots were amended with 15 t ha^{-1} of compost. The number of experimental units was 32. Tables 3.1, 3.2 and 3.3 give selected properties of soils and organic amendments used in the field experiments in 2002, 2003 and 2004.

Table 3.1 *Chemical properties of sandy and gravely soil. Somyaga, 2002, Burkina Faso*

Soil texture	OM (%)	N-total (g kg^{-1})	P-total (g kg^{-1})	Clay (%)	pH-H2O	pH-KCl
Sandy	0.50	0.32	0.09	18.5	5.25	4.5
Gravely	0.60	0.34	0.09	33.0	5.60	4.6

Table 3.2 *Zaï pit nutrient content at sowing (see text for explanation) as a function of organic amendment and soil texture. Somyaga, 2002, Burkina Faso, n= 32*

	Gravely		Sandy	
	Compost	Manure	Compost	Manure
OM (%)	1.60 (0.03)	1.53 (0.68)	1.17 (0.25)	1.12 (0.45)
N-total (g kg^{-1})	0.66 (0.02)	0.68 (0.17)	0.54 (0.08)	0.51 (0.17)
P-total (g kg^{-1})	0.33 (0.10)	0.16 (0.05)	0.22 (0.07)	0.14 (0.06)
Zn-total (mg kg^{-1})	44.7 (4.85)	39.7 (10.1)	21.1 (8.63)	18.4 (6.06)
Zn-available (mg kg^{-1})	3.97 (1.87)	1.85 (0.10)	3.20 (1.00)	2.12 (0.62)
pH-H2O	7.56 (0.60)	6.77 (0.26)	7.69 (0.56)	7.01 (0.03)
pH-KCl	6.97 (0.87)	5.73 (0.20)	6.90 (0.77)	6.02 (0.13)

Values in brackets = standard deviation

Table 3.3 *Chemical properties of compost and farmyard manure used in 2002, 2003 and 2004 field experiments*

	Farmyard manure	Compost 2002	Compost 2003	Compost 2004
OM (%)	18.6	11.5	8.4	14.1
N-total (g kg^{-1})	6.0	5.0	4.3	5.7
P-total (g kg^{-1})	1.3	1.6	1.26	1.28
Zn-total (mg kg^{-1})	50.2	62.5	44.6	68.5

3.2.3 Crop husbandry

All management was done by the farmers, though supervised by research assistants, in order to synchronize timing of operations between replicates. Plots were cultivated using the traditional planting pits or Zaï. The average planting pit was 25 cm in diameter and 15 cm deep. The distance between pits within the row was 0.5 m and the distance between rows was 0.8 m, resulting in 25000 pits per ha. The pits were made by the farmers and organic amendment and inorganic fertilizers were applied during the preparation of the pits. The same volume of organic amendment was applied (two handfuls) per planting pit which corresponded to 15 t ha^{-1} for compost and 10 t ha^{-1} for farmyard manure, i.e. the quantity enough to support crop production according to estimates of local farmers (Dakio, 2000).

Pits were sown with 3-5 seeds of the improved and drought tolerant sorghum (*Sorghum bicolour* (L.) Moench) variety IRAT 204, with a growing cycle of 90 days. The plant number per pit was reduced to two at the first hand weeding, 2 weeks after emergence. Plots were also hand weeded at flowering and once more during grain filling.

From each experimental plot, soil samples were taken at 0-10 cm at sowing, 50% flowering and maturity. For each experimental unit, samples from five planting pits were taken at random and thoroughly mixed. At sowing there was still a 2 cm layer organic amendment on top of the soil. Since sample depth is 10 cm, this included 2 cm organic amendment and 8 cm soil. At the second and third sampling organic amendment was already completely worked in the soil and no separate layers could be distinguished. Samples were packed in 10 l plastic bags and carried to the Kamboinse Research Centre for drying and chemical analyses.

3.2.4 Greenhouse experiment

In addition to the field experiments a greenhouse experiment was carried out at the Research Centre of Kamboinse, 10 km north of Ouagadougou, Burkina Faso, in 2003. The experiment started on July 25, 2003 and ended on November 30, 2003. Plastic pots of 15 litres were filled with a mixture of sandy acidic soil and compost on July 25, 2003. The pots contained 21 kg of soil. The sandy soil was collected from the site where the field experiment of 2003 was conducted. The compost was collected from farmers and was similar to the one applied in the field experiment of 2003. Before planting, all pots were watered up to field capacity and were re-watered back to field capacity after weighing twice a day. The treatments included all combinations of two compost doses (5 kg pot^{-1}, equivalent of 200-250 mg of total Zn and 10 kg pot^{-1}, equivalent of 400-450 mg of total Zn), three Zn treatments (no Zn, Zn at sowing or Zn at anthesis; Zn applied as zinc sulphate, $ZnSO_4$; 370 mg Zn pot^{-1}) and three levels of P (no P, P at sowing or P at anthesis; P applied as triple super phosphate, TSP; 3.44 g P pot^{-1}).

Pots were randomly arranged in the greenhouse and all treatments were replicated three times. In each pot, five sorghum (cv. IRAT 204) seeds were sown on July 27, 2003; 2 weeks after emergence, the population was thinned back to two plants per pot. Soil samples were taken in the pots from the 0-10 cm horizon, at sowing, 50% flowering and maturity.

3.2.5 Sample analysis

The soil samples were pre-dried in direct sun light and subsequently oven-dried at 60 °C for 48 hours. The samples were ground and sieved at 2 mm. The total Zn soil samples was assessed after mineralization using a mixture of sulphurous acid (H_2SO_4) and salicylic acid ($C_7H_6O_3$) at the presence of hydrogen peroxide (H_2O_2) and selenium (as a catalyst). Available Zn was assessed using 5 g of the air dried sample placed in a 250 ml plastic bottle fitted with an air-tight screw cap and after adding 50 ml of 1% EDTA. The suspension was mixed on a reciprocating shaker for 1 h and filtered through Watman paper No. 542 (Norvell, 1989). Total and available Zn were determined by Atomic Absorption Spectrometry (AAS) method. Soil total C, N and P were determined using respectively the Walkey-Black (Black, 1965), Kjeldahl and colorimetric methods. P available and soil pH were respectively determined by Bray I method and pH meter (Peech, 1965).

3.2.6 Statistical analysis

Excel was used for primary data processing. The analysis of variance was performed using GENSTAT (7^{th} Edition). The means were separated using the least significant difference (LSD) at the probability of 5%. During the ANOVA, in 2002, farmers were used as replications while in 2003 and 2004 blocks represented the replications.

3.3 Results

Rainfall differed between years (Figure 3.1). Total rainfall during the cropping seasons 2002 and 2004 was slightly lower (543 mm and 583 mm) compared to the long term average (1961-1990) for the area (600 mm), while it was higher in 2003 (732 mm). Rainfall distribution was poor during the cropping year 2003 compared to 2002 with recurrent drought during the most sensitive growth stages. Rainfall distribution was fairly normal in 2002. In 2004 it was normal from sowing to flowering, but from flowering to maturity severe drought occurred.

3.3.1 Soil chemical changes after organic and inorganic amendments

Zn and organic matter content of the compost that was used were comparable for 2002 and 2004 while they were lower in the 2003 experiment (Table 3.3). Organic amendment increased soil organic matter, N total, P total and Zn total (Tables 3.1 and 3.2). Soil organic amendments also increased soil pH by 2 units compared to the original soil pH. No significant difference was observed between sandy and gravely soil for soil organic matter, N total, P total, available Zn and soil pH. The total zinc was higher in the gravely soil. Soil pH decreased from sowing to flowering and thereafter remained stable until maturity (Figure 3.2). The same pattern was observed over the three cropping seasons and for the greenhouse experiment in 2003 (Figures 3.2 & 3.3). There was a large difference between cropping seasons for soil pH. Soil pH was lower in 2003 than in 2002 and 2004. Soil pH was not affected by Zn or P fertilizer.

3.3.2 Zn availability

Zn availability was different for the three cropping seasons and sampling periods (Figure 3.1) and (Table 3.3). Zn availability was not consistently affected by soil texture *per se*. The two soil textures differed in their clay content; Table 3.1 shows higher clay content for the gravely soil than for the sandy one. The effect of soil texture on Zn availability interacted differently with Zn application and organic amendment type for all sampling periods (Table 3.4).

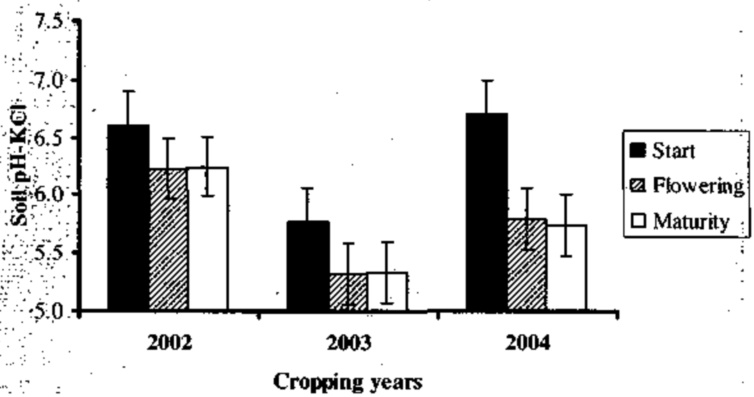

Figure 3.2 *Soil pH-KCl at different growth stages in a sandy compost amended soil in Somyaga in 2002, 2003 and 2004. Bars are standard errors of means*

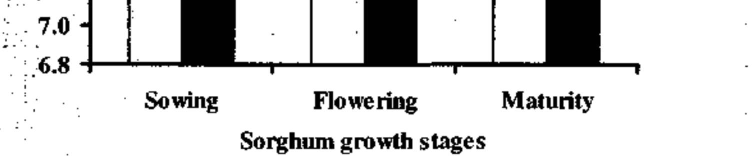

Figure 3.3 *Soil pH-KCl changes during sorghum growth stages, greenhouse experiment 2003. 5 kg= 5 kg of compost per pot, 10 kg = 10 kg of compost per pot. Bars are standard errors of means*

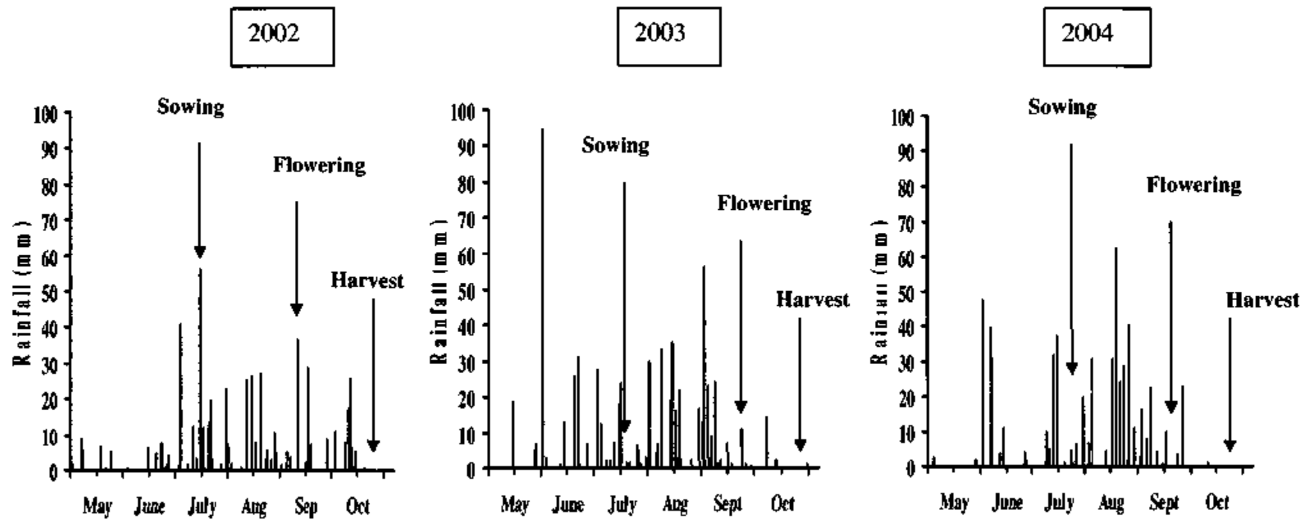

Figure 3.1 *Rainfall distribution and crop phenology in Somyaga in 2002, 2003 and 2004*

Table 3.4 *Zn availability as affected by organic amendment type, soil texture and Zn and/or P application at different sorghum growth stages. Field experiment, Somyaga in 2002, n= 32.* [1] *= organic amendment,* [2] *= farmyard manure. At sowing: LSD-main effect= 3.21, LSD-two way= 3.54, LSD- three was= 6.43; At flowering: LSD-main effect= 2.88, LSD-two way= 4.08; At maturity: LSD-main effect= 5.57, LSD-two way= 7.88*

Zn available (mg kg^{-1})								
			-Zn			+Zn		
Growth stage	Soil texture	OA[1]	-P	+P	*Mean*	-P	+P	*Mean*
Sowing	Gravely	Compost	3.98	3.45	*3.71*	17.1	15.7	*16.4*
		FYM[2]	1.85	4.10	*2.97*	13.6	15.8	*14.7*
		Mean	*2.91*	*3.77*		*15.3*	*15.7*	
	Sandy	Compost	3.20	2.85	*3.02*	36.5	40.2	*38.4*
		FYM	2.12	3.15	*2.63*	15.9	23.2	*19.6*
		Mean	*2.66*	*3.00*		*26.2*	*31.7*	
	Zn: p <.001, Soil: p <.001, OM: p= 0.003, Soil x Zn: p <.001, Soil texture x OM: p= 0 .014, Soil x OM x Zn: p= 0.011							
			-Zn			+Zn		
			-P	+P	*Mean*	-P	+P	*Mean*
Flowering	Gravely	Compost	4.50	4.00	*4.25*	8.00	8.00	*8.00*
		FYM	2.00	3.00	*2.50*	7.50	6.50	*7.00*
		Mean	*3.25*	*3.50*		*7.75*	*7.25*	
	Sandy	Compost	4.50	5.00	*4.75*	20.0	20.5	*20.2*
		FYM	2.00	3.50	*2.75*	5.00	11.5	*8.25*
		Mean	*3.25*	*4.25*		*12.5*	*16.0*	
	OM: p= 0.007, Zn: p<.001, Soil x Zn: p= 0.033							
			-Zn			+Zn		
			-P	+P	*Mean*	-P	+P	*Mean*
Maturity	Gravely	Compost	2.00	3.00	*2.50*	11.0	20.5	*15.7*
		FYM	1.00	2.00	*1.50*	6.50	10.5	*8.50*
		Mean	*1.50*	*2.50*		*8.80*	*15.5*	
	Sandy	Compost	2.50	3.00	*2.75*	30.0	35.5	*32.7*
		FYM	1.00	2.50	*1.75*	16.0	10.5	*13.2*
		Mean	*1.75*	*2.75*		*23.0*	*23.0*	
	OM: p= 0.015, Zn: p <.001, soil texture: p= 0.050, OM x Zn: p= 0.032							

At sowing in the 2002 cropping season, interactions were found between soil texture, Zn application and organic amendment type. In no Zn application, gravely and sandy soils showed comparable Zn availability and this was consistent over the organic amendment types. With Zn fertilizer, Zn availability was higher for sandy soil than for the gravely soil when applied together with compost (from 38.4 vs 16.4 mg kg^{-1}) while it was not different when applied with farmyard manure (19.6 vs 14.7 mg kg^{-1}). At flowering and in 2002 cropping season, there was a significant interaction between soil texture and Zn fertilizer. With no Zn fertilizer, Zn availability was the same for gravely and sandy soils. With Zn fertilizer, Zn availability was higher for sandy soil (14.2 mg kg^{-1}) than for gravely one (7.50 mg kg^{-1}). At maturity the main effect soil texture affected Zn availability.

Zn availability was significantly affected by organic amendment type at all sampling periods, but at sowing and at harvest the interactions overruled the main effect. Zn availability was higher in compost amended plots than in the farmyard manure ones at flowering (9.31 mg kg^{-1} against 5.12 mg kg^{-1}). At maturity, a significant interaction occurred between organic amendment type and Zn application: with no Zn fertilizer, Zn availability was comparable for compost and farmyard manure. With Zn fertilizer, Zn availability was higher for treatments with compost (24.2 mg kg^{-1}) than for those with farmyard manure (10.9 mg kg^{-1}). Zn application showed the most important impact on Zn availability for all sampling periods and the discussed interactions never overruled the main effects (Tables 3.4 and 3.5).

Table 3.5 *Zn availability as affected by inorganic fertilizers in compost amended sandy Luvisol at different sorghum growth stages. Data from Somyaga, 2003, n= 32*

Zn availability (mg kg^{-1})									
Sowing				Flowering			Maturity		
	-P	+P	*Mean*	-P	+P	*Mean*	-P	+P	*Mean*
-Zn	2.20	3.50	*2.85*	1.38	1.58	*1.48*	1.90	1.70	*1.80*
+Zn	28.3	25.6	*26.9*	12.7	8.32	*10.5*	14.9	12.5	*13.7*
Mean	*15.2*	*14.5*		*7.03*	*4.95*		*8.40*	*7.10*	
Statistics	*Zn: p<.001, LSD= 8.32*			*Zn: p<.001 LSD= 3.95*				*Zn: p<.001 LSD= 4.70*	

In the 2004 field experiment, Zn availability was affected by soil texture only at flowering: the sandy soil (9.67 mg kg^{-1}) showed higher Zn availability than the gravel one (6.74 mg kg^{-1}). In the same way as in the 2002 and 2003 field experiments, Zn application showed the most important effect on Zn availability (Table 3.6). Zn application increased Zn availability from 3.5 mg kg^{-1} to 26.9 mg kg^{-1} at sowing, from 2.61 mg kg^{-1} to 15.3 mg kg^{-1} at flowering and from 2.60 mg kg^{-1} to 15.0 mg kg^{-1} at maturity.

Overall, Zn fertilizer showed the most important impact on Zn availability in all cropping years studied. Figure 3.4 shows that with Zn fertilizer there was a linear correlation between Zn total and Zn availability which was not found when no Zn was applied. For all cropping seasons, Zn availability was not affected by P application.

3.3.3 Zn availability in the greenhouse experiment

In the greenhouse experiment of 2003, Zn availability was much higher than in the field experiments (Tables 3.7-3.9). The results showed higher Zn availability at higher organic amendment dose than with the lower dose at sowing (48.1 mg kg^{-1} against 22.9 mg kg^{-1}), flowering (53.8 mg kg^{-1} against 40.4 mg kg^{-1}) and maturity (51.1 mg kg^{-1} against 38.7 mg kg^{-1}) (Tables 3.7-3.9). At harvest, a significant interaction was found between organic amendment dose and Zn application timing (Table 3.9). The effect of the higher compost dose was higher when Zn was applied at anthesis than when it was applied at sowing or when no Zn was applied. Zn application and timing showed the most important impacts on Zn availability.

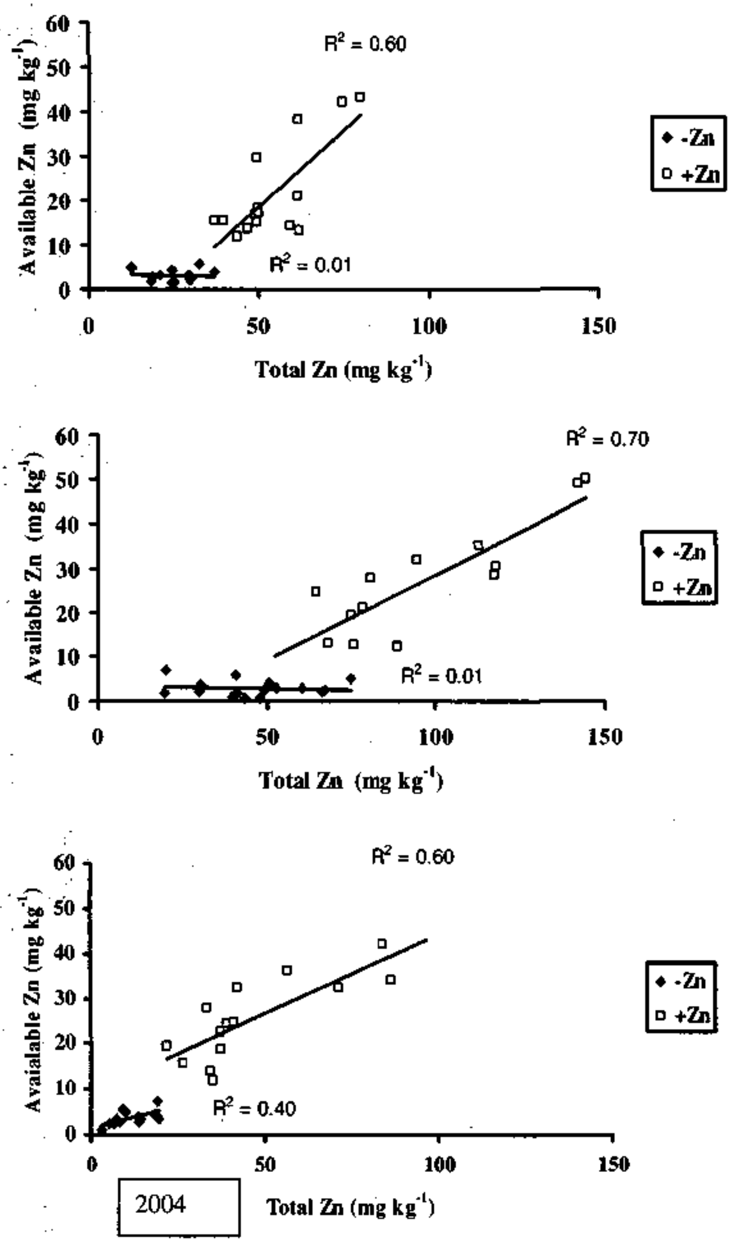

Figure 3.4 *Soil Zn availability as a function of Zn total in the soil. Field experiments, Somyaga 2002, 2003 and 2004*

At all sampling periods, Zn application resulted in significantly higher Zn availability than no Zn application. Zn availability was higher when Zn was applied at anthesis than when it was applied at sowing independent of organic amendment dose; at 50% flowering (69.8 mg kg^{-1} against 47.9 mg kg^{-1}) and maturity (63.8 mg kg^{-1}against 45.9 mg kg^{-1}). As found in the field experiments, P application did not affect Zn availability at all. At sowing, Zn availability in the low compost dose with Zn application was comparable to Zn availability in the high compost dose without Zn application.

Table 3.6 *Zn availability as affected by inorganic fertilizers and soil texture in compost amended Luvisol at different sorghum growth stages. Field experiment, Somyaga, 2004, n=32*

Zn availability (mg kg^{-1})							
		-Zn			+Zn		
Growth stage	Soil texture	-P	+P	*Mean*	-P	+P	*Mean*
Sowing	Gravely	2.30	4.20	*3.25*	23.3	25.8	*24.5*
	Sandy	2.80	4.50	*3.65*	25.7	29.8	*27.7*
	Mean	*2.55*	*4.35*		*24.5*	*27.8*	
		Zn: p<.001, LSD= 7.09					
		-Zn			+Zn		
		-P	+P	*Mean*	-P	+P	*Mean*
Flowering	Gravely	0.83	2.16	*1.49*	10.9	13.0	*11.9*
	Sandy	2.12	3.85	*2.98*	16.6	16.1	*16.3*
	Mean	*1.47*	*3.00*		*13.7*	*14.5*	
		Zn: p<.001, LSD= 2.28; Soil texture: p= 0.031, LSD= 2.28					
		-Zn			+Zn		
		-P	+P	*Mean*	-P	+P	*Mean*
Maturity	Gravely	1.90	3.00	*2.45*	16.4	13.7	*15.0*
	Sandy	2.20	3.00	*2.60*	15.4	14.6	*15.0*
	Mean	*2.05*	*3.00*		*15.9*	*14.1*	
		Zn: p<.001, LSD= 4.64					

Table 3.7 *Zn availability at sowing as affected by compost dose and P and Zn fertilizer timing. Greenhouse experiment 2003, n= 54.*

Zn available (mg kg^{-1})

Compost dose	P treatment	No Zn	Zn applied at sowing	*Mean*
5 kg pot^{-1}	No P	18.6	33.0	*25.8*
	P at sowing	18.6	28.2	*23.4*
	Mean	*18.6*	*30.6*	
10 kg pot^{-1}	No P	32.3	79.1	*55.7*
	P at sowing	33.8	78.3	*56.0*
	Mean	*33.0*	*78.7*	
	Dose: p<.001, LSD= 5.19; Zn: P<.001, LSD= 5.51			

Table 3.8 *Zn availability at 50% flowering as affected by compost dose and P and/or Zn fertilizer timing. Greenhouse experiment 2003, n= 54*

Zn available (mg kg^{-1})

Compost dose	P treatment	No Zn	Zn applied at sowing	Zn applied at anthesis	*Mean*
5 kg pot^{-1}	No P	15.1	39.0	61.3	*38.5*
	P at sowing	15.3	44.7	64.0	*41.3*
	P at anthesis	16.0	43.5	64.2	*41.2*
	Mean	*15.5*	*42.4*	*63.2*	
10 kg pot^{-1}	No P	35.7	49.3	69.7	*51.6*
	P at sowing	31.0	51.3	78.5	*53.6*
	P at anthesis	29.3	59.0	80.9	*56.4*
	Mean	*32.0*	*53.2*	*76.3*	
	Dose: p<.001, LSD= 2.70; *Zn: p<.001, LSD= 3.40*				

Table 3.9 *Zn availability at maturity as affected by compost dose and timing of P and Zn fertilizer. Greenhouse experiment 2003, n= 54*

Zn available (mg kg-1)

Compost dose	P treatment	No Zn	Zn applied at sowing	Zn applied at anthesis	*Mean*
5 kg pot^{-1}	No P	16.5	42.0	54.2	*37.6*
	P at sowing	21.7	42.3	53.6	*39.2*
	P at anthesis	19.8	42.7	55.7	*39.4*
	Mean	*19.3*	*42.3*	*54.5*	
10 kg pot^{-1}	No P	29.5	50.5	66.2	*48.7*
	P at sowing	31.2	50.5	74.6	*52.1*
	P at anthesis	31.1	47.5	78.6	*52.4*
	Mean	*30.6*	*49.5*	*73.1*	
	Dose: p<.001, LSD= 2.60; *Zn: p<.001, LSD= 3.18;* *Dose x Zn: p=0.003, LSD= 4.49*				

3.3.4 P availability

P availability was different for identical treatments for the three cropping seasons (Tables 3.10-3.12). It was on average higher in 2002 than in 2003 and 2004. The soil texture did not affect P availability for both the 2002 and 2004 cropping season.

Without P fertilizer, compost and farmyard manure amended plots showed comparable P availability in 2002. When P was added, compost amended plots showed higher P availability than farmyard manure amended ones. This was consistent over the sampling periods (Table 3.10). P application showed the most important impact on P availability for all cropping seasons (Tables 3.10-3.12). Zn application did not affect P availability.

In the greenhouse experiment, organic amendment dose and P timing were important for P availability (Tables 3.13-3.15). P availability was different depending on the timing of P. P availability was always higher when P was applied at anthesis than when it was applied at sowing (Tables 3.14 and 3.15). The higher compost dose gave higher P availability at sowing and anthesis. A significant interaction was found between compost dose and P application at maturity (Table 3.15). Without P application the two doses showed comparable P availability. When P was applied, P availability was higher for the high compost dose than for the lower one.

Table 3.10 *P availability as affected by organic amendment type, soil texture and Zn and/or P application at different sorghum growth stages. Field experiment, Somyaga in 2002, n= 32. FYM = farmyard manure, OA = organic amendment*

P available (mg kg^{-1})								
			-P			+P		
Growth stage	Soil texture	OA	-Zn	+Zn	*Mean*	-Zn	+Zn	*Mean*
Flowering	Gravely	Compost	8.70	9.00	*8.85*	54.7	55.8.	*55.25*
		FYM	4.70	5.00	*4.85*	31.5	28.6	*30.05*
		Mean	*6.70*	*7.00*		*43.1*	*42.2*	
	Sandy	Compost	9.00	9.00	*9.00*	57.5	59.0	*58.2*
		FYM	3.70	3.50	*3.60*	33.0	33.4	*33.2*
		Mean	*6.35*	*6.25*		*45.2*	*46.2*	
			OM: p< .001, LSD= 6.24; P: p <.001, LSD= 6.24					
			OM x P: p< 0.001, LSD= 8.82					

P available (mg kg^{-1})								
			-P			+Zn		
Growth stage	Soil texture	OA	-Zn	+Zn	*Mean*	-Zn	+Zn	*Mean*
Maturity	Gravely	Compost	7.30	8.20	*7.75*	48.1	50.0	*49.1*
		FYM	3.30	3.70	*3.50*	25.0	23.8	*24.4*
		Mean	*5.30*	*5.95*		*36.5*	*36.9*	
	Sandy	Compost	8.50	7.90	*8.20*	50.1	48.5	*49.3*
		FYM	2.60	3.00	*2.80*	17.3	18.4	*17.8*
		Mean	*5.55*	*5.45*		*33.7*	*33.4*	
			OM: p< .001, LSD= 5.46; P: p <.001, LSD= 5.46;					
			OM x P: p< 0.001, LSD= 7.73					

Table 3.11 *P availability as affected by inorganic fertilizers in compost amended sandy Luvisol at different sorghum growth stages. Field experiment Somyaga, 2003, n= 32*

P available (mg kg-^{1})						
	Flowering			Maturity		
	-P	+P	*Mean*	-P	+P	*Mean*
-Zn	6.50	36.2	*21.3*	5.50	31.0	*18.2*
+Zn	6.60	39.6	*23.1*	5.30	27.6	*16.4*
Mean	*6.55*	*37.9*		*5.40*	*29.3*	
P: *p<.001 LSD= 16.28*				P: *p<.001 LSD= 12.08*		

Table 3.12 *P availability as affected by inorganic fertilizers and soil texture in compost amended Luvisol at different sorghum growth stages. Field experiment, Somyaga, 2004, n=32*

P available (mg kg-^{1})

		-P			+P		
Growth stage	Soil texture	-Zn	+Zn	*Mean*	-Zn	+Zn	*Mean*
Sowing	Gravely	5.40	5.10	*5.25*	68.7	70.5	*69.6*
	Sandy	5.30	5.40	*5.35*	69.9	67.8	*68.8*
	Mean	*5.35*	*5.25*		*69.3*	*69.2*	
		P: p<.001, LSD= 9.37					

		-P			+P		
Growth stage	Soil texture	-Zn	+Zn	*Mean*	-Zn	+Zn	*Mean*
Flowering	Gravely	2.40	4.40	*3.40*	36.0	31.9	*33.9*
	Sandy	3.50	4.20	*3.85*	36.2	37.1	*36.6*
	Mean	*2.95*	*4.30*		*36.1*	*34.5*	
		P: p<.001, LSD= 11.82					

		-P			+P		
Growth stage	Soil texture	-Zn	+Zn	*Mean*	-Zn	+Zn	*Mean*
Maturity	Gravely	2.06	2.50	*2.28*	24.0	25.3	*24.6*
	Sandy	2.47	3.00	*2.73*	21.1	20.4	*20.7*
	Mean	*2.26*	*2.75*		*22.5*	*22.8*	
		P: p<.001, LSD= 2.55					

Table 3.13 *P availability at sowing as affected by compost dose and P and Zn fertilizer. Greenhouse experiment 2003, n= 54*

P available (mg kg^{-1})

Compost dose	P treatment	No Zn	Zn at sowing	*Mean*
5 kg pot^{-1}	No P	11.4	12.6	*12.0*
	P at sowing	86.4	83.4	*84.9*
	Mean	*48.9*	*48.0*	
10 kg pot^{-1}	No P	15.6	15.4	*15.5*
	P at sowing	105.7	107.2	*106.4*
	Mean	*60.6*	*61.3*	
	Dose: p<.001, LSD = 1.68; P: P<.001, LSD = 1.78			

Table 3.14 *P availability at flowering as affected by compost dose and P and/or Zn fertilizer timing. Greenhouse experiment 2003, n= 54*

P available (mg kg-1)

compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	11.11	10.93	11.66	*11.2*
	P at sowing	70.13	67.4	69.09	*68.9*
	P at anthesis	90.47	91.34	90.3	*90.7*
	Mean	*57.2*	*56.5*	*57.1*	
10 kg pot^{-1}	No P	15.94	15.80	16.05	*15.9*
	P at sowing	77.7	76.49	75.82	*76.7*
	P at anthesis	108.01	105.09	105.28	*106.1*
	Mean	*67.2*	*65.8*	*65.7*	
	Dose: p<.001, LSD = 1.31; P: P<.001, LSD = 1.61				

Table 3.15 *P availability at maturity as affected by compost dose and timing of P and Zn fertilizer application. Greenhouse experiment 2003, n= 54*

P available (mg kg^{-1})

Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	9.45	9.03	9.68	*9.38*
	P at sowing	46.80	47.6	45.2	*46.5*
	P at anthesis	64.93	62.66	64.05	*63.8*
	Mean	40.4	39.7	39.6	
	No P	12.31	12.30	12.72	*12.4*
10 kg pot^{-1}	P at sowing	64.38	66.85	69.04	*66.7*
	P at anthesis	76.68	80.23	80.33	*79.1*
	Mean	51.1	53.1	54.0	
	Dose: p<.001, LSD = 2.71; P: P<.001, LSD = 3.31				
	Dose x P: P<.001, LSD = 4.69				

3.4 Discussion and conclusions

3.4.1 Effects of Zn application and timing

The effectiveness of zinc sulphate in increasing Zn availability in agricultural soils was reported earlier (Frossard & Sinaj, 1997; Cakmak *et al.*, 1999; Frossard *et al.*, 2000; Kashem & Singh, 2002; Katyal, 2004). Also for Sahelian soils this was confirmed by our field and greenhouse experiments. Zn application showed the most important impact on Zn availability compared to the other studied factors and independent of soil and organic amendment type. Zn application in the Zaï system seems therefore a most promising way to improve Zn availability in these degraded soils of northern Burkina Faso as recommended also for other soils (Rengel *et al.*, 1999; Rupa *et al.*, 2003). Interestingly, the ratio available zinc over total zinc was much improved by the Zn fertilizer application indicating that the buffer capacity of the soil for free zinc sulphate was not large. This avoids that a large proportion of added zinc was immediately immobilized and thus implies potentially a good uptake and productivity of the applied zinc.

The results from the greenhouse experiment showed that Zn application at anthesis makes more Zn available at flowering and at maturity than when Zn was applied at sowing. This also indicates that the zinc applied at sowing was partially taken up by the crop or gradually immobilized. In the latter case, applying Zn at anthesis would make more zinc available during grain filling, which could be important for grain quality but this suggests additional work for farmers and this is only possible if such a late Zn application simultaneously increases crop yield.

3.4.2 Year to year variability

Zn availability after Zn fertilizer application differed between years for comparable soil texture and organic amendments. The higher Zn availability in 2002 throughout the year does not seem to be linked to the amount applied with the compost as the compost total Zn was comparable between 2002 and 2004 (Table 3.3). The rainfall distribution differed between years (Figure 3.1) and the drier soil conditions prior to sampling at flowering and harvest in 2003 and 2004 might be part of the explanation for the lower Zn availability at those sampling moments. Erenoglu (2002) based on a literature review indicated that under drought stress conditions, Zn is bound to the soil particles which decreases the amount of free Zn in the soil solution. Variability between years could have been created also by the fact that we have used a new field every year. Therefore, soils may have been different in their capacity tp immobilize the applied zinc. The pH patterns from sowing to maturity for the three cropping seasons (Figure 3.2) do not show a clear correlation with the variability in Zn availability between the cropping seasons. In the 2003 field experiment, the pH at sowing was lower (~5.75) compared to 2002 and 2004 (~ 6.5) and normally in the best Zn availability range (Rengel *et al*, 1999). The variability in rainfall pattern is therefore potentially an important source of variability in Zn availability after Zn fertilizer application in the Sahel.

3.4.3 Soil texture

The original chemical and physical characteristics of the sandy and gravely soils affected Zn availability. Available Zn was equal for the sandy soil and the gravely soil (Table 3.2) while total Zn was higher in the gravely soil. A larger part of the total Zn was fixed by the gravely soil probably by the clays minerals since the other factors susceptible to decrease Zn availability (i.e., soil pH and organic matter) were similar for the two soil textures (Tables 3.1 and 3.2). Clay minerals are reported as effective in Zn adsorption (Rupa *et al.*, 2003; Alam & Raza, 2001; Erenoglu, 2002). Our results are supported by Rengel *et al.* (1999) who reported higher Zn availability for a Laffer sandy soil with chemical and physical characteristics close to our sandy soil (pH: 5.8, low organic matter content) compared to Paaloa soil (pH 6.3), because of the lower binding capacity of the sandy soil. The interaction revealed by our data in the 2002 field experiment between Zn application, the two organic amendments and the two soil textures at sowing could be due to the fact that part of Zn supplied by the organic amendment was also fixed by soil minerals in the gravely soil.

3.4.4 Organic amendment type and dose

Zn availability after Zn fertilization was affected by organic amendments. This could be partly explained by the fact that compost supplies more Zn to the soil (Table 3.2). The other soil chemical characteristics (soil pH, organic matter) susceptible according to the literature to change the Zn availability were similar after the two organic amendments were applied. The compost used in the field experiments was produced by farmers at home and is composed of crop residues, farmyard manure, and an important proportion of household refuse, which may have supplied more micronutrients to the mixture (Traore & Stroosnijder, 2005). Farmyard manure is a mixture of cow dung, cow urine, and cereal straw (sorghum and/or millet) without extra source of minerals. Gomez (1998) also found lower micronutrient content in organic manure from crop residues than in waste from households refuse. Illera *et al.* (2000) have reported that micronutrients are present in wastes and bio-solids as carbonates, sulphides, organically bound, adsorbed, or exchangeable forms. But, more investigation is needed to determine the chemical composition of the various compost ingredients.

From the greenhouse experiment it appears that doubling the organic amendment dose over the current practice also increases Zn availability. Similar work reported by Dvorak *et al.* (2003) indicated significantly higher Zn availability with triple sludge application dose than with single dose. However, increasing the compost dose in the actual Sahel production conditions is not realistic because the total quantity of organic manure produced by farmers is already insufficient to cover all their agricultural land (Traore & Stroosnijder, 2005).

3.4.5 Effects on P availability and P by Zn interactions

The phosphorus balance is reported by many previous studies being negative for most of the soils of West Africa and strongly limiting crop production (Bationo *et al*, 1998; Buekert *et al.*, 1998; Compaore *et al.*, 2001, Ouedraogo, 2004). For the Burkina Faso Sahelian zone, the total P loss per hectare and per year was estimated at 4.17 kg (Bationo *et al.*, 1998) which shows the importance of P application for a sustainable crop production in the area. P availability observed in the control treatments in our field experiments are close to the average value of 5.2 mg kg^{-1} of P Bray 1 reported by Compaore *et al.* (2001) for 36 soils in Burkina Faso. P availability under organic amendment alone is too limited to support a good crop production. The application of P fertilizer is therefore necessary for improved crop productivity. P availability after fertilizer application was higher for the compost amended plots than for the farmyard manure amended ones. Compost application adds slightly more P to the soil and increases slightly more the soil pH than does farmyard manure (Tables 3.2 & 3.3). The difference does not translate into a significantly higher P availability in compost amended plots unless P fertilizer is also applied (Table 3.10). There are some indications that the higher P availability in compost amended plots is due to higher organic acid and humic substances produced during compost decomposition than during animal manure decomposition (Mengel

& Kirkby, 1987; FAO, 2004). As with Zn the higher dose applied in the pot experiment leads to a higher P availability, but the practical implications are minor.

No interactions was observed between P and Zn application and these results are opposite to most of the results found in the literature on the combined application of P and Zn fertilizers (Buerkert *et al*; 1998; Cakmak *et al.*, 1999). We hypothesize that this is because organic amendments have increased Zn availability already above the critical level of 0.5 mg kg^{-1} (Dobermann & Fairhrust, 2000) leading to such interactions even though no critical level was reported for the Sahel conditions.

3.4.6 Conclusions

In summary, we can conclude that Zn availability and P availability can be enhanced independently through respectively zinc sulphate and TSP applications. The positive effects on both Zn and P were such that more of the total Zn and P in the soil was available after applications. When applied with compost on sandy soils the application of zinc seemed slightly more effective, but differences were not such that application in combination with either farmyard manure or on gravely soils should be avoided. Whether the positive effects on availability do translate in higher uptake and biomass production will be reported in the following chapters.

Chapter 4

Combining Zn, P and organic amendments in sorghum production in the Sahel

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4. Combining Zn, P and organic amendments in sorghum production in the Sahel

4.1 Introduction

Crop production in the Sahel is strongly limited by water and nutrient shortage because it takes place in areas with a low potential where soils are inherently infertile and rainfall is low and erratic. A major challenge in the future will be to feed a population with growth rates exceeding 3% per annum (Buekert et al., 1998). Continuous and intensive cropping without restoration of the soil fertility has depleted the nutrient base of most soils (Bationo et al., 1998). Soil organic matter, the most important source of nutrients for crop production in the region, is almost lacking or very low (Pieri, 1989). The improvement of soil organic matter content is therefore a key for soil fertility management across cropping systems and environments (Ayuk, 2001). Moreover, external fertility will have to be added also to enhance system fertility and compensate fertility that is exported through sale of products.

Since the 1980s, an increasing number of farmers in the Sahel have adopted soil and water conservation measures and applied soil organic amendments. This has improved soil chemical and physical properties (porosity, structure, water holding capacity) (Mando and Miedema 1997; Ouedraogo et al., 2000, Zougmore, 2003) and has resulted in higher crop yields. Roose et al. (1992) reported that by using compost or farmyard manure in the planting pit or zaï system, sorghum yield was significantly increased.

One of the most limiting nutrients for crop production in the Sahel is phosphorus. The P balance is negative for all cropping systems thus jeopardizing the sustainability of crop production in the Sahel. Buekert et al. (1998) reported that the application of phosphorus and millet crop residues can increase millet grain yields several-fold and can enhance the sustainability of the current production system. The combined application of organic and inorganic amendments remains the most promising way to improve cereal production in the Sahel (Zougmore, 2003; Ouedraogo, 2004; INERA, 2003).

Many studies were carried out to evaluate the effect of soil organic amendments on crop productivity in the Sahel (Bado and Hien, 1998; Buekert et al., 1998; Zougmore, 2003). These studies have rarely associated the effect of micronutrients, such as Zn, with crop productivity, although micronutrients are necessary to reinforce the effect of macronutrients (Katyal, 2004). According to Katyal (2004), Zn deficiency interferes with P metabolism, a problem that can be countered by application of Zn fertilizer. Cakmak et al. (1999) in a literature review reported that Zn fertilizer was able to significantly increase cereal yields.

Sorghum is the most important crop in the Sahel because of its adaptation to erratic climatic conditions and to conditions of low soil fertility. In Burkina Faso, the sorghum area is about 1.3 million ha with a total production of 1.2 million t yr^{-1} (Ministère de l'Agriculture, 2000). It represents the first cereal of the country and the total production was increased from 612,000 to 1,033,700 tons between 1984–1998 (Ministère de l'Agriculture, 2000). The production is mainly destined to consumption by households of producers, only a small percentage is sold on the market.

The objectives of the current study were to evaluate differences in effect on sorghum yield of Zn and P fertilization alone or in combination. These effects were studied in conjunction with (1) two types of organic amendments as practised by farmers; (2) organic amendments when applied to different soil types and during different seasons, (3) different organic amendment doses.

We hypothesize that sorghum production is improved with the combined application of Zn and P fertilizers and that effects are dependent on soil type, dose and type of organic amendments and timing of Zn and P fertilizers, but quantification is needed to design interventions aimed at small scale subsistence farmers.

4.2 Materials and methods

4.2.1 Field experiments

Site description

On-farm experiments were carried out in farmers' fields in the village of Somyaga in northern Burkina Faso (13°06'–14°26' latitude North, 1°43' – 2°55 longitude West), in the soudano-sahelian zone in 2002, 2003 and 2004. Annual rainfall is between 400 and 700 mm with a cropping season of 4 months (June – September). There are two main soil types in the area: Luvisols and Regosols (Mando, 2000). Both have poor structure and a low mineral and organic matter content (Pieri, 1989). Of these soil types we selected sandy and gravely luvisols for our on-farm experiments, given their relative importance among agricultural soils in Burkina Faso (Mando, 2000).

Experiment design

The experiment was a randomized block design; the size of each experimental unit was 25 m^2 (5 m × 5 m) and the distance between the plots was 1 m. Treatments in all three years included the four combinations of two levels of Zn fertilizer (no Zn and 3.5 kg Zn ha^{-1} as $ZnSO_4$, 25%) and two levels of P fertilizer (no P and 37.5 kg P ha^{-1} as triple super phosphate, TSP, 43%). The rate of applied P corresponds to the amount needed to correct soil P deficiency in the area (Compaore et al., 2001).

In 2002, the four fertilizer treatments were combined in a 2 × 2 × 2 factorial set-up with two organic manure types (compost, 15 t ha^{-1} and farmyard manure, 10 t ha^{-1}). These treatments were tested on both sandy and gravely Luvisols in fields of two farmers who cultivated both soil types.

In 2003, the four fertilizer treatments were tested in eight blocks on a sandy Luvisol field of a single farmer amended with 15 t ha^{-1} of compost.

In 2004, the four fertilizer treatments were tested again on both a sandy and a gravely Luvisol in four blocks per soil type. The eight blocks were distributed over the fields of two farmers. Plots were amended with 15 t ha^{-1} of compost and 50 kg N ha^{-1} (urea, 46%).

Tables 3.1, 3.2 and 3.3 give selected properties of soils and organic manures used in field experiments in 2002, 2003 and 2004.

Crop husbandry and sampling

All management was done by the farmers, though supervised by research assistants, in order to synchronize timing of operations between replicates. Plots were cultivated using the traditional planting pits or 'zaï' (Reij et al. 1996).

The average pit was 25 cm in diameter and 15 cm deep. The distance between pits within the row was 0.5 m and the distance between rows was 0.8 m, resulting in 25,000 pits per ha. The pits were made by the farmers and organic manure and inorganic fertilizers were applied during the preparation of the pits. The organic manure was applied at two handfuls per seedbed which corresponded to 15 t ha^{-1} for compost and 10 t ha^{-1} for farmyard manure, i.e. the quantity enough to support crop production according to estimates of local farmers (Dakio, 2000).

Pits were sown with 3–5 seeds of the improved and drought tolerant sorghum (*Sorghum bicolour* (L.) Moench.) variety IRAT 204, with a growing cycle of 90 days. The plant number per pit was reduced to two at the first weeding, 2 weeks after emergence. Plots were also weeded at flowering and a last time during grain filling.

From each experimental plot, sorghum plants were sampled at 50% flowering and at maturity. Sorghum plants were cut at 5 cm above the ground and plants from five random planting pits were mixed and represented the experimental unit. These samples were collected in 10 l plastic bags and processed at Kamboinsé research centre (see below).

4.2.2 Greenhouse experiment

A greenhouse experiment was carried out in 2003 at the Kamboinsé Research Centre, 10 km north of Ouagadougou, Burkina Faso. The experiment started on July 25 2003 and terminated on November 30, 2003. Plastic pots of 15 litres were filled with 21 kg of a mixture of sandy acidic soil and compost. The sandy soil was collected from the site where the field experiment of 2003 was conducted. The compost was collected from farmers and was similar to the one applied in the field experiment of 2003. Before planting, all pots were watered to field capacity and were re-watered back to field capacity after weighing twice a day during the entire experiment. The treatments included all combinations of two compost doses (5 kg pot^{-1} and 10 kg pot^{-1}, equivalent of 200–250 mg and 400–450 mg of total Zn, respectively), three Zn treatments (no Zn, Zn at sowing and Zn at anthesis, Zn applied as $ZnSO_4$; 370 mg Zn pot^{-1}) and three levels of P (no P, P at sowing and P at anthesis, P applied as triple super phosphate, TSP; 1.5 g P pot^{-1}).

Pots were randomly arranged in the greenhouse and all treatments were replicated three times. In each pot, five sorghum (cv. IRAT 204) seeds were sown on July 27, 2003; 2 weeks after emergence, the population was thinned back to two plants per pot. Above ground biomass (stem + leaves + panicles) was harvested at 50% flowering and maturity.

4.2.3 Sample analysis and data processing

At maturity the grains were separated from the panicles and the emptied panicles were mixed with stem and leaves. The samples were pre-dried in direct sun light and subsequently oven-dried at 60°C for 48 hours. Sorghum grain harvest index was calculated by dividing grain dry weight by total above ground biomass production. The analysis of variance (ANOVA) was performed using GENSTAT (7th Edition). The means were separated using the least significant difference (LSD) at $P < 5\%$. During the ANOVA of the experiment in 2002, farmers were used as replications while in the experiments of 2003 and 2004 blocks represented the replications.

4.3 Results

4.3.1 Rainfall distribution

As expected in the Sahel, the rainfall varied markedly over the years of experimentation (Figure 4.1). Total rainfall during the cropping seasons 2002 (543 mm) and 2004 (583 mm) was slightly lower than the long term average (1961-1990) for the area (600 mm), while it was higher in 2003 (732 mm). Rainfall distribution was fairly normal in 2002 while rain events were rare after flowering in 2003 and 2004. In 2003, only two rain events were recorded after 50% flowering (September 11): on September 20 (11.0 mm) and October 03 (14.4 mm). In 2004, only one rain event was recorded after 50% flowering (September 20): on September 22 (23.2 mm). Especially in 2004 the crop suffered from severe drought and of locusts in the area. Grains on many sorghum plants were not mature at that time, especially not on the sandy soil.

4.3.2 Total above ground biomass

Sorghum biomass production differed between years (Tables 4.1, 4.2 and 4.3). At both flowering and maturity, biomass production was higher in 2004 (273 and 443 g m^{-2}) than in 2003 (187 and 378 g m^{-2}) and 2002 (140 and 310 g m^{-2}). The effect of soil type on biomass production was different for 2002 and 2004 and depended on time of sampling. In the 2002 field experiment, biomass production at flowering was similar for sandy and gravely soils; at maturity, the sandy soil (342 g m^{-2}) had produced more biomass than the gravely soil (279 g m^{-2}) (Table 4.1). In the 2004 field experiment, no significant differences were observed between the sandy and the gravely soils at flowering or maturity (Table 4.3). Data from the 2002 field experiment show at both sampling periods that biomass production was not significantly different between compost amended plots and farmyard amended plots (Table 4.1). Effects of inorganic Zn and P application were most important and consistent (Tables 4.1, 4.2, and 4.3). The increase obtained by both inorganic fertilizer applications depended on the cropping season and sampling period. In general, Zn application had a much smaller effect on biomass production than P application, but both effects were highly significant in all three field seasons. Effects of Zn and P were largest in the 2004 field experiment. No significant Zn × P interaction was observed in any of the field experiments.

The results from the greenhouse pot experiment in 2003 show that the effect of compost dose on biomass production differed between sampling periods. At flowering, no significant difference was observed between the higher (31 g pot^{-1}) and the lower (26 g pot^{-1}) compost dose (Figure 4.1a). At maturity, the higher compost dose resulted in more (80 g pot^{-1}) biomass than the lower (70 g pot^{-1}) one (Figure 4.1b). In the same way as found for field experiments, Zn and P application increased biomass production independent of compost rate with the largest effect of P application. The effect of both inorganic fertilizers was highest when Zn or P was applied at sowing (Figs 4.1a and b).

4.3.3 Grain yields and harvest index

In 2002, the grain yield was between 0.44 and 1.87 t ha^{-1} while the straw yield ranged between 0.98 and 2.50 t ha^{-1} (Figure 4.2). In 2003, the straw yield was higher than in 2002 ranging between 1.54 t ha^{-1} and 3.56 t ha^{-1} while the grain yield was lower (between 0.30 and 1.40 t ha^{-1}) (Figure 4.2). In 2004, the straw yield was much higher than in 2002 and 2003. Sorghum grain yield in 2004 was comparable to the one in 2003 (between 0.34 and 1.40 t ha^{-1}), so again lower than in 2002 (Figure 4.2). The biomass in the greenhouse pot experiment cannot be easily compared to that produced in the fields, but the slope of the regression lines of the straw and grain yield as functions of total biomass produced are comparable to those observed in the 2003 field experiment (Figure 4.3).

Only in the 2002 field experiment, sorghum grain yield was affected by soil type: sorghum grain yield was higher for the sandy soil (1310 kg ha^{-1}) than for the gravely soil (998 kg ha^{-1}) (Table 4.4). No significant differences were observed between the two organic amendment types (Tables 4.4). Zn and P fertilizer applications significantly increased sorghum grain yield in all experimental years (Tables 4.4–4.6). The positive effect of Zn application ranged on average from 195 to 222 kg ha^{-1} whereas the positive effect of P application ranged on average from 402 to 472 kg ha^{-1}. No interactions between the two nutrients were observed.

Table 4.1 *Effects of soil type, organic manure type and inorganic fertilizer application on sorghum biomass yield (g m^{-2}). Data from Somyaga, 2002, n= 32. FYM = farmyard manure.*

Soil type	OM	Flowering						Maturity					
		–Zn			+Zn			–Zn			+Zn		
		–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	89	141	*115*	136	190	*163*	209	320	*264*	272	381	*326*
	FYM	82	123	*102*	113	173	*143*	180	286	*233*	221	362	*291*
	Mean	*85*	*132*		*124*	*181*		*194*	*303*		*246*	*371*	
Sandy	Compost	128	173	*151*	140	179	*159*	308	371	*340*	335	405	370
	FYM	110	159	*134*	134	161	*147*	252	359	*305*	322	379	350
	Mean	*119*	*166*		*137*	*170*		*280*	*365*		*328*	*392*	
		Zn: p = 0.038, LSD = 26; *P: p = 0.002, LSD = 26*						*Zn: p = 0.007, LSD = 34, P: p < 0.001, LSD = 34; Soil type: p = 0.001, LSD = 34*					

Table 4.2 *Effects of inorganic fertilizer application on sorghum biomass yield (g m^{-2}) in compost amended sandy soil. Data from Somyaga, 2003, n= 32.*

	Flowering			Maturity		
	–P	+P	*Mean*	–P	+P	*Mean*
–Zn	149	200	*174*	310	393	*351*
+Zn	175	222	*198*	357	453	*405*
Mean	*162*	*211*		*333*	*423*	
	Zn: p = 0.001, LSD=29; P: p = 0.002, LSD= 29			*Zn: p = 0.036 LSD =50; P: p < 0.001, LSD =50*		

Table 4.3 *Effects of inorganic P and Zn fertilizer application on sorghum biomass yield (g m^{-2}) in compost amended gravelly and sandy soil. Data from Somyaga, 2004, n= 32.*

	Flowering						Maturity					
	- Zn			+Zn			- Zn			+Zn		
	- P	+P	*Mean*	- P	+P	*Mean*	- P	+P	*Mean*	- P	+P	*Mean*
Gravely	192	272	*232*	222	359	*290*	319	456	*387*	401	546	*473*
Sandy	215	279	*247*	246	368	*307*	325	486	*405*	413	563	*488*
Mean	*203*	*275*		*234*	*363*		*322*	*471*		*407*	*554*	
	Zn: p = 0.009, LSD= 21; P: p <0.001, LSD= 21						*Zn: p <0.001, LSD= 3;, P: p <0.001, LSD= 39*					

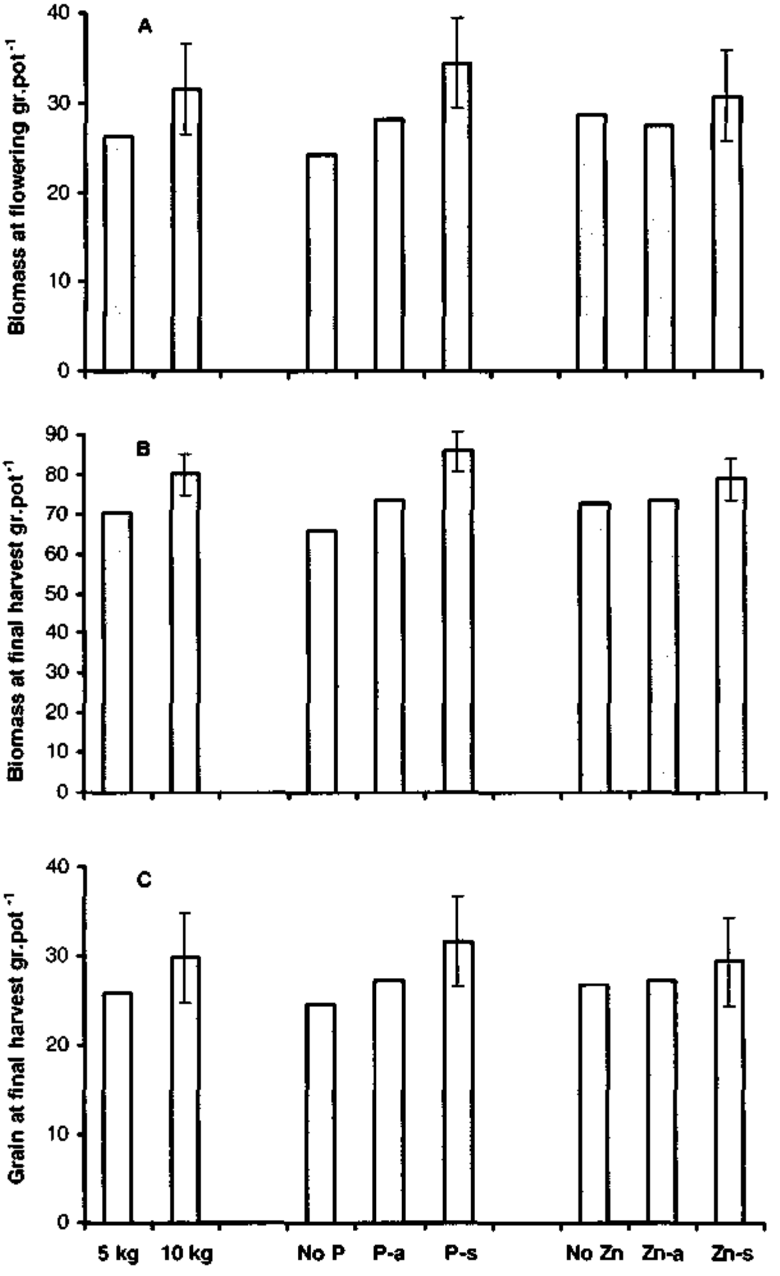

Figure 4.1 *Main effects of compost dosage (5 or 10 kg/pot) and P and Zn fertilizer application and timing on sorghum biomass yield flowering (A) and maturity (B) and grain yield at maturity (C). Pot experiment, 2003, n= 54. , P-s = P at sowing, P-a = P at anthesis, Zn-s= Zn at sowing, Zn-a = Zn at anthesis. Bars indicate LSDs for comparison between main effects, no significant interactions between treatments were observed.*

The results from the greenhouse pot experiment in 2003 (Figure 4.1c) also showed no effect of the compost dose but confirmed that Zn and P application both improved sorghum grain yield. Zn applied at sowing generated a higher grain yield (30 g pot^{-1}) than when Zn was applied at anthesis (27 g pot^{-1}). Also P application at sowing generated a higher sorghum grain yield (32 g pot^{-1}) than when P was applied at anthesis (27 g pot^{-1}). When comparing the averages of the identical treatments (compost sandy amended plots), sorghum harvest index (HI) was always in the order 2002 >2003 >2004. This was consistent over Zn and/or P fertilizer application. Only in 2004, soil type significantly affected HI with the HI being higher for sorghum from the gravely soil than for sorghum grown on sandy soil (Table 4.9).

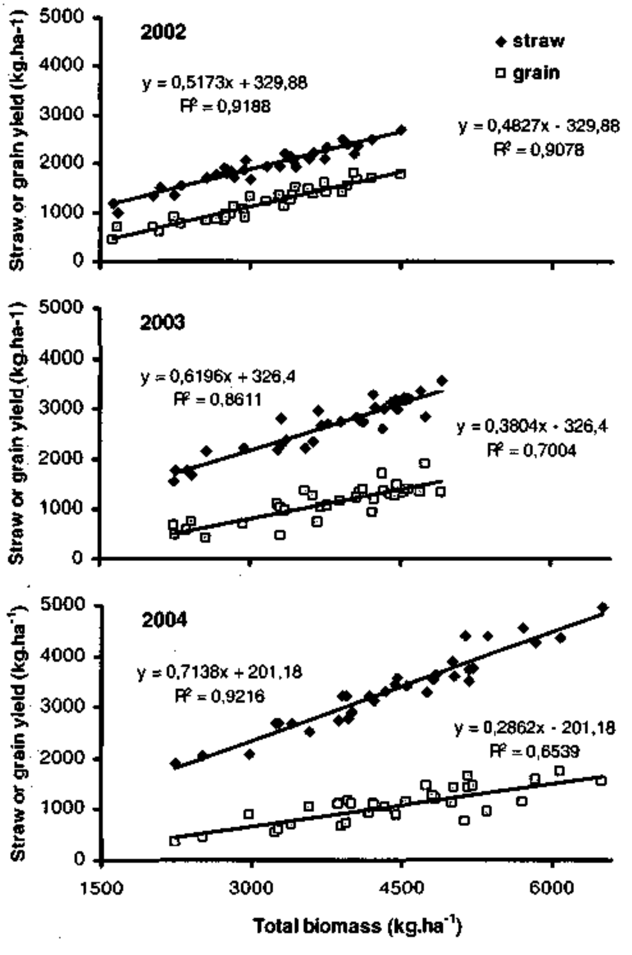

Figure 4.2 *Sorghum grain and straw yield as a function of total biomass production. Field experiments, Somyaga, 2002, 2003 and 2004.*

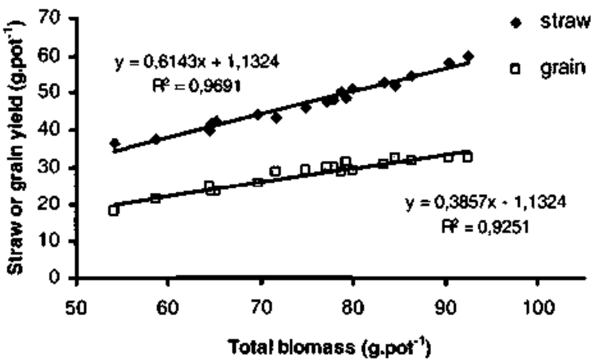

Figure 4.3 *Sorghum grain and straw yield as a function of total biomass production. Greenhouse pot experiment, 2003.*

Table 4.4 *Effects of soil type, organic amendment type and P and Zn fertilizers on sorghum grain yield (kg ha^{-1}). Field experiment in Somyaga in 2002, n=32. OMan = organic manure; FYM = farmyard manure.*

		–Zn			+Zn		
Soil type	OMan	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	638	1290	*964*	822	1530	*1180*
	FYM	642	918	*780*	873	1270	*1070*
	Mean	*640*	*1105*		*847*	*1401*	
Sandy	Compost	1120	1560	*1340*	1250	1640	*1450*
	FYM	790	1450	*1119*	1220	1470	*1350*
	Mean	*955*	*1500*		*1240*	*1560*	
	Zn: p = 0.024, LSD = 178;P: p<.001, LSD= 178;						
	Soil type: p = 0.002, LSD = 178						

Table 4.5 *Effects of P and Zn fertilizers in a sandy composted soil on sorghum grain yield (kg ha^{-1}). Field experiment in Somyaga in 2003, n=32.*

	–P	+P	*Mean*
–Zn	839	1170	*1000*
+Zn	985	1460	*1220*
Mean	*912*	*1310*	
	Zn: p = 0.035, LSD = 204; P: p <.001, LSD = 204		

Table 4.6 *Effects of P and Zn fertilizers and soil type on sorghum grain yield (kg ha^{-1}). Field experiment in Somyaga in 2004, n=32.*

	–Zn			+Zn		
Soil type	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	799	1420	*1110*	1020	1470	*1250*
Sandy	680	1120	*899*	945	1350	*1150*
Mean	*739*	*1270*		*983*	*1410*	
	Zn: p = 0.035, LSD = 193; P: p <.001, LSD = 193					

No significant difference was found between the two organic amendment types (Table 4.7). Zn application increased HI only in the 2003 field experiment (Table 4.8). P application increased HI in the 2002 and 2003 field experiments. In the 2003 field experiment, the impact of Zn application on HI was comparable to the effect of P application. The three field experiments did not show significant Zn × P interactions for harvest index. The harvest index in the greenhouse pot experiment could be derived from Figure 4.3, but does not bear agronomic relevance as the plants were not grown in a canopy structure.

Table 4.7 *Effects of soil type, organic amendment type and P and Zn fertilizers on sorghum harvest index (kg kg^{-1}). Field experiment in Somyaga in 2002, n=32. OA = organic amendment; FYM = farmyard manure.*

		−Zn			+Zn		
Soil type	OA	−P	+P	*Mean*	−P	+P	*Mean*
Gravely	Compost	0.29	0.38	*0.34*	0.35	0.43	*0.39*
	FYM	0.35	0.34	*0.34*	0.34	0.36	*0.35*
	Mean	*0.32*	*0.36*		*0.34*	*0.39*	
Sandy	Compost	0.35	0.44	*0.40*	0.37	0.39	*0.38*
	FYM	0.34	0.39	*0.37*	0.38	0.41	*0.40*
	Mean	*0.34*	*0.41*		*0.37*	*0.40*	
	P: p = 0.017, LSD = 0.03						

Table 4.8 *Effect of inorganic fertilizers applied in a sandy composted soil on sorghum harvest index (kg kg^{-1}). Field experiment in Somyaga in 2003, n=32.*

	−P	+P	*Mean*
−Zn	0.24	0.29	*0.26*
+Zn	0.28	0.34	*0.31*
Mean	*0.26*	*0.31*	
	Zn: p = 0.009, LSD = 0.03; *P: p = 0.004, LSD = 0.03*		

Table 4.9 *Effect of inorganic fertilizers and soil type on sorghum harvest index (kg kg^{-1}). Field experiment in Somyaga in 2004, n=32.*

	−Zn			+Zn		
Soil type	−P	+P	*Mean*	−P	+P	*Mean*
Gravely	0.25	0.31	*0.28*	0.26	0.27	*0.26*
Sandy	0.20	0.23	*0.21*	0.23	0.24	*0.23*
Mean	*0.22*	*0.27*		*0.24*	*0.25*	
	Soil type : p = 0.03, LSD = 0.04					

4.4 Discussion

4.4.1 Sorghum production and rainfall distribution

Sorghum grain yield was variable over the field experiments carried out in different years. The poor rainfall distribution (Figure 3.1), especially after flowering in the 2003 and 2004 cropping seasons, might have hampered normal sorghum grain production. This is also indicated by the overall lower harvest index (Figure 4.2, Tables 4.7–4.9) in those years compared to 2002. One of the most limiting crop production factors in the Sahel is indeed water availability (Breman, 1997; Stroosnijder and Van Rheenen, 2001). The grain yield was most affected by rainfall variation: during the two cropping seasons with lower grain yields, severe drought stress very likely occurred after flowering. A drought experiment carried out by Samarah et al. (2004) in a greenhouse showed that drought stress during the grain filling stage affects the number and the size of grains and reduces both grain yield and total dry matter production. Farmers should avoid water stress especially during the grain filling period. This can be done by improving further soil and water conservation measures in order to increase water infiltration and reduce losses due to runoff. Further investigations in the field of green water use efficiency (Stroosnijder, 2003) are needed to better underline the options that avoid the impact of a water stress on crop production. The presented data show that in years like 2003 and 2004 the intensive and otherwise effective zaï system could not avoid water stress. Interestingly, though, even under such relatively adverse conditions nutrient application of Zn and P fertilizers alone and in combination gave higher grain and biomass yields and thus also increased the water use efficiency.

4.4.2 Soil type and organic amendment type

In the 2002 experiment, sorghum grain yield was affected by soil type: the sandy soil gave better yield than the gravely soil. This can be attributed to better availability and uptake of nutrients when grown on the sandy soil than on the gravely one. These conclusions are supported by Delville (1996) who found also higher sorghum grain yields on the sandy soil than on the gravely soil. Initial chemical and physical characteristics of the soil are important factors for crop production in the Sahel. In the 2004 field experiment, no significant difference was observed between the sandy and the gravely soil. This was probably associated with the drought stress at the end of the season which impeded the expression of the soil effect. It could also be that the extra rainfall in 2002 was more effectively captured and made productive on the sandy than on the gravely soil as in the course of the season the pits in the zaï system tends to become more shallow allowing more runoff. In 2004, also N was added at sowing, but this cannot explain the observed lack of difference between the soil types as inherent N was comparable between soil types. The extra N provided in 2004 could be the cause for the higher total biomass (4470 kg ha^{-1}) and straw (3450 kg ha^{-1}) production in 2004 compared to 2002 (3550 and 1390 kg ha^{-1}, respectively) and 2003 (3780 and 2500 kg ha^{-1}, respectively). Potentially this could have resulted in a higher grain yield also in a more favourable year.

No significant differences were observed between sorghum grain production after application of compost or farmyard manure. These findings are in contrast to previous reports from the same area (Dakio, 2000). A possible reason for this discrepancy could be that the farmyard manure and compost used in the previous studies were from different farmers and thus from different raw material, whereas in our experiments farmyard manure and compost were produced by the same farmer and thus from the same basic material. This assumption is supported by Hassen et al. (1997) and Gomez (1998) who claim that the response of soil organic amendment is influenced by the quality of the parent material of the organic amendment.

Among all factors studied, P application most strongly increased both sorghum grain and straw yield. Our results confirm the conclusions from previous studies in the same agroclimatic zone and soil chemical and physical conditions (Bado and Hien, 1998; Buerkert et al., 1998; Traore, 1998; Compaore et al., 2001; Mando, 2000). P application improved crop yield as almost all the soils in the Sahel are very low in available P (Bationo et al., 1998), often to the extent that the uptake of many other macronutrients (e.g., N, K) is also impeded. Zn application also increased sorghum grain yield but to a much lower extent than P application. The combined application of Zn and P gave the highest grain yield, implying an additive effect of the two fertilizers treatments in the tested range.

The harvest index data (Figure 4.3 and Tables 4.7–4.9) indicate that improving total biomass production implies improving the harvest index, even in the years with very poor rainfall during grain filling. Therefore the chances of overuse of water early in the season to produce biomass at the expense of later grain production seem low. Soil organic amendment combined with Zn and P fertilizer can therefore be attractive to farmers in the Sahel with self food sufficiency as first objective.

Given the availability on the market of P and not of Zn fertilizer the best option at this moment for farmers to increase production in the zaï system seems to be P application. This corresponds to earlier findings (Zougmore, 2003). Given the positive effect of Zn on production we observed there seems a role for Zn fertilizers or at least Zn enriched P fertilizers in the area. The fact that sorghum yield reacted positively to Zn application in the tested system is an indication that P application alone will potentially lead to dilution of Zn in the cereal and this may have a negative effect on grain Zn mass fraction (Buerkert et al., 1998). This in its turn could have negative effects on seed performance in a next year and on the nutritional quality of the grain (Graham and Welch, 2000). Further research therefore on the nutritional quality of sorghum produced in the different fertilization systems is on its way.

Chapter 5

Combining Zn, P and organic amendments to enhance sorghum Zn uptake from degraded Sahelian soils

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Submitted to *Plant and Soil*

5. Combining Zn, P and organic amendments to enhance sorghum Zn uptake from degraded Sahelian soils

5.1 Introduction

Zinc is essential for the normal healthy growth and reproduction of plants (Marschner, 1995). When the supply of plant available zinc is inadequate, not only crop yields will be reduced but also the quality of crop products for use as food or feed can be expected to be sub-optimal. In plants, zinc plays a key role as a structural constituent or regulatory co-factor of a wide range of different enzymes in many important biochemical pathways. Zinc deficiency in the plant retards development and maturation of the panicles of grain crops (Alloway, 2004). Crops grown on soils poor in Zn or with a low Zn bio-availability are also poor in this element. As in soils and plants, Zn deficiency is also a common nutritional problem in humans, predominantly in developing countries where diets are rich in cereal-based foods and poor in animal products (Cakmak *et al.*, 1999). Enhancing Zn in plant derived food is one way to improve human health in developing countries where and when the local population cannot afford food sources from which zinc can be taken up easily in large enough quantities in the human gut. Therefore research on bio-fortification carried out by many groups focuses on options to improve Zn density and availability in cereals foods (Cakmak *et al.*, 1999; Frossard *et al.*, 2000). Increasing Zn uptake from the soil is a first step to improve Zn levels in the food chain.

Low-input production of cereals on the predominantly acidic soils in the Sahel in West Africa is affected by limited and erratic water supply and a low availability of nutrients of which phosphorus is arguably the most important (Bado and Hien, 1998; Bationo *et al.*, 1998; Compaore *et al.*, 2001; Traore *et al.*, 2001). Compaore *et al.* (2001) reported a P value (1.12 mg P kg^{-1} soil) for the Sahelian zone of Burkina Faso, far below the critical value for normal crop functioning (5 mg P kg^{-1} soil). Recently adopted soil organic amendments, soil and water conservation measures and the use of local rock phosphate have improved the crop production in the Sahel (Bationo *et al.*, 1998; Buekert *et al.*, 1998). Much research and extension efforts have been placed so far on macronutrients (NPK) and limited information is available on the uptake of micronutrients from the current organic amendment as practised by farmers. To what extent Zn can contribute to improving crop production in current production systems developing in reaction to soil degradation in Burkina Faso is unknown. Many workers, though, have reported a positive effect of soil organic amendment on Zn uptake (e.g. Rengel *et al.*, 1999; Almas and Singh, 2001). This was ascribed to the fact that micro organisms release metal chelating compounds easily taken up by roots, rather than to the zinc applied with these amendments. Rengel *et al.* (1999) and Ehlken and Kirchner (2002) reported that in general Zn uptake was affected by soil physical and chemical characteristics, and that Zn uptake was usually lower from soils with a fine texture (high clay content) than from soils with a coarse texture. Also growing conditions modify Zn uptake (Katyal, 2004). The quantity of Zn taken up and the speed of uptake are greatly influenced by soil moisture content. Callot *et al.* (1982) reported that in soils with 20% moisture element diffusion is twice that in a soil with 10% water. Such differences in water content are very common throughout the rainy season in semi-arid areas. Zn uptake can be increased potentially through inorganic Zn application (Cakmak *et al.*, 1999; Grusak *et al.*, 1999; Rupa *et al.*, 2003). The combined application of Zn and organic amendments was considered by Rupa *et al.* (2003) as the suitable way to increase Zn uptake.

Increasing Zn uptake under Sahelian conditions requires an understanding of the impact of soil organic amendments and of additional application of inorganic Zn on Zn uptake. In fact, the uptake of Zn by cereals with the combined application of organic and inorganic P and Zn fertilisers has received little attention. It can be expected that effective improvement of Zn uptake by cereals is related to the phenology of the crop so that timing of soil chemical changes in relation to timing of crop phenology will co-determine effectiveness of soil organic amendments in relation with Zn uptake. As stated above P is the most limiting macro-nutrient in the area. An interaction between Zn and P availability is likely to occur with P fertiliser application (Erenoglu, 2002).

The effects of Zn and P application in combination with organic amendments on sorghum productivity have been reported elsewhere (Chapter 4). In this paper we will evaluate Zn and P uptake by sorghum (*Sorghum bicolor* (L.) Moench) under field conditions in on-farm studies in northern Burkina Faso of: (1) the currently used soil organic amendments, when used on (2) different soils types and in different rainy seasons, and combined with (3) Zn and P fertiliser applications. In addition a pot experiment was carried out to assess differences in effect of different organic amendment doses applied in combination with Zn and P fertilisers at different phenological stages of sorghum growth.

We hypothesize that at current Zn uptake levels, the observed changes in availability (Chapter 3) will not only enhance biomass and grain production (Chapter 4) but also improve both Zn and P uptake by sorghum and Zn mass fraction (Zn-MF) in above ground dry matter.

5.2 Materials and methods

5.2.1 Field experiments

Site description

In 2002, 2003 and 2004 on-farm experiments were carried out in farmers' fields in the soudano-sahelian zone in northern Burkina Faso, near Ouahigouya (13°06'-14°26' latitude North, 1°43'-2°55 longitude West). Long term average annual rainfall in the area is between 400 and 700 mm with a cropping season of 4 months (June - September). There are two main soil types in the area: Luvisols and Regosols (Mando, 2000). Both have poor structure and low mineral and organic matter contents (Pieri, 1989). All experiments were done on Luvisols, either the gravely (gravel >25% in the top 20 cm) or the sandy soil type (Table 3.1).

Experiment design

The experiments all had a randomized block design; the size of each experimental unit was 25 m^2 (5 m × 5 m) and the distance between the plots was 1 m. Treatments in all three years included the four combinations of two levels of Zn fertiliser (no Zn and 3.5 kg Zn ha^{-1} as $ZnSO_4$, 25%) and two levels of P fertiliser (no P and 37.5 kg P ha^{-1} as triple super phosphate, TSP, 43%). The applied dose of P corresponds to the amount reported as sufficient to correct soil P deficiency in the area (Compaore *et al.*, 2001).

In 2002, the four fertiliser treatments were combined in a 2×2×2 factorial set-up with two organic amendment types (compost, 15 t ha^{-1} or farmyard manure, 10 t ha^{-1}). These treatments were tested on both gravely and sandy Luvisols in fields of two farmers who cultivated both soil types.

In 2003, the four fertiliser treatments were tested in eight blocks on fields of a single farmer. The sandy Luvisol plots were amended with 15 t ha^{-1} of compost.

In 2004, the four fertiliser treatments were tested again on both a gravely and sandy Luvisol in four blocks per soil type. The eight blocks were distributed over the fields of two farmers. Plots were amended with 15 t ha^{-1} of compost.

Tables 3.1, 3.2 and 5.3 give selected properties of soils and organic manures used in the 2002–2004 field experiments.

Crop husbandry

All management was done by the farmers, though supervised by research assistants, in order to synchronize timing of operations between replicates. Plots were cultivated using the traditional planting pits or 'zaï' (Reij *et al.*, 1996). The average pit was 25 cm in diameter and 15 cm deep. The distance between pits within the row was 0.5 m and the distance between rows was 0.8 m, resulting in 25,000 pits per ha. Organic manure and inorganic fertilisers were applied during the preparation of the pits. Both organic amendments were applied at two handfuls per zaï pit which corresponded to 15 t ha^{-1} for compost and 10 t ha^{-1} for farmyard manure, i.e. quantities enough to support crop production according to estimates of local farmers (Dakio, 2000).

Pits were sown with 3 – 5 seeds of the improved and drought tolerant sorghum variety IRAT 204, which has a growing cycle of 90 days. The plant number per pit was reduced to two at the first weeding, 2 weeks after emergence. Plots were also weeded at flowering and half way grain filling.

5.2.2 Pot experiment

In 2003, a pot experiment was carried out in a greenhouse at the Kamboinsé Research Centre, 10 km north of Ouagadougou, Burkina Faso. Plastic 15 litre pots were filled with a mixture of soil and compost on July 25, 2003. The pots contained 21 kg of soil. The soil was collected from a sandy field on the site where the 2003 field experiment was conducted. The compost was collected from farmers and was similar to the one applied in the field experiment of 2003. Before planting, all pots were watered to field capacity and twice a day during the experiment pots were re-watered back to field capacity after weighing. The treatments included all combinations of two compost doses (5 kg pot^{-1}, equivalent of 200 – 250 mg of total Zn and 10 kg pot^{-1}, equivalent of 400 – 450 mg of total Zn), three Zn treatments (no Zn, Zn at sowing and Zn at anthesis, Zn applied as zinc sulphate, $ZnSO_4$ at 370 mg Zn pot^{-1}) and three P treatments (no P, P at sowing and P at anthesis, P applied as triple super phosphate, TSP at 1.51 g P pot^{-1}).

Pots were randomly arranged in the greenhouse and all treatments were replicated three times. In each pot, five sorghum seeds (cv. IRAT 204) were sown on July 27, 2003; 2 weeks after emergence, the population was thinned back to two plants per pot.

5.2.3 Sampling and analysis

In field and pot experiments, sorghum plants were sampled at 50% flowering and at maturity. From each plot in the field, plants from five planting pits were combined. Sorghum plants sampled were cut 3 cm above the ground. At maturity the grains were separated from the panicles and the empty panicle structures were mixed with stems and leaves.

Samples were stored in 10 l plastic bags and dried at Kamboinsé Research Centre. The samples were pre-dried in direct sun light and subsequently oven-dried at 60 °C for 48 hours. The samples were ground and sieved at 2 mm. The samples were digested using a mixture of sulphurous acid (H_2SO_4) and salicylic acid ($C_7H_6O_3$) at the presence of hydrogen peroxide (H_2O_2) and selenium (as a catalyst). Total Zn was determined hereafter by the Atomic Absorption Spectrometry (AAS) method. Laboratory analyses were carried at INERA (Institut de l'Environnement et de Recherches Agricoles) and BUNASOLS (Bureau National des Sols) in Ouagadougou, Burkina Faso.

5.2.4 Data analysis

Zn and P uptake and Zn recovery were calculated using the following equations (for the pot experiment the data were obtained pot^{-1} rather than m^{-2}):

Zn (or P) uptake (mg m^{-2}) = [Zn (or P) mass fraction in above ground plant parts (mg kg^{-1})] × [dry weight of above ground plant parts (kg m^{-2})] (1)

Zn recovery (%) = 100 × [Zn uptake in withZn treatments (mg m^{-2}) – Zn uptake in no-Zn treatments (mg m^{-2})/ Amount of applied to with-Zn (mg m^{-2})] (2)

The change in uptake between flowering and maturity (ΔUP, mg m^{-2}) is therefore by definition:

$$\Delta UP = \Delta DM \times MF_{FLOW} + \Delta MF \times DM_{FLOW} + \Delta DM \times \Delta MF \quad (3)$$

With:
DM_{FLOW} = dry matter at flowering (kg m^{-2})
MF_{FLOW} = mass fraction at flowering (mg kg^{-1})
ΔDM = change in dry matter between flowering and maturity (kg m^{-2})
ΔMF = change in mass fraction between flowering and maturity (mg kg^{-1})

The role of the change in dry matter (or mass fraction) in the total change in uptake is calculated as the relative increase in dry matter (or mass fraction) divided by the relative increase in dry matter plus the relative increase in mass fraction, so in formula:

$$\text{Relative contribution of } \Delta DM \text{ to } \Delta UP = \frac{\left[\frac{DM_{MAT} - DM_{FLOW}}{DM_{FLOW}}\right]}{\left[\frac{DM_{MAT} - DM_{FLOW}}{DM_{FLOW}}\right] + \left[\frac{MF_{MAT} - MF_{FLOW}}{MF_{FLOW}}\right]} \quad (4)$$

$$\text{Relative contribution of } \Delta MF \text{ to } \Delta UP = \frac{\left[\frac{MF_{MAT} - MF_{FLOW}}{MF_{FLOW}}\right]}{\left[\frac{DM_{MAT} - DM_{FLOW}}{DM_{FLOW}}\right] + \left[\frac{MF_{MAT} - MF_{FLOW}}{MF_{FLOW}}\right]} \quad (5)$$

This by definition then partitions the effect of change in DM and MF through the term $\Delta DM \times \Delta MF$ in formula (1) in proportion to their respective relative increase.

Excel was used for primary data processing. The analysis of variance (ANOVA) was performed using GENSTAT (7^{th} Edition). The means were separated using the least significant difference (LSD) at 5% probability. For the 2002 experiment farmers were used as replications.

5.3 Results

Zn mass fraction in above ground biomass (Tables 5.1, 5.2 and 5.3)

In all three years (Tables 5.1 – 5.3) the Zn-MF tended to be higher at maturity than at flowering, while the overall levels were different between seasons. Soil type *per se* did not affect Zn mass fraction in the above ground biomass (Zn-MF) in any year (Tables 5.1 – 5.3), but a significant interaction was found between soil type and Zn application in the 2004 field experiment (Table 5.3). Without Zn fertiliser, the Zn-MF was comparable between plants growing on gravely soils (32.8 mg kg^{-1}) and plants growing on sandy soils (29.0 mg kg^{-1}).

With Zn fertiliser, the Zn-MF was higher when plants were growing on the sandy soil (72.1 mg kg^{-1}) than when growing on the gravely one (60.1 mg kg^{-1}). The effects of Zn and P application on Zn-MF gave a relatively simple picture in the 2003 experiment (Table 5.2). Only Zn fertiliser enhanced the Zn-MF, both at flowering and at maturity and irrespective of P application levels. A comparable simple effect of treatments can be seen at flowering in 2004. At maturity in 2004, neither the interaction between Zn and soil type (see above) nor the interaction between Zn and P application changed the positive effect of Zn application on Zn-MF. The effects in the 2002 field experiment were the most complicated to interpret due to the interactions, but also in this year, Zn application always increased Zn-MF irrespective of the interactions.

The application of P in 2002 increased Zn-MF at flowering and at maturity, but at maturity the effect was much stronger when P was applied in combination with compost and Zn, which causes the two and three way interactions with P. In 2004 the main effect of P was overruled by the interaction with Zn as P only increased Zn-MF when no Zn was applied.

The effect of compost vs farmyard manure (FYM) strongly depended on either Zn application (as assessed at flowering) or both Zn and P application (as assessed at maturity). Compost tended to give a higher Zn-MF, but the effects were stronger when Zn was applied simultaneously.

Zn uptake

The average amount of Zn taken up by sorghum at flowering, of treatments that were used in all three years (sandy soils, compost and different levels of Zn and P fertilisers) was slightly higher in the 2002 field experiment (5.44 mg m^{-2}) than in the 2003 (3.46 mg m^{-2}) and 2004 (3.26 mg m^{-2}) experiments (Tables 5.4 – 5.6). Zn uptake between flowering and maturity was much larger in all treatments than uptake before flowering. Averaging again over comparable treatments, Zn uptake at maturity was higher in 2004 (23.9 mg m^{-2}) than in 2003 (11.9 mg m^{-2}) and 2002 (14.9 mg m^{-2}). The largest increase in Zn uptake was reached through Zn application in all years and irrespective of soil type and organic amendment type that was applied (Tables 5.4 – 5.6). Also P application had in most cases a positive effect on Zn uptake but the effect was smaller. The significant interactions in 2002 did not overrule the main effect of P but indicates the effect was larger in the presence of Zn fertilisation. The significant interaction between Zn and P application observed at maturity in 2004 (Table 5.6) was due to the slightly lower additional effect of P application on Zn uptake when Zn was also applied compared to the effect when no Zn was applied.

A four-way interactions was found at maturity in 2002 between soil type, organic manure type and Zn and P application. This overruled the main effects of organic manure type and soil type and the two- and three-way interactions. With no Zn fertiliser, no significant differences were observed between gravely and sandy Luvisols or between organic manure types. The positive effect of P on Zn uptake in the absence of Zn fertiliser was not significant when applied on farm yard manure amended gravely soil. With Zn and P fertilisers, the compost amended sandy soil showed higher Zn uptake than the gravely one. The Zn uptake was better from compost amended plots when Zn and P were applied and when Zn was applied without P on gravely soils. The two-way interactions at flowering in 2002 indicate that Zn uptake from farmyard manure amended plots was lower than from compost amended plots and this effect was larger when Zn was applied and it was larger on sandy plots, although the main effect of organic manure type was not compromised by the interaction.

Table 5.1 Above ground biomass Zn mass fraction as affected by soil type, organic amendment (OA) type and Zn and P fertilisers. Data from the 2002 field experiment, n=32.

At flowering: LSD- main effect= 5.47, LSD-2 way interactions= 7.71

At maturity: LSD- main effect= 3.35, LSD-2 way interactions= 4.75, LSD-3 way interactions= 6.70

		Zn mass fraction in biomass (mg kg^{-1} DM)											
Soil type	OA	Flowering						Maturity					
		–Zn			+Zn			–Zn			+Zn		
		–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	8.5	16.7	*12.6*	32.5	36.3	*34.4*	12.6	26.6	*19.6*	41.0	64.8	*53.0*
	FYM*	2.8	4.0	*3.4*	15.0	25.3	*20.1*	10.2	20.9	*15.5*	27.7	41.2	*34.4*
	Mean	*5.7*	*10.3*		*23.7*	*30.8*		*11.4*	*23.7*		*34.3*	*53.0*	
Sandy	Compost	8.8	17.0	*12.9*	48.6	50.4	*49.5*	15.2	26.6	*20.9*	45.4	81.6	*63.5*
	FYM	2.6	8.1	*5.4*	16.6	21.5	*19.0*	9.2	20.8	*15.0*	28.3	38.9	*33.6*
	Mean	*5.7*	*12.6*		*32.6*	*35.9*		*12.2*	*23.7*		*36.9*	*60.2*	

	Zn	*P*	*OM*	*Zn x P*	*Zn x OM*	*OM x P*	*OM x Zn x P*
Flowering	**	*	**	*ns*	*	*ns*	*ns*
Maturity	**	**	**	*	**	*	*

FYM= Farmyard manure

Table 5.2 *Above ground biomass Zn mass fraction as affected by Zn and P fertilisers on compost amended sandy Luvisol. Data from the 2003 field experiment, n=32.*

	Zn mass fraction (mg kg^{-1} DM)					
	Flowering			Maturity		
	–P	+P	*Mean*	–P	+P	*Mean*
–Zn	11.9	15.1	*13.5*	25.3	26.5	*25.9*
+Zn	21.7	23.3	*22.5*	34.2	36.9	*35.5*
Mean	*16.8*	*19.2*		*29.7*	*31.7*	
	Zn: p<.001, LSD= 2.42			*Zn: p<.001, LSD= 4.85*		

Table 5.3 *Above ground biomass Zn mass fraction as affected by Zn and P fertilisers on compost amended gravely and sandy Luvisols.Data from the 2004 field experiment, n= 32.*

	Zn mass fraction (mg kg^{-1} DM)											
	Flowering						Maturity					
	–Zn			+Zn			–Zn			+Zn		
	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	4.10	7.30	*5.70*	11.0	14.5	*12.7*	20.8	44.8	*32.8*	59.1	61.1	*60.1*
Sandy	2.70	6.00	*4.35*	17.5	18.2	*17.7*	14.6	43.5	*29.0*	67.5	76.7	*72.1*
Mean	*3.40*	*6.65*		*14.2*	*16.3*		*17.7*	*44.1*		*63.3*	*68.9*	
	Zn: p<.001, LSD= 4.47						*Zn: p<.001, LSD= 5.10* *P: p<.001, LSD= 5.10* *Zn x P: p<.001, LSD= 7.21* *Soil type x Zn: p= 0.011, LSD= 7.21*					

Table 5.4 *Zn uptake as affected by soil type, organic amendment (OA) type and Zn and P fertilisers. Data from 2002 field experiment, n= 32.*
At flowering: LSD-main effect= 0.73, LSD-2 way interactions= 1.03
At maturity: LSD-main effect= 1.58, LSD-2 was interactions= 2.23, LSD-3 was interactions= 3.15, LSD-4 way interactions= 4.46

		Zn uptake (mg m^{-2})											
Soil type	OA	Flowering						Maturity					
		–Zn			+Zn			–Zn			+Zn		
		–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	0.40	2.35	*1.37*	4.44	6.97	*5.70*	2.75	8.88	*5.81*	13.7	24.8	*19.2*
	FYM*	0.23	0.49	*0.36*	1.71	4.41	*3.06*	1.88	6.14	*4.01*	6.35	15.6	*11.0*
	Mean	*0.31*	*1.42*		*3.07*	*5.69*		*2.31*	*7.51*		*10.0*	*20.2*	
Sandy	Compost	1.14	2.98	*2.06*	6.44	11.2	*8.82*	4.79	10.2	*7.49*	12.8	31.8	*22.3*
	FYM	0.29	1.45	*0.87*	2.24	3.49	*2.86*	2.27	8.05	*5.16*	9.38	15.6	*12.5*
	Mean	*0.71*	*2.21*		*4.34*	*7.34*		*3.53*	*9.12*		*11.1*	*23.7*	

	Zn	*P*	*OM*	*Soil*	*Zn x P*	*Zn x OM*	*OM x P*	*P x soil*	*OM x soil*	*OM x Zn x P*	*Soil x OM x Zn x P*
Flowering	**	**	**	*	*	**	*ns*	*ns*	*	*ns*	*ns*
Maturity	**	**	**	*	*ns*	**	*	*	*ns*	*	*

*FYM= Farmyard manure

Table 5.5 *Zn uptake as affected by Zn and P fertilisers on compost amended sandy Luvisol. Data from 2003 field experiment, n= 32.*

	Zn uptake (mg m^{-2})					
	Flowering			Maturity		
	–P	+P	*Mean*	–P	+P	*Mean*
-Zn	1.78	3.09	*2.43*	8.0	10.6	*9.3*
+Zn	3.85	5.12	*4.48*	12.4	16.7	*14.5*
Mean	*2.81*	*4.10*		*10.2*	*13.6*	
	Zn: p<.001, LSD= 2.42 *P: p<.001, LSD= 2.42*			*Zn: p<.001, LSD= 2.74* *P: p= 0.015, LSD= 2.74*		

Table 5.6 *Zn uptake as affected by Zn and P fertilisers on compost amended gravely and sandy Luvisols. Data from 2004 field experiment, n= 32.*

	Zn uptake (mg m^{-2})											
	Flowering						Maturity					
	–Zn			+Zn			–Zn			+Zn		
	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	0.80	2.01	*1.40*	2.54	5.17	*3.85*	6.6	19.9	*13.2*	29.9	38.8	*34.3*
Sandy	0.57	1.43	*1.00*	4.35	6.67	*5.51*	4.7	22.3	*13.5*	31.4	37.4	*34.4*
Mean	*0.68*	*1.72*		*3.44*	*5.92*		*5.7*	*21.1*		*30.6*	*38.1*	
	Zn: p<.001, LSD=1.60 *P: p= 0.041, LSD= 1.60*						*Zn: p<.001, LSD= 2.68* *P: p<.001, LSD= 2.68* *Zn x P: p = 0.001, LSD= 3.79*					

Table 5.7 *Zn uptake at 50% flowering as affected by the dose of compost and the timing of P and Zn fertiliser supply. Data from the 2003 pot experiment, n= 54.*

		Zn uptake (mg pot^{-1})			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	0.34	0.94	0.61	*0.63*
	P at sowing	0.58	1.52	1.16	*1.09*
	P at anthesis	0.60	1.22	0.79	*0.87*
Mean		*0.51*	*1.23*	*0.85*	
10 kg pot^{-1}	No P	0.73	1.52	0.98	*1.08*
	P at sowing	1.10	2.11	1.46	*1.56*
	P at anthesis	1.11	1.97	1.91	*1.66*
Mean		*0.98*	*1.87*	*1.45*	
	*OM***	*Zn***	*P***	*OM x P**	
LSD	*0.12*	*0.15*	*0.15*	*0.21*	

Table 5.8 *Zn uptake at maturity as affected by the dose of compost and the timing of P and Zn fertiliser supply. Data from the 2003 pot experiment, n= 54.*

		Zn uptake (mg pot^{-1})			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	1.99	3.29	3.35	*2.88*
	P at sowing	3.12	4.47	4.77	*4.12*
	P at anthesis	2.75	3.48	4.99	*3.74*
Mean		*2.62*	*3.75*	*4.37*	
10 kg pot^{-1}	No P	2.74	5.89	6.27	*4.97*
	P at sowing	5.13	7.15	9.93	*7.40*
	P at anthesis	4.78	6.30	11.1	*7.39*
Mean		*4.22*	*6.45*	*9.10*	

	*OM***	*Zn***	*P***	*OM x P***	*OM x Zn***	*OM x Zn x P***
LSD	*0.25*	*0.31*	*0.31*	*0.43*	*0.43*	*0.75*

The pot experiment 2003

In the pot experiment in 2003 there was a clear positive effect of doubling the compost dose from 5 to 10 kg pot^{-1} on Zn uptake, both at flowering (1.43 against 0.8 mg pot^{-1}) and at maturity (6.56 against 3.59 mg pot^{-1}), which was not compromised by the two- or three-way interactions (Tables 5.7 and 5.8). Interactions between compost dose and timing of Zn and P application were found at maturity and between compost dose and timing of P application at flowering. At flowering, with the lower compost dose, Zn uptake was higher when P was applied at sowing (1.09 mg pot^{-1}) than when it was applied at anthesis (0.87 mg pot^{-1}), while Zn uptake in pots without P application was lower than with the other two treatments (Table 5.7). With the higher compost dose, Zn uptake was comparable when P was applied at sowing or anthesis. All three main effects were significant irrespective of the interaction. At maturity, the three-way interaction was significant as Zn uptake was higher at the higher compost dose with P when Zn was applied at anthesis compared to Zn applied at sowing. The main effects of Zn and P application, though, were not compromised by these interactions (Table 5.8). The effects of timing of application of Zn differed between compost application dose and between sampling dates. Overall, the effects of timing of Zn were minor compared to the effects of application *per se*, while the effect of timing of P was not significant.

Zn recovery

The proportion of Zn recovered by the sorghum crop was less than 10% in all field experiments. The fraction of recovered Zn was appreciably higher in 2004 (8.6%) than in 2002 (3.6 %) and 2003 (1.8%). The differences between years were larger than differences within years and between treatments. No significant difference was observed between the gravely and the sandy soil neither in 2002 (Table 5.9) nor in 2004 (Table 5.10). In the 2002 experiment, the fraction of Zn recovered was higher with compost than with farmyard manure when P was also applied. Despite this interaction, the application of P improved the Zn recovery in 2002 and 2004, but not in 2003 (1.55% in –P and 1.87% in +P).

Table 5.9 *Proportion of Zn recovered as affected by soil type, organic amendment type and P fertiliser. Data from the 2002 field experiment, n= 32.*

	Zn recovery (% of Zn applied)					
	Compost			FYM		
	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	2.70	6.30	*4.50*	1.40	3.90	*2.65*
Sandy	2.10	7.10	*4.60*	2.10	3.80	*2.95*
Mean	*2.40*	*6.70*		*1.75*	*3.85*	
	OM: p= 0.001, LSD= 0.84;					
	P: p< 0.001, LSD= 0.84;					
	OM x P: p= 0.018, LSD= 1.20					

Table 5.10 *Proportion of Zn recovered as affected by soil type, organic amendment type and P fertiliser. Data from the 2004 field experiment, n= 32.*

	Zn recovery (% of Zn applied)		
	–P	+P	*Mean*
Gravely	6.60	8.78	*7.69*
Sandy	7.62	9.41	*8.51*
Mean	*7.11*	*9.09*	
	P: p= 0.037, LSD=1.76		

P uptake

For comparable treatments P uptake, like Zn uptake, was higher at maturity than at flowering in all field experiments (Tables 5.11 – 5.13). P application significantly increased P uptake in all the cropping seasons, irrespective of observed interactions with either Zn or organic amendment type. In the 2002 field experiment, an interaction was found between Zn and P fertilisers at flowering and maturity as Zn only enhanced P uptake when applied together with P fertiliser (Table 5.11). Zn did not affect P uptake in the 2003 experiment at flowering but at maturity in the 2003 experiment and in the 2004 experiment Zn application enhanced P uptake (Tables 5.12 and 5.13). In the 2002 field experiment, at maturity, an interaction was found between organic amendment and P fertiliser. Without P fertiliser, sorghum grown on compost and farmyard manure amended plots had comparable P uptake. When P fertiliser was applied, sorghum grown on compost amended plots showed higher P uptake (Table 5.11). At flowering compost gave a higher P uptake irrespective of fertiliser applications.

In the 2004 field experiment (Table 5.15), the plants grown on the sandy soil had higher P uptake than those grown on the gravely soil at both flowering and maturity. In the

2002 field experiment no significant difference was observed between the two soil types (Table 5.11).

In the 2003 pot experiment, both at flowering and at maturity, there was an interaction between compost dose and P and Zn applications on P uptake (Tables 5.14 and 5.15). At both sampling periods P applied at sowing gave either as much or more P uptake than when it was applied at anthesis. The interaction made interpretation of the effect of Zn application or doubling the compost dose less unambiguous. At flowering, the effect of P fertiliser application at sowing on P uptake was higher when Zn was applied at sowing for the lower compost dose. With a higher compost dose, Zn fertiliser timing did not significantly affect P uptake.

Relative contribution of changes in dry matter and mass fraction to changes in uptake

The change in uptake of Zn between flowering and maturity was in three of the four experiments mainly caused by the increase in dry matter, rather than by the increase in ZnMF of the above ground dry matter. Only in the 2004 field experiment was the contribution of increase in ZnMF most important (Table 5.16). For P the trend was the same in all experiments and dry matter contributed most to change in P uptake in all years. In the pot experiment even a decrease in the MF of P was observed between flowering and maturity as indicated by the negative contribution of change in the MF of P to change in P uptake (Table 5.16).

5.4 Discussion

Uptake of Zn and P and above ground biomass Zn mass fraction (ZnMF) differed between the three cropping seasons, especially at maturity. These differences seemed related to differences in rainfall distribution especially after flowering, as the lower uptake after flowering in 2003 and to some extent also in 2004 correspond with lower Zn and P availability reported in Chapter 3. In all studies, most of the total Zn (>70%) and P (45 – 62%) in the crop at harvest was taken up after flowering. The post-flowering Zn uptake was higher than the amount needed for the biomass production during this period, leading to a simultaneous increase in dry matter and in ZnMF. Also the P uptake after flowering was accompanied by both an increase in dry matter and in PMF.

5.4.1 Zn and P uptake and Zn and P fertilisers

The effects of Zn and P fertilisers were different in magnitude between the seasons. When conditions were less favourable for production of biomass, like in 2003, both uptake and Zn-MF were low (Tables 5.3 and 5.5). It has to be noted, though, that the rainfall conditions in 2004 seemed equally bad, but uptake and MF of Zn were higher than in both 2002 and 2003 for comparable treatments. While also Zn availability at flowering seemed higher in 2004 than in 2003 (Chapter 3). The role the provided N application has played in this cannot be well analysed from the available data.

In all the studies, Zn and P application generated significantly higher Zn and P uptake. The interactions with factors like soil type (2002) and organic matter type (2002) did not change this general picture much. The interactions between Zn and P in some of the experiments also did not change anything to the overall positive effect of Zn application on both Zn uptake and sorghum biomass Zn-MF. The improvement of Zn uptake can be attributed to a higher availability following the application of Zn fertiliser (Chapter 3).

When no Zn was applied, P application enhanced both Zn uptake and Zn-MF. The effects on both improved uptake and increased Zn-MF implies that under the field conditions tested, P fertiliser did not lead to a dilution of Zn over the larger amount of biomass as observed by others (Erenoglu, 2002). The biomass production was enhanced in all three years (Traore *et al.*, 2006 b) and this explained 33 – 81% of the increase in Zn uptake while the remaining 67 – 19% was explained by the enhanced MF. The positive impact of P fertiliser on Zn uptake was also reported in earlier work (Mengel and Kirkby, 1987; Chowdhury *et al.*, 1997; Gianquinto *et al.*, 2000; Erenoglu, 2002).

Both P and Zn fertilisers proved to enhance P uptake. The enhanced uptake of P was mainly concentrated during the period between flowering and maturity. P uptake was highest when P and Zn fertilisers were combined. These results show that micronutrients are necessary for better resource use efficiency of macronutrients which corresponds well to the conclusions from Wit (1992) and Katyal (2004). As for Zn the effect of the fertilisers on uptake worked both through enhanced biomass production (accounting for 17 – 62%) and through enhanced biomass P-MF (accounting for 38 – 83%).

Table 5.11 *P uptake as affected by soil type, organic amendment (OA) type and Zn and P fertilisers. Data from the 2002 field experiment, n= 32.*
At flowering: LSDmain effect = 10.3, LSD-2 way interactions=14.5
At maturity: LSD-main effect= 34.4, LSD-2 way interactions= 48.6
FYM= Farmyard manure

		P uptake (mg m^{-2})											
Soil type	OA	Flowering						Maturity					
		–P			+P			–P			+P		
		–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*
Gravely	compost	15.1	30.7	*22.9*	38.8	97.7	*68.2*	35.6	53.6	*44.6*	145	337	*241*
	FYM	9.20	22.6	*15.9*	31.5	59.1	*45.3*	20.2	51.1	*35.6*	70	207	*138*
	Mean	*12.1*	*26.5*		*35.1*	*78.4*		*27.9*	*52.3*		*107*	*272*	
Sandy	compost	22.2	32.8	*27.5*	47.5	86.1	*66.8*	60.5	78.2	*69.3*	185	365	*275*
	FYM	15.5	26.7	*21.1*	42.0	71.3	*56.6*	29.3	72.5	*50.9*	105	242	*173*
	Mean	*18.8*	*29.7*		*44.7*	*78.7*		*44.9*	*75.3*		*145*	*303*	

	Zn	*P*	*OM*	*Zn x P*	*OM x P*
Flowering	**	**	*	*	*ns*
Maturity	**	**	*	**	*

Table 5.12 *P uptake as affected by Zn and P fertilisers on compost amended sandy Luvisol. Data from the 2003 field experiment, n= 32.*

	P uptake (mg m^{-2})					
	Flowering			Maturity		
	–P	+P	*Mean*	–P	+P	*Mean*
–Zn	31.5	56.3	*43.9*	68.5	121	*94.7*
+Zn	40.8	62.2	*51.5*	84.5	156	*122*
Mean	*36.1*	*59.2*		*76.5*	*140*	
	P: p<.001, LSD = 8.34			*P: p<.001, LSD = 24.8* *Zn: p= 0.03, LSD = 24.3*		

Table 5.13 *P uptake as affected by Zn and P fertilisers on compost amended gravely and sandy Luvisols. Data from the 2004 field experiment, n= 32.*

	P uptake (mg m^{-2})											
	Flowering						Maturity					
	–P			+P			–P			+P		
	–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*	–Zn	+Zn	*Mean*
Gravely	26.3	49.7	*38.0*	70.9	98.7	*84.8*	64.3	91.0	*77.6*	155.5	206.5	*181.0*
Sandy	51.8	77.4	*64.6*	104.5	152.0	*128.2*	76.6	125.2	*100.9*	183.8	256.5	*220.1*
	39.0	*63.5*		*87.7*	*125.3*		*70.4*	*108.1*		*169.6*	*231.5*	
	Soil type: p= 0.006, LSD = 23.8						*Soil type: p= 0.029, LSD = 27.6*					
	P: p<.001, LSD = 20.6						*Zn: p<.001, LSD = 3.94*					
	Zn: p= 0.002, LSD = 20.6						*P: p<.001, LSD = 24.0*					

Table 5.14 *P uptake at 50% flowering as affected by the dose of compost and the timing of P and Zn fertilisers supply. Data from the 2003 pot experiment, n= 54.*

		P uptake (mg pot^{-1})			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	3.67	5.19	5.14	*4.67*
	P at sowing	10.4	17.0	14.8	*14.0*
	P at anthesis	7.51	9.20	8.07	*8.26*
Mean		*7.19*	*10.5*	*9.32*	
10 kg pot^{-1}	No P	6.43	9.43	7.72	*7.86*
	P at sowing	17.2	17.4	16.3	*16.9*
	P at anthesis	13.7	14.2	14.3	*14.0*
Mean		*12.4*	*13.7*	*12.8*	

	*OM***	*Zn***	*P***	*OM x P**	*Zn x P**	*OM x Zn x P**
LSD	*1.65*	*2.02*	*2.02*	*2.86*	*2.86*	*4.96*

Table 5.15 *P uptake at maturity as affected by the dose of compost and the timing of P and Zn fertilisers supply. Data from the 2003 pot experiment, n= 54.*

		P uptake (mg pot^{-1})			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	11.9	16.0	16.6	*14.9*
	P at sowing	20.5	22.8	22.7	*22.0*
	P at anthesis	18.2	19.3	18.8	*18.8*
Mean		*16.9*	*19.4*	*19.4*	
10 kg pot^{-1}	No P	16.7	20.3	17.0	*18.0*
	P at sowing	24.7	25.1	23.5	*24.4*
	P at anthesis	18.9	22.2	22.3	*21.1*
Mean		*20.1*	*22.5*	*20.9*	

	*OM***	*P***	*Zn**	*OM x Zn***	*Zn x P***	*OM x Zn x P***
LSD	*0.67*	*0.82*	*0.82*	*1.16*	*1.42*	*2.01*

Table 5.16 *Relative contribution of change in dry matter (ΔDM) and of change in mass fraction of Zn (ΔZnMF) or P (ΔPMF) to the change in uptake of respectively Zn (ΔZnUP) or P (ΔPUP) between flowering and maturity for all treatments in the four different experiments*

	Contribution to *ΔZnUP* of		Contribution to *ΔPUP* of	
Experiment	ΔDM	ΔZnMF	ΔDM	ΔPMF
2002 field	0.66	0.34	0.76	0.24
2003 field	0.59	0.41	0.91	0.09
2004 field	0.16	0.84	0.84	0.16
2003 pot	0.69	0.31	1.13	- 0.13

5.4.2 Zn and P mass fraction and uptake and organic amendment type and dose

There was no difference in Zn uptake by the crops grown in 2004 on either a gravely or a sandy Luvisol (Table 5.8) at any of the fertiliser treatments. The difference in Zn uptake in 2002 between crops grown on a sandy soil compared to crops grown on a gravely soil were not accompanied by significant differences in biomass Zn-MF, and were accounted for 83% by an enhanced biomass production. In fact, the interactions in Zn uptake between Zn fertiliser, P fertiliser, organic amendments and soil type were such that only a slightly higher Zn uptake was significant on sandy soil when compost was applied as well as Zn and P. In general the differences between the soil types were therefore negligible and did not confound the fertiliser effects. The direct linkage between Zn and P uptake and ZnMF and production conditions also seems to be behind the interactions between soil types, types of organic matter and P and Zn applications (the 2002 and 2004 experiments). The comparison of compost and farmyard manure (FYM) amendments to both soil types showed always a higher uptake after compost application in combination with Zn fertiliser. Zn taken up from plots amended with compost was higher than Zn uptake in plots amended with farmyard manure. These results are mainly related to the higher ZnMF (explaining 82% of the increase) for sorghum grown on compost amended plots than for sorghum grown on the farmyard manure ones (Table 5.3). The possibility for compost to increase Zn uptake can be attributed to its effect on Zn availability (Chapter 3). As soil pH and organic matter content after application of the two amendment types were comparable it seems plausible that the quality differences of the organic amendments generated differences in Zn uptake, which is in line with the conclusions from previous studies (Corey *et al.*, 1987; Balik *et al.*, 2002).

The results from the pot experiment in 2003 indicate that Zn uptake can be improved by increasing the organic manure dose which is in concordance with the results reported by Mohammad and Athamneh (2004) on sewage sludge. Increasing Zn uptake with increasing organic amendment dose is an encouraging result since Zn uptake from the high compost dose without Zn and P fertilisers was comparable to Zn uptake in the lower compost dose with Zn and P fertilisers. But the results from the pot experiment are to be verified in field conditions. Also, the optimization of the use of available organic manure resources to either fertilise a larger area at the current dose or to concentrate larger volumes on a smaller area will be needed, rather a decision at farm level than at plot level (Chapter 2).

Changes in P uptake were in line with changes in Zn uptake. P uptake was affected by soil type only in 2004 and no interaction was found between Zn and P fertiliser application. The sandy soil allowed higher P uptake than the gravely one mainly through a higher biomass production (Chapter 4) on the sandy soil than on the gravely one explaining 73% of the enhanced uptake. P availability, though, was comparable for the two soil types (Chapter 3). P uptake was higher for sorghum grown on compost amended plots than for sorghum grown on farmyard manure amended ones. This was in line with the higher P availability in compost amended plots than in farmyard manure amended ones (Chapter 3). The higher availability and related higher uptake of P with the use of compost was mainly due to an enhanced MF of P (80%) and only marginally due to a difference in dry matter production (20%).

5.4.3 Zn and P uptake with Zn and P timing

Timing of Zn and/or P fertiliser application as studied in the pot experiment did seem to give different Zn and P uptake and ZnMF in above ground biomass. The differences, though, were rather small and extrapolation to field conditions is difficult. The small difference in uptake, which were not related to differences in biomass or grain yield (Chapter 4) and the organisational difficulty to explain to farmers late fertiliser applications are enough reasons to start with simple application of Zn fertilisers to enhance Zn-MF and biomass production (at sowing) rather than to advocate late application in order to enhance uptake (Cakmak *et al.*, 1999). Nevertheless, the pot experiment in 2003 indicated that further optimization of Zn uptake and Zn-MF through a higher organic manure dose and a good timing of P and Zn fertilisers is possible.

5.4.4 Zn recovery

The percentage recovery of Zn fertilisation by sorghum above ground biomass was very low (less than 10%). An important proportion of applied Zn remained in the soil which is in line with Rupa *et al.* (2003). According to these authors, plants utilize only 1 to 4% of the freshly applied Zn and the rest goes into the formation of different Zn compounds of varying solubility and availability to plants. It can expected that Zn remaining in the soil can be used by the subsequent crops (Cakmak *et al.*, 1999; Rengel *et al.*, 1999; Frossard *et al.*, 2000), but further investigations are needed to assess the long-term effect of Zn application in the Sahel conditions. P fertiliser improved the fraction of Zn recovered which can be attributed to the positive impact of P fertiliser on biomass production and above ground biomass Zn-MF.

The reported studies have shown that application of Zn fertiliser in combination with organic amendments and P fertiliser improved availability and biomass and grain production (Chapter 3, 4). With the effects on biomass mass fraction and uptake reported here it is shown that the effects go beyond increasing biomass and in fact will lead to biomass with an enhanced P and Zn-MF which implies a higher quality of at least the stover for animal feeding. The consequences of the improved quality of the stover for animal feed in terms of digestibility and animal health cannot be quantified without further studies, but would make an assessment of the economics of Zn fertiliser or Zn enriched P-fertiliser more complete. Finally the improvements in Zn mass fraction in the above ground dry matter are accompanied by higher sorghum productivity leading to improved food security. If it simultaneously would lead to more Zn in the grain it would have an additional nutritional security effect. The analysis of the within-plant allocation to the grain and grain Zn mass fraction is therefore on its way.

Chapter 6

Can sorghum grain quality be improved by applying inorganic Zn and P fertilisers and organic amendments?

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6. Can sorghum grain quality be improved by applying inorganic Zn and P fertilisers and organic amendments?

6.1 Introduction

Zn deficiency in humans is widespread throughout the world: an estimated two billion people suffer from Zn deficiency (Rengel *et al.*, 1999). It is most prevalent in human populations that rely heavily on a monotonous diet of cereal-based foods (Bouis *et al.*, 2000; Magen and Imas, 2004). Increasing the amount of micronutrients in plant foods for human consumption is a challenge that is particularly important for developing countries. Theoretically, this could be achieved by increasing the total level of micronutrients in the edible part of staple crops, such as cereals and pulses (Frossard *et al.*, 2000). Consequently, a massive international effort is underway to enhance Zn in major cereals in order to improve Zn quantities in the diet of populations that do not have ready access to zinc rich food sources (White and Broadley, 2005). Increasing Zn concentration in cereal grain is in principle possible through agricultural measures (Rengel *et al.*, 1999; Frossard *et al.* 2000, Cakmak *et al.*, 1999). Earlier studies have shown that the easiest way to increase Zn concentration in the grains is Zn application to the soil or on leaves (Cakmak *et al.*, 1999; Grusak *et al.*, 1999; Rengel *et al.*, 1999; Rupa *et al.*, 2003). The increase in grain Zn mass fraction (MF) resulting from Zn fertilisation is influenced by soil chemical and physical characteristics and environmental conditions (Balik *et al.*, 2002; Erenoglu, 2002; Khairiah *et al.*, 2004). Rengel *et al.* (1999) reported a lower Zn-MF in wheat grains harvested from Paaloa soil than when grown on slightly acidic sandy Laffer soil.

For farmers in northern Burkina Faso the major constraint to cereal production is obviously not Zn. Soils are poor in phosphorus and nitrogen (Bationo *et al.*, 1998; Buekert *et al.*, 1998; Gandah *et al.*, 2003; Zougmore, 2003, Ouedraogo, 2004). Moreover, the low organic matter content leads to soil erosion problems and poor soil water retention (Zougmore *et al.*, 2003). Developments in the area are an increased intensity of organic manure use (Reij *et al.*, 1996), and application of P fertiliser. Most of the studies undertaken in the area were oriented toward the effectiveness of organic fertiliser and macronutrient supply in increasing crop production in face of a rapidly growing population (Bationo *et al.*, 1998; Mando and Stroosnijder, 1999; Buekert *et al.*, 2000). No results are therefore available on the impact of organic amendments as practised in the Sahel on Zn-MF in cereals grains. Rengel *et al.* (1999) and Rupa *et al.* (2003) have reported that soil organic amendments improve Zn uptake and accumulation in the grains, because of their important effects on soil chemical properties. They concluded that the combined use of organic and mineral fertilisers might be necessary to increase micronutrient mass fraction in the grain. The improvement of cereal yield in the Sahel by soil organic amendments either or not combined with P fertiliser may even lead to dilution of Zn in the grains, necessitating additional Zn input into the system to avoid negative health effects. However, it will be difficult to monitor these effects in the short term. Nevertheless, it seems an important step to enhance our understanding of the Zn levels that could be attained and the role played by organic and inorganic fertilisation in determining currently obtained Zn levels.

Zn uptake in the human gut is co-determined by several so-called anti nutritional compounds (ANC). Among these ANC, *myo*-inositol 1,2,3,4,5,6-hexakis dihydrogen phosphate (IP6), also known as phytate or phytic acid, is of great importance (Buekert *et al.*, 1998). In small grain crops, from 64 to 80% of grain P is stored as phytate (Raboy, 2000). IP6 is necessary for embryo protection and nutrition at the early growth stages of the plant, it is considered an important antioxidant that suppresses lipid peroxidation in dormant seed and prevents colon cancer in humans. The P and micronutrients locked up in IP6 are poorly available to monogastrics. IP6 may therefore severely hamper the bio-availability of Zn (Buekert *et al.*, 1998). Phytate also includes the IP-5 or lower phosphate saturated inositol forms. These forms are also relevant in food, but occur at very low levels in plant seeds before the seeds germinate.

Our study is focussed on Zn, IP6 and IP6: Zn molar ratios. P application – as is introduced in the study area – is likely to enhance IP6-MFs in the grains (Buekert *et al.*, 1998). The exact effects of Zn and P application and their possible interactions cannot be easily predicted from currently available knowledge.

This paper reports part of a comprehensive study for which effects of treatments on Zn and P availability in the soil (Chapter 3), crop yield (Chapter 4) and crop Zn and P uptake (Chapter 5) have already been reported. Here the following research questions are addressed: (1) how does Zn uptake in the grain relate to the Zn taken up after flowering and the Zn present in the straw or the biomass? (2) What are the Zn and IP6-MFs in sorghum (*Sorghum bicolor* (L.) Moench) grains grown in the current production system; (3) What changes can be obtained by the use of inorganic Zn and/or P application; (4) Do these effects change with the timing of inorganic Zn and P application? (5) How consistent are these effects over years, organic amendment types and soil types relevant under current farming practices in the study area.

6.2 Materials and methods

6.2.1 Field experiments

Site description

On-farm experiments were carried out in farmers' fields in northern Burkina Faso (13°06'–14°26' N, 1°43'–2°55 W), in the Soudano-sahelian zone in 2002, 2003 and 2004. Annual rainfall in the study area is between 400 and 700 mm, the cropping season is 4 months (June–September). There are two main soil types in the area: Luvisols and Regosols (Mando, 2000), of which the Luvisols are the more dominant agricultural soils. Both have poor structure and low mineral and organic matter content (Pieri, 1989). Experiments were carried out on gravely and sandy Luvisols.

Experiment design

In each year, the experiment was a randomized block design; the size of each experimental unit was 25 m^2 (5 m × 5 m) and the distance between the plots was 1 m. Treatments in all three years included the four combinations of two levels of Zn fertiliser (no Zn or 3.5 kg Zn ha^{-1} as $ZnSO_4$, 25%) and two levels of P fertiliser (no P or 37.5 kg P ha^{-1} as triple super phosphate, TSP, 43%). The applied P dose corresponds to the amount needed to correct soil P deficiency in the area (Compaore *et al.*, 2001).

In 2002, the four fertiliser treatments were combined in a 2 × 2 × 2 factorial set-up with two organic manure types (compost, 15 t ha^{-1} or farmyard manure, 10 t ha^{-1}). These eight treatments were tested on both gravely and sandy Luvisols in fields of two farmers who cultivated both soil types, providing a total of 32 experimental units.

In 2003, the four fertiliser treatments were tested on fields of a single farmer in eight blocks on a sandy Luvisol amended with 15 t ha^{-1} of compost (32 experimental units).

In 2004, the four fertiliser treatments were tested again on both a sandy and gravely Luvisol in four blocks per soil type (32 experimental units). The eight blocks were distributed over the fields of two farmers. Plots were amended with 50 kg N ha^{-1} in the form of urea and 15 t ha^{-1} of compost

Properties of the soils and organic amendments have been reported earlier (Chapter 3, Tables 3.1 -3.3).

Crop husbandry

All management was done by the farmers, though supervised by research assistants, in order to synchronise timing of operations between replicates. Plots were cultivated using the traditional planting pits or 'zaï' (Reij *et al.*, 1996). The average pit was 25 cm in diameter and 15 cm deep. The distance between pits within the row was 0.5 m and the distance between rows was 0.8 m, resulting in 25,000 pits per ha. The pits were made by the farmers and organic manure and inorganic fertilisers were applied during the preparation of the pits. The organic amendments were applied at two handfuls per planting pit which corresponded to 15 t ha^{-1} for compost and 10 t ha^{-1} for farmyard manure, i.e. the quantity enough to support crop production according to estimates of local farmers (Dakio, 2000).

Pits were sown with 3–5 seeds of the improved and drought tolerant sorghum (*Sorghum bicolor* (L.) Moench) variety IRAT 204, with a growing cycle of 90 days. The plant number per pit was reduced to two at the first weeding, 2 weeks after emergence. Plots were also weeded at flowering and during grain filling.

From each experimental plot, grain samples were collected at maturity and stored in 10 litre plastic bags and carried to a drying space at Kamboinsé research centre.

6.2.2 Greenhouse experiment

A greenhouse experiment was carried out at the Research Centre of Kamboinsé, 10 km north of Ouagadougou, Burkina Faso, in 2003. The experiment was sown on July 27 and harvested on November 30. Plastic pots of 15 litres were filled with a mixture of sandy acidic soil and compost. The pots contained 21 kg of soil. The sandy soil was collected from the site where the field experiment of 2003 was conducted. The compost was collected from farmers and was similar to the one applied in the field experiment of 2003. Before planting, all pots were watered to field capacity and were re-watered back to field capacity after weighing twice a day. The treatments included all combinations of

- two compost rates: 5 kg pot^{-1} (equivalent of 200–250 mg of total Zn), or 10 kg pot^{-1} (equivalent of 400–450 mg of total Zn);
- three Zn treatments: no Zn, Zn at sowing or Zn at anthesis (Zn applied as zinc sulphate, $ZnSO_4$; 370 mg Zn pot^{-1}); and
- three P treatments: no P, P at sowing or P at anthesis (P applied as triple super phosphate, TSP; 1.51 g P pot^{-1}).

Pots were randomly arranged in the greenhouse and all treatments were replicated three times. Number of experimental units was 54. In each pot, five sorghum (cv. IRAT 204) seeds were sown; 2 weeks after emergence, the population was thinned back to two plants per pot. At maturity, sorghum grain samples were taken from each pot.

6.2.3 Sample and data analysis

The grains samples were pre-dried in direct sun light and subsequently oven-dried at 60 °C for 48 hours. The samples were ground and sieved at 2 mm.

Plant samples were digested using a mixture of sulphurous acid (H_2SO_4) and salicylic acid ($C_7H_6O_3$) in the presence of hydrogen peroxide (H_2O_2) and selenium (as a catalyst). Total Zn was determined hereafter by Atomic Absorption Spectrometry (AAS).

For IP6 analysis dried powder of the grain samples was digested in 1 ml HCl (0.5N) at 100 °C for 15 minutes. The solution was diluted 10 × in mQ-water. Total IP6 was determined by HPLC-analysis on Dionex AS11 column Detection by suppressed conductivity.

IP6: Zn molar ratios were calculated assuming a molar weight for IP6 of 651 and for zinc of 65.

Microsoft Excel was used for primary data processing. The analyses of variance (ANOVA) were performed using GENSTAT 8th Edition. The means were separated using the least significant difference (LSD) at 5% probability. In the ANOVA of the 2002 experiment, farmers were used as replications while in 2003 and 2004 blocks represented the replications. For analyses of the correlation between gain zinc yield and zinc uptake during different periods of crop development the generalised linear models procedure of GENSTAT was used.

6.3 Results

6.3.1 Rainfall

The rainfall varied markedly over the years of experimentation (Chapter 3, Figure 3.1). Total rainfall during the cropping seasons 2002 (543 mm) and 2004 (583 mm) was slightly lower than the long term average (1961-1990) for the area (600 mm), while it was higher in 2003 (732 mm). Rainfall distribution was fairly normal in 2002 while rain events were rare after flowering in 2003 and 2004. In 2003, only two rain events were recorded after 50% flowering (September, 11): on September 20 (11.0 mm) and October 03 (14.4 mm). In 2004, only one rain event was recorded after 50% flowering (September 20): on September 22 (23.2 mm). Especially in 2004 the crop suffered from severe drought throughout the grain filling period.

6.3.2 Sorghum grain Zn mass fraction (Zn-MF)

Year-to-year differences were large; comparison of equivalent treatments gives an average grain Zn-MF of 41.1, 18.3 and 42.0 for 2002, 2003 and 2004, respectively. Organic manure type, soil type and Zn and P fertiliser application all affected Zn-MF in the grain in 2002 (Table 6.1). Interactions were found between soil type and Zn and between soil type and P application. Zn application increased Zn mass fraction (Zn-MF) on both soil types, but the effect was larger on sandy soil (from 22.4 to 56.7 mg kg^{-1}) than on gravely soil (from 20.6 to 44.4 mg kg^{-1}). When no Zn was applied grain Zn-MF was identical for grain from both soil types. P application increased grain Zn-MF less on sandy soil (with 15 mg kg^{-1} from 32.1 to 47.1 mg kg^{-1}) than on gravely soil (with 20 mg kg^{-1} from 22.7 to 42.4 mg kg^{-1}). Also the main effects of Zn and P application were highly significant. The main effect of soil type was overruled by the interaction with Zn but not by the interaction with P. Application of compost resulted in a slightly higher grain Zn-MF (38.1 mg kg^{-1}) than application of farmyard manure (34.0 mg kg^{-1}). This effect was consistent over the applications of Zn and P and independent of the soil type.

Table 6.1 *Sorghum grain Zn-MF (mg kg^{-1}) as affected by soil type, organic amendment type and Zn and P fertilisers. Field experiment in Somyaga in 2002, n = 32.*

		Grain Zn-MF (mg kg^{-1} DM)					
		–Zn			+Zn		
Soil type	OM	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	14.8	33.2	*24.0*	37.0	55.4	*46.2*
	FYM	7.54	27.1	*17.3*	31.5	53.7	*42.2*
	Mean	*11.2*	*30.2*		*34.3*	*54.5*	
Sandy	Compost	16.1	31.5	*24.2*	49.1	67.0	*58.0*
	FYM	12.1	29.2	*20.6*	50.1	60.7	*55.4*
	Mean	*14.5*	*30.3*		*49.6*	*63.8*	

	*OM**	*Zn***	*P***	*Soil type***	*Soil type × Zn***	*Soil type × P**
LSD	*2.27*	*2.27*	*2.27*	*2.27*	*3.21*	*3.21*

* Significant at $p<0.05$

** Significant at $p<0.01$

Table 6.2 *Sorghum grain Zn-MF (mg kg⁻¹) as affected by Zn and P fertilisers in a sandy composted soil. Field experiment in Somyaga in 2003, n = 32.*

	Grain Zn-MF (mg kg^{-1} DM)		
	–P	+P	*Mean*
–Zn	15.9	17.6	*16.7*
+Zn	19.2	20.4	*19.8*
Mean	*17.6*	*19.0*	
	Zn: p< 0.001, LSD = 1.55		

In the 2003 field experiment, Zn application had a highly significant but rather limited effect on grain Zn-MF while P application did not affect the Zn-MF at all (Table 6.2).

In the field experiment in 2004, results were comparable to those obtained in 2002 for the main effects of the studied factors, but no significant interactions were observed between the factors (Table 6.3). The sorghum grown on the sandy soil showed higher grain Zn-MF (42.0 mg kg^{-1}) than the sorghum grown on the gravely soil (28.7 mg kg^{-1}). Zn-MF was increased with Zn application (from 22.7 to 48.0 mg kg^{-1}) and P application (from 27.7 to 43.0 mg kg^{-1}). The grain Zn-MF on sandy soil with compost, Zn and P application was comparable for 2002 and 2004 with 67.0 and 62.2 mg kg^{-1} respectively, as were mass fractions for other identical treatment combinations. The grain Zn-MFs in 2003 were lower than those in 2002 and 2004, when Zn and/or P was applied.

Table 6.3 *Sorghum grain Zn-MF (mg kg^{-1}) as affected by Zn and P fertilisers and soil type. Field experiment in Somyaga in 2004, n = 32.*

	Grain Zn-MF (mg kg^{-1} DM)					
	–Zn			+Zn		
Soil type	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	9.30	28.3	*18.8*	30.0	47.2	*38.6*
Sandy	18.9	34.1	*26.5*	52.6	62.2	*57.4*
Mean	*14.1*	*31.2*		*41.3*	*54.7*	
	Zn: p<.001; LSD = 4.58; P: p<.001, LSD = 4.58; Soil type: p = 0.007, LSD = 4.58					

In the 2003 greenhouse experiment again Zn application increased sorghum grain Zn-MF (Table 6.4). The organic manure dose and timing of inorganic Zn and P application showed a significant interaction. When Zn was applied, the higher compost dose gave a higher Zn-MF, irrespective of Zn application timing and of whether or when P was applied. At the lower compost dose, Zn application increased Zn-MF marginally only when P was applied (either at sowing or at anthesis). At the higher compost dose, Zn application always enhanced grain Zn-MF. When P was applied in combination with the lower compost dose no effect was observed on the grain Zn-MF. At the higher compost dose, P applied at sowing or anthesis had an equal and significant effect on Zn-MF when Zn was applied at anthesis. Generally ranges of grain Zn-MF in the pot experiment of 2003 were similar to the ranges found in the 2002 and 2004 field experiments, and higher than in the 2003 field experiment.

Table 6.4 *Sorghum grain Zn-MF (mg kg^{-1}) as affected by the dose of organic compost and the timing of Zn and P fertiliser supply. Greenhouse experiment 2003, n = 54.*

		Grain Zn-MF (mg kg^{-1}DM)			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	19.1	22.2	25.0	*22.1*
	P at sowing	18.6	22.5	33.8	*25.0*
	P at anthesis	18.7	20.6	27.5	*22.3*
Mean		*18.8*	*21.8*	*28.8*	
10 kg pot^{-1}	No P	20.9	34.6	36.3	*30.6*
	P at sowing	21.6	32.6	52.8	*35.6*
	P at anthesis	22.9	37.1	59.9	*40.0*
Mean		*21.8*	*34.8*	*49.7*	

	*OM***	*Zn***	*P***	*Zn × P***	*Zn× OM***	*P x OM***	*Zn × P × OM**
LSD (0.05)	*3.10*	*3.80*	*3.80*	*6.59*	*5.38*	*5.39*	*9.32*

* Significant at $p<0.05$
** Significant at $p<0.01$

Sorghum grain Zn yield and Zn taken up during different growth stages

The correlation between sorghum grain Zn yield and Zn taken up by the crop before flowering, after flowering or during the full crop cycle differed both within and between experiments (Figure 6.1 for 2002, Table 6.5 for all experiments). There was also a positive correlation between zinc taken up after flowering and zinc taken up before flowering in all experiments. In all experiments the correlation between grain zinc yield and zinc uptake was strongest for zinc taken up after flowering and total zinc uptake. In the different experiments different factors were included in the model that best accounted for variation in grain zinc yield (Table 6.5), generally by allowing different intercepts for different treatments or treatment levels. Only in four cases also differences in slopes were significant (P<0.05), i.e. P*X (2002), Zn*X (2003, pot experiment) and twice OM*X (2002 and 2003 field experiment) (Table 6.5). In the first two cases this concerned the correlation between grain Zn yield and uptake before flowering, only the slope differences related to the organic matter treatments were relevant for the relation with total zinc uptake.

6.3.3 Sorghum grain IP6 mass fraction (IP6-MF)

Sorghum grain IP6-MF was different for the three cropping seasons. Sorghum grain IP6-MF for comparable treatments (sandy soil, compost, all combinations of Zn and P) was on average higher in 2002 (5.32 mg g^{-1}) than in the 2003 (2.98 mg g^{-1}) and 2004 (2.65 mg g^{-1}) field experiments.

Soil type affected sorghum grain IP6-MF only in the 2002 field experiment, and not in the 2004 experiment. In 2002, the soil type main effect and two-way interactions including soil type were overruled by the significant three-way interaction between soil type, organic manure type and Zn application (Table 6.6). Sorghum grain IP6-MF was comparable for sandy and gravely soil without Zn application. When Zn was applied sorghum grains from the compost-amended sandy soil showed higher IP6-MF than the ones from the compost-amended gravely soil. This effect was not significant when farmyard manure was applied. An interaction was also observed between organic amendment type and P and Zn fertilisers.

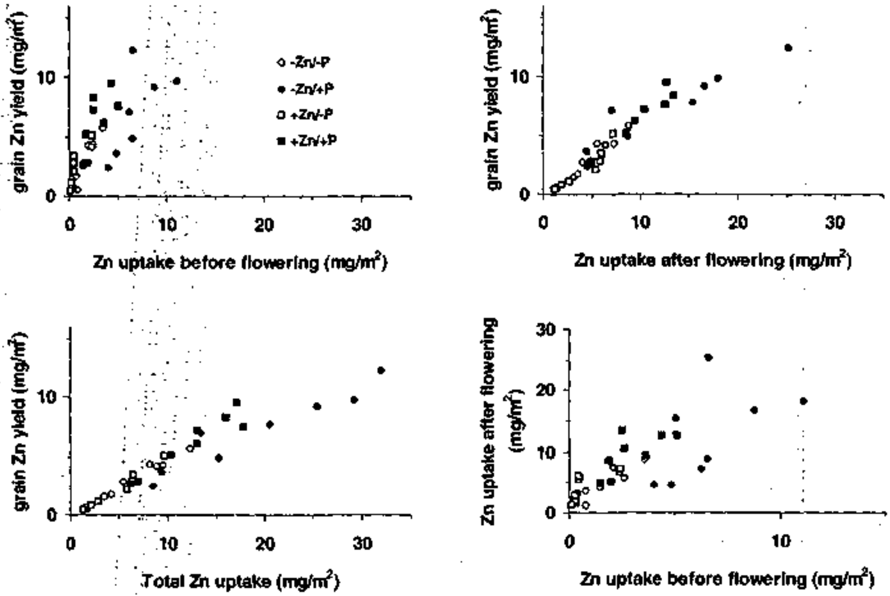

Figure 6.1 *Correlations between grain zinc yield and zinc uptake during different crop growth periods and between zinc uptake after flowering and zinc uptake before flowering for the 2002 field experiment. The statistics of the regression analyses are summarised in Table 6.5.*

Compost application resulted always in higher sorghum grain IP6 than farmyard manure application. But when no Zn was applied the difference between the two organic manure types was higher without P application (1.82 mg g^{-1}) than with P application (0.97 mg g^{-1}). When Zn was applied the opposite situation was observed and the difference between the two organic manure types was higher with P application (1.64 mg g^{-1}) than without P application (0.56 mg g^{-1}). The main effect of P application was significant in 2002 irrespective of the above interactions and it significantly affected grain IP6-MF in all the cropping seasons (Tables 6.6–6.8). The main effect of Zn application on sorghum grain IP6 was only significant in the 2002 field experiment (Tables 6.6–6.8). The interactions with P application in 2004 overruled the Zn main effect. Zn only affected IP6-MF when no P was applied simultaneously.

Table 6.5 *Summary of regression analyses of the relations between grain Zn yield and Zn uptake before flowering, Zn uptake after flowering or Zn uptake during the full crop growth, and the relation between Zn uptake after flowering and Zn uptake before flowering in all three field experiments and the 2003 pot experiment.*

model includes: Variable (=X) *Additional significant model terms*	**Total variance** *Residuals*	**Total df** *Res. df*	F-value	% variance accounted for
2002 field, grain Zn yield (mg m^{-2}) (=Y)	**9.709**	**31**		
Zn uptake before flowering (mg m^{-2})	*3.760*	*30*	<0.001	61.2
P, Zn, Soil type, Soil type Zn, P*X, X^2*	*0.482*	*24*	<0.001	95.0
Zn uptake after flowering (mg m^{-2})	*0.896*	*30*	<0.001	90.8
X^2	*0.595*	*29*	<0.001	93.9
Total Zn uptake (mg m^{-2})	*0.949*	*30*	<0.001	90.2
*OM, OM*X, Soil type*	*0.422*	*27*	<0.001	95.7
2003 field, grain Zn yield (mg m^{-2}) (=Y)	**0.643**	**31**		
Zn uptake before flowering (mg m^{-2})	*0.294*	*30*	<0.001	54.2
P	*0.254*	*29*	0.02	60.4
Zn uptake after flowering (mg m^{-2})	*0.366*	*30*	<0.001	43.0
P,Zn	*0.191*	*28*	0.001	70.3
Total Zn uptake (mg m^{-2})	*0.252*	*30*	<0.001	60.8
*OM, OM*X, Soil type*	*0.174*	*28*	0.002	72.9
2004 field, grain Zn yield (mg m^{-2}) (=Y)	**22.78**	**31**		
Zn uptake before flowering (mg m^{-2})	*16.5*	*30*	0.001	27.5
Zn	*13.7*	*29*	0.01	40.1
Zn uptake after flowering (mg m^{-2})	*12.8*	*30*	<0.001	43.7
none	-	-	-	-
Total Zn uptake (mg m^{-2})	*12.0*	*30*	<0.001	47.3
*Soil type, Soil type*X*	-	-	-	-
2003 pot, grain Zn yield (mg pot^{-1}) (=Y)	**0.150**	**53**		
Zn uptake before flowering (mg pot^{-1})	*0.084*	*52*	<0.001	44.3
*Zn, OM, P, OM*Zn, P*Zn, Zn*X*	*0.009*	*39*	<0.001	93.8
Zn uptake after flowering (mg pot^{-1})	*0.039*	*52*	<0.001	74.2
*Zn, OM, P, OM*Zn, P*Zn, OM*P*	*0.009*	*39*	<0.001	94.1
Total Zn uptake (mg pot^{-1})	*0.010*	*52*	<0.001	93.2
none	-	-	-	-
Zn uptake after flowering (mg m^{-2} or pot^{-1})(=Y)				
2002 field, Zn uptake before flowering(mg m^{-2})	*13.13*	*30*	<0.001	56.8
*P, Zn, Soil type, P*X*	*4.86*	*26*	<0.001	84.0
2003 field, Zn uptake before flowering (mg m^{-2})	*8.64*	*30*	0.005	20.8
none				-
2004 field, Zn uptake before flowering (mg m^{-2})	*93.56*	*30*	<0.001	30.8
Zn, P	*11.36*	*28*	<0.001	90.6
2003 pot, Zn uptake before flowering (mg pot^{-1})	*0.669*	*52*	0.025	7.5
*Zn, OM, P, OM*Zn, P*Zn, OM*P, OM*P*Zn, Zn*X*	*0.009*	*33*	<0.001	98.7

In the greenhouse experiment of 2003, the high compost dose gave higher IP6-MFs than the lower dose (Table 6.9). P application resulted in higher sorghum grain IP6 than no P application. No significant difference was observed between P application at sowing or at anthesis.

Table 6.6 *Sorghum grain IP6-MF (mg g^{-1}) as affected by Zn and P fertilisers, organic amendment type and soil type. Field experiment in Somyaga in 2002, n =32.*

		Sorghum grain IP6 (mg g^{-1})					
		–Zn			+Zn		
Soil type	OM	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	Compost	2.10	5.57	*3.84*	3.33	7.32	*5.32*
	FYM	0.50	4.50	*2.52*	3.13	6.38	*4.75*
		1.32	*5.03*		*3.23*	*6.85*	
Sandy	Compost	2.40	5.43	*3.91*	4.21	9.22	*6.72*
	FYM	0.33	4.56	*2.45*	3.30	6.89	*5.09*
		1.37	*5.00*		*3.75*	*8.06*	

	*OM***	*Zn***	*P***	*Soil type***	*Soil type × Zn***	*Soil type × OM**	*Soil type × OM × Zn**	*OM × Zn × P***
LSD	*0.23*	*0.23*	*0.23*	*0.23*	*0.32*	*0.32*	*0.45*	*0.45*

* Significant at $p<0.05$

** Significant at $p<0.01$

Table 6.7 *Sorghum grain IP6-MF (mg g^{-1}) as affected by Zn and P fertilisers in a sandy composted soil. Field experiment in Somyaga in 2003, n =32.*

	Sorghum grain IP6 (mg g^{-1})		
	–P	+P	*Mean*
–Zn	2.35	3.81	*3.08*
+Zn	2.28	3.50	*2.89*
	2.32	*3.65*	
	P: p<.001, LSD = 0.42		

Table 6.8. *Sorghum IP6-MF (mg g^{-1}) as affected by Zn and P fertilisers and soil type. Field experiment in Somyaga in 2004, n = 32.*

	Sorghum grain IP6 (mg g^{-1})					
	–Zn			+Zn		
Soil type	–P	+P	*Mean*	–P	+P	*Mean*
Gravely	1.21	3.14	*2.18*	2.21	4.29	*3.25*
Sandy	1.09	3.65	*2.37*	2.41	3.43	*2.92*
Mean	*1.12*	*3.53*		*2.36*	*3.64*	*2.65*
	Zn: p = 0.021, LSD = 0.56; P: p<.001, LSD = 0.56; Zn × P: p = 0.05, LSD = 0.80					

Table 6.9 *Sorghum IP6-MF (mg g^{-1}) as affected by compost dose and the timing of Zn and P fertiliser supply. Greenhouse experiment 2003, n = 54.*

		Sorghum grain IP6 (mg g^{-1})			
OM rate	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	2.52	3.19	3.39	*3.04*
	P at sowing	4.26	3.84	3.78	*3.96*
	P at anthesis	4.29	3.99	3.80	*4.03*
Mean		*3.63*	*3.67*	*3.66*	
10 kg pot^{-1}	No P	3.40	3.12	3.33	*3.28*
	P at sowing	5.39	5.69	5.03	*5.37*
	P at anthesis	4.53	4.35	4.23	*4.37*
Mean		*4.44*	*4.38*	*4.20*	

Sig	*P***	*OM**
LSD	*0.55*	*0.45*

* Significant at $p<0.05$
** Significant at $p<0.01$

6.3.4 IP6: Zn molar ratio

Considering comparable treatment combinations, IP6: Zn molar ratio in sorghum grains was on average higher in the field experiment in 2003 (20) than in 2002 (16) and 2004 (8). As for Zn and IP6 the results in 2002 were most complicated to interpret. Soil type did not affect the ratio in the 2002 field experiment (Table 6.10). In the 2004 field experiment a significant three-way interaction was found between soil type, Zn and P applications (Table 6.12), which overruled the main effects of both Zn and P. IP6: Zn molar ratio was significantly reduced by Zn application only on the gravely soil when no P was applied.

Table 6.10 *IP6: Zn molar ratio as affected by Zn and P fertilisers, organic amendment (OM) type and soil type. Field experiment in Somyaga in 2002, n =32.*

		IP6:Zn molar ratio					
		−Zn			+Zn		
Soil type	OM	−P	+P		−P	+P	
Gravely	Compost	17.4	19.9	*18.6*	10.6	15.7	*13.1*
	FYM	9.34	19.8	*14.6*	11.8	14.0	*12.9*
		13.4	*19.8*		*11.2*	*14.8*	
Sandy	Compost	17.1	20.4	*18.7*	10.3	16.3	*13.3*
	FYM	3.35	18.6	*11.0*	7.82	13.4	*10.6*
		10.2	*19.5*		*9.06*	*14.6*	

Significance	*Zn**	*P***	*OM***	*OM × Zn**	*OM × P**	*OM × Zn × P**
LSD	*1.73*	*1.73*	*1.73*	*2.45*	*2.45*	*4.91*

* Significant at $p<0.05$
** Significant at $p<0.01$

Table 6.11 *IP6: Zn molar ratio as affected by Zn and P fertilisers in a sandy composted soil. Field experiment in Somyaga in 2003, n = 32.*

	IP6: Zn molar ratio		
	–P	+P	
–Zn	17.6	26.0	*21.8*
+Zn	14.1	20.5	*17.3*
	15.8	*23.2*	
	P: p<.001, LSD = 3.22;		
	Zn : p = 0.009, LSD = 3.22		

Table 6.12 *IP6: Zn molar ratio as affected by Zn and P fertilisers and soil type. Field experiment in Somyaga in 2004, n = 32.*

	IP6:Zn molar ratio					
	–Zn			+Zn		
Soil type	–P	+P		–P	+P	
Gravely	14.4	13.1	*13.7*	4.13	10.5	*7.31*
Sandy	7.31	13.5	*10.4*	5.71	6.98	*6.34*
	10.8	*13.3*		*4.92*	*8.74*	
	Zn: p = 0.002, LSD = 2.65;					
	P: p = 0.014, LSD = 2.65;					
	Soil type × Zn × P: p = 0.045, LSD = 7.49					

The three-way interaction between organic amendment type, Zn and P in 2002 overruled the main effect of organic amendment type and the two way interactions between organic amendment and Zn and organic amendment and P, as well as the main effects of zinc and P. In the 2002 field experiment, the grains from compost amended plots had a higher ratio than those from farmyard manure amended ones only when no Zn and no P were applied (Table 6.10). Zn application reduced the ratio only when combined with no P and with compost, or when combined with P application and farm yard manure. P application increased the ratio in 2002 only when combined with farmyard manure at no Zn application or when combined with compost and Zn application (Table 6.10). In 2003 (Table 6.11) the IP6: Zn molar ratio increased with P application, while the effect of Zn application was to reduce the IP6: Zn molar ratio.

Compost dose, P and Zn timing in the pot experiment all proved to affect IP6: Zn molar ratio, but interactions between Zn and compost dose and between Zn and P overruled main effects of P, Zn and compost dose. The high compost dose showed lower IP6: Zn molar ratio than the low compost rate when Zn was applied either at sowing or at anthesis. Zn applied at anthesis showed lower IP6: Zn molar ratio than when it was applied at sowing, which in turn gave a lower ratio than when no zinc was applied, but only when P was applied. The effect of P application was to increase the IP6: Zn molar ratio when no Zn was applied or when P was applied at sowing and Zn was applied at sowing (Table 6.13). Timing of P application did increase the ratio slightly more when applied at sowing while no Zn was applied.

Table 6.13 *IP6: Zn molar ratio as affected by compost dose and the timing of Zn and P fertiliser supply. Greenhouse experiment 2003, n = 54.*

		IP6:Zn molar ratio			
Compost dose	P treatment	No Zn	Zn at sowing	Zn at anthesis	*Mean*
5 kg pot^{-1}	No P	15.7	17.0	16.0	*16.2*
	P at sowing	27.0	20.4	16.7	*18.0*
	P at anthesis	27.1	23.0	13.3	*21.1*
Mean		*23.3*	*20.1*	*15.3*	
10 kg pot^{-1}	No P	19.3	10.8	11.4	*13.8*
	P at sowing	29.7	21.3	11.1	*20.7*
	P at anthesis	22.7	12.6	8.33	*14.5*
Mean		*23.9*	*14.9*	*10.3*	

Significance	*Zn***	*P***	*OM**	*Zn × P**	*Zn × OM**
LSD	*2.42*	*2.42*	*1.97*	*4.18*	*3.42*

* Significant at $p<0.05$
** Significant at $p<0.01$

6.4 Discussion

6.4.1 Zn mass fraction (Zn-MF)

Grain Zn-MF increases with both Zn and P fertilisers in most of the studied situations. This is the consequence of the positive impact of these fertilisers on Zn uptake as reported in Chapter 5. These results are in line with those reported by Rupa *et al.* (2003) for soils with similar chemical characteristics and Cakmak *et al.* (1999), Grusak *et al.* (1999) and Rengel *et al.* (1999) for more alkaline conditions.

The soil type affected sorghum grain Zn-MF differently only when Zn was applied. The possible reason for that could be that the gravely soil with 78% more clay reduced the availability and uptake of the applied Zn (Chapter 3 and 5), thus leading to a higher grain Zn-MF for sorghum grown on the Zn amended sandy soil than for sorghum grown on the Zn amended gravely soil.

The very low grain Zn-MF in 2003 (a year with hardly any rain during grain filling) indicates that Zn in the grain may primarily come directly from Zn uptake during grain filling, rather than from re-translocation within the plant. The difference in grain Zn-MF in fact was accompanied by a much greater relative difference in Zn uptake as reported earlier (Traore *et al.*, 2006c). This is probably why Grusak *et al.* (1999) reported that plants suffering from nutrient deficiency during reproductive development may rely totally on reserves within the roots, stem and leaves for nutrient content of seeds. It can be seen from figure 6.1 that in 2002 most zinc was taken up by the crop after flowering, this was also found in the other experiments (data not shown). The combination of the much stronger correlation between grain zinc yield and uptake after flowering on the one hand and much higher uptake after flowering on the other hand seems to indicate that the zinc allocated to the grain is mainly the zinc taken up during grain filling. The clearly weaker correlation between grain zinc yield and zinc uptake in the 2003 and 2004 field experiments was observed in years when total uptake was much lower and more variable probably due to the dry conditions during grain filling. This supports the assumption that a limited amount of zinc can be accounted for by the zinc taken up before flowering. Had more zinc be taken up during grain filling both the total uptake and the correlation between grain Zn yield and uptake after flowering had been higher. The lack of differences in slopes of the relation between grain zinc yield and uptake after flowering for the different levels of P or Zn fertiliser application indicates the applications did not affect the physiology of grain allocation, but merely changed the uptake.

The fact that in 2004, when rainfall during grain filling was also rather poor, grain Zn-MF was comparable to that in 2002 under good rainfall conditions is an indication that differences in weather conditions are not easy to interpret, while also the added nitrogen in 2004 may have played a role. The higher grain Zn-MF in 2004 was accompanied by a much higher Zn uptake (Chapter 5) The moderate effects on grain quality in the 2003 experiment highlights the need for enough water in the soil during grain filling for an adequate Zn uptake and allocation to the grain. This can be manipulated to some extent by farmers through improved soil and water conservation practices that allow capture of all rainfall, avoiding runoff losses (Stroosnijder, 2003). As the Zn and P fertiliser effects on productivity has been positive even under those conditions (Chapter 4), the lack of effect on quality in years with very poor conditions during grain filling does not hamper the economic efficiency, while in such years the quantity of food that is available will be of more importance than the quality of this food. The pot experiment has indicated that there may be advantage in applying more compost than current practice and that if this were done with Zn application at early flowering it would further enhance grain Zn-MF. This does not at present seem a realistic option, though, in the context of these farming systems as compost is not readily available and increasing application doses will be at the expense of the area that can be manured, while the additional complication of applying fertilisers at flowering simply for the sake of quality does not fit major goals of farmers (Chapter 2).

6.4.2 Sorghum grain IP6-MF and Zn bio-availability

The improved mass fraction following organic and/or inorganic amendments does not necessarily lead to more Zn bio-availability for humans consuming the grains. In fact, the enhanced grain Zn-MFs were always accompanied by an enhanced grain IP6-MF, though, this is more strongly so when P fertiliser was applied. The same results were reported by Buekert *et al.* (1998) for pearl millet *Pennisetum glaucum* L. with the application of P and crop residues to acid sandy soils in Niger. The IP6: Zn molar ratio has been indicated by Cakmak *et al.* (1999) as a suitable estimation of Zn bio-availability in food and for risk of occurrence of Zn deficiency in humans. The IP6:Zn ratio under farmers' practices, which include either compost or farmyard manure applications as used in the reported field experiments were rather high given reported critical levels of 15 for bio-availability to human consumers (Rengel *et al.*, 1998). Addition of Zn alone could improve quality and yield, but as P application has a larger effect on yield, this does not seem a logical option for farmers. As P application alone enhances IP6-MF more than it does Zn-MF the ratio increases leading to lower bioavailability of the extra accumulated Zn. When we consider the periodic food shortages in the Sahel (Buekert *et al.*, 1998) because of erratic climatic conditions, any discussion of possible negative effects of P-fertiliser application on the nutritional quality of cereals can appear of minor importance. This seems particularly true if one considers the large benefits in terms of grain yield increases after the application of P and the fact that with larger grain consumption also the total Zn intake increases (Buekert *et al.*, 1998). The combined application of Zn and P fertilisers keeps the IP6: Zn ratio roughly at its current level, but at much higher yield levels (Chapter 4), and at much higher grain Zn-MF. The food quality of such grains can be further improved by degradation of phytate prior to consumption and this can be done by applying appropriate food processing methods.

The above on Zn and IP6-MFs holds for P and Zn application to compost amended sandy soils. The reported interactions between these treatments and soil type or organic amendments, though, do not make the general story very much different. Without Zn and P application the soils and organic amendments give comparable results. With Zn and/or P application the advantages for grain quality seem slightly less with farmyard manure and on gravely soils, but the differences are not putting the advantages at stake altogether. Polycarpe *et al.* (2006) reported a two-fold difference between sorghum accessions (14.5 – 34 mg kg^{-1}) in grain Zn-MF studied in northern Benin. This indicates that there may be further scope to enhance grain Zn-MF if the here tested fertility management options were combined with different genotypes. Obviously, also further understanding of the applicability of these results to other soils in the Sahel and at other rainfall patterns or for other cereals like millet or maize is needed.

6.5 Concluding remarks

On the basis of the current study the most important conclusions are:

- Zn and IP6-MFs are increased with Zn and/or P application, but P application affects IP6-MF more than it does Zn-MF, while Zn affects Zn-MF more than it does IP6-MF;
- The combined application of Zn and P leads to the highest grain Zn-MF and generally also to the highest grain IP6-MF;
- IP6/Zn molar ratio is increased with P application and decreases with Zn application;
- At the tested doses of P and Zn fertiliser, the IP6:Zn molar ratio is of the same order of magnitude when either no P and Zn are applied or when Zn and P fertilisers are combined;
- Rainfall conditions affect both Zn and IP6-MF leading to large differences between years in both MFs and in their ratio, the latter as year-to-year changes in the MF are different between Zn and IP6;
- The extent of the effect of P and Zn fertilisers on sorghum grain Zn and IP6-MF tends to differ between soil and organic amendment type, but not the trend of these effects.
- The zinc allocated to the grains seems to come mainly from uptake during grain filling, and fertiliser application did not change the relation between grain zinc yield and uptake after flowering, but led to more grain allocation through enhanced uptake.

Overall, organic amendments associated with P and Zn fertilisers are good options for higher crop yield and reasonable grain quality. But for higher Zn bio-availability, the IP6 in the sorghum grain produced under such conditions should be degraded to IP-3 or lower saturated IP forms prior to consumption. Proper food processing will be needed to counter the negative effect of IP6 on Zn bio-availability, as the lower IP6:Zn molar ratio that can be obtained without P fertilisation would imply too high a cost in forsaken productivity.

Chapter 7

Effect of water stress on sorghum yield and grain quality (P, Zn and phytate) in the Sahel

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Submitted

7. Effect of water stress on sorghum yield and grain quality (P, Zn and phytate) in the Sahel

7.1 Introduction

Crop production in the Sahel relies almost exclusively on erratic rainfall with poor distribution in time and space. The consequence is a variable crop yield. Many studies have revealed the negative impact of water stress on crop production in the Sahel (Graef and Haigis, 2001, INERA 2003). Water stress due to drought is a key factor constraining economic development and threatening food security. Water stress has severe consequences on both soil and plant factors. In plants, water stress corresponds to the situation in which leaf water potential and turgor are reduced enough to interfere with normal plant functions. For Zhang (1997) temporary or permanent water stress limits the growth and the performance of cultivated plants more than any other environmental factor.

Under severe water stress there is an arrest of photosynthesis, disturbance of metabolism and ultimately the plant dies (Zhang, 1997). Samarah et al. (2004) indicated that water stress reduces dry matter accumulation and the size and weight of seeds depending upon the time, duration and severity of the stress. Nutrient availability, uptake and transport are also impaired when water is insufficient (Mengel and Kirkby, 1987; Hesterman and Carter, 1990; Isaakidis et al., 2004). Water stress also has an important impact on nutrient mass fractions of the grain. Especially when water stress occurs during the grain filling stage it has been observed to increase the concentration of nutrients in seeds of several crops (Farghali and Saleh, 2001; George and Niessan, 2002, Samarah et al., 2004), including the concentrations of micronutrients.

It is well documented that cereals may contain high concentrations of anti nutritional compounds (phytates, polyphenols) which reduce the availability of micronutrients for human metabolism (Cakmak et al., 1999; Bouis et al, 2000; Frossard et al., 2000). From these compounds, phytate is arguably the most important and will therefore be considered in this study as well as the phytate/Zn molar ratio necessary to evaluate the Zn bio availability. Phytate is a generic name used for inositol phosphates of which the inositol hexa-cis phosphate (IP6) is the major component in dry seeds of cereals. The effect of water stress on both micronutrients and IP6 mass fractions in grain cereals under organic and inorganic amendments conditions has received little attention.

The main objective of the current study was to evaluate in a pot experiment, the effects of combining soil organic and inorganic amendments on sorghum (*Sorghum bicolor* (L.) Moench) grain yield and grain Zn and IP6 mass fractions under different soil water conditions. We hypothesize that water stress changes: a) Zn availability in the soil, b) Zn uptake by sorghum, c) sorghum grain Zn mass fraction, and d) sorghum grain phytate mass fraction. We assume that the effects listed above will be different depending on whether water stress is imposed during the early stages or during grain filling.

7.2 Materials and methods

7.2.1 Experimental design

The experiment was carried out in a greenhouse at the Kamboinsé Research Centre, 10 km north of Ouagadougou in Burkina Faso. The experiment was initiated on July 27 and terminated on November 18, 2004. Plastic pots of 15 litres were filled with a mixture of sandy acidic Luvisol and compost in a weight ratio of 2:1 on July 27, 2004. The pots contained 14 litres or 21 kg of medium (14 kg soil and 7 kg of compost). This soil/compost mixture was chosen to simulate a farmers' practice called 'zaï'. In this soil and water conservation practice, farmers do not broadcast organic amendments but mix organic amendments in the planting holes. In the top 14 liters of these planting pits the soil/organic amendment ratio is comparable to that in our pots. The characteristics of the sandy soil and compost are summarized in Table 7.1.

Table 7.1 *Chemical properties of the (sandy) soil and compost used in the greenhouse experiment, 2004.*

	Clay (%)	C-total (%)	N-total (%)	P-total ($g\ kg^{-1}$)	Zn-total ($mg\ kg^{-1}$)	pH-water
Soil	18.5	0.92	0.06	0.9	2.7	5.25
Compost	-	8.19	0.57	1.28	68.5	-

The soil and compost were collected from the site where a previous field experiment was conducted (Chapter 3). The sandy acidic Luvisol was collected from a farmers' field (Zorome Boukary) in Somyaga in northern Burkina Faso. The compost used in the pots was produced by a farmer (Zorome Boureima dit Barry) from the same village.

After filling with the mixture, the pots were watered till field capacity (FC[1]) and the water was allowed to redistribute through the pots during 3 days before sorghum was planted. A perforated PVC tube of 2 cm diameter was inserted in the middle of the pots to facilitate pot watering. Inorganic fertilizers (urea, triple super phosphate (TSP), and $ZnSO_4$) were mixed with this water.

Sorghum seeds of the cultivar IRAT 204 were pre-germinated to create uniformity for all pots and four seeds were sown in the pots on August 1, 2004. Seedlings were thinned to two per pot after two weeks.

Pots in well-watered treatments (NS) were daily watered till field capacity. The water status of pots was monitored by weighing the pots twice a day (morning and afternoon). Pot weights were corrected for plant weight using an empirical relation between height and plant weight that was determined in a separate experiment. It was made sure that soil water

[1] Data from a previous experiment gave the following values for soil physical properties: pF 2.5 (field capacity, FC, n = 4) = 16.6 ± 2.3 % weight (% w), pF 4.2 (permanent wilting point, WP, n = 4) = 6.15 ± 0.2 % weight (% w) and soil bulk density (BD, n = 9) = 1.56 ± 0.06 ($g\ cm^{-3}$). The % volume at FC and WP were calculated as: pF 2.5 (% volume) = pF 2.5 (% weight) × BD = 16.6 × 1.56 = 25.9 % volume and pF 4.2 (% volume) = pF 4.2 (% weight) × BD = 6.15 * 1.56 = 9.6 % volume. Mass of water at FC = 25.9 % × 14 000 (pot volume filled with mixture) = 3630 g and at WP = 1350 g.

conditions were always in the 'readily available water' (RAW) range (Figure 7.1). For sorghum this RAW is assumed to be 55 % (Allen et al., 1998) of the total available water (TAW). TAW is the amount of water between FC and wilting point (WP).

From September 7 to 17, 2004 (30–40 days after emergence, during early panicle formation) 36 pots were exposed to a 10 days water stress (S1). From October 15 to 25, 2004 (70–80 days after emergence, during grain filling), a second set of 36 pots was exposed to water stress (S2). In the water stressed pots, water stress was induced by withholding irrigation. At the beginning of the stress periods, pots were left to dry till a predetermined moisture content of 11.3 % (volume), determined by daily weighing. This value corresponds to the situation where 90 % of the total available water (TAW) is depleted, see Figure 7.1.

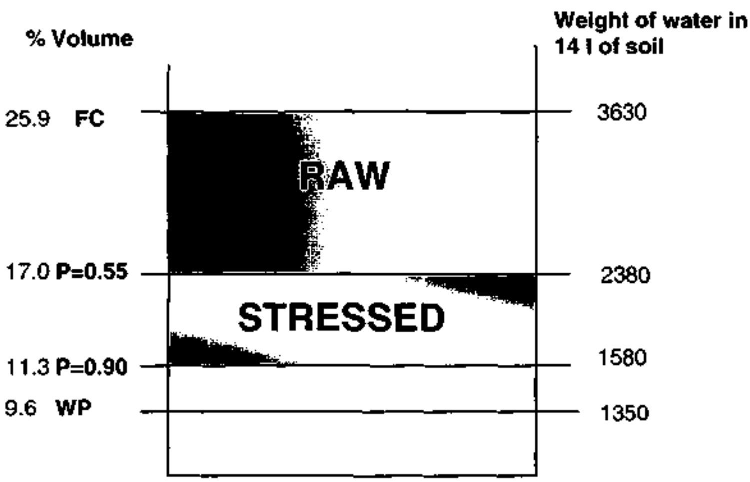

Figure 7.1 *Moisture content limits that define stress in the pot experiment. For explanation see text.*

During the stress period the volumetric moisture content in the pots was kept between the lower limit of 11.3 % (or 90 % depletion of TAW) and 17.0 % (or 55 % depletion of TAW). With a medium volume of 14 liters this corresponds to amounts of water between 1580 and 2380 grams (see also Figure 7.1) or a difference of only 800 grams. This made it necessary to weigh the pots twice a day and to irrigate small amounts when the lower limit was reached. After each 10-day stress period, the stressed pots were again watered till field capacity.

Pots were placed in the greenhouse in six blocks (repetitions) and the treatments were randomly placed within the blocks. The treatment structure consisted of all combinations of two P levels (–P, +P applied as TSP; 6.88 g P_2O_5 pot^{-1}) and two Zn levels (–Zn, +Zn applied as $ZnSO_4$; 0.74 g Zn pot^{-1}). All pots received 1.8 g N pot^{-1} as urea.

7.2.2 Sampling and analysis

For each treatment, three soil samples were taken from three pots at random at 0–20 cm before sowing sorghum (August 1, 2004), at 50 % flowering (September 25, 2004) and at maturity (November 18, 2004). Three samples of sorghum above ground biomass were collected at 50 % flowering and at maturity in three pots. For each treatment, sorghum grains from three pots were harvested at maturity.

Soil and plant samples were stored in plastic bags and sun-dried at the Kamboinsé Research Centre and a sub-sample of 20 g was prepared for chemical analysis. These sub-samples were ground over a 2 mm mesh sieve. Total soil and plant Zn was mineralized using a mixture of sulfurous acid (H_2SO_4) and salicylic acid ($C_7H_6O_3$) in the presence of hydrogen peroxide (H_2O_2) and selenium (as a catalyst). Zn available in the soil was analyzed using 5 g of air dried soil placed in a 250 ml plastic bottle fitted with an air-tight screw cap and 50 ml of 1% EDTA. The suspension was mixed on a reciprocating shaker for one hour and filtered through Watman paper No. 542 (Norvell, 1989). Solutions for total and available Zn were analyzed by Atomic Absorption Spectrometry (AAS). For phytate analysis a sample of dried powder from grains was extracted in 1 ml HCl (0.5 N) at 100 °C for 15 minutes. The solution was diluted 10 × in mQ-water. Total phytate was determined by HPLC-analysis on a Dionex AS11 column Detection by suppressed conductivity.

Data were analyzed using analysis of variance (ANOVA) and the means were separated using the least significant difference (LSD) at a probability of 5 %. Zn uptake, Zn harvest index and phytate/Zn molar ratio were calculated as follows:

- Zn uptake at flowering (mg pot^{-1}) = [Zn mass fraction in above ground plant parts (mg kg^{-1})] × [dry weight of above ground plant parts (kg pot^{-1})],
- Zn uptake at maturity (mg pot^{-1}) = [Zn in straw (mg kg^{-1}) × straw dry weight (kg pot^{-1}] + [Zn in grain (mg kg^{-1}) × grain dry weight (kg pot^{-1})],
- Zn harvest index = Zn in grain (mg pot^{-1}) / [Zn in straw (mg pot^{-1}) + Zn in grain (mg pot^{-1})],
- Phytate/Zn molar ratios were calculated assuming a molar weight for IP-6 of 651 and for zinc of 65.

7.2.3 Water stress measurement

To have an independent check of actual water stress levels, the water status of the plants was monitored by measuring the leaf water potential. Leaf water potential was measured using a leaf hygrometer/psychrometer model L-51 coupled with an HR-33T Dew Point Micro voltmeter. The measurements were done on the two upper most developed leaves, in the middle of the leaf every day from 10–14 h. The measurement concerned four stressed pots and four non-stressed pots every day. One plant per pot was selected and the measurement was repeated twice per day which makes for each water regime 4 plants × 2 leaves × 2 replications =16 values.

The section of the leaf tissue to be tested was cleaned with distilled water then inserted in the lateral slot of the sensor body. A small bead of 90 % lanolin oil and 10 % wax was placed on the base of the chamber. The chamber was clamped and sealed to the leaf. The system was allowed to reach equilibrium. Leaf water potential was calculated using the following equation: reading value (mV)/ -0.47 mV bar^{-1}.

7.3 Results and analysis

7.3.1 Water stress imposition

Impact of water stress on leaf water potential

The application of the S1 was associated with an abundant rainfall period (early September) with high air humidity and low incoming light. Therefore, the impact of S1 on the physiology of the plants was only minor and the results show that the effect of this early water stress was very low compared to the control situation. This is why nothing is reported here on leaf water potential during that period.

Plants subject to water stress during grain filling (S2) showed a gradual decrease in leaf water potential from the first to the fourth day after stress imposition (from -2 bars to -5 bars) and a rapid decrease from the fourth to the fifth day, fell till -8.5 bars (Figure 7.2) and then water was added. Leaf water potential in stressed pots remained between -4 bars and -8 bars over the 10 days stress period. For well-watered plants, leaf water potential was around -2 bars.

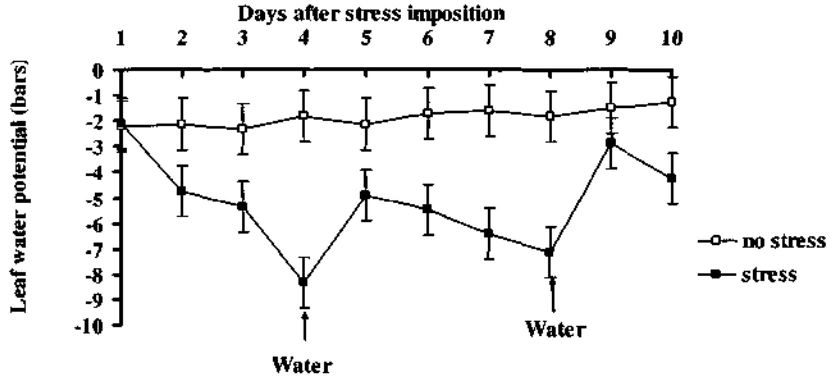

Figure 7.2 *Leaf water potential (10–14 h) during water stress imposed at grain filling(S2) measured by leaf hygrometer/psychrometer model L-51 coupled with an HR-33T Dew Point Micro voltmeter. Pot experiment, 2004. Average and SD of 10 measurements*

Impact of water stress on sorghum straw dry weight and grain yield

At 50 % flowering sorghum biomass was only affected by P application. P application significantly increased sorghum biomass yield (Table 7.2). Nor Zn application neither stress imposition affected biomass yield at flowering.

At maturity both straw dry weight and grain yield were affected by water stress and P and Zn fertilizers (Table 7.3). A significant three-way interaction between water stress and Zn and P fertilizers was found for the straw yield. Without Zn and P fertilizers, sorghum straw yield was comparable for NS and S1 and higher than for S2. Without Zn and with P fertilizer, the straw yield was in the order NS > S1 > S2. The same order was observed with Zn application and without P. With the combined application of both fertilizers the straw yield was comparable for S1 and S2 and lower than for NS (Table 7.3). The main effects of stress, P and Zn fertilizers were also significant.

Table 7.2 *Sorghum biomass (dry weight) at flowering as affected by water stress and Zn and P fertilizers. Pot experiment, 2004. NS = no stress, S1 = 10-days stress during panicle formation.*

	Sorghum biomass yield (g pot^{-1})					
	–Zn			+Zn		
	–P	+P	*Mean*	–P	+P	*Mean*
NS	9.93	11.7	*10.8*	11.1	13.3	*12.2*
S1	9.75	10.9	*10.3*	10.9	12.6	*11.7*
Mean	*9.84*	*11.3*		*11.0*	*12.9*	
	P: p=0.032, LSD = 1.55					

Table 7.3 *Sorghum yield (straw and grain dry weight) at maturity as affected by water stress and Zn and P fertilizers. Pot experiment, 2004. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

		Sorghum yield (g pot^{-1})					
		–Zn			+Zn		
		–P	+P	*Mean*	–P	+P	*Mean*
Straw	NS	31.0	36.7	*33.8*	34.2	36.2	*35.2*
	S1	30.2	31.7	*31.0*	30.4	33.7	*32.1*
	S2	20.3	24.7	*22.5*	23.1	32.1	*27.6*
	Mean	*27.2*	*31.0*		*29.2*	*34.1*	
Grain	NS	25.7	29.3	27.5	27.2	30.0	*28.6*
	S1	24.8	26.0	25.4	25.2	28.3	*26.7*
	S2	15.2	19.1	17.1	17.9	26.5	*22.2*
	Mean	*21.9*	*24.8*		*23.4*	*28.3*	

	Stress	*Zn*	*P*	*Stress x Zn*	*Stress x P*	*Stress x Zn x P*
Straw	*** 0.89[a]*	*** 0.73*	*** 0.73*	*** 1.26*	*** 1.26*	*** 1.78*
Grain	*** 1.51*	** 1.23*	*** 1.23*	** 2.13*	** 2.13*	*ns*

* *Significant at p<0.05, ** Significant at p<0.01, ns= non significant, a= LSD*

For sorghum grain yield, significant interactions were found between stress and P or Zn fertilizers. Without Zn, sorghum grain yield was in the order NS > S1 > S2. With Zn application, sorghum grain yield was comparable for NS and S1 and higher than for S2. This was consistent with or without P application (Table 7.3).

7.3.2 Zn availability as affected by P and Zn fertilizers and water stress

Zn availability in the soil was significantly increased by applying Zn fertilizer from sowing until maturity (Table 7.4), independent of P application. At flowering, Zn availability was affected by the previous water stress. Zn availability was lower in the water-stressed pots than in the control pots (Table 7.4). At maturity, Zn availability was also affected by water stress imposition and Zn fertilizer. Zn availability was higher in stressed pots than in the control pots and was also higher after Zn application than without Zn fertilizer. An interaction was observed between water stress and Zn fertilizer. Without Zn fertilizer, Zn availability was in the order S2 > S1 > NS. With Zn fertilizer, Zn availability was comparable for NS and S1 pots while it was highest for S2 pots (Table 7.4). At all sampling periods P application did not affect Zn availability.

Table 7.4 *Zn availability in the soil as affected by P and Zn fertilizers and water stress. Pot experiment 2004, n= 36. NS= no stress, S1= 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

		Available Zn (mg kg^{-1})					
		– Zn			+Zn		
		– P	+P	*Mean*	– P	+P	*Mean*
Start	NS	22.4	21.4	*21.9*	63.6	68.0	*65.8*
Flowering	NS	49.1	48.9	*49.0*	67.1	70.5	*68.8*
	S1	30.6	32. 4	*31.5*	59.7	57.3	*58.5*
	Mean	*39.8*	*40.6*		*63.4*	*63.9*	
Maturity	NS	43.2	44.7	*43.9*	62.7	62.5	*62.6*
	S1	53.0	54.1	*53.5*	65.1	64.6	*64.8*
	S2	59.6	60.8	*60.2*	68.2	71.6	*69.9*
	Mean	*51.9*	*53.2*		*65.3*	*66.2*	

	Stress	*Zn*	*Stress x Zn*
Start	-	**14.3	-
Flowering	* 7.29[a]	**7.29	*Ns*
Maturity	**2.98	**2.43	*4.21

* *Significant at p<0.05, ** Significant at p<0.01, ns= non significant, a= LSD*

7.3.3 Zn uptake as affected by P and Zn amendments and water stress

Water stress, Zn and P fertilizers all affected Zn uptake at 50 % flowering (Table 7.5). A significant interaction was found between water stress and Zn fertilizer and between Zn and P fertilizers. Without Zn fertilizer, Zn uptake was comparable for NS pots and S1 ones. With Zn fertilizer, Zn uptake was higher for NS pots than for S1 ones. This was consistent over the P treatments. Without Zn fertilizer the effect of P was not significant, while with Zn fertilizr P application increased Zn uptake. The main effect Zn application was significant despite these interactions.

At maturity, Zn uptake was also affected by water stress, Zn and P fertilizer (Table 7.5). A significant interaction was observed between stress, Zn and P application. Without Zn and P fertilizers Zn uptake was comparable for all the water regimes. Without Zn application, but with P, Zn uptake was comparable for NS and S1 pots but higher than for S2 ones. The same order was found when Zn was applied, but without P. With the combined application of Zn and P, Zn uptake was not different for S1 and S2 pots but lower than for NS pots.

Table 7.5 *Zn uptake by above ground biomass (stem + leaves + panicle) at flowering and at maturity as affected by P and Zn fertilizers and water stress. Pot experiment 2004 n= 24. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

Zn uptake (mg pot^{-1})

		– Zn			+Zn		
		– P	+P	*Mean*	– P	+P	*Mean*
50% flowering	NS	0.16	0.26	*0.21*	0.76	1.54	*1.15*
	S1	0.09	0.15	*0.12*	0.29	0.54	*0.42*
	Mean	*0.13*	*0.21*		*0.53*	*1.04*	
Maturity	NS	0.82	2.51	*1.67*	3.56	4.24	*3.90*
	S1	0.69	2.28	*1.49*	3.07	3.62	*3.35*
	S2	0.53	1.34	*0.94*	2.08	3.58	*2.83*
	Mean	*0.68*	*2.04*		*2.90*	*3.81*	

	Stress	*Zn*	*P*	*Stress x Zn*	*Zn x P*	*Stress x Zn x P*
Flowering	***0.16[a]*	***0.16*	**0.16*	***0.22*	**0.22*	*ns*
Maturity	*** 0.28*	***0.23*	***0.23*	*ns*	*ns*	**0.57*

**Significant at p<0.05, ** Significant at p<0.01, ns= non significant, a= LSD*

7.3.4 Zn mass fraction in sorghum straw and grain as influenced by Zn and P fertilizers and water stress

Zn mass fraction (ZnMF) in sorghum biomass was affected by stress, P and Zn fertilizer (Tables 7.6 and 7.7). But the effect of stress was overruled by that of Zn application.

At flowering, ZnMF was higher for sorghum grown in NS pots than for sorghum grown under the S1 regime. The difference was much higher with Zn application than without Zn fertilizer. P application increased ZnMF only when Zn fertilizer was applied (Table 7.6).

At maturity, without Zn fertilizer, ZnMF in the sorghum straw was comparable for the NS and S1 treatments but higher than for the S2 treatments. Once Zn was applied, ZnMF was in the order NS > S1 > S2. The main effect of Zn application was significant, despite the different interactions. ZnMF was increased by P application only when no Zn was applied.

Sorghum grain ZnMF was also affected by water stress, Zn and P fertilizers. An interaction was found between stress and Zn. Without Zn application, ZnMF was higher under S2 than under NS while S1 did not differ from either NS or S2. Once Zn was applied, ZnMF was in the order NS < S1 < S2. The main effects of Zn and of P application were highly significant (Table 7.7).

Table 7.6 *Zn mass fraction in sorghum biomass at 50 % flowering as affected by water stress and P and Zn fertilizers. Pot experiment 2004, n= 36. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

	Zn mass fraction (mg kg^{-1})					
	– Zn			+Zn		
	– P	+P	*Mean*	– P	+P	*Mean*
NS	16.6	23.4	*20.0*	68.4	94.0	*81.2*
S1	9.60	13.6	*11.6*	27.0	42.6	*34.8*
Mean	*13.1*	*18.5*		*47.7*	*68.3*	

	*Stress***	*Zn***	*P***	*Stress x Zn***	*Zn x P**
LSD	*5.00*	*5.00*	*5.00*	*7.07*	*7.07*

** Significant at p<0.05, ** Significant at p<0.01*

Table 7.7 *Zn mass fraction in sorghum yield biomass at maturity (straw and grain) as affected by water stress and P and Zn fertilizers. Pot experiment 2004, n= 36. NS= no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

		Zn mass fraction (mg kg^{-1})					
		– Zn			+Zn		
		– P	+P	*Mean*	– P	+P	*Mean*
Straw	NS	17.5	50.8	*34.2*	83.9	89.6	*86.8*
	S1	12.8	46.9	*29.9*	68.9	78.8	*73.9*
	S2	11.2	34.6	*22.9*	57.0	61.9	*59.5*
	Mean	*13.8*	*44.1*		*69.9*	*76.8*	
Grain	NS	15.4	18.0	*16.7*	26.5	33.2	*29.9*
	S1	17.5	25.9	*21.7*	33.9	43.9	*38.9*
	S2	20.6	30.3	*25.5*	42.0	60.4	*51.2*
	Mean	*17.8*	*24.7*		*34.1*	*45.8*	

	Stress	*Zn*	*P*	*Stress x Zn*	*Zn x P*
Straw	***4.97[a]*	***4.06*	**4.06*	***7.03*	***9.94*
Grain	*** 6.30*	***5.10*	***5.10*	**8.92*	*ns*

* *Significant at p<0.05, ** Significant at p<0.01, ns= non significant, a= LSD*

Zn harvest index (ZnHI) differed between water stress treatments and P and Zn fertilizers. ZnHI was on average in the order: S2 > S1 > NS. Stress imposition increased ZnHI (Table 7.8). A significant interaction was found between Zn and P application. ZnHI was comparable for all treatments receiving either P or Zn or both. Only without any fertilizer application the ZnHI was clearly higher. This overruled the main effects of Zn and P fertilizers.

7.3.5 P taken up in sorghum above ground biomass, sorghum grain phytate mass fraction and Zn bioavailability as influenced by water stress and P and Zn fertilizers

Both P taken up and grain phytate mass fraction were affected by stress and P and Zn fertilizers (Tables 7.9 and 7.10). Significant interaction was found between stress, Zn and P fertilizers (Table 7.9). Without Zn and P fertilizers P uptake was lower for S2 than for NS and S1.

Table 7.8 *Zn harvest index as affected by P and Zn fertilizers and water stress. Pot experiment, 2004, n= 36. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

	Zn harvest index (ZnHI)					
	– Zn			+Zn		
	– P	+P	*Mean*	– P	+P	*Mean*
NS	0.46	0.25	*0.36*	0.19	0.23	*0.21*
S1	0.54	0.34	*0.44*	0.31	0.27	*0.29*
S2	0.56	0.36	*0.46*	0.37	0.44	*0.41*
Mean	*0.52*	*0.32*		*0.29*	*0.31*	

	Stress	*Zn*	*P*	*Zn x P*
Significance	**	**	*	**
LSD	*0.06*	*0.05*	*0.05*	*0.07*

** Significant at p<0.05, ** Significant at p<0.01*

Table 7.9 *P uptake in sorghum above ground biomass as affected by water stress and P and Zn fertilizers. Pot experiment 2004, n= 36. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

	P uptake (mg pot $^{-1}$)					
	– Zn			+Zn		
	– P	+P	*Mean*	– P	+P	*Mean*
NS	31.3	52.8	*42.0*	38.9	48.4	*43.6*
S1	32.6	35.1	*33.9*	33.6	43.8	*38.7*
S2	19.2	27.0	*23.1*	24.0	38.0	*31.0*
Mean	*27.7*	*38.3*		*32.1*	*43.4*	

	*Stress***	*Zn**	*P***	*Stress x Zn x P**
LSD	*3.71*	*3.03*	*3.03*	*7.43*

** Significant at p<0.05, ** Significant at p<0.01*

Without Zn and with P fertilizer P uptake was in the order NS > S1 > S2. When Zn was applied and without P fertilizer, P taken up was similar for NS and S1 and higher than for S2. With the combined application of Zn and P, P uptake was higher for NS than for S2 and comparable for S1 and NS.

Phytate grain mass fraction was on average comparable for S1 (3.92 mg kg^{-1}) and S2 (3.52 mg kg^{-1}) on the one hand and between S1 and NS (4.18 mg kg^{-1}) on the other, but was significantly lower for S2 than for NS. Both P and Zn fertilizers increased phytate mass fraction but the effect of P fertilizer was stronger than the effect of Zn fertilizer (Table 7.10).

Table 7.10 *Sorghum grain phytate mass fraction as affected by water stress and P and Zn fertilizers. Pot experiment 2004, n= 36. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

	Grain phytate mass fraction (mg g^{-1} DM)					
	– Zn			+Zn		
	– P	+P	*Mean*	– P	+P	*Mean*
NS	2.81	4.68	*3.75*	3.42	5.78	*4.60*
S1	2.49	4.11	*3.30*	3.58	5.47	*4.53*
S2	2.14	3.75	*2.95*	3.23	4.94	*4.09*
Mean	*2.48*	*4.18*		*3.41*	*5.40*	

	*Stress**	*Zn***	*P***
LSD	*0.46*	*0.37*	*0.37*

* *Significant at p<0.05, ** Significant at p<0.01*

Sorghum grain Zn bio-availability was evaluated using the Phytate/Zn molar ratio as recommended by many authors (Rengel et al., 1999; Cakmack et al., 1999; Bouis et al., 2000). Phytate/Zn molar ratio was significantly increased with P application (from 12.3 to 16.6). In contrast, the ratio was decreased by Zn application (from 16.0 to 12.3) (Table 7.11). Water stress also affected the ratio and it was on average higher for NS (18.3) than for S2 (10.7), while S1 (14.2) was intermediate and not significantly different from either NS or S2. These effects of water stress seemed to be affected by the Zn fertilizer application, but the interaction between stress and Zn fertilizer treatment was not significant.

Table 7.11 *Sorghum grain phytate/Zn molar ratio as affected by water stress and P and Zn fertilizers. Pot experiment 2004, n= 36. NS = no stress, S1 = 10-days stress during panicle formation, S2 = 10-days stress during grain filling.*

	Sorghum grain phytate/Zn molar ratio					
	– Zn			+Zn		
	– P	+P	*Mean*	– P	+P	*Mean*
NS	17.1	23.4	*20.2*	13.3	19.6	*16.4*
S1	14.3	14.7	*14.5*	10.2	17.8	*14.0*
S2	11.1	15.5	*13.3*	7.63	8.46	*8.04*
Mean	*14.2*	*17.9*		*10.4*	*15.3*	

	*Stress**	*Zn**	*P**
LSD	*4.44*	*3.62*	*3.62*

* *Significant at p<0.05*

7.4 Discussion

The water stress during grain filling was effective as shown by the decreased leaf water potential during the stress period, while plants survived and panicles were not fully sterile. The minimum leaf water potential value (–8.5 bars) in plants subject to stress is far above the –15.7 bars reported by Sanchez-Diaz and Kramer (1971), the reason being that in our experiment, the pots were not allowed to dry till wilting point because the aim was that plants survived and produced seeds, mimicking often observed drought periods during grain filling in the field.

7.4.1 Sorghum grain yield, Zn and P fertilizers and water stress

The negative effects of water stress on sorghum grain yield observed in this pot experiment are similar to those reported in field experiments in northern Burkina Faso carried out by INERA (2003) and Zougmore et al. (2000). This pot experiment showed also that the negative impact of water stress on sorghum grain yield was more important without Zn and P fertilizers than with these fertilizers. These fertilizers especially the P are therefore of importance for sorghum production in the Sahel as reported by previous workers (Bationo et al., 1998; Bado and Hien, 1998; Buekert et al., 1998). In combination with the earlier reported yield effects of Zn and P applications in the field (Chapter 4), even during adverse rainfall conditions, we conclude that farmers do not risk crop failure due to Zn and P fertilizer applications.

7.4.2 Zn uptake and Zn mass fraction

Zn uptake was higher for sorghum grown in NS pots than for sorghum grown in stressed (S1 and S2) pots. This can be explained by the lower Zn availability observed during the stress period (Table 7.4). From these results we can state that part of the applied Zn was fixed by soil particles during the stress period since the difference between the no stress and the stressed pots was much higher with Zn than without Zn fertilizer. Furthermore, the pots with lower Zn taken up showed at maturity higher Zn availability. Our conclusions are in the same line with those reported earlier for wheat (Erenoglu, 2002; Lower and Orians, 2003; Al-Karaki et al., 2004) although these experiments were carried out under alkaline soil conditions.

The analysis of variance showed higher grain ZnMF for sorghum grown under stress conditions than for sorghum grown under an optimal water regime (Table 7.7). But sorghum grain yield obtained under the stress conditions, especially under S2, was much lower than grain yield found under the well watered condition (Table 7.3). The lower ZnMF under optimal water supply can be attributed to a dilution of Zn in the well watered grain due to a higher grain production (Table 7.3). The first objective of farmers in the Sahel is food self sufficiency (Chapter 2); therefore a yield decrease due to water stress will be negatively appreciated by farmers although the ZnMF is increased.

The application of P and Zn significantly increased both sorghum grain yield and Zn mass fraction and the effect of fertilizers was much higher under well watered conditions than under water stress conditions. The use of P and Zn fertilizers is essential to support both good crop production and Zn mass fraction. Improvements in soil and water conservation that lead to enhanced water availability especially during critical growth stages would enhance the positive effects of fertilizers. Farmers should avoid water stress by using soil and water conservation measures which reduce rainfall losses due to runoff. More investigations are needed in the field of green water use efficiency (GWUE), being the ratio transpiration over rainfall (Stroosnijder, 2003).

7.4.3 Phytate mass fraction and Zn bioavailability

Phytate MF was decreased by water stress when it occured during grain filling and the observed values were close to those found in the 2003 and 2004 field experiments during which a drought was observed at the end the cropping season (Chapter 6). The lower phytate MF in the water stressed sorghum grain can be attributed to a lower P uptake as shown in Table 7.9.

The bioavailability of Zn was improved with water stress if we base our analysis on the critical phytate/Zn molar ratio level of 15 reported by Cakmak et al. (1999). But, the negative effects of water stress on sorghum grain yield are overruling any possibly positive effects on sorghum grain quality.

7.5 Conclusions

The results clearly showed that the system that was used to impose a non-fatal water stress worked well. The results showed also that Zn availability in the soil, sorghum grain yield, ZnMF in sorghum above ground biomass, Zn and P uptake by sorghum above ground biomass, sorghum grain phytate MF and phytate/Zn molar ratio were all affected by water stress and Zn and P fertilizer application. Water stress negatively affected Zn availability in the soil, Zn and P uptake and sorghum grain yield. These factors were significantly improved with Zn and/or P fertilizer application independent of water regime. But the effect of the fertilizers was much higher under well watered conditions than under water stress conditions. Sorghum above ground ZnMF was lower for stressed plants than for the well watered ones. The same was observed for grain phytateMF. The water stress on sorghum grain production was larger than on sorghum Zn uptake leading to an improved nutritional quality of sorghum grain by increasing the grain ZnMF and decreasing the phytate/Zn molar ratio. But the negative impact of the water stress on sorghum grain yield obviously overrules any positive effect on sorghum grain quality. The food demand in the Sahel and the necessity for rural farmers to take up enough Zn would urge the use of Zn and P fertilizers in farmers' field as stated in Chapter 6. But, further investigation in the field of green water use efficiency should be undertaken to better underline the possibilities to avoid water stress under Sahelian conditions with the objective to both maintain the productivity and ensure a quality end product.

Chapter 8

Synthesis

8. Synthesis

In this chapter the findings of all previous chapters are synthesized. In section 1 the problem and the challenge, the research questions and the approach are recalled. Section 2 gives the main findings on Zn husbandry. Section 3 explains which soil organic amendment (SOA) might be attractive to farmers in the Sahel and why. Section 4 discusses what is needed for the large scale adoption of the improved SOA. In Section 5 we elaborate on institutional and policy implications.

8.1 The problem, challenge, questions and approach

8.1.1 The problem and the challenge

In developing countries, short Zn supply is limiting both crop yield and human health. Zinc deficiency is believed to contribute to child mortality, to impaired mental and physical development, decreased work output, and to morbidity from infections. Improving Zn in staple foods and/or improved bio-availability of Zn from staple foods would already greatly improve public health.

In the Sahel, agricultural development has so far only focused on increasing productivity of the land, especially relating to the staple crops millet and sorghum. In Burkina Faso, soil and water conservation (SWC) techniques adopted by farmers after the drought of the 1980s and 1990s, have improved both water and nutrient availability. Adoption of SWC techniques was accompanied by the systematic adoption of soil organic amendments (SOAs) necessary to value the investment in SWC techniques. Using SWC and SOA increased crop yield in the Sahel. Potentially, this improvement of yield may also improve Zn mass fractions (MF) in the grains, or indeed may decrease it through dilution.

Zn bio-availability for humans is hampered when the phytic acid (IP-6, the main form of phosphorus accumulation in the grain) to Zn molar ratio is too high (Frossard *et al.*, 2000). P is one of the most limiting nutrients for crop production in the Sahel. Although its application significantly increases cereal yield, there is potentially also an effect on grain Zn mass fraction (MF) and grain IP-6 MF and on their ratio. Therefore, it is a major challenge to design cereal production techniques resulting in a higher Zn MF in combination with a lower (or at least similar) IP-6 MF. The main objective of the current PhD project was to assess possible effects of the application of SOAs (already part of farmers' practices) and of inorganic fertilizers on yield and quality (in terms of Zn MF and IP-6:Zn molar ratio) of sorghum in the Sahel.

8.1.2 The research questions and the approach

The current study addresses the following research questions:

1. How are Zn availability (in the soil) and uptake (in the plant) influenced by type of SOA, Zn and P fertilizer application (amount and timing)?

2. What are the effects of different SOAs and Zn and P fertilizers on yield and Zn MF of sorghum grain?
3. Are there interactions between Zn and P fertilizer applications and between Zn application and drought stress?
4. What are possible modifications of SOAs, as practiced by farmers in the Sahelian zone of Burkina Faso, which increase both sorghum grain yield and its Zn MF?
5. What are the chances that modified SOAs will be adopted by farmers and what are the institutional and policy implications?

The methodology used to address the above questions was a combination of farmers' field monitoring, on-farm research and on-station greenhouse experiments.

During the first year (2002), a farmers' survey was carried out to investigate the farmers' perceptions of sorghum grain quality, of the effects of organic amendments on yield and grain quality and of the relation between sorghum grain quality and health of children and adults. Also, a survey of planting pits, locally called Zaï, with different soil types and SOAs was carried out to provide information on soil chemical properties, on Zn uptake and Zn MF in sorghum.

In the second year (2003), field and pot experiments were carried out. In the field, the effect of organic and inorganic soil amendments on sorghum grain yield and Zn MF was studied, while in the pot experiment, the effect of fertilization timing on micronutrient availability, uptake and MF was tested. In the third year (2004) field and pot experiments further precised the findings from 2002 and 2003.

8.2 Main findings in Zn husbandry

8.2.1 Zn availability in the soil

Without Zn application no difference was observed between the sandy and the gravelly soil. When Zn was applied, Zn availability was either the same or higher for sandy soil than for gravelly soil. P availability was comparable for both soil types.

Zn and P application significantly increased Zn and P availability and were higher in plots amended with compost than for those amended with farmyard manure. Zn and P availability were higher for the high compost dose than for the lower one.

Zn availability was different for the three cropping seasons probably due to the combination of large variability in rainfall distribution and in the quality of organic amendments used in the respective experiments. In none of the experiments an interaction was observed between fertilizer treatment effects on Zn and P availability.

8.2.2 Zn uptake

Zn and P uptake varied between cropping seasons. In general improved uptake followed improved availability. When applied as inorganic fertilizer, more Zn and P were taken up from sandy soils than from gravely soils. Zn and P uptake from compost amended plots were higher than from farmyard manure amended plots.

Sorghum grain and straw Zn yield (uptake) increased with Zn or P fertilizer. Zn fertilizer increased straw Zn yield more than grain Zn yield. The highest grain and straw Zn yield was obtained when Zn and P fertilizers were combined.

In the pot experiment, the highest Zn uptake was obtained when P was applied at sowing and Zn at anthesis, whereas the highest P uptake was generated by Zn and P fertilizers applied at sowing.

The fraction of Zn recovered in above ground sorghum biomass was low and was improved by applying P. More than 90% of the Zn applied remained in the soil.

8.2.3 Zn and IP-6 mass fractions

There were interactions with soil type and SOA type. Effects of fertilizer applications on both MFs were generally larger with compost than with farmyard manure and larger on sandy than on gravely soils. Grain Zn MF and IP-6 MF increased with Zn or P application.

With the higher compost dose in the pot experiment both Zn and IP-6 were further enhanced. Timing of Zn application only affected Zn MF.

The IP-6:Zn molar ratio decreased with Zn application and increased with P application, resulting in comparable ratios when no fertilizer was applied or when both fertilizers were applied simultaneously.

8.2.4 Effect on yield

In 2002, biomass, grain and straw yields were significantly higher on sandy than on gravelly soil. No significant differences were observed between compost and farmyard manure application.

Zn and P application increased biomass, grain and straw yields but effects were smaller for Zn than for P application. On average 210 kg ha^{-1} extra grain was produced with Zn application against 450 kg ha^{-1} extra grain with P application. Zn application only increased harvest index in the 2003 experiment. P application increased harvest index in all three years. Interactions between P and Zn application were not significant.

In the greenhouse pot experiment no significant differences were found between the high and low compost rate. Grain and straw yields were higher when Zn or P was applied at sowing than when it was applied at anthesis.

8.2.5 Effect of drought

In the field experiments, sorghum grain yield varied considerably between years, partly due to variation in rainfall distribution. In the 2004 pot experiment Sorghum grain yield was affected by water stress and it was lower for plants subject to water stress at grain filling than for those subject to a well-watered regime. The latter difference was associated with weather conditions before flowering which were not conducive to stress induction.

Important variability for Zn and P availability was also observed between the cropping seasons which could be related to different soil moisture conditions due to large variability in rainfall distribution. As a consequence Zn and P uptake varied between cropping seasons.

A large inter-annual variability was observed for Zn and IP-6 mass fractions, and for their ratio. Grain Zn MF of 50 mg kg^{-1} with an IP-6:Zn molar ratio of around 15 is possible with Zn and P application in years with favourable rainfall distribution during grain filling. In the pot experiment Zn uptake by sorghum was lower for stressed plants; which left larger quantities of Zn available in the soil at maturity. During the 2003 and 2004 rainy seasons water stress occurred during grain filling, but under field conditions this did not lead to large Zn availability at maturity. It has to be noted, though, that in the pot experiment the soil was re-watered for some time after the stress period, while there had been no recent rains at maturity in the field experiments.

Sorghum grain Zn MF and Zn harvest index were higher for stressed plants than for the well watered ones which can be attributed to a Zn dilution for the well watered plants. Alternatively the ratio between germ and endosperm could have been larger under stressed conditions which would equally lead to a higher grain Zn MF.

Water stress decreased sorghum grain IP-6:Zn molar ratio compared to well watered grains. But the negative effect of the water stress on the sorghum grain yield should be regarded as a larger disadvantage than the advantage from the improved IP-6:Zn molar ratio.

8.3 Is improved nutrient management attractive to farmers?

The cultivation system used in our field experiments was the planting pit system locally known as Zaï. This Zaï technique is the most widely adopted SWC measure in the Sahelian zone of Burkina Faso. The fundamental reason for its success is the combination of soil fertility improvement with water conservation leading to an improved (and more secure) productivity. The planting pits combine three types of conservation practices on degraded crusted soils, i.e. soil conservation, water conservation, and erosion protection. Zaï also concentrates manure (compost, animal manure and household waste) and is therefore a means of economizing on its use. Because of the wide-spread adoption of the technique many Sahelian farmers are nowadays breeding livestock for manure production.

The allocation of organic matter to different fields is aimed at increasing production with the objective to meet the family food needs. But, no significant difference in sorghum grain yield was found between fields amended with compost or farmyard manure. However, Zn MF for sorghum grain from compost amended plots was higher than for the sorghum grains from farmyard manure amended ones. Therefore, compost amendment appears to be better to achieve both high grain yield and Zn MF. During the farm survey, the farmers reported the same choice but their preference was based on total grain production and not on grain quality. Nevertheless, this is a good entry point for participative development to show farmers that the quality of the organic amendment is making a difference.

The greenhouse experiment of 2003 showed that sorghum grain Zn MFs were all higher for the high compost dose than for the low one. These results hint the possibility to increase sorghum grain Zn MF further by combining an increased dose of organic amendment with Zn fertilizer. Increasing the amount of organic amendment per ha does, however, mean reducing the cropping area covered with organic amendments. As the grain production is not enhanced equivalently this would lower total grain production for a household, which would be unacceptable.

Zn or P fertilizer combined with organic amendment significantly increased sorghum grain yield, although the effect of P fertilizer was much larger (Chapter 4). This was consistent over the two SOA types, and no interactions between Zn and P were observed. The two fertilizers also affected sorghum grain Zn MF and it was highest when Zn and P fertilizers were combined. However P fertilizer alone significantly increased sorghum grain phytate MF which countered the effect of enhanced Zn, as the increased phytate:Zn molar ratio indicates a loss in bio-availability of the Zn. Combined application of P and Zn fertilizer, on the contrary, resulted in a comparable bio-availability of the Zn as indicated by the same phytate:Zn molar ratio.

The current soil and water conservation system (Zaï) does gain in productivity by inorganic Zn and P application. As there are no interactions between the effects of these fertilizers on yield and their effect was also observed in poor rainfall years there seems to be scope for development of Zn enriched P fertilizers for the area. The additional advantage that can be expected of such fertilizers over pure P fertilizers is an improved grain quality. Increasing both grain yield and Zn MF with the Zn and P fertilizers could be attractive to farmers.

Soil moisture conditions were decisive for both sorghum grain yield and Zn MF. Sorghum grain yield was lower under water stress conditions than under well watered conditions; especially when the stress occurred during the grain filling stage. The opposite situation was observed for sorghum grain Zn MF, probably due to Zn dilution under well watered conditions. In the Sahel an early ending of the rainy season is common and the rainfall data of 2003 and 2004 cropping seasons are therefore no exceptions. Farmers should avoid water stress especially during the grain filling period and this can be done to some extent by applying soil and water conservation measures in order to increase water infiltration and reduce losses due to runoff. Further investigations to increase the ratio between transpiration and rainfall (green water use efficiency) are needed (Stroosnijder, 2003 and 2005).

In the light of all the conclusions, we can state that there is an improved SOA combining good crop production and higher grain Zn MF and this SOA can be of interest to farmers. The IP6:Zn ratio under farmers' practices, were rather high given reported critical levels of 15 for bio-availability to human consumers. Addition of Zn alone could improve quality and yield, but as P application is more effective in yield increment, this does not seem a logical option to farmers. However, P application significantly increases IP6 MF. As P application alone increases IP6 MF more than Zn MF the ratio increases, leading to lower bioavailability of the extra accumulated Zn. The combined application of Zn and P fertilizers keeps the IP6:Zn ratio roughly at its current level, but at much higher yield levels (Chapter 6) which can be attractive to farmers.

Before farmers will adopt an improved SOA aiming for improved health, there are a number of prerequisites:

1. they should also be convinced of the positive effect of the proposed SOA on both crop yield and food quality;
2. make farmers "meet" the advantages, while still working on improvements like water use efficiency to avoid negative impact of a water stress on grain yield;
3. Zn and P fertilizers should be accessible (physically and economically) to farmers;
4. farmers should be aware of the consequences of micronutrient deficiencies on their family health and the relation between food quality and these deficiencies.

8.4 What are the chances that the proposed soil amendment will be adopted by farmers?

The average intensity of fertilizer use throughout Sub-Saharan Africa (roughly 8 kg per ha) remains much lower than elsewhere (Jayne et al., 2003). So far, adoption by farmers of a soil amendment which includes mineral fertilizers will take up time; even though it increases both cereals grain yield and quality. In Burkina Faso a FAO study in 2004 showed that farm level rates of return can be highly attractive for a technology, and even more when the environmental impacts on society at large are included, but adoption in practice remains very limited. In general, farm households adopt those practices and technologies that suit their objective best given their own resource endowments, constraints and socio-economic environment in which they operate. Profitability is then one of the most important conditions for adoption. Despite the calculated farm level rates of return, the application of a modern technology such as fertilizers still is reserved for cash crops like cotton and it is limited for cereals because farmers are often unable to sell the surplus production at a price that covers their costs.

The application of local solutions is therefore more likely to increase the chance for technologies adoption. For instance, local rock phosphate (Burkina phosphate for Burkina) can be used as phosphorus fertilizer source to supply P at lower cost (6000 FCFA for 100 kg) than water soluble P fertilizer (35000 FCFA for 100 kg) (Bationo et al., 1998; FAO, 2004). In Burkina Faso, the potential for rock phosphate production exists at Kodjari (Northern Burkina Faso) and it has been mined on a small scale (current production of 1000 t per year) (FAO, 2004). The effectiveness of the rock phosphate can be significantly increased through combination with composting (Akande et al., 2005). Composting organic waste with rock phosphate is being already used by some farmers in our experimental area and this is a good entry point.

Zn fertilizer used during our field and greenhouse experiments (Zn sulphate) may not be accessible to farmers because of the same reasons listed above for soluble P fertilizer. One possible solution could be use of urban waste in farmers' compost pits to increase the level of micronutrients. We hypothesized at the start of the research that industrial activities would add an important quantity of Zn to the urban waste. Unfortunately in Burkina Faso there are few industrial activities in the big towns and the only companies able to supply Zn (SIFA and

CBTM) in the urban waste are located in the western part of the country far away from the sorghum production areas. So, the use of an organic waste rich in Zn in northern Burkina Faso is not realistic at all because of the transport cost of urban waste from the western part of the country to the northern part.

The second possibility to make Zn fertilizer available can be to fortify the local rock phosphate with Zn fertilizer. Such Zn-phosphate fertilizer can be used in farmers' compost pit during the production of organic matter. Since Zn is not easily lost by leaching, the compost produced under such condition will be rich in both Zn and P. More investigations are needed to understand the conditions of production and use of Zn and P fortified compost in order to supply the extension service with a decision support document.

Another possibility could have been the use of Zn-fortified seed to be distributed or sold to farmers at an affordable price. Zn-fortified seeds were already tested on wheat and were efficient in increasing both grain yield and Zn MF (Malakouti et al., 2005). But, no results were reported for Zn fortified sorghum seeds and our production area conditions are different (acidic soils) from those reported by Malakouti et al. (alkaline soils). Furthermore, the formal seed supply system has failed in Burkina Faso to ensure farmers' accessibility to high quality seed of improved varieties. Hence the Zn-fortified seed solution will not be easily accessible to farmers in the Sahel.

Overall, the use of Zn-phosphate fertilizer can be considered as suitable solution for farmers in the Sahel. Before farmers can use the Zn-phosphate fertilizer a number of prerequisites will be necessary:

1. The relevance of the results reported here for a wider range of soils and agro-climatic zones in the Sahel should be studied;
2. The methods, conditions of composting the Zn-phosphate fertilizer should be better understood under Sahelian conditions;
3. Distribution channels of phosphate rock fortified with Zn should be well organized to make it available to users at affordable prices.
4. Studies of application effects on 2^{nd} and 3^{rd} year crops and effects of repeated input are also needed as the studies so far looked at effects of first time applications only.

8.5 Institutional and policy implications

Zn deficiency affects two billion people in the world and is more prevalent in developing countries with an invariable diet of cereal based foods. These deficiencies are contributing to lethargic national development efforts and a viscous cycle of poverty for massive numbers of underprivileged people. At national and international levels efforts are made to overcome micronutrient deficiencies.

Because agriculture is the primary source of all micronutrients for human, agricultural systems must be contributing to meet nutritional needs (Welch, 2005). National governments and donors should address the threat of micronutrient deficiency through policies and programs that promote increased micronutrient density in the staple food.

Current intervention programs (i.e. food fortification and supplementation programs) to alleviate the problem have not proven to be effective or sustainable in many countries (Bouis et al., 2000). Furthermore, these programs are very expensive and would require an important percentage of the gross domestic product (GDP) in developing countries (Bouis et al., 2000).

For lack of more precise estimates, the benefit-cost analysis here simply assumes that Zn and P fertilizers will generate for Burkina Faso a grain production of 1.95 million tons for a total sorghum area of 1.3 million hectares. The total grain production was calculated based on sorghum grain yield during our field experiments. At the current sorghum price of 185 US $ per ton in Burkina Faso this is equivalent to 361 million US $ for the 1.95 million tons with a fertilizer cost of 312 million US $ for the1.3 million hectares. This implies a net benefit of 49 million US $ and an extra Zn of 101 kg in the food. A fortification program would require 100 million US $ per year (20 US $ per person and per year for 5 million people).

Significant policy changes will be required to establish an environment that makes agricultural inputs easily available, that encourages farmers to use these inputs more efficiently, and that helps to improve local extension services and farmer support. Efficient and adequate organizational arrangements would be essential for supplying Zn fortified phosphate rock in the right quantity at a reasonable price. Fertilizers should never be distributed for free to farmers. But subsidizing the prices could help to make fertilizers accessible to farmers, as a start up.

Developing countries still lack the necessary research and extension facilities for promoting fertilizer use and associated technologies. Research is needed to develop site specific recommendations including the use of Zn-phosphate enriched compost amendments and to enable extension services to educate farmers on fertilizer use.

In order to increase the chance for adoption of improved soil amendment, the following activities should be supported by the government:

1. Creation of a diffusion agency to make the innovation available to all the farmers and their organizations;
2. Selection and implementation of strategies that include pricing and promotional communication in order to induce adoption.

These activities should not only be created for adoption of a single technology but for all the agriculture innovations necessary for sustainable crop production in the Sahel. A strong political commitment and a comprehensive approach are necessary to make the application of the proposed soil amendment successful.

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Summary

Summary

In developing countries, short supply of Zinc is limiting both crop yield and human health. Improving Zn bio-availability in staple foods would greatly improve public health. It's therefore a major challenge to design cereal production techniques resulting in higher Zn mass fractions (MF) in combination with a lower phytic acid (IP-6, the main form of phosphorus accumulation in the grain) MF. In northern Burkina Faso, soil and water conservation (SWC) and soil organic amendments (SOAs) techniques adopted by farmers have improved both water and nutrient availability which consequently increased crop yields. Potentially, this improvement in yield may also improve the bio-availability of Zn from staple foods. This research investigated possible modifications of SOAs as currently practiced by farmers, which increase both the quality and the yield of sorghum in the Sahel.

The research generated information on farmers' perception of the effects of SOAs on grain yield and quality, their knowledge of the relation between sorghum grain quality and health of children and adults. The research provided also information on the quality of SOAs that are being applied; changes in soil chemical characteristics; sorghum grain and straw yield; plant Zn uptake and Zn and IP-6 MFs and the effect of water stress on Zn availability, Zn uptake and Zn and IP6 MFs.

These results were used to design a soil amendment combining high crop yield and grain quality

Chapter 2: Sorghum quality, organic matter amendments and health; farmers' perception in Burkina Faso, West Africa

This paper takes local ecological, cultural and socio-economic aspects into account through a household survey in northern Burkina in 2002. Farmers' knowledge was compared with available scientific information. The results showed that organic matter production is a function of the number of animals owned and the availability of labour and equipment. Organic resources are allocated to various fields according to soil texture and the crop to be grown. Farmers were unable to link micronutrient deficiency in the soil directly to food quality and human health. However, they indicated some disorders (e.g., fatigue in adults, stunted growth of children, anaemia) which are associated with a low level of micronutrients in the diet. For the design of organic amendments combining improvements in grain yield and food quality in the Sahel, the relation between organic amendment and food quality must be better understood by scientists and explained to farmers.

Chapter 3: Soil availability of Zn and P following the application of compost, manure and Zn and P fertilizers to acidic agricultural soils in the Sahel

In order to get information on the effect of soil organic amendments on Zn and P availability in the soil, three on-farm experiments and one greenhouse experiment were carried out. The experiments in the field consisted of a full factorial design with the factors: soil type (gravely

and sandy), soil organic amendments (compost and farmyard manure), Zn fertilizer and P fertilizer. The treatments in the greenhouse experiment included all combinations of two compost doses; three Zn treatments and three levels of P.

The results indicated that without Zn application no difference was observed between the two soil types. When Zn was applied, Zn availability was in most cases identical for both soil types or higher for sandy soil than for the gravelly one. P availability was comparable for both soil textures. Zn and P availability were higher in plots amended with compost than for those amended with farmyard manure. Zn and P fertilizers significantly increased Zn and P availability independent of organic amendment type and soil texture. Zn and P availability were higher for the high compost dose than for the lower one. No interactions between P and Zn were expressed by data. Important variability for Zn and P availability was observed between the cropping seasons which could be related to soil moisture conditions as well as differences in the quality of organic amendments applied each year. For higher Zn availability in Sahelian agricultural soils, the combined application of organic amendment and Zn fertilizer is needed.

Chapter 4: Combining Zn, P and organic amendments in sorghum production in the Sahel

In view of potential micro-nutrient limitations to crop productivity a research program was carried out on the effects of zinc fertilization in conjunction with organic amendments and P fertilizer application. Sorghum (*Sorghum bicolor* (L.) Moench) production was evaluated in three on-farm experiments in 2002, 2003 and 2004 and in one greenhouse experiment, on Sahelian acidic agricultural soils. The treatments were similar to those reported for Chapter 3.

The results showed variable sorghum grain and straw yield over the three cropping years due to variation in rainfall distribution. Sorghum grain and straw yields were significantly higher on sand than on gravely soil while they were comparable for compost and farmyard manure. Zn application increased grain and straw yields but effects were rather small. P application significantly increased yields in all three years. Interactions between P and Zn application were not significant. No significant differences were found between the high and low compost rate. Sorghum grain and straw yields were higher when Zn or P was applied at sowing than when they were applied at anthesis.

The current soil and water conservation system (zaï) does gain in productivity by inorganic Zn and P application. As there are no interactions between the effects of these fertilizers on yield and their effects were also observed in years with poor rainfall there seems to be scope for development of Zn enriched fertilizers for the area. The additional advantage that can be expected from such fertilizers is an improved grain quality.

Chapter 5: Combining Zn, P and organic amendments to enhance sorghum Zn uptake from degraded Sahelian soils

Limited Zn and P uptake reduces yield and quality of cereals grown in the Sahel. Changes in P and Zn uptake are expected to interact. Therefore options to simultaneously enhance Zn and P uptake by sorghum (*Sorghum bicolor* (L.) Moench) were evaluated on Sahelian degraded

Luvisols in Northern Burkina Faso in three on-farm experiments in 2002-2004 and in one greenhouse pot experiment.

Zn and P uptake and mass fraction (MF) in above ground biomass, varied between cropping seasons but were always enhanced when Zn and P fertilizers were applied. When Zn fertilizer was applied more Zn and P were taken up from sandy soils than from gravely soils and Zn and P uptake from compost amended plots was higher than from farmyard manure amended plots. In the pot experiment the highest Zn uptake was obtained when P was applied at sowing and Zn at anthesis, whereas the highest P uptake was generated by Zn and P fertilizers applied at sowing.

The fraction of Zn recovered in sorghum above ground biomass was low and was improved by applying P. More than 90% of the applied Zn remained in the soil. On degraded Luvisols in the Sahel, Zn and P uptake can be successfully improved with the combined application of organic amendments and Zn and P fertilizers.

Chapter 6: Can sorghum grain quality be improved by applying inorganic Zn and P fertilisers and organic amendments?

Short Zn supply is limiting both crop yield and human health. It is a major challenge to design cereal production techniques resulting in more grain yield, a higher Zn mass fraction (MF) and a lower (or at least similar) IP6-MF. Possible components for such techniques were evaluated in 2002, 2003 and 2004 on acidic sandy and gravely soils in three on-farm experiments in northern Burkina Faso and one pot experiment in 2003.

Grain Zn yields and grain Zn and IP6-MFs increased with Zn or P application. There were interactions with soil type and type of organic amendment: effects on both MFs were generally larger with compost than with farmyard manure and larger on sandy than on gravely soils. With the higher compost dose both Zn and IP6-MFs were further enhanced while timing of Zn application only affected Zn-MF. The IP6 : Zn molar ratio decreased with Zn application and increased with P application, resulting in comparable ratios when no fertiliser was applied or when both fertilisers were applied.

A large inter-annual variability was observed for grain Zn yield and grain Zn and IP6-MFs, and for their ratio. Grain Zn-MF of 50 mg kg^{-1} with an IP6 : Zn molar ratio of about 15 is possible with Zn and P application in years with adequate rainfall distribution during grain filling. Overall, organic amendments associated with P and Zn fertilisers are good options for higher crop yield and reasonable grain quality. But for higher Zn bio-availability, the IP6 in the sorghum grain produced under such conditions should be degraded prior to consumption. Proper food processing will be needed to counter the negative effect of IP6 on Zn bio-availability.

Chapter 7: Effects of water stress on sorghum (*Sorghum bicolor* (L.) Moench) **grown on Sahelian sandy acidic Luvisol**

Crop production in the Sahel is subject to frequent drought periods leading to variable crop yield with different harvest quality. The current study was initiated to monitor the effect of water stress on Zn uptake by sorghum (*Sorghum bicolor* (L.) Moench.), sorghum grain yield, Zn and IP-6 MFs in the grain. A pot experiment was carried out in a greenhouse at Kamboinsé Research Center in Burkina Faso. Treatments included all combinations of one level of compost, two levels of P, two Zn levels and three water stress treatments (no stress as control, NS; stress during early panicle formation, S1; or stress during grain filling, S2).

The results showed that sorghum grain yield was reduced by water stress compared to the control treatment. Stressed plants took up less Zn and P independent of the timing of the stress. But, Zn and P fertilizers improved sorghum grain yield, Zn and P uptake independent of the water regime. The effect of fertilizers was more important under well-watered conditions. Sorghum grain Zn MF was higher for stressed plants than for the well-watered ones. The opposite situation was found for IP-6 MF. Water stress has decreased sorghum grain IP-6 : Zn molar ratio compared to well-watered grains. But, water stress decreased more sorghum grain yield than it improved the IP-6 : Zn molar ratio. In the Sahel with many food unsecured and Zn deficient households the use of P and Zn fertilizers are necessary as well as good soil and water conservation measures

Conclusions

In the light of all the above detailed conclusions, it can be stated that soil organic amendments combined with Zn and P fertilizers significantly increased sorghum grain yield and keeps the IP6:Zn ratio roughly at its current level, but at much higher yield levels. This can be attractive to farmers in the Sahel who are looking for food sufficiency as their first objective. But, the IP6:Zn ratios reported here were rather high given reported critical levels of 15 for bio-availability to human consumers. Therefore, the IP6 in the sorghum grain produced under such conditions should be degraded prior to consumption. Proper food processing will be needed to counter the negative effect of IP6 on Zn bio-availability, as the lower IP6:Zn molar ratio that can be obtained without P fertilisation would imply too high a cost in forsaken productivity.

Samenvatting

In ontwikkelingslanden worden zowel gewas opbrengsten als humane gezondheid gelimiteerd door tekorten in zink (Zn). Door de biologische beschikbaarheid van Zn in het basisvoedsel te verbeteren zou de humane gezondheid sterk kunnen verbeteren. Daarom is het een belangrijke uitdaging om graanproductietechnieken te ontwikkelen die resulteren in een hoger zink massa fractie (MF) in combinatie met een lagere IP-6 massa fractie (IP-6 is de belangrijkste vorm van fosfor accumulatie in graan). In noord Burkina Faso hebben de door de boeren toegepaste bodem- en waterconservering (SWC) en de toevoeging van organisch materiaal aan de bodem (SOA), zowel de water- als de nutriëntenbeschikbaarheid verbeterd. Dit resulteerde in hoger gewasopbrengsten. Deze verbetering in gewasopbrengsten zou ook de biologische beschikbaarheid van zink in het voedsel kunnen verbeteren. Tijdens dit onderzoek in de Sahel zijn mogelijke aanpassingen in de op dit moment toegepaste SOA's bestudeerd. Gekeken is naar de invloed van de aanpassingen op zowel de kwaliteit van de sorghum als op opbrengst.

Er is informatie verzameld over de perceptie van boeren m.b.t. de effecten van SOA's op graankwaliteit en -opbrengst en over hun kennis van de relatie tussen sorghum kwaliteit en de gezondheid van kinderen en volwassen. Ook zijn bestudeerd: de kwaliteit van de SOA's die worden toegepast, de veranderingen in de chemische samenstelling van de bodem, de sorghum graan- en stro-opbrengsten, zink opname door het gewas, Zn-MF en IP-6 MF's en het effect van watertekorten op zinkbeschikbaarheid, -opname en Zn-MF en IP-6 MF's. De resultaten van het onderzoek zijn gebruikt om een ontwerp te maken van een SOA die zowel tot kwantitatieve als kwalitatieve opbrengstverbeteringen kan leiden.

Hoofstuk 2: Sorghum kwaliteit, organische stof bemestingen en gezondheid; perceptie van boeren in Burkina Faso, West Afrika

Hoofdstuk 2 behandelt de lokale ecologische, culturele en sociaal economische aspecten van het onderzoek. In 2002 is een enquête gehouden onder huishoudens in noordelijk Burkina Faso. De kennis van de boeren is vergeleken met wetenschappelijke kennis. Uit de resultaten blijkt dat er een relatie is tussen de organische stof productie en het aantal dieren per huishouden. Ook beschikbare arbeid en werktuigen staan in relatie tot de organische stof productie. De toediening van organische stof is afhankelijk van de grondsoort en de gewasplanning. Boeren bleken niet in staat om een direct verband te leggen tussen een gebrek aan micro-nutriënten in de bodem, de kwaliteit van voedsel en gezondheid. Echter, een aantal gezondheidsverschijnselen (vermoeidheid bij volwassenen, verstoorde groei bij kinderen, bloedarmoede) werd wel in verband gebracht met een laag micro-nutriënten niveau in voeding. Om een afgewogen ontwerp te kunnen maken van SOA's ter verbetering van zowel de kwantiteit en de kwaliteit van de graanopbrengst moet de relatie tussen organische bemesting en voedselkwaliteit beter worden onderzocht en worden uitgelegd aan boeren.

Hoofdstuk 3: Beschikbaarheid van Zn en P in de bodem na de toediening van compost, mest en Zn en P kunstmest aan zurige landbouwgronden in de Sahel

Om meer informatie te verkrijgen over het effect van organische bemesting op Zn en P beschikbaarheid in de bodem zijn drie veldexperimenten en één experiment in een kas uitgevoerd. Voor de veldexperimenten in een factorieel ontwerp met drie factoren gebruikt: bodemtype (grindhoudende- en zandige bodems), organische bemestingen (compost en mest) en kunstmest (Zn en P). De behandelingen in de kas bevatten alle combinatie van de twee organische bemestingen; drie Zn en drie P niveau's.

Zonder Zn toevoeging werd geen verschil gevonden tussen de twee bodemtypen. Met Zn toevoeging was de Zn beschikbaarheid in de meeste gevallen gelijk voor beide bodemtypen, maar soms hoger voor de zandige bodem dan voor de grindhoudende bodem. Zowel Zn als P beschikbaarheid waren hoger voor de velden met compost toediening dan met mest toediening. Zn en P kunstmest verhoogden de Zn en P beschikbaarheid significant, onafhankelijk van organische bemesting of bodemtype. Bij een hogere dosis compost werd de Zn en P beschikbaarheid hoger dan bij een lagere dosis compost. Uit de data kon geen interactie tussen Zn en P worden vastgesteld.

De variatie in Zn en P beschikbaarheid was groot tussen de verschillende groeiseizoenen, wat kan worden herleid tot de variatie in beschikbaarheid van het bodemvocht en variatie in de kwaliteit van de organische bemesting.

Voor hogere beschikbaarheid van Zn in de landbouwgronden in de Sahel, moet een combinatie van organische bemesting en Zn kunstmest worden toegepast.

Hoofdstuk 4: Het combineren van Zn, P en organische bemestingen t.b.v. de productie van sorghum in de Sahel

Gezien de potentiële beperking van micro-nutriënten op de gewasproductie is onderzoek gedaan naar de effecten van zink bemesting in combinatie met organische bemestingen en P toediening. De productie van sorghum (*Sorghum bicolor* (L.) Moench) is gedurende drie achtereenvolgende jaren (2002 -2004) bepaald in drie veldexperimenten en in één experiment in een kas, op zurige landbouwgronden. De behandelingen waren gelijk aan die zoals beschreven in Hoofdstuk 3. Als een gevolg van variatie in neerslag was de opbrengst van sorghum graan en stro over de drie jaren ongelijk. Zowel de sorghumgraan- als de sorghumstro opbrengst was hoger op de zandgrond dan op de grindhoudende grond, maar vergelijkbaar voor de compost en de mesttoediening. De toediening van Zn had een (minimaal) positief effect op graan en stro opbrengsten. In alle drie de jaren, verhoogde de toediening van P de opbrengst significant. Er zijn geen significante interacties tussen Zn en P gevonden. Hoge of lage hoeveelheden compost hadden ook geen significante invloed op de opbrengst. De opbrengsten waren hoger wanneer Zn en P bij zaaien werden toegediend dan wanneer ze werden toegediend bij anthesis.

In het toegepaste SWC systeem (zaï) verbetert de productiviteit van sorghum door de toediening van Zn en P kunstmest. Aangezien er geen interacties tussen Zn en P geconstateerd zijn, en aangezien het positieve effect van de toediening ook gevonden is in jaren met geringe neerslag lijkt het verrijken van kunstmest met Zn nuttig te zijn in de onderzochte regio van de Sahel. Een extra toegevoegde waarde van dergelijke verrijkte kunstmest zou een verhoogde graan kwaliteit van de sorghum zijn.

Hoofdstuk 5: Gecombineerde toediening van Zn, P en organisch materiaal met als doel de opname van Zn uit gedegradeerde Sahel bodems door sorghum te verbeteren

In de Sahel zijn door een beperkte opname van Zn en P de gewasopbrengsten en de gewaskwaliteit beperkt. Onderzocht is wat de effecten zijn van het gelijktijdig stimuleren van Zn en P opname door Sorghum (*Sorghum bicolor*, (L.) Moench). Het onderzoek vond plaats op gedegradeerde Luvisolen in noordelijk Burkina Faso in drie veldexperimenten en één potexperiment in een kas.

Zn en P opname en hun massa fracties varieerden over de verschillende gewasjaren, maar waren altijd hoger bij Zn en P bemesting. De opname van Zn en P was bij Zn kunstmest toediening hoger op zandige gronden dan op grindhoudende bodems. Bij compost toediening was de Zn en P opname hoger dan bij mest toediening. Bij het potexperiment in de kas werd de hoogste Zn opname verkregen bij de behandeling: P toediening bij zaaien en Zn toediening bij anthesis; de hoogste P opname werd verkregen bij gelijktijdige toediening van Zn en P bij zaaien.

De fractie Zn in de bovengrondse sorghum biomassa was laag en verbeterde door P toediening. Meer dan 90% van de toegediende Zn bleef achter in de bodem.

Op gedegradeerde Luvisolen in de Sahel kan de opname van Zn en P succesvol worden verbeterd door een gecombineerde toediening van organische stof en Zn en P kunstmest.

Hoofdstuk 6: Kan de kwaliteit van sorghum verbeteren door de toediening van Zn en P kunstmest en organische bemesting?

Tekorten in Zn zijn limiterend voor zowel gewasopbrengst als voor de menselijke gezondheid. Het is een belangrijke uitdaging om gewasproductietechnieken te ontwikkelen die resulteren in een hogere graanopbrengst, een hogere Zn-MF en een lagere (of in ieder geval gelijke) IP6-MF. Mogelijke componenten van een dergelijke techniek zijn gedurende drie jaar (2002-2004) getest in zowel een veldexperiment als een potexperiment in een kas in het jaar 2003. De experimenten vonden plaats op zandige bodems en op grindhoudende bodems.

Zowel de graan Zn opbrengst, graan Zn-MF en IP6-MF verhoogden door Zn of P toediening. Er waren interacties met bodemtype en soort organische bemesting: de effecten op beide MF waren hoger met compost dan met mest en groter op zandige bodems dan op de grindhoudende bodems. Bij de hoge compost dosis waren zowel Zn-MF en IP6-MF hoger; het tijdstip van de Zn toediening had alleen invloed op de Zn-MF. De molaire IP6:Zn verhouding verlaagde door Zn toediening en verhoogde door P toediening met als resultaat vergelijkbare ratio's wanneer er geen kunstmest werd toegediend of wanneer beide werden toegediend.

Er was een grote variatie in graan Zn opbrengst, graan Zn-MF, IP6-MF en de IP6:Zn verhouding tussen de jaren. Een Zn-MF voor graan van 50 mg kg^{-1} met een molaire IP6:Zn verhouding van 15 is mogelijk met toediening van Zn en P in jaren met een goede verdeling van de neerslag tijdens de rijpingsperiode.

Organische bemesting in combinatie met P en Zn kunstmest zijn een goede optie voor een hogere gewasopbrengst en redelijke graankwaliteit. Maar voor een hogere bio-beschikbaarheid van Zn, moet de IP6 in het sorghumgraan voor consumptie worden verminderd. Een goede verwerking van voedsel is nodig om de negatieve effecten van IP6 op de Zn bio-beschikbaarheid te verminderen.

Hoofstuk 7: Effecten van waterstress op Sorghum (*Sorghum bicolor* (L.) Moench) productie op zurige zandige Luvisolen in de Sahel.

In de Sahel zijn er regelmatig perioden van droogte tijdens het groeiseizoen. Hierdoor is er een grote variatie in de gewasproductie, zowel kwantitatief als kwalitatief. We onderzochten het effect van waterstress op Zn opname bij Sorghum (*Sorghum bicolor* (L.) Moench), de graanopbrengst, en de Zn-MF en IP-6 MF in het graan tijdens een potexperiment in een kas van het Kamboisé onderzoekscentrum in Burkina Faso. Behandelingen bestonden uit alle combinaties van één niveau van composttoediening, twee niveaus van P, twee niveaus van Zn en drie waterstress niveaus (geen stress, NS; stress tijdens het beginstadium van graanontwikkeling, S1 en stress tijdens het afrijpen van het graan, S2).

Graanopbrengst verminderde door waterstress, vergeleken met de NS conditie. Planten met stress namen minder Zn en P op, onafhankelijk van het tijdstip van de stress. Echter, Zn en P kunstmest verbeterden de graanopbrengst en de Zn en P opname, onafhankelijk van de stress conditie. Het effect van de kunstmest was hoger bij de NS conditie. Sorghum graan Zn-MF was hoger voor de planten onder stress condities dan onder de NS conditie. Het tegenovergestelde werd gevonden voor de IP-6-MF. Waterstress verminderde de molaire IP6:Zn verhouding in het graan. Waterstress had meer negatieve gevolgen voor de graanopbrengst dan positieve gevolgen voor de molaire IP-6:Zn verhouding. In de Sahel, waar veel huishoudens niet zeker zijn van voldoende voedsel en waar Zn deficiëntie voorkomt, zijn zowel Zn en P kunstmest, als goede bodem- en waterconserveringstechnieken nodig.

Conclusie

Gezien het voorafgaande kan worden gesteld dat organische bemestingen in combinatie met Zn en P kunstmest resulteert in verhoogde sorghum opbrengsten, terwijl gelijktijdig de IP6:Zn verhouding ongeveer gelijk blijft. Dit kan interessant zijn voor boeren in de Sahel die er naar streven om zelfvoorzienend te zijn. Echter, de IP6:Zn verhoudingen die we gevonden hebben bij de experimenten zijn hoog, gegeven het kritieke niveau van 15 voor bio-beschikbaarheid bij menselijke consumptie. De relatief hoge verhouding, ontstaan bij deze productie methode, moet worden verminderd voordat tot consumptie kan worden overgegaan. De juiste voedselverwerking zal moeten plaatsvinden om de negatieve effecten van IP6 op de Zn bio-beschikbaarheid teniet te doen. De lagere IP6:Zn verhouding die wordt verkregen zonder P kunstmest staan niet in verhouding tot de gemiste opbrengst bij graanproductie zonder P.

Annex 1:

Field questionnaire

Theme: farmers' perception on organic manure production and use and the relation between food quality and family health

Question no 1: Farmers' Province ……………………………………..

Question no 2: Farmers Village ……………………………………..

1 Household structure

Question no 3: Name of household head ……………………………………..

Question no 4: Age of household head
|_|_|_|_| Years

Question no 5: Education level of household head
Alliterated [ ]
Primary school [ ]
Secondary school [ ]
Madersa (Muslim school) [ ]

Question no 6: Family structure

	Over 30 Years	20 –30 years	15-20 years	under 15 years
Men				
Women				

Question no 7: Number of married men in the family
|_|_| Men married

Question no 8: Number of wives
|_|_| Wives

Question no 9: What are your activities? (Rank your answers)
Crop production [ ]
Livestock breeding [ ]
Trade [ ]
Others activities [ ]

Question no 10: Agriculture equipments

Equipment	Number	Functionality	
		yes	no
Donkey plough			
Cow plough			
Cart			
Plough cows			
Donkeys			
Horse			

Question no 11: Livestock fluctuation

Animal specie	Actual number	Number sold past growing season	Number bought past growing season	Consumption past growing season	Others output past growing season (gift, mortality, etc.)
Cows					
Sheep					
Goat					
Donkey					
Horse					

Question no 12: Livestock management

Animal specie	Gazing area			Animals shed			
	Natural fodder	at home	Fixed around the houses	Hangar	Parc	House	Other
Cows							
Sheep							
Goats							
Donkeys							
horses							

Question no 13: Why are you breeding livestock (rank the answers)

- Financial purposes [ ]
- Organic matter production [ ]
- Animal strength [ ]
- Other [ ]

2. Crop production

Question no 14: Identification of cultivated fields during the growing season 2001/2002

Filed Number	Localization	Ownership				Surface (ha)	Crop past season	Soil texture (gravel, sand, clay, silt, or mixed)	Applied CES measures		
		owner	loam	gift	Others				Zai	Zai + Stone line	Zai+ earth line
1											
2											
3											
4											
5											
6											
7											

Question no 15: Applied fertilization during the growing season 2001/2002

Filed Number	Localization	Fertilization type and quantity (units= carts, barrow, bags, etc.)											
		Compost		Farmyard manure		Household waste		Mineral fertilizer (NPK)		Urea		Others	
		Qtity	Unit	Qtity	Unit	Qtity	Unit	Qtity	Unit	Qtity	Unit	Qtity	Unit
1													
2													
3													
4													
5													
6													
7													

Question no 16: Organic manure production and application during the growing season 2001/2002

Nature	Production place			Production method				Qtity	Production starting date	Production ending date	Fertilized fields (number)	Period of manureapplication	Number of labor and number of days
	Home	Field	Other	Pits	Pile	Animals shed	Other						
Compost													
Farmyard manure													
Household waste													
Other s													

Question no 17: What material do you use in your compost pit (rank your answers according to the quantity of each material)

Crop residues [ ]
Farmyard manure [ ]
Others [ ]

Question no 18: What material do you use for farmyard production (rank your answers according to the quantity of each material)

Crop residues [ ]
Others [ ]

Question no 19: What material do you have in your household waste:

....

Question no 20: Which organic matter technique production do you prefer and why (rank your responses):

Organic matter with good quality [ ]
Easier technique [ ]
Others [ ]

Question no 21: How many persons did you use for your compost production:
Digging the pit: |_|_| pers
Fill the pit: |_|_| pers
Return organic matter: |_|_| pers
Withdraw compost from the pit: |_|_| pers

Question no 22: Why do you apply organic matter in the field:......................

Question no 23: What quantity of organic matter do you applied per pit (handful, plate, etc.) and at which frequency:
|_|_| Handfuls or plates, etc.

Every year: [ ]
Once every two years: [ ]
Others : [ ]

Question no 24: The organic matter you have produced last year was it enough to cover all your fields?

Yes [ ]
No [ ]

Question no 25: If the answer is No, how did you manage for the remaining fields

I took some from acquaintances [ ]
I buy from the market [ ]
I don't fertilize the remaining fields [ ]
Others to precise [ ]

Question no 26: Organic manure types' classification. Rank the organic manures according to your experience and give for each choice the reason.

Number	Nature	Reason
1		
2		
3		
4		

Question no 27: During organic manure application do you reserve a type for a specific field?

Yes [ ]

No [ ]

Question no 28: If yes, which one do you applied to which field and why do you adopt such allocation?..

Question no 29: According to your experience do you thing that some organic manures are giving better crop yield than others. If Yes, say which are the best and why..

Question no 30: Do you think that some organic manure types give better grain quality than others? If yes, which one gives the best grain quality and how do you describe a good grain quality..............................

Question 31: Crop production during the growing season 2001/2002

Number	Localization	Crop	Production (cart, basket, bags, etc.)	Yield appreciation (reason)			Grain quality appreciation (reason)		
				good	average	bad	good	average	bad
1									
2									
3									
4									
5									
6									

Question no 32: Production destination

Crop	consumption	sell	buy	Others
	(Basket, bag etc.)			
Sorghum				
Millet				
Peanut				
Cowpea				

Question no 33: Is your last growing season production enough for your family?
Yes [ ]
No [ ]

Question no 34: How many meals do you eat per day?
|_|_| Meals

Question no 35: What is the main composition of your meals (rank answers)

- Sorghum porridge + sauce without meat [ ]
- Sorghum porridge + sauce with meat [ ]
- Sorghum porridge without sauce [ ]
- Others meals to precise [ ]

Question no 36: Do you have preferences for some cultivars or grain quality? If yes what are your criteria? (Rank your answer)

- Grain color [ ]
- Size of the grain [ ]
- Quality of porridge [ ]
- Meal taste [ ]
- Others [ ]

Question no 37: Do you think that the quality of grain changes with organic fertilization type? If yes say which organic fertilization gives the best food quality.

Question no 38: Do you take into account the quality criteria when fertilizing your fields.

- Yes [ ] 1
- No [ ] 2

Question no 39: If yes or no say why?
....

3. Food and human health

Question no 40: During the last growing season was one member of your family sick?

	Disease (name in French or local language)	Period of year	Causes
Men			
women			
Children			

Question no 41: According to your experience what are the diseases attributed to a bad nutrition?..

Question no 42: At which period these sicknesses are common?
(growing season or dry season). /...

Question no 43: What are the solutions for these sicknesses?......................................
....

Question no 44: Do you have children lay off school? If yes say why? (Rank your answers)

Incapacity to follow the regular school program [ ]
Behavior at school [ ]
Others [ ]

Question no 45: According to you what are the reason of that incapacity to follow the regular school program?...

Question no 46: do your ladies loose blood when they are pregnant
....

Question no 47: According to you how do you avoid such sickness?.......................
....

Question no 48: Are you available to participate to a field experiment in order to improve the quality of your cereals. If yes, say why?

Yes [ ] 1
No [ ] 2

Curriculum vitae

TRAORE Karim was born in Loumana, Burkina Faso on the 24th of April 1966. After completing his primary and secondary school respectively at Loumana primary school and Lycee Municipal Banfora, he joined Ouadougougou University, Burkina Faso in 1986 where he obtained a DEUG II in chemistry and biology in 1989, a License in rural development techniques in 1990, a Master in science and rural development techniques in 1991 and an Engineer degree in rural development, option: agronomy in June 1992. From June to December 1992 he worked for a natural resource management project in Ouagadougou, Burkina Faso. From January 1993 to March 1995 he was hired as the Famine Early Warning System (FEWS) project representative assistant at the United State Agency for International development (USAID) in Burkina Faso where he was committed to collect and analyze data on crop production and write reports on food security in Burkina Faso. He was also in charge of the training of people from Ministry of Agriculture on satellite images use for crop production estimation. Since May 1995 he joined Burkina Faso National Institute for Agriculture researches (INERA) as an agronomist. His research activities are focused on a) developing and experimenting soil and water conservation methods in western Burkina Faso, b) integration of cover crops in the farming system to improve soil fertility, and protect against runoff and soil erosion, c) improving the productivity of cotton based system through crop rotation and soil organic amendment, d) using isotopic methods to assess nutrients availability and uptake. In 2002, he was admitted to the PhD Sandwich Fellowship of Wageningen University (INREF-program) within Erosion and Soil and Water Conservation Group. He studied the effects of soil amendments and drought on Zinc husbandry and grain quality in Sahelian sorghum. Mr TRAORE is Member of IAEA and coordinator for INERA Burkina Faso. He is the National coordinator for information and exchange center on cover crops in Africa (CIEPCA). He is also member of the following networks: ROCARS (research on sorghum), AFNET (research on soil fertility). Karim TRAORE can be reached at karim_traore24@yahoo.fr

Research programme "From Natural Resources to Healthy People"

The research for this thesis has been part of the programme ***From Natural Resources to Healthy People: Food-based Interventions to Alleviate Micronutrient Deficiencies.*** This is one of the programmes sponsored by the Interdisciplinary Research and Education Fund (INREF) of Wageningen University. INREF aims to stimulate development-oriented research and education through programmes designed and implemented in partnership with research institutes in developing countries. The programmes aim to build relevant capacity in local research institutions to solve actual problems. The main partners in our programme were China Agricultural University, Beijing and the Jiangsu Provincial Center for Disease Control and Prevention, Nanjing, both from China, the National Institute for Environment and Agricultural Research, INERA from Burkina Faso and the University of Abomey–Calavi from Benin. In total eight staff members from these institutes, including the author of this thesis, received a PhD training.

The micronutrient malnutrition problem

Chronic micronutrient deficiencies, particularly of vitamin A, iron and zinc, lead to impaired mental and physical development and decreased work output, and contribute to morbidity from infections. Pregnant women and children are vulnerable groups. Animal products are good sources of desired micronutrients, but most people in West Africa and China depend largely on sorghum and rice, respectively, for their daily food. These plant-based foods contain limited amounts of micronutrients while they also contain anti-nutritional factors such as phytic acid and polyphenols that inhibit absorption of micronutrients by humans.

Next to the nutritional quality, the production of enough food is an important problem as population growth leads to higher demands for food and more permanent cropping, both increasing pressure on natural resources. In West Africa, soil and water conservation measures are being developed to prevent soil erosion, nutrient and water losses and to maintain or even increase yields. In China, the introduction of aerobic rice systems aim to reduce water use per kg of rice, maintaining yields similar to the current flooded rice systems.

Programme strategies to improve the supply of micronutrients

The increasing demand for food stipulates that improvements in food quality cannot be accepted when they are at the expense of food quantity. Any solution should be in line with sustainable natural resource management.

The programme applied a food chain approach (figure) in sorghum and (aerobic) rice to explore synergies and trade-offs between different interventions along the chain.

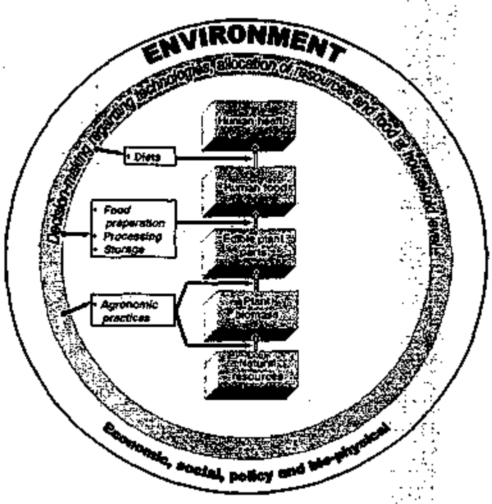

Diagram of the food chain

The food chain approach is indicated showing how external conditions like the economic and bio-physical environment set the stage for decision making at the household level. These decisions in their turn determine practices which have a direct impact on the processes at different points in the food chain. Research in the programme has been done related to each of the three types of interventions.

Agronomic practices should aim to increase uptake and allocation of micronutrients from soil to edible plant parts, while keeping accumulation of anti-nutritional factors low. Research has focussed on effects of genotype, environment & management and their interaction on micronutrient/phytic acid molar ratio in seed. This has led to recommendations on choice of genotype, fertiliser and water use.

Food processing aims to concentrate desired micronutrients in end products and inactivate anti-nutritional factors. Research focussed on effects of milling and processing on micronutrient/phytic acid molar ratio in food, leading to recommendations on optimal combinations of unit operations.

Nutrition studies aim to validate the results in humans. Research focussed on dietary composition, determination of methods to measure impact and evaluation of effects of some of the proposed changes upstream in the food chain on micronutrient uptake in vulnerable groups. This has led to insight in sources of micronutrient and anti-nutritional factors and in the potential contribution of an intervention in the staple food.

At the end of the programme an analysis will be made to determine the relative impact of the different proposed measures along the chain for the final aim: improved micronutrient nutrition of targeted vulnerable groups.

PE&RC PhD Education Statement Form

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of Literature (3 credits)

- Effects of soil amendments and drought on Zn husbandry and grain quality in Sahelian sorghum (2002)

Writing of Project Proposal (5 credits)

- Effects of soil amendments and drought on Zn husbandry and grain quality in Sahelian sorghum (2002)

Post-Graduate Courses (2 credits)

- Crop physiology parameters measurements, CERRAS, Senegal (2003)

Deficiency, Refresh, Brush-up and General Courses (9 credits)

- Erosion modeling (2002)
- Ecophysiology (2002)
- Organic matter (2002)

PhD Discussion Groups (6 credits)

- INREF discussion seminar, Ouagadougou (2003)
- INREF discussion seminar, Wageningen (2005)
- INREF discussion seminar, Beijing (2005)

PE&RC Annual Meetings, Seminars and Introduction Days (1 credit)

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International Symposia, Workshops and Conferences (4 credits)

- International workshop on sustainable dry land agriculture systems, Niger (2003)
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Abstract
In developing countries, short Zn supply is limiting both crop yield and human health. Improving Zn in staple foods and/or improved bio-availability of Zn from staple foods would already greatly improve public health. It's therefore a major challenge to design cereal production techniques resulting in higher Zn mass fractions (MF) in combination with a lower IP-6 MF. In northern Burkina Faso, soil and water conservation (SWC) and soil organic amendments (SOAs) techniques adopted by farmers have improved both water and nutrient availability. Using these techniques crop yield increased in the Sahel. Potentially, this improvement of yields may also improve Zn MF in the grains and/or bio-availability of Zn from staple foods. The main objective of the current PhD program was to investigate possible modifications of SOAs as practice by farmers, which increase both the quality and the yield of sorghum in the Sahel. To fulfil the above objective a combination of farmers' field monitoring, on farm research, on station experiments and greenhouse experiments were carried out in 2002, 2003 and 2004. The experiments consisted of a full factorial design with the factors: organic soil amendments (compost or farmyard manure), Zn fertilizer and P fertilizer. Sorghum grain and straw yields varied considerably between years and they were affected by soil types. But no differences were observed between organic amendment types. Zn and P application significantly increased biomass and grain yield but did more with P application. Interactions between P and Zn application were not significant. Grain Zn MF and IP 6 MF increased with Zn or P application. Effects on both MFs were larger with compost than with farmyard manure and larger on sandy than on gravely soils. With the higher compost dose both Zn and IP-6 were further enhanced. Timing of Zn application only affected Zn MF. The IP-6: Zn molar ratio decreased with Zn application and increased with P application, resulting in comparable ratios when no fertilizer was applied or when both fertilizers were applied simultaneously. Grain Zn MF of 50 mg kg^{-1} with an IP-6: Zn molar ratio of around 15 is possible with Zn and P application in years with adequate rainfall distribution during grain filling. The food quality of such grains can be further improved by degradation of phytate prior to consumption.

Résumé
Dans les pays en voie de développement, la carence en Zn limite le rendement des cultures et la santé humaine. L'enrichissement et l'amélioration de la biodisponibilité en Zn des aliments contribueraient à l'amélioration de la santé des populations. La mise au point de techniques de production capables de générer des récoltes avec des teneurs élevées en Zn et faible en IP-6 est un défit pour ces pays. Dans la zone nord du Burkina Faso, l'adoption de techniques de conservation des eaux et des sols et des amendements organiques a amélioré la disponibilité en eau et en éléments nutritifs. Grâce à ces techniques le rendement des cultures a nettement augmenté dans le sahel. Potentiellement, l'amélioration des rendements pourrait être accompagnés d'une amélioration de la teneur ou de la biodisponibilité en Zn des aliments. L'objectif principal du présent programme PhD a consisté à étudier les possibilités de modifications des amendements organiques tels que pratiqués par les producteurs afin de mettre au point des amendements capables d'augmenter la qualité et le rendement du grain de sorgho au sahel. Pour atteindre cet objectif, des enquêtes terrains et des recherches en milieu paysan et en serre ont été conduites en 2002, 2003 et 2004. Les expérimentation ont consisté en des essais factoriels composés de: amendements organiques (compost et fumier), Fertilisation en Zn en P. Les résultats ont montré des rendements sorgho grain et paille très variables selon les années et affectés par le type de sol. Aucune différence significative n'a été observée entre les types d'amendements organiques. L'application du Zn et du P a significativement augmenté les rendements en biomasse et grain du sorgho avec un impact plus important pour le P. L'interaction entre le Zn et le P n'était pas significative. Les teneurs des graines de sorgho en Zn et en IP-6 ont augmenté avec l'application du Zn et du P. La teneur en ces éléments était plus large pour le compost que pour le fumier et plus large pour les sols sableux que pour les sols gravillonnaires. La forte dose de compost a augmenté la teneur en Zn et en IP-6 pendant que la période d'application du Zn a influencé seulement la teneur en Zn. Le ratio molaire IP 6 : Zn a diminué avec l'application du Zn et augmenté avec l'application du P ce qui résulte en des ratios comparables lorsque aucune fertilisation minérale n'est apportée ou lorsque le Zn et le P sont simultanément appliqués. Une teneur graine en Zn de 50 mg kg^{-1} avec un ratio molaire IP-6 : Zn autour de 15 est possible avec l'application du Zn et du P pour les années avec distribution adéquate des pluies pendant le remplissage des graines. La qualité de la nourriture de ces graines pourrait être améliorée par la dégradation des phytates avant la consommation.

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