1 General introduction

Phosphorus, with nitrogen and potassium, plays a major role in crop production. It occurs in all plants, but quantities are much smaller than those of nitrogen and potassium. In tropical soils, phosphorus (P) is one of the major nutrient elements limiting crop production. This is not due to a shortage of total P in the soil, but to plant P availability. Total contents of P in soils range from about 100 to 2500 kg ha^{-1} in the upper 20 cm of soil; plant available P reaches from 15 in virgin to 231 kg ha^{-1} in cultivated soils (Tisdale and Nelson, 1975). The principal reason for the low plant availability of P is that many tropical soils have extremely high capacities to fix P. Phosphorus-fixing soils are able to retain large amounts of P before they provide satisfactory crop growth. Fixation is understood as the transformation of soluble forms of P into less soluble ones after they react with the soil.

If only Ferralsols, Acrisols and Plinthosols are considered as P fixing soils and Nitosols, which in suborders as well might have P fixing capacities are excluded, it is evident that more than 50% of the total area in tropical regions are affected by P fixation and the subsequent problems for agriculture (FAO, 1990). Against the background of a rapid population growth, these areas have a need for an improvement of soil fertility in terms of a higher plant P availability which will increase the sustainability of these land use systems.

The high fixation capacity of P in tropical soils is caused by their residual accumulation of Fe- and Al-oxydes/hydroxydes and a decreased pH during a long formation time under a humid climate. This fixation is dependent on the variable charge of the oxydes/hydroxides in the soil. At a low pH the higher proton concentration in the soil solution leads to an increased non-specific adsorption of P. Also the positive charge of oxydes/hydroxides, and thus the specific adsorption of PO_4^- on functional groups will increase. This adsorption has a high affinity and the PO_4^- anion is strongly bound, due to the formation of oxygen bridges (Sample et al., 1980).

But plants adapted to these problems by the development of different strategies. For example are they able to increase the pH of the soil (Marschner, 1999). This decreases the adsorption of P and increases the P concentration in the soil solution, thus more P is plant available. Roots can affect the rhizosphere pH by an imbalanced uptake ratio of cations and anions and the subsequent release of H^+ or HCO_3^- to compensate this imbalanced uptake of ions. For example is a nitrate supply correlated with a higher rate of HCO_3^- net release than of H^+ excretion, and with ammonium the reverse is the case (Marschner, 1999). Gahoonia et al. (1992) found that also the direct exchange with HCO_3^- for phosphate adsorbed at the oxydes/hydroxides might play a role for nitrate fed plants on acid soils. For various pasture grasses grown in phosphorus-deficient acid soils depletion of phosphorus in the rhizosphere and increase in rhizosphere pH has been found to be closely associated (Armstrong and Heylar, 1992).

The rhizosphere pH may also change by the excretion of organic acids. But it seems that the major P mobilizing process through this excretion is a ligand exchange in the rhizosphere releasing phosphorus from oxydes/hydroxides. The important role of this mechanism was emphasised by Gardner et al. (1983). He found that organic acids excreted by white lupine roots on a P deficient soil enhanced the P mobility in the rhizosphere and improved the P nutrition of the plant.

The high P fixation complicates the economical use of mineral P fertilizer. If P deficiency in soils can be corrected by an application of 20 to 50 kg P ha^{-1} it is not a problem. But tropical acid soils require partly up to 1000 - 5600 kg P ha^{-1} until they provide sufficient P for a profitable crop production (Sanchez and Uehara, 1980). This appears in front of a background, where costs for mineral fertilizer are high and the budget of farmers in these areas for mineral fertilizers are limited.

The use of mycorrhiza fungi could be an alternative to increase P uptake efficiency of applied P fertilizers. The occurrence of mycorrhiza is very common in agricultural plants. One beneficial aspect of this symbiosis according the P nutrition of plants is the exploration of a larger soil volume by mycorrhizal hyphae. This increases the surface area of absorption through the hyphae network (Sanders and Tinker, 1975; Tinker 1978). The hyphae are able to excrete organic acids and phosphatases (Parfitt, 1979; Moawad 1986), solubilizing organic bound P. Additionally, soil P may move faster into the hyphae (Cress et al., 1979).

The introduction of legumes as green manure into crop rotation is an effective economic way for maintaining soil fertility. Many reports in the literature give evidence that leguminous plants can derive a double benefit from a combined inoculation with effective vesicular-arbuscular mycorrhizal strains and rhizobium especially under P stress conditions resulting in: improved availability of phosphorus for legume growth and nodule formation, increased N uptake and, subsequently, enhanced plant growth. Waidyanatha (1978) found with *Pueraria phaseoloides* and *Stylosanthes guianensis* that both nodulation and nitrogen fixation were depressed unless the legumes were inoculated with mycorrhiza.

The P nutrition of plants is influenced by adding organic materials to the soil. If organic material returns to the soil several factors complicates the prediction of its behaviour according the plant availability. In the material mineralization of organic components and immobilisation of mineral nutrients like P occurs. These processes are influenced differently by the C:P and C:N ratio of the residues and its carbon constituents composition. Many other factors like soil pH or the P concentration of soil and soil solution are also of importance (Stanford and Pierre, 1953).

During mineralization organic bound P has to be hydrolysed by phosphatases, resulting in a release of inorganic P into the soil solution. Hydrolysing enzymes can originate from mycorrhizae hyphae, from bacteria or they can be exuded by roots. Tarafdar and Claassen (2003) found that wheat plants under sterile conditions secreted phosphatases in response to the presence of organic P in the soil solution. They concluded that the organic P might be responsible for the increase in P influx to wheat plants. Nannipieri et al. (1978) and McGill and Cole (1981) suggested that high inorganic P concentrations in soil inhibit phosphatase activity. These findings point out the importance of organic P for the P nutrition of plants.

All these mechanisms show that plants may differ in their P efficiency. In crop rotation systems P efficient plants could serve as a “pitman”: Phosphorus in soil pools that can not be accessed by P inefficient plants can be depleted by efficient ones. The following crop could benefit either from a higher solubility of P in the soil, caused from the preceding crop, or from P that is released by its remaining root material in the soil, or its mulch material if plant residues remain on the field (Mc Laughlin et al., 1980).

In mixed cropping systems the P efficient plant could alter the plant availability of soil P. From this, the intercropped P inefficient plant could benefit according growth and P uptake.

Objectives:

The general objectives of this work were:

1. To identify how plant residues in crop rotations affect the growth of following crops.
2. To assess the effect of mixed cropping systems with P efficient and P inefficient plant components on the growth and P nutrition of the P inefficient plant.

This study is divided into two main chapters. Chapter 2 is addressed to the effect of plant residues on the P nutrition of maize. The results of an incubation study, a pot and a field experiment are presented. Chapter 3 deals with the effect of mixed cropping on the P nutrition of maize. This was investigated in a pot and a field experiment. At the end an overall discussion is given and conclusions are drawn.

2 The effect of plant residues on the P nutrition of maize

2.1 Introduction

An elementary process in the overall impact of plant residues on the growth of succeeding crops is the release of mineral nutrients and nutrient containing complexes from organic residues. Several studies give information about the release and mineralization of N from plant residues (Vanlauwe et al., 1996, Bending et al. 1998). The knowledge about the release of P from plant residues is comparatively small.

The release of P from organic residues left on the soil surface seems to be fast. Auerswald et al. (1997) found a considerable amount of inorganic P that was leached out of deadwood in the soil surface runoff water within the first year. Schomberg and Steiner (1999) found in incubation experiments with mesh bags a different result on the release and the immobilization of P among different plant species. During an 11 months incubation period on the soil surface under different water regimes, the residues of maize and winter wheat had nearly the same P concentrations than at the beginning of the incubation. The residues of sorghum and summer wheat showed a moderate decrease in the P concentrations, whereas the residues of alfalfa already after one month had a 50% lower P concentration than at the start of the experiment. The differences in these P dynamics were more a function of the residue type, which is related to the chemical characteristics of the residues, than of the water regime. Surface residues are subject to more frequent and extreme wetting and drying events than incorporated ones, which may alter the pattern and degree of residue decomposition (Franzluebbers et al., 1994).

The sustainability of cropping systems can be improved by the incorporation of plant residues in rotation cropping systems. Among various factors like ameliorating the soil by better physical soil conditions or a reduced erosion by wind or water (Mac Rae and Mehuys, 1985; Smith et al., 1987) the nutritional status and the availability of nutrients can be improved and soil organic matter contents (Doran and Smith, 1987; Power, 1990) as well as the nutrient retention can increase (Drinkwater et al.; 1998; Dinnes et al., 2002). In relation to the nutritional status many authors focused on the nitrogen supply to succeeding crops by leguminous cover crops (Smith et al., 1987; Sustainable Agriculture Network, 1998). But crops, used as green manure, may also have consequences for the P nutrition of following crops. A better physical condition of the soil allows the following crop to establish a deeper and denser root system, an important factor for phosphorus acquisition of plants (Nielsen, 1979). Other important factors of phosphorus acquisition, that can be affected, are the development and length of root hairs (Gahoonia et al., 1997, Jungk, 2001), the concentration of P in the soil solution (Jungk and Claassen, 1997; Nielsen and Barber, 1978), or the soil bulk density and water holding capacity.

During decomposition of crop residues the soil pH changes and organic acids are excreted by microorganisms. Both factors influence the solubility and therefore the availability of P (Gahoonia et al., 1992). But the incorporation of cover crops can also change chemical-biological parameters affecting P acquisition from soil. The rate of mycorrhizal infection of roots is important for the acquisition of P from soil (Tinker et al., 1992; Marschner, 1999) and the colonization of mycorrhiza is dependent on soil characteristics like organic C concentrations (Martin et al., 2001) which is closely related to the input of plant residues.

If residues are placed on the soil surface microbial decomposition delivers only comparatively small amounts of P to the soil and seems to be slower than the one of residues incorporated into the soil (Douglas et al., 1980). This might be caused by more extreme living conditions for microorganisms in/on surface-placed residues than on the ones incorporated in the soil. A major reason for this are different water regimes; surface-placed residues are exposed more often to desiccation or inundation than incorporated ones (Schomburg et al., 1994). But if in rotation systems the preceding crops are incorporated and decompose, the following crop may benefit from inorganic P that is released during the process of decomposition. Also large pools of labile organic P forms are released. These forms can be mineralized in the soil and supplement P from labile (i.e. easy plant available) inorganic P pools (Tiessen et al., 1994). Increased soil test P values after the incorporation of plant residues were found by Black and White (1973) and McLaughlin et al. (1988) and it has been reported that mineralization can supply significant amounts of plant P in grasslands (Cole et al., 1977), and perhaps in some perennial (Havlin et al., 1984) and organic (Oehl et al., 2001) agricultural systems.

White and Ayoub (1983) studied the effect of decomposing plant residues with varying P contents on the $NaHCO_3$-extractable P content of a soil. Only residues with low C:P ratios increased the extractable P level in a high P-containing soil. Bumaya and Naylor (1988) found that the effects of organic residues on P sorption and extractable P levels were dependent on the P concentration of the residues, the added amounts, soil moisture during incubation and incubation time of the residues with the soil. Extractable P increased and P sorption decreased by adding plant residues with a P concentration larger than 1 g kg^{-1} and at application rates equal or greater than 5% (w/w). This effect was highest shortly after adding the plant material. With time extractable P decreased and P sorption increased. Other authors reported a net P immobilization when the total P concentration of added plant tissues was below 2 to 3 g kg^{-1} (Yadvinder-Singh et al., 1992).

However, the importance of decomposition for the release of P from plant residues is not clear. Mc Laughlin et al. (1988) found that 50% of the ^{33}P labelled residues of the legume *Medicago lupulina* was extractable from soil at the beginning of the experiment. After 15 days of decomposition only 4% of the ^{33}P initially added was found in the residues. They attributed the rapid release of P to the high proportion of inorganic P initially present in the residues. A fast release of P from residues which were incorporated into the soil was also confirmed by Salas et al. (2003). The authors found a rapid release of P from organic material of sorghum (*Sorghum bicolor,* L.) and sunnhemp (*Crotalaria juncea,* L.), which were added to the soil. Already 5 days after adding the residues to the soil 75% and 77% of the total P content of sorghum and sunnhemp was released, respectively. The release of P was detected by a decreased concentration of total P in the remaining plant residues. It was independent from the utilization of C by the microbes and consequently independent from the decomposition. Autolysis of the plant cells and hydrolysis of phosphate esters by plant phosphatases seemed to play the key role.

On the other hand plant residues in the soil may not only release P (mainly via autolysis and hydrolysis); as well an immobilization of large amounts of P via microbial incorporation may occur. This was also confirmed by Salas et al. (2003) in the cited study. Here after 5 days P immobilization occurred and the P concentration in the residues increased. Regarding immobilization the plant residues of the two species differed. The residues of sorghum had 60 days after incorporation similar P concentrations than at the beginning of the study. The residues of sunnhemp had only 25% of the total P amount that they contained at the beginning of the experiment.

Since soil is a complex system there is a competition for available P by microorganisms and soil P sorption (Groffman et al.,1987, Bumaya and Naylor, 1988). This can decrease the plant P availability. However results about this topic are contradictory.

Hypotheses

The following hypotheses were stated:

1. The release of P from plant residues is mainly as organic P. The release of inorganic P is comparatively small. Both releases are closely related to the decomposition of the plant material.
2. If plant residues are added to the soil, the released organic P will be mineralized and increase P availability in the soil.
3. Immobilization of P is mainly by microorganisms and is related to the composition of the plant residues. Chemical immobilization is negligible.
4. The growth and P nutrition of maize will be enhanced if grown on soil that was amended with plant residues.

Because the P dynamics of plant residues left on the soil surface is of importance for assessing processes governing the P nutrition of plants growing on soils with residues from preceding crops, two incubation studies were conducted (chapter 2.2.). The release of inorganic and organic P from crop residues of three different plant species over time was tested. Assessments were done on the role of decomposition and chemical and biological immobilisation of P. The consecutive two chapters (2.3 and 2.4) deal with the effect of plant residues in the soil on the P nutrition of following crops. In chapter 2.3 a pot experiment is presented in which shoot and root residues of different crops were mixed with the soil. The effects on the growth and P nutrition of following maize and on soil P availability parameters were determined and it was assessed if the buried residues immobilised or released P. In chapter 2.4, the relevance of the described processes were evaluated in the field. It was tested, if in crop rotation systems the preceding crops had any effect on the growth and P nutrition of following maize. Since in this experiment beside other plants legumes were used, some statements were done on the effect on the nitrogen nutrition of the maize.