The use of maize-pigeon pea intercropping to enhance organic phosphorus cycling and maize yields in Malawi

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Introduction

In older, highly-weathered soils typical of tropical and subtropical regions such as Malawi, phosphorus (P) is often the main factor limiting crop production[1]. This is in part due to the high abundance of aluminum and iron oxides in these regions, which are known to strongly bind plant-available phosphate ions[2]. Thus, while total soil P content may be adequate, the high P binding capacity of these soils makes both native soil P and added P fertilizers only sparingly soluble. To avoid this issue, most recommended fertilizer application rates are in excess of plant requirements, yet due to low fertilizer accessibility and high costs across Southern Africa, most subsistence farmers use less than the recommended fertilizer rates, if any. As a result, the soils are mined of nutrients and crop yields continue to decline.

In Malawi, maize (*Zea mays*) is the dominant agricultural crop and food source, and continuous maize monocropping is the most common agricultural practice. Yet despite an initial boost in maize yields following the implementation of a heavily subsidized fertilizer program, maize yields have become stagnant over the past decade, with peak yields over one thousand times lower than the most productive countries[3]. As such, alternative strategies are being sought to increase yields that do not rely solely on mineral fertilizers. One such method for managing plant-available P in acidic tropical soils is to promote the storage of soil P in organic forms, including microbial biomass, as this may provide a slow yet continuous source of P to plants and thus reduce sorption to soil particles[4]. While the most common approach to increasing soil organic P is through the application of organic amendments, in Malawi organic soil amendments such as manure and plant residues are rarely available due to their primary importance as fuel and fodder.

Instead, another approach to increasing soil organic P may be to improve soil structure through changes in agricultural management practices, such as increasing crop biodiversity through intercropping two or more different plant species. Increases in soil aggregation have long been known to improve soil structure by increasing the storage of soil organic matter and nutrient cycling by physically protecting these compounds from biological and physical degradation and erosion[5]. Not only does this enhanced protection reduce nutrient losses from the system, it also increases the organic matter storage capacity, thus increasing nutrient availability to growing plants. Although most research in this field has focused on soil organic carbon, recent studies have indicated that organic P may be stored in a similar manner[6], which would be particularly beneficial for tropical soils. Thus, intercropping maize with a local and preferably nutritious edible crop that does not directly compete with maize for resources may be a potential strategy for improving soil structure and consequently soil fertility and crop nutrient uptake within these highly degraded soils of Malawi.

For this project, I chose to intercrop maize with pigeon pea (*Cajanus cajan*). Pigeon pea is a grain legume with the ability to biologically fix large amounts of N without the need for inoculation, has a high biomass production potential, high protein and nutrient content, and is climatically suitable to Eastern Africa[7]. In addition to its effect on N dynamics, several studies have shown a positive impact of pigeon pea on P dynamics, including the ability to use sparingly soluble P pools through the exudation of organic acids[8] and phosphatase enzymes[9], as well as its particularly high internal plant P use efficiency[10]. While these studies collectively point to the ability of pigeon pea to access P pools typically less available to other crops, including maize, they do not give any indication of how these P uptake strategies change in an intercropping system, nor if the neighboring intercropped species can benefit by this released P.

Objectives and hypotheses

The main objectives of this project were thus to determine if the maize-pigeon pea intercropping system was able to i) increase biological nitrogen fixation by pigeon pea compared to sole pigeon pea, ii) increase soil aggregation and storage of C, N, and P pools within the soil aggregate size fractions compared to sole maize, and iii) increase maize production and nutrient (N and P) uptake compared to sole maize.

I hypothesized that pigeon pea plants intercropped with maize would have a higher proportion of biological nitrogen fixation compared to sole pigeon pea due to stimulation of the associated rhizobial bacteria as maize and pigeon pea roots compete for soil N. Secondly, I postulated that the intercropped systems would have increased soil aggregation compared to sole maize, which would subsequently increase the amount of C, N, and P stored within the soil aggregate fractions. Finally, as a result of the increased N fixation and nutrient storage, I expected increased yield and nutrient uptake of intercropped maize compared to sole maize by nutrient transfer via rhizospheric root interactions.

These objectives were accomplished through the use of field trials in Linthipe and Ekwendeni, Malawi set up by my collaborators from the International Institute of Tropical Agriculture (IITA) and Michigan State University (MSU) (Fig. 1), as well as a controlled greenhouse trial at ETH Zurich located at a field research center in Lindau, Eschikon (Fig. 2).

Research findings and conclusions

As hypothesized, aggregation of intercropped soils was significantly higher compared to sole maize, increasing by 52 and 111% in the macroaggregates and microaggregates, respectively (Fig. 3). Furthermore, the microaggregates of the intercropped soils had significantly higher concentrations of C, N, and P pools (particularly organic P) compared to the sole maize soils (Table 1). This finding is particularly exciting because it shows that, contrary to the popular belief that significant changes in soil fertility through organic practices requires several years, significant improvements in soil structure and nutrient enrichment can occur in only one growing season, and through simple and inexpensive changes in crop management strategies.

Regarding maize yields, I did not find significant differences in maize biomass in the intercropped treatments compared to the sole maize treatments. However, maize in the intercropped system was significantly enriched in N compared to sole maize, which is an important precursor to improved plant growth and grain production. Therefore, it is possible that a single growing season was not long enough to build adequate soil N stocks necessary for increased maize production. Similarly, although the soil aggregates of the intercropped treatments had increased soil nutrient storage, it is possible that the maize plants were not able to access these nutrients within a single growing season. It is likely, however, that over time these soil aggregates will become exposed to mineralization and solubilization events which will release nutrients from these protected fractions, leading to increased growth and yield in subsequent years. Thus, in future trials we will measure crop biomass and yields over multiple years.

As expected, we found that the intercropped pigeon pea had a significantly higher percentage of nitrogen derived from the atmosphere compared to sole pigeon pea (Fig. 4). It is thus likely that the source of the increased N for the maize within the intercropped treatments was due to a within-season transfer of biologically fixed N from neighboring pigeon pea plants via rhizospheric root interactions. This is promising because it shows that significant enrichment of N can occur very soon following the implementation of this intercropping system, which is clearly important for subsistence farmers who do not have the resources to purchase mineral N fertilizers, nor the luxury of time to wait for improvements in soil fertility and plant nutrient availability.

Potential for rural development

This is the first study that I am aware of which assesses the impact of intercropping systems on soil aggregation and P speciation at the soil aggregate level in order to understand how chemically different P pools are physically stabilized by rhizospheric root interactions and how this in turn effects crop yields. Although an immediate response to maize yields was not seen, these results show that a simple change in plant management was able to improve soil structure and nutrient storage capacity at the soil aggregate level, which will potentially impact nutrient cycling and crop yield in the future. Furthermore, because this system uses a high-protein, edible crop, it also diversifies the local diet of both human and livestock within the region.

Following the interesting and promising results from this project, I am incredibly interested in continuing this work as a post-doctoral researcher in order to determine the long term effect of this cropping system on maize yields and nutrient storage, as well as determining which specific organic P compounds are stored within the soil, and to what degree these compounds can become plant-available over time. I am currently in the processing of submitting four manuscripts resulting from this work to highly regarded open-access journals so that local researchers and extension agents can use this data for their own research and outreach purposes. If funded, I also plan to return to Malawi for further work in the field trials, where I will present my work in person to the local farmers and community members.

References

[1] Bekunda M, Sanginga N, Woomer PL (2010) Restoring soil fertility in sub-Sahara Africa. Advances in Agronomy 108:183-286.
[2] Cornell RM, Schwertmann U (2003) The iron oxides: structure, properties, reactions, occurrences, and uses. Wiley-VCH Berlag GmbH & Co. KGaA, Weinheim. pp 1-646.
[3] FAO STAT (2014) Maize yields across Malawi. Accessed 24 May 2016. http://faostat3.fao.org/browse/Q/QC/E
[4] Oberson A, Pypers P, Bünemann EK, Frossard E (2011) Management impacts on biological phosphorus cycling in cropped soils. E.K. Bünemann, A. Oberson, E. Frossard (Eds.). Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Soil Biology, 26 Springer, Heidelberg. pp. 431-458.
[5] Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Research 79:7-31.
[6] Nesper M, Bünemann EK, Fonte SJ, Rao IM, Velásquez JE, Ramirez B, Hegglin D, Frossard E, Oberson A (2015) Pasture degradation decreases organic P content of tropical soils due to soil structural decline. Geoderma 257-258:123-133.
[7] Odeny DA (2007) The potential of pigeonpea (*Cajanus cajan* (L.) Millsp.) in Africa. Natural Resources Forum. 31:297-305.
[8] Ae N, Arihara J, Okada K, Yoshihara T, Otani T, Johansen C (1993) The role of piscidic acid secreted by pigeonpea roots grown in an Alfisol with low-P fertility. Genetic aspects of plant mineral nutrition. Springer Netherland. 279-288.
[9] Ascencio J (1996) Growth strategies and utilization of phosphorus in *Cajanus cajan* L. Millsp. and *Desmodium tortuosum* (Sw.) DC under phosphorus deficiency.
[10] Adu-Gyamfi JJ, Fujita K, Ogata S (1989) Phosphorus absorption and utilization efficiency of pigeon pea (*Cajanus cajan* (L) Millsp.) in relation to dry matter production and dinitrogen fixation. Plant Soil 119:315-324.

Figures

Figure 1: Maize and pigeon pea plants within intercropping field trial in Linthipe, Malawi.

Figure 2: Maize and pigeon pea plants in greenhouse trial at Lindau, Eschikon.

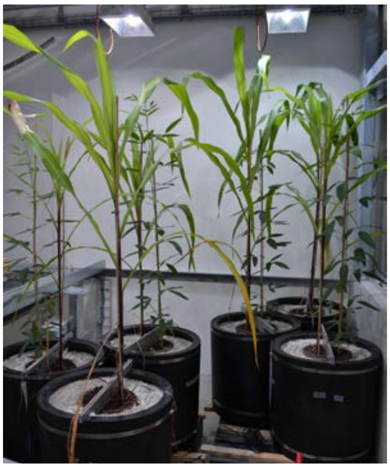

Figure 3: Soil aggregate distribution within each plant and root barrier treatment as a percentage of soil weight within each aggregate size fraction. Significant differences between plants for each treatment (Solid = monocropping; Mesh = 30 µm mesh barrier between plant species; None = intercropping) are designated with lower case letters, while significant differences between treatments for a particular plant are designated with upper case letters (p<0.05). Error bars are the standard error of the mean (n=3).

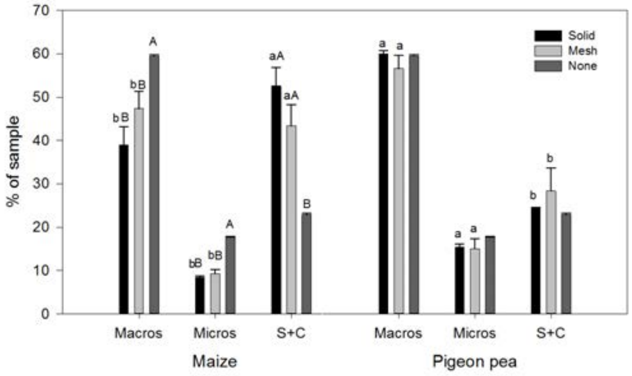

Figure 4: Total amount of N (g N plant^{-1}) fixed by pigeon pea and the percentage of N derived from air (Ndfa) within each root barrier treatment (Solid = monocropping; Mesh = 30 µm mesh barrier between plant species; None = intercropping). Different lower case letters indicate significant differences in the percentage of Ndfa between root barrier treatments (p<0.05).

Tables

Table 1: Nutrient concentration of the microaggregate fraction (53 – 250 µm) in nutrient kg^{-1} aggregate fraction. Differences between plants and treatments were analyzed using a means separation by Tukey HSD analysis. Significant differences between maize (M) and pigeon pea (PP) for each treatment (Solid = monocropping; Mesh = 30 µm mesh barrier between plant species; None = intercropping) are designated with lower case letters, while significant differences between treatments for a particular plant are designated with upper case letters (p<0.05). Numbers in parentheses are the standard error of the mean (n=3). Values with * indicate significance at p<0.1.

Nutrient	Unit	Plant	Treatments					
			Solid		Mesh		None	
Total P	mg P kg^{-1}	M	321 (22)	bB	328 (32)	bB	483 (7)	A
		PP	473 (8)	aAB	435 (20)	aB	483 (7)	A
Microbial P	mg P kg^{-1}	M	1.4 (0.2)	bB	1.8 (0.6)	bAB	2.9 (0.3)	A
		PP	2.5 (0.1)	a	2.6 (0.4)	a	2.9 (0.3)	
Available P	mg P kg^{-1}	M	1.2 (0.1)	bB	1.2 (0.1)	b*B	1.8 (0.3)	A
		PP	1.7 (0.2)	a	1.6 (0.2)	a*	1.8 (0.3)	
Oxide-P	mg P kg^{-1}	M	73 (3)	bB	79 (4)	bB	101 (3)	A
		PP	98 (2)	a	94 (5)	a	101 (3)	
Organic P	mg P kg^{-1}	M	29 (3)	bB	45 (9)	bB	84 (4)	A
		PP	77 (3)	a	75 (10)	a	84 (4)	
Ca-P	mg P kg^{-1}	M	28 (2)	aA	25 (1)	aAB	21 (1)	B
		PP	20 (1)	b	20 (2)	b	21 (1)	
Total C	g C kg^{-1}	M	20 (2)	bB	20 (1)	bB	25 (1)	A
		PP	25 (1)	a	24 (1)	a	25 (1)	
Total N	mg N kg^{-1}	M	974 (69)	b	962 (19)		1247 (10)	
		PP	1323 (63)	a	1177 (59)		1247 (10)	