Physical and Chemical Parameters of Common Soils in the Central Plateau Region of Haiti

Ryan Elliott Stewart

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science in Crop and Soil Environmental Sciences

Wade Thomason, Committee Chair
Steven Hodges
Michael Mulvaney

May 31, 2012
Blacksburg, Virginia

Keywords: organic matter fractions, Central Plateau Region, Haiti, phosphorus, rhizosphere

Physical and Chemical Parameters of Common Soils in the Central Plateau Region of Haiti

Ryan E. Stewart

ABSTRACT

Soil degradation is a common occurrence in Haiti that is mainly caused by the cultivation of marginal lands and deforestation, which both contribute to the excessive erosion rate seen in the country today. The Central Plateau of Haiti is a mountainous region in which a majority of the population is rural and practices subsistence agriculture on hillsides and steeply-sloping land. Essential plant nutrients, such as nitrogen (N) and phosphorus (P), are commonly a limiting factor in crop production, yet fertilizer is unavailable or is too expensive for smallholder farmers to purchase. This study was conducted to a) evaluate organic matter and nutrient stocks of various soils in the Central Plateau region, along with other chemical and physical characteristics and b) to evaluate the phosphorus-scavenging ability of commonly-grown crops to isolate those that may benefit subsequent smallholder yields. Soils from four locations in the Central Plateau were assessed for organic matter in labile and non-labile fractions as well as for cation exchange capacity (CEC), total organic carbon (C) and N, pH, texture, and other characteristics. Results indicated that most of the soil (92%) was contained within aggregates, and organic matter was mainly present in stable, slowly-decomposing fractions. Seven species were evaluated in a controlled-environment pot experiment for bulk and rhizosphere soil P and pH, plant dry weight, and above- and below-ground P tissue content as indicators of the species' ability to solubilize P from the soil. Velvet bean (*Mucuna pruriens* (L.) DC) produced the most biomass and was able to take up the most P, though lablab (*Lablab purpureus* (L.) Sweet), took up comparable amounts of P.

ACKNOWLEDGMENTS

I would like to begin by expressing my gratitude to my advisor, Dr. Wade Thomason, for your guidance and support throughout my two years here at Virginia Tech. I learned so much from the whole research and writing process, and through that, I have developed a deep appreciation for agricultural research. I would also like to thank my committee, Dr. Steve Hodges and Dr. Mike Mulvaney, for your valuable assistance and careful review of my manuscript. I am grateful to Kiran, Mike, Hunter, Cleiton, Julie, and Abbey for all the help you guys gave me, and to Steve Nagle, for showing me how to properly work in a lab and for putting up with my mess. Lastly I would like to thank Robert Badio, Herby Etienne, and Guillaine Warne for their immense help on our trip to Haiti and in sample collection, and my parents, Bill and Ginette Stewart, for their encouragement and support during these two years.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter II

Chapter III

LIST OF TABLES

Chapter II

Chapter III

LIST OF ABBREVIATIONS

Abbreviation	Meaning	Page
C	carbon	ii
Ca	calcium	7
CA	Conservation Agriculture	9
CEC	cation exchange capacity	ii
cPOM	coarse particulate organic matter	20
DI	de-ionized	23
EC	electrical conductivity	23
HF	heavy fraction	20
ICP	inductively-coupled plasma	24
K	potassium	7
LF	light fraction	18
M	macroaggregate (250µm-8mm)	24
m	microaggregate (53µm-250µm)	24
Mg	magnesium	7
Ms+c	macroaggregate silt and clay	25
N	nitrogen	ii
Na	sodium	24
P	phosphorus	ii
POM	particulate organic matter	18
S	sulfur	8
SOC	soil organic carbon	8
SOM	soil organic matter	2
SPT	sodium polytungstate	25
S+C	whole soil silt and clay	24

CHAPTER I - INTRODUCTION

THE CONDITION OF SOILS IN HAITI

Many Haitian soils have been severely degraded over the last few centuries as a result of deforestation, cultivation of steeply-sloping land, and low-input intensive agriculture (Isaac et al., 2003; McClintock, 2004; Williams, 2011). These practices have led to extensive erosion, shallower soils, and lower productivity (Jaffe, 1989), which has resulted in limited crop yields and exacerbated the poverty of rural farmers. According to Zimmerman (1986), crop yields in Haiti are among the lowest in the world.

Deforestation, mainly due to agricultural clearing and the demand for wood as a household fuel (Stevenson, 1989), has increased the rate of soil erosion in Haiti. Tree roots hold soil in place and allow water to infiltrate more readily, reducing the potential for soil to be washed away. Reduced vegetative cover, along with the steep slopes that characterize much of the country's land area, has contributed to the erosion of the country's soils. It is estimated that 36.6 million tons of soil is lost per year nationally (Jolly et al., 2006; Sperling et al., 2010). In many places, especially on hillsides, erosion has exposed bedrock (McClintock, 2004).

According to Pellek, (1992), the most serious problem affecting the Haitian agricultural sector is erosion. Sperling et al. (2010) estimate that 30-50% of farmers are using land that is steeply sloped, while Williams (2011) reports that about a third are working land that is not considered suitable for cultivation. Soil from these unprotected landscapes is easily carried away by the torrential rainfall (3000 mm annually in some places) that characterizes Haiti's rainy seasons (Oates, 2001). Precipitation from intense tropical storms often exceeds the soil's infiltration capacity and causes runoff and subsequent erosion (Paskett and Philoctete, 1990). It is estimated that more than 80% of the rain falling on steep bare slopes cannot infiltrate and becomes runoff (Zimmerman, 1986).

The availability of soil nutrients for plant uptake is a major yield-limiting factor of these soils, yet chemical fertilizer use is not widespread in Haiti due to its expense and lack of availability. A study conducted by Martinez et al. (1991) with smallholder farmers in Les Cayes found that most did not fertilize their maize, largely because the cheaper of the two nitrogen sources in the region, urea, was scarcely available. Continuous intensive agriculture without replenishing soil nutrients and organic matter through inputs has been shown to reduce soil productivity over time (Stoorvogel et al., 1993; Drechsel et al., 2001). According to Sperling et al. (2010), only the liberal use of chemical fertilizers will correct the nutrient deficiencies present in Haiti's soils.

Deforestation, cultivation of steeply-sloping land, and low-input intensive agriculture can have large impacts on physical and chemical properties of soil. The removal of surface vegetation resulting from deforestation causes a decline in soil organic matter (SOM), which in turn lowers the soil's water-holding capacity, CEC, and resistance to erosion. In addition, the force of raindrops falling onto bare soil breaks up soil aggregates and causes smaller particles to fill in pores, further increasing the erosion rate (Hobbs et al., 2007). Soil loss following erosion removes nutrient-rich upper horizons and further reduces organic matter content. In impoverished rural systems, there is an agricultural trend to shorten the duration of fallow periods within crop rotations, which leads to a depletion of organic matter reserves and essential nutrients (Clermont-Dauphin et al., 2004).

Phosphorus is an important nutrient that is needed for vigorous plant growth and the production of reproductive parts (Havlin et al., 2005). However, it is commonly the major limiting factor in many agricultural ecosystems (Kamh et al., 1999; Lynch and Brown, 2000; Bossa et al., 2005). Low N and P availability are major limitations in bean production in highly weathered tropical soils (Dorcinvil et al., 2010). Shannon et al. (2001) studied five agricultural soils formed with differing parent material, elevation, and moisture regime throughout Haiti, all of which contained low P levels. A study by Guthrie and Shannon (2004) in which plant available P was measured, found that five out of six soils they described in southern Haiti were considered very low in available P.

DESCRIPTION OF SUBSISTENCE AGRICULTURE IN HAITI'S CENTRAL PLATEAU REGION

Farming is the principal occupation of approximately 60% of the population. Many farmers practice subsistence agriculture with much of the labor done by hand or with simple tools (McClintock, 2004). Primary cultivation is performed either by hand or with animal power, though in the more mountainous areas of the Central Plateau, plowing with oxen is rare because the land is too steep for the animals to be effective. Typical land preparation in this case involves clearing the aboveground biomass with a hand sickle and then burning the residue before tillage with a pick (McClintock, 2004). In a limited number of fields, weed and crop residues are left on the field to decay, protecting soil from erosion as well as adding to soil organic matter (McClintock, 2004). Since most Haitian farmers own a small amount of land, fields are rarely fallowed due to the need to continually produce food for their families (Sperling et al., 2010).

Land tenure in Haiti is an intricate system of verbal agreements in which plots are leased, bought, sublet, inherited, and gifted (Smucker et al., 2000). The typical plot is very small (less than half of a hectare) as a result of the subdivision of land upon inheritance (Zimmerman, 1986). To avoid notary fees and the risk of losing land from updating surveys, most land transactions among peasants are done informally, without legal documents (Smucker et al., 2000). Property rights are therefore largely insecure and not well-defined (Smucker et al., 2000; Dollsca et al., 2007). Haiti's land tenure system is sometimes considered the key constraint in rural development and agricultural intensification (Smucker et al., 2000).

Crops commonly grown are pigeon pea (*Cajanus cajan*), cowpea (*Vigna unguiculata*), maize (*Zea mays* L.), sorghum (*Sorghum vulgare* Pers.), peanut (*Arachis hypogaea*), common yellow and black beans (*Phaseolus sp.*), cassava (*Manihot utilissima*), sweet potato (*Ipomoea batatas* Lam.), and various vegetables (McClintock, 2004; Sperling et al., 2010). Fields are intercropped for increased food security (if one of the crops fails, there will still be a harvest of something else) and for staggered harvesting periods, so that food is available at different periods during the year (Sperling et al., 2010). Maize is planted between March and June and is traditionally intercropped with beans, cassava, peanuts, or sweet potato in some combination, while sorghum is grown during the dry season and not intercropped (Watts, 1979). Planting methods involve hand sowing seeds or the use of a dibble stick; some farmers gather weed residues into mounds and cover the mounds with topsoil to provide organic matter for the seed (McClintock, 2004). Weeds are generally controlled through intensive tillage before planting and through hand weeding (2-3 times) throughout the growing season (McClintock, 2004). The weed residue is left on the soil as fertilizer for the crop. After the harvest, tubers, grains, and seeds are consumed or traded for household goods; some are stored in elevated granaries (Sorenson and Chung, 1973; McClintock, 2004).

Maize, plantain (*Musa acuminata*), and cassava are grown for consumption, while coffee (*Coffea Arabica* L.), cacao (*Theobroma cacao* L.), and mango (*Mangifera indica* L.) are grown for export as well (Smucker et al., 2005). Intermediary traders known as “madame saras” buy produce, arrange for its transport and storage, and sell it to other wholesalers in markets throughout Haiti (Sorenson and Chung, 1973). Madame saras do not usually carry more than 270 US dollars in working capital (Smucker et al., 2005), and are limited in the amount of goods they transport at a time and by the transportation infrastructure in the Central Plateau (Sorenson and Chung, 1973).

The climate of the Central Plateau is humid subtropical with large local variations due to the mountainous topography, though annual precipitation varies between 1016 to 1524 mm (Erlich et al., 1987). Rainfall mainly occurs in two periods throughout the year, the spring rains from April to June, and the fall rains from August to October (White, 1992). This bimodal distribution allows multiple cropping seasons per year. During the rainy seasons, beans are grown in the highlands to avoid disease, but during the dry season, they are grown in the lowlands where they can be irrigated (Erlich et al., 1987).

SOIL RESOURCES

Guthrie and Shannon (2004) described nine upland soils throughout Haiti; six of them formed over limestone, while the others formed from siliceous limestone and shale colluvium, limestone colluvium, and basalt. Four were classified as Mollisols, three as Alfisols, one as an Inceptisol, and the last as an Entisol. Their pHs ranged from 6.8 to 8.3, CEC from 6.20 to 58.05 $\text{cmol}_c\ \text{kg}^{-1}$ soil, plant available P from 0.0022 to 0.0538 Mg ha^{-1}, and organic matter content from 0.6 to 12.3%. Guthrie and Shannon (2004) found these soils had high organic matter content and CEC considering the large amount of erosion they had experienced, though were low in plant available P and micronutrients caused by the generally high pH. The authors concluded that large fertilizer inputs would be needed to achieve maximum yields from these soils.

Farmers in the Central Plateau are forced to deal with many yield-limiting factors, such as steep terrain, widespread soil erosion, and poor soil fertility. The Central Plateau is an upland region of Haiti with a landscape dominated by alluvial plains overlying calcareous limestone and conglomerates (White, 1992). These soils have been intensely cultivated for years without significant fertilizer input and are subsequently severely depleted of nutrients. A study by Clermont-Dauphin et al. (2004) found low P availability to be the most limiting factor in common bean production in highland soils of Haiti, followed by low potassium (K) and magnesium (Mg) availability. Low P availability may be partly caused by high calcium (Ca) concentrations in the soil as Ca reacts with P to form insoluble calcium phosphates, which are unavailable to plants (Havlin et al., 2005). Clermont-Dauphin et al. (2004) discovered that due to the limestone bedrock, soil CEC was commonly saturated with Ca, though organic matter was the dominant contributor to the CEC. McClintock (2004) found that crops displayed sulfur (S) and N deficiencies as well.

Soil organic matter is another important component of agricultural soils that is found in low concentrations in the Central Plateau (Sperling et al., 2010). Lower SOM levels in tropical soils are common because of high temperatures and increased decomposing activity of soil microbes (Panwar et al., 2010). A lack of SOM contributes to nutrient leaching, decreased soil porosity, and a decrease in structural stability of the soil (Havlin et al., 2005). Conversely, additions of SOM improve soil structure and water retention capability (Pellek, 1992). Soil organic matter acts as a reservoir for nutrients; nutrient cations are held in a form that is readily accessible to plants, but they are not rapidly leached out of the soil by rainwater (Brady and Weil, 2008). Factors influencing the amount of SOM present in a soil are aggregate stability and clay content. Soil aggregates have been shown to physically protect SOM from decomposition by microbes (Six et al., 1998), while a higher clay content allows more organic material to be trapped in ultra-micropores (< 1 µm) that are too small for microbes to access (Brady and Weil, 2008).

Much of the SOM is composed of soil organic carbon (SOC) due to the large percentage of C (about 45%) in plant tissue (Havlin et al., 2005). Organic soil amendments, such as manures, are another significant source of SOC (Panwar et al., 2010; Abbas et al., 2012). Soil organic carbon has been attributed to soil productivity, increased crop production, and agricultural sustainability, and is of interest to researchers because of its role as a sequestration site for atmospheric C (West and Post, 2002).

CONSERVATION AGRICULTURE

Conservation agriculture (CA) is a set of management practices that may be implemented by Haitian farmers to help counteract the extreme soil degradation that is occurring from traditional farming practices, and it has been shown to be effective in various locations worldwide (Qin et al., 2010; Thierfelder and Wall, 2010; Van den Putte et al., 2010). According to the Food and Agriculture Organization of the United Nations (FAO), CA is "an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely: 1) continuous minimum mechanical soil disturbance, 2) permanent organic soil cover, and 3) diversification of crop species grown in sequences and/or associations." A goal of this management approach is to minimize inputs by a more efficient use of natural resources (such as rainwater, organic matter, and native soil organisms) while maintaining a permanent soil cover (Knowler and Bradshaw, 2007). However, due to the risk-averse nature of resource poor farmers, such as those farming hillsides in Haiti, adoption of these practices is often very slow or nonexistent (Shannon et al., 2001).

Conservation agriculture involves practices such as no-till, where soil is minimally disturbed during planting (Hobbs et al., 2007), and strip tillage, where typically less than a third of the soil surface is tilled (Laryea et al., 1991). Other CA practices involve cover cropping with legumes (for non-chemical weed control and N fixation), manure collection and spreading (as an organic fertilizer source), and the construction of residue bunds and rock walls that prevent erosion and capture SOM (McClintock, 2004; Hobbs et al., 2007).

The use of alley cropping, residue bunds, and rock walls is especially important on steeply sloping tropical lands, such as can be found in Haiti's Central Plateau. By reducing erosion, these practices in marginal areas help to stabilize watersheds and preserve downstream areas from sediment loading (Pellek, 1992). Upland alley cropping involves the use of a woody or leguminous species planted in hedgerows along the contour that will help keep soil in place while a cash crop is grown in the alleys formed between them (Paskett and Philoctete, 1990). This cultural practice has seen promising results in previous works in Haiti because it provides erosion control, soil moisture conservation, and organic matter and nutrient addition (Isaac et al, 2004; Bossa et al., 2005). Alley cropping with regular additions of hedgerow clippings provides a residue cover for the soil as well as a nutrient source for the cash crop (Juo and Thurow, 1997). Isaac et al. (2003) found that clippings from the hedgerow species leucaena (*Leucaena leucocephala* [Lam.] de Wit) applied as a mulch and incorporated into the soil increased surface SOC and total N in Haiti. In Haiti, a *rampe de paille* is a residue bund composed of sticks, straw, and other dead plant material that is woven into a linear structure along a contour and tied to stakes that are driven into the ground (Pellek, 1992). This structure slows runoff velocity and catches sediment, developing a small terrace upslope of the barrier. Rock walls, which serve a similar purpose, may be suitable for steep land with abundant rocks on the surface to provide building material, but require more labor to maintain. A steep lands erosion study in the Philippines by Dano and Siapno (1992) found that rock walls reduced erosion from cropped lands by 61%, but required regular maintenance to remain effective.

Conservation agriculture practiced in Haiti may improve the country's rural agricultural production. Investigating the allocation of SOM under common agricultural systems in the Central Plateau would add to the knowledge of soil resources in Haiti. A study of the nutrient-solubilizing ability of crops commonly grown for consumption could identify certain species that effectively scavenge P and other nutrients in low nutrient soils, such as those that can be found in the Central Plateau region. A potential result could be the identification of crop species that are most useful in providing P for succeeding crops and a subsequent yield increase. The present study attempts to address these two issues in the following chapters.

OBJECTIVES

The overall objective of this research is to evaluate soil physical and chemical properties of select sites in the Central Plateau region of Haiti and how crops may influence nutrient supply and plant availability. The specific objectives are: 1) to assess the current level of SOC and total N in whole soil and in various soil fractions and 2) to identify dual-purpose food/cover crop species that are able to solubilize the largest amount of P by measuring rhizosphere pH and P concentrations in the rhizosphere and in the plant.

REFERENCES

Abbas, F., A. Faras, H. Valenzuela, and S. Fares. 2012. Carbon dioxide emissions from an organically amended tropical soil. Journal of Sustainable Agriculture 36:3–17.

Bossa, J., J. Adams, D. Shannon, and G. Mullins. 2005. Phosphorus and potassium release pattern from leucaena leaves in three environments of Haiti. Nutrient Cycling in Agroecosystems 73:25-35

Brady, N., and R. Weil. 2008. The nature and properties of soils. 14th ed. Pearson Prentice Hall, Columbus, OH.

Clermont-Dauphin, C., Y. Cabidoche, and J. Meynard. 2004. Diagnosis on the sustainability of an upland cropping system of southern Haiti. Agriculture, Ecosystems, and Environment 105:221-234.

Dano, A., and F. Siapno. 1992. The effectiveness of soil conservation structures in steep cultivated mountain regions of the Philippines. p. 399-405. *In* Proc.of the Chengdu Symposium, July 1992, Chengdu, China.

Dollsca, F., J. McDaniel, L. Teeter, and C. Jolly. 2007. Land tenure, population pressure, and deforestation in Haiti: The case of Forêt des Pins Reserve. Journal of Forest Economics 13:277-289.

Dorcinvil, R., D. Sotomayor-Ramirez, and J. Beaver. 2010. Agronomic performance of common bean (*Phaseolus vulgaris* L.) lines in an Oxisol. Field Crops Research 118:264-272.

Drechsel, P., D. Kunze, and F. Penning de Vries. 2001. Soil nutrient depletion and population growth in sub-Saharan Africa: A Malthusian nexus? Population and Environment: A Journal of Interdisciplinary Studies 22.

Erlich, M., F. Conway, N. Adrien, F. LeBeau, L. Lewis, H. Lauwerysen, et al. 1987. Haiti country environmental profile: a field study. USAID, Port-au-Prince, Haiti.

Guthrie, R., and D. Shannon. 2004. Soil profile descriptions for steeplands research sites in Haiti. Auburn University, Auburn, AL.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil Fertility and Nutrient Management: An Introduction to Nutrient Management. 7th Edition. Pearson/Prentice Hall. Upper Saddle River, NJ.

Hobbs, P., K. Sayre, and R. Gupta. 2007. The role of conservation agriculture in sustainable agriculture. The Philosophical Transactions of the Royal Society B 363:543-555.

Isaac, L., C. Wood, and D. Shannon. 2003. Pruning management effects on soil carbon and nitrogen in contour-hedgerow cropping with Leucaena leucocephala (Lam.) De Wit on sloping land in Haiti. Nutrient Cycling in Agroecosystems 65:253-263.

Isaac, L., D. Shannon, and C. Wood. 2004. Hedgerow pruning management effects on maize yield and nitrogen uptake in an alley cropping system in Haiti. Agronomy Journal 96:1632-1640.

Jaffe, J. 1989. Land use, soil degradation, and farmer decision-making: A sondeo report of Cavalier, Despa, Kols, and Saut Matherine, Haiti. USAID.

Jolly, C., D. Shannon, M. Bannister, G. Flauretin, J. Dale, B. Alvin, and P. Lindo. 2006. Income efficiency of soil conservation techniques in Haiti. p.156-163. *In* N. Badrie (ed.) Proc. 26th West Indies Agricultural Economics Conference, July 2006, San Juan, Puerto Rico.

Juo, A., and T. Thurow. 1997. Sustainable technologies for use and conservation of steeplands. Texas A&M and Texas Agricultural Experiment Station, College Station, Texas

Kamh, M., W. Horst, F. Amer, H. Mostafa, and P. Maier. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant and Soil 211:19-27.

Knowler, D., and B. Bradshaw. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food Policy 32:24-48.

Laryea, K., P. Pathak, and M. Klaij. 1991. Tillage systems and soils in the semi-arid tropics. Soil and Tillage Research 20:201-218.

Lynch, J., and K. Brown. 2000. Topsoil foraging - an architectural adaptation of plants to low phosphorus availability. Plant and Soil 237:225-237.

Martinez, J., G. Sain, and M. Yates. 1991. Toward farm-based policy analysis: concepts applied in Haiti. Agricultural Economics 5:223-235.

McClintock, N. 2004. Regenerative agriculture for Haiti's Central Plateau - A sustainable foundation for food and nutrition security, Zanmi Lasante Paris.

Oates, P. 2001. Solar disinfection for point of use water treatment in Haiti. M.Eng. thesis. Massachusetts Institute of Technology, Boston.

Panwar, N., P. Ramesh, A. Singh, and S. Ramana. 2010. Influence of organic, chemical, and integrated management practices on soil organic carbon and soil nutrient status under semi-arid tropical conditions in central India. Communications in Soil Science and Plant Analysis 41:1073-1083.

Paskett, C., and C. Philoctete. 1990. Soil conservation in Haiti. Journal of Soil and Water Conservation 45(4): 457-459.

Pellek, R. 1992. Contour hedgerows and other soil conservation interventions for hilly terrain. Agroforestry Systems 17:135-152.

Qin, S., C. Hu, X. He, W. Dong, J. Cui, and Y. Wang. 2010. Soil organic carbon, nutrients and relevant enzyme activities in particle-size fractions under conservational versus traditional agricultural management. Applied Soil Ecology 45:152-159.

Shannon, D., J. Lea, L. Isaac, and S. Belfort. 2001. Productive land use systems project: Haiti., South-East Consortium for International Development and Auburn University, USAID/Haiti Economic Growth Office.

Six, J., E. Elliott, and K. Paustian. 1998. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Science Society of America Journal 63:1350-1358.

Smucker, G., T. White, and M. Bannister. 2000. Land tenure and the adoption of agricultural technology in Haiti, 9th Biennial Conference of the International Associaltion for the Study of Common Property, Victoria Falls, Zimbabwe, June 2002.

Smucker, G., G. Fleurantin, M. McGahuey, and B. Swartley. 2005. Agriculture in a fragile environment: Market incentives for natural resource management in Haiti. USAID.

Sorenson, L, and D. Chung. 1973. Grain marketing and market system development in Haiti. USAID.

Sperling, L., D. Brick, J. Ludger, J. Montgerard, M. Louis, F. Yueto, et al. 2010. Seed system security assessment, Haiti, USAID.

Stevenson, G. 1989. The production, distribution, and consumption of fuelwood in Haiti. The Journal of Developing Areas 24:59-76.

Stoorvogel, J., E. Smaling, and B. Janssen. 1993. Calculating soil nutrient balances in Africa at different scales. Fertilizer Research 35:227-235.

Thierfelder, C., and P. Wall. 2010. Rotation in conservation agriculture systems of Zambia: Effects on soil quality and water relations. Experimental Agriculture 46:309-325.

Van den Putte, A., G. Govers, J. Diels, K. Gillijns, and M. Demuzere. 2010. Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. European Journal of Agronomy 33:231-241.

Watts, R. 1979. Nutrient availabilities affecting growth of corn and sorghum on three Haitian soils. M.Sc. thesis. Virginia Tech., Blacksburg.

West, T., and W. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal 66:1930-1946.

White, T. 1992. Peasant cooperation for watershed management in Maissade, Haiti: factors associated with participation. Working Paper - Environmental and Natural Resources Policy and Training Project:Vol 4: 38pp.

Williams, V. 2011. A case study of desertification in Haiti. Journal of Sustainable Development 4:20-31.

Zimmerman, T. 1986. Agroforestry - a last hope for conservation in Haiti? Agroforestry Systems 4:255-268.

CHAPTER II - CHARACTERIZATION OF SOIL ORGANIC MATTER AND OTHER PHYSICAL AND CHEMICAL CHARACTERISTICS OF SELECT SOILS IN THE CENTRAL PLATEAU REGION OF HAITI

INTRODUCTION

Soil organic matter acts as a reservoir for nutrients and increases soil water holding capacity and aggregate stability (Gulde et al., 2008). Management practices such as reducing or eliminating tillage (Six et al., 1998a; Jacobs et al., 2010), leaving crop residue in place in fields (Smith et al., 1992), and the use of high residue production cropping systems are known to increase SOM, but beneficial changes associated with these practices are not often seen within five to seven years (Sequeira and Alley, 2011). Certain fractions of SOM have a turnover rate of a few days to a year. These active or labile fractions of SOM are often defined and measured due to their quick response to changes in land management practices (McLauchlan and Hobble, 2004; Wander, 2004; Tan et al., 2007; Marin-Spiotta et al., 2008) and their sensitivity to changes in total SOM (Carter, 2002). Most soils contain a large stable (or recalcitrant) pool of SOM, with a much smaller active pool that is derived from recently added plant and animal residues (Brady and Weil, 2008).

Labile SOM fractions can be extracted using physical fractionation procedures based on the size and density of SOM particles (Christensen, 2001; McLauchlan and Hobble, 2004; Wander, 2004). These procedures assume that the associations and spatial distribution of soil particles and the degree to which SOM is bound to minerals are important to how it functions in the soil (Gregorich et al., 2006). The size-based procedure involves sieving to determine the particulate organic matter (POM) fraction, while the density-based procedure utilizes a liquid with a specific density to extract the light fraction (LF) (Wander, 2004). Sometimes, both procedures are combined to separate the LF from mineral-associated organic matter for each particle- and aggregate-size class (Six et al., 1998b; Del Galdo et al., 2003).

Aggregates have been studied due to their potential to physically protect organic matter from decomposition (Adu and Oades, 1977; Gulde et al., 2008). Soils with a higher level of aggregation tend to mineralize a smaller proportion of their total N because it is not as accessible to microbes (Sollins et al., 1984). Tillage, or any other disturbance of the soil, breaks up aggregates, which exposes organic matter that was previously inaccessible to microbes to oxidation (Golchin et al., 1994) and leads to organic matter decomposition (Six et al., 1998b). Light fraction organic matter usually accounts for <30% of the total SOM in tilled soils, whereas in forest soils it is often higher (Boone, 1994). Microaggregates, the smaller aggregates that are 50-250µm in size, are important in the development of soil structure because they can be bound together by roots or fungal hyphae to form larger aggregates (Tisdall and Oades, 1979; Elliott, 1986). The stability of macroaggregates (aggregates >250µm) is strongly influenced by land management and organic matter content; an increase in organic matter is associated with an increase in macroaggregate formation in a soil (Tisdall and Oades, 1982).

MATERIALS AND METHODS

Terminology

In this thesis, the aggregate terminology of Del Galdo et al. (2003) will be used; macroaggregates are water-stable aggregates 250µm to 8mm in size, while microaggregates are water-stable aggregates 53-250µm in size. Coarse particulate organic matter (cPOM) will be considered organic matter that is >250µm in size that is protected inside macroaggregates. The LF will be defined as organic matter that has a density of <1.85 g cm^{-3}, the solution density used in Del Galdo et al.'s (2003) procedure. The LF is composed of organic matter that is not associated with mineral particles and, with a high turnover rate, is more responsive to management practices than the organic matter that is associated with mineral particles (Murage et al., 2006).

Recalcitrant fractions can also be measured using a density-based fractionation procedure. These fractions consist of organic matter that is highly aromatic and stable (Tiessen and Stewart, 1983) and that is protected from decomposition by a close association with mineral particles (Murage et al., 2006). Recalcitrant organic matter changes slowly over time and does not significantly affect soil fertility in the short- and medium- time scales (Tiessen and Stewart, 1983). This procedure isolates the heavy fraction (HF), which will be defined as the material remaining after the LF has been recovered.

Sample Collection

Four locations were sampled in the Central Plateau Region of Haiti between 12 and 14 May 2011 (Figure 2.1). The Corporant farm near the town of Mirebalais is managed by Zanmi Agrikol and is located on alluvium on the floodplain of the Artibonite River (18° 53’ N, 72° 05’

W, 120.7 m elevation). Experimental fields at this farm have been extensively tilled and cropped for at least the previous 17 years. Common crops in the rotation include maize, common bean, sorghum, peanut, okra (*Abelmoschus esculentus* [L.] Moench), and carrot (*Daucus carota* L.). The Lachateau farm near the town of Boucan Carré is also managed by Zanmi Agrikol and is located in a valley bottom on colluvium (18° 55’ N, 72° 07’ W, 158.5 m elevation). Similarly, this farm has been extensively tilled and planted to maize, common bean, sorghum, peanut, cassava, pigeon pea, and plantain. History prior to 2008 is undocumented but fields have been in constant cultivation, with no fallow, since at least 2008. The Maissade farm is operated by Caritas Diocésaine de Hinche and is located on a mountainside (19° 9’ N, 72° 06’ W, 291.4 m elevation). Relevant fields on this farm showed evidence of cultivation, but were in grassland prior to beginning this study. The Bas Cange site is near the town of Cange and is located in a valley bottom on colluvium (18° 55’ N, 71° 59’ W, 182.3 m elevation). Similar to the first two sites described, these fields have been extensively tilled and planted to food crops in the recent past. These locations were chosen to represent a cross section of agriculture landscapes employing subsistence farming systems in the Central Plateau region. Three composite soil samples consisting of 12-15 individual cores were taken from Corporant, Lachateau, and Maissade, while one composite sample was taken from Bas Cange. Samples were taken at depth intervals of 0-5cm, 5-10cm, and 10-15cm with a 3-cm-diameter soil probe. Three soil bulk density cores were taken from Corporant, Lachateau, and Maissade down to 15cm using copper cylinders with an interior diameter of 5cm at depth intervals of 0-2.5cm, 2.5-5cm, 5-10cm, and 10-15cm. All samples were shipped to Virginia field-dry where they were air-dried and further processed.

Figure 2.1. Satellite imagery indicating the approximate location of the four sample locations in Haiti's Central Plateau.

Texture

The procedure described by Gee and Bauder (1986) was used to determine soil texture. A 40g subsample from each sample/depth combination was ground to pass a 2mm sieve and placed in a 250mL bottle along with 100mL 5% hexametaphosphate. The bottle was shaken for 2hrs on an orbital shaker at 180rpm, then the material in the bottle was rinsed into a 1L sedimentation tube in preparation for the hydrometer procedure. The sedimentation tubes were brought up to the 1L mark with de-ionized (DI) water and placed in a water bath to regulate temperature. A blank sedimentation tube was prepared in order to account for solution viscosity; 100mL of 5% hexametaphosphate was added and then the tube was brought up to the 1L mark with DI water. Twenty-four hours later, after the suspensions in the tubes had equilibrated with the ambient air temperature, a plunger was used to thoroughly stir the suspension and a Buoyocous hydrometer was carefully inserted. Hydrometer readings from each sedimentation tube were taken at 30s, 60s, 3min, 10min, 30min, 90min, and 24hrs.

Bulk Density, pH, and Electrical Conductivity

Each bulk density core was split into four depth intervals (0-2.5cm, 2.5-5cm, 5-10cm, and 10-15cm) and dried at 105°C to constant weight. Oven-dried weight was recorded and the volume of each cylindrical segment determined and the density of soil calculated. Soil pH and electrical conductivity (EC) were measured in a 2:1 water/soil suspension.

Cation Exchange Capacity

Two grams of soil was added to 20mL 1M ammonium acetate adjusted to pH 8.5 with 14.8N NH_4OH and shaken for 2hrs at 180rpm according to the procedure suggested by Normandin et al. (1998). The mixture was then filtered through a 45µm filter under vacuum and the extract was analyzed for Ca, sodium (Na), Mg, and K using Inductively-Coupled Plasma Atomic Emission Spectrometery (ICP) (Spectro Analytical Instruments, Kleve, Germany). Cation exchange capacity was estimated through the summation of these cations, assuming no exchangeable acidity was present.

Organic Carbon and Nitrogen

A 5g subsample was ground to pass a 2mm sieve and put into a 50mL centrifuge tube along with 20mL 1M HCl using the modified Loeppert and Suarez (1996) procedure to remove inorganic carbon. The tubes were shaken at 180rpm for 1hr and then the contents were filtered under vacuum and rinsed with ~30mL DI water to remove excess HCl. Material left on the filter was dried, reground to pass a 2mm sieve, and further ground on an automatic mortar grinder (Retsch RM200, Haan, Germany). One gram of ground material was analyzed for organic C and total N by dry combustion at 900°C (LECO Corp., St Jose, MI, USA) according to the procedure by Schepers et al. (1989).

Organic Matter Fractions

Aggregate separation and organic matter fractionations were carried out according to the procedure used by Del Galdo et al. (2003) with slight modifications as shown in Figure 2.2. Forty grams of soil from each sample was sieved to pass an 8mm sieve and divided into three water-stable size fractions (macroaggregates [M] 250µm-8mm, microaggregates [m] 53µm-250µm, and silt+clay [S+C] <53µm) by wet sieving using the procedure described by Elliott (1986). The sample was poured onto a 250µm sieve and slowly lowered into DI water. Capillary action allowed the soil to completely wet and minimized disaggregation. The sieve was moved up and down manually 50 times a distance of 3cm over two minutes to ensure the complete isolation of the M fraction, then dried in an oven at 60°C. The material that had passed the 250µm sieve was poured onto a 53µm sieve and the same process repeated to isolate the m fraction. The S+C that had passed the 53µm sieve was collected and dried in an oven at 60°C. All fractions were then weighed.

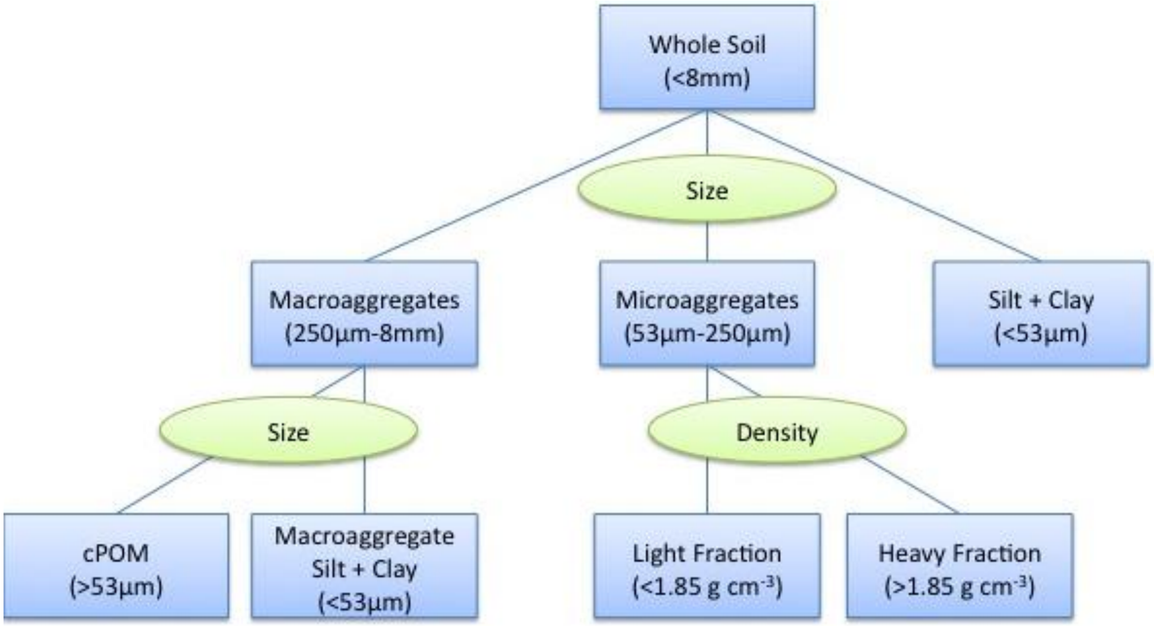
The M fraction was then divided into cPOM and macroaggregate silt+clay (Ms+c) by using the wet sieving method in Elliott (1986). Macroaggregates were placed into a 200mL bottle along with 35mL DI water and 20 4mm glass beads and shaken at 180rpm for 1hr. The material was then washed onto a 53µm sieve and the same wet sieving procedure was used to separate the cPOM and the Ms+c. Both fractions were then dried in an oven at 60°C and weighed.

The microaggregate fraction was further separated by density using sodium polytungstate (SPT) at 1.85g cm^{-3} as the density solution. The microaggregate fraction was placed into a 50mL centrifuge tube along with 35mL SPT solution and shaken gently 10 times. Material on the sides and cap of the tube was rinsed back into the suspension with DI water and the tube centrifuged at 36g for 30min to consolidate the heavy fraction. The supernatant was transferred via aspiration and filtered through a 20µm nylon filter. The material remaining on the filter (the LF) was rinsed onto a small aluminum tray with DI water and dried at 60°C, then weighed. The material left in the centrifuge tube (the HF) was also dried at 60°C. All fractions (S+C, cPOM, Ms+c, LF, and HF) were analyzed for organic C and total N by dry combustion at 900°C (Schepers et al., 1989).

Analyses

Analysis of variance and means for relevant soil physical and chemical and soil OM fractions were calculated using the GLM procedure of the SAS software package with all sources of variation treated as fixed effects (SAS Institute, 2008). Tukey's means separation was carried out using PROC GLM in SAS comparing among depth within locations, and over sampling locations by depth to compare sites. Means were considered different at the 0.05 level of significance. Bulk density data were analyzed separately with the UNIVARIATE procedure because not all locations were sampled. Since only one sample was taken at Bas Cange, only mean values are presented for this location.

Figure 2.2. Soil organic matter fractionation scheme and description of size and density classes modified from Del Galdo et al. (2003).



RESULTS AND DISCUSSION

Physical Characteristics

Cation exchange capacity averaged over all three depths was 19.77, 52.33, 32.62, and 21.28 $\text{cmol}_c\ \text{kg}^{-1}$ soil for Corporant, Lachateau, Maissade, and Bas Cange, respectively (Table 2.1). Lachateau and Maissade had the highest CEC values, which was likely due to their large clay content (51% and 46%), respectively. The CEC did not vary with depth at any of the locations, though at each depth increment, Lachateau > Maissade > Corporant. Calcium dominated the exchange complex at all locations with a saturation of 87-95%. Guthrie and Shannon (2004) found similar results in calcareous Haitian highland soils formed from limestone parent material. Carbon and N percentage did not change with depth (Table 2.1) and ranged from 1.33% C at Lachateau to 2.04% C at Maissade and from 0.13% N at Lachateau to 0.25% N at Bas Cange. Maissade had greater C concentrations than Corporant or Lachateau in the 0-5cm depth and more than Lachateau at the 5-10cm depth (Table 2.1). Whole soil C/N ratios were lowest at Bas Cange (12.19) and highest at Maissade (16.02) averaged over all depths. These results are comparable to those found by other authors studying soils under tropical agroecosystems (11.0-21.0 [Sotomayor-Ramirez et al., 2006], 15.4-21.7 [Beldini et al., 2010], and 8.9-16.5 [Posada and Schuur, 2011]). Soil pH values, averaged across depths, were 8.10 at Corporant, 8.04 at Lachateau, 8.01 at Maissade, and 8.21 at Corporant. Soil pH increased with depth at Lachateau, though it did not differ by depth across sites (Table 2.1). Electrical conductivity was 0.26, 0.32, 0.31, and 0.28mS cm^{-1} at Corporant, Lachateau, Maissade, and Bas Cange, respectively, and did not differ by depth across locations or among depths at each location (Table 2.2). Soil textural class was sandy clay loam at Corporant, clay at Lachateau and Maissade, and silty clay loam at Bas Cange (Table 2.3). Bulk density increased with depth at

Corporant and Lachateau from 0.91 to 1.66 and 1.11 to 1.41g cm^{-3} respectively, though it did not increase at Maissade (Table 2.4).

Organic Matter Fractions

Over all locations and depths, the M, m, and S+C fractions comprised about 80%, 12%, and 8% of the whole soil by weight, respectively (Tables 2.5, 2.6, and 2.7). Similar results were obtained by other authors (Ayuke et al., 2011; Del Galdo et al., 2003) who found that macroaggregates made up the largest percentage of soil. The cPOM fraction ranged from 8% to 60% of the M fraction, with the Bas Cange cPOM contributing little (<10%) and the Corporant cPOM contributing the most (60%). The M fraction was larger at Maissade than at Corporant for all depths (Table 2.5). This could reflect the fact that Maissade had been in fallow when the samples were taken, as the absence of recent cultivation would allow plant roots and fungal hyphae to promote the formation of macroaggregates (Tisdall and Oades, 1980). Corporant had a larger m fraction than Lachateau or Maissade at each depth, a larger LF at 0-5cm, and a larger HF than Maissade at all depths (Table 2.6). Across all soils and all depths, the m fraction consisted mostly of HF (>99%), while the remaining <1% was LF. Lachateau had a larger bulk soil S+C percentage than Maissade at the 0-5cm depth (Table 2.7).

Averaging over locations and depths, the majority of SOC was in the M fraction (82%), with about half of the SOC in the recalcitrant Ms+c fraction. About 10% of the SOC was found in the m fraction, with the remaining 8% in the S+C fraction. The HF contains a large majority (>90%) of the microaggregate SOC, results comparable to those obtained by Sequeira and Alley (2011) who worked on acidic Virginia soils. This indicates that the labile density-based fraction (LF) contributed little to total SOC, and that the vast majority of the water-stable aggregates sized 53-250µm was associated to some degree with mineral particles. Zotarelli et al. (2007)

observed that under native vegetation, the LF-C comprised 16% of the total SOC, though under no-till and conventionally-tilled fields, LF-C dropped to less than 10%, which are similar to findings obtained in this study, in which all soils were tilled. Similar trends existed with total N over depths and locations, with about 83%, 11%, and 6% in the M, m, and S+C fractions, respectively (Tables 2.5, 2.6, and 2.7). At Corporant, cPOM-C was smaller than at Lachateau or Maissade at all depths (Table 2.5). Across locations, no difference was observed in HF-N for each depth (Table 2.6). Corporant had a larger S+C-C content than the other locations and more S+C-N than Maissade at all depths (Table 2.7).

Most of the organic matter in the Corporant, Lachateau, Maissade, and Bas Cange soils was associated with mineral particles and was therefore relatively stable with a slow turnover rate. However, a small portion of the SOM was labile, not associated with minerals, and decomposes relatively quickly. Over all soils and depths, the LF had a wider C/N ratio than the HF, with an average C/N ratio of 17.1 and 6.0 for the LF and HF, respectively (calculated from Table 2.6). Other studies found similar results (30.0 and 16.7 for LF and HF respectively in soils from the Pacific Northwest and Costa Rica using a density solution of 1.60g cm^{-3} [Sollins et al., 1984] and 32.0 and 19.7 respectively in weathered soils from the Brazilian Amazon using a density solution of 1.37g cm^{-3} [Beldini et al., 2010]). Material with a low or narrow C/N ratio is expected to be decomposed by microorganisms more quickly than material with a higher C/N ratio (Pineiro et al., 2006; Posada and Schuur, 2011) though results from this study seem to contradict this expectation. Sollins et al. (1984) found similar results, and proposed that the degree of protection of organic matter inside aggregates controls its rate of decomposition, as opposed to the material's C/N ratio. Most of the SOC and SON (82% for both) in these soils was likely occluded or protected inside macroaggregates, which contributed to the formation of more stable forms of organic matter in these soils.

CONCLUSION

The soils in this study were typical of cultivated soils found in upland regions in Haiti. They formed over calcareous parent material and subsequently have an alkaline pH and a CEC that was dominated by Ca. Most of the soil was contained within aggregates >53µm (>90%), which protect organic matter from decomposition by microbes. The largest portion of SOC was present in the recalcitrant fractions that are associated with mineral particles (Ms+c, HF, and S+C) and therefore would be expected to decompose more slowly than the labile fractions (cPOM and LF), which are composed of more recent organic additions to the soil.

Table 2.1. Soil chemical and physical characteristics from four selected crop fields in the Central Plateau of Haiti sampled in 2011. Values were compared among depths at each location (lowercase letters) and among locations at each depth (capital letters).

Location	Depth	Ca	K	Mg	Na	CEC[†]	N	C	C/N	pH	EC[‡]
	cm	——cmol$_c$ kg^{-1} soil——					---------%---------				mS cm^{-1}
Corporant	0-5	17.79 a[§],C[¶]	0.23 a,C	0.88 a,C	0.06 a,B	18.96 a,C	0.17 a,A	1.55 a,B	13.81 a,B	8.10 a,A	0.23 a,A
	5-10	19.04 a,C	0.29 a,A	1.02 a,C	0.05 a,B	20.39 a,C	0.19 a,AB	1.73 a,AB	13.78 a,B	8.10 a,A	0.33 a,A
	10-15	18.66 a,C	0.20 a,B	1.05 a,C	0.05 a,B	19.96 a,C	0.19 a,A	1.67 a,A	13.22 a,B	8.10 a,A	0.23 a,A
	Mean	18.50	0.24	0.98	0.05	19.77	0.18	1.65	13.60	8.10	0.26
Lachateau	0-5	50.62 a,A	0.64 a,A	2.39 a,B	0.16 a,A	53.81 a,A	0.16 a,A	1.63 a,B	15.19 a,A	7.98 a,A	0.34 a,A
	5-10	50.63 a,A	0.40 b,A	2.08 ab,B	0.11 b,A	53.22 a,A	0.13 b,B	1.33 b,B	15.29 a,AB	8.01 b,A	0.35 a,A
	10-15	47.71 a,A	0.34 b,A	1.83 b,B	0.08 b,B	49.95 a,A	0.11 b,A	1.04 b,A	14.59 a,AB	8.13 b,A	0.28 b,A
	Mean	49.65	0.46	2.10	0.12	52.33	0.13	1.33	15.02	8.04	0.32
Maissade	0-5	27.97 a,B	0.42 a,B	3.71 a,A	0.11 a,A	32.22 a,B	0.20 a,A	2.10 a,A	16.08 a,A	7.96 a,A	0.31 a,A
	5-10	28.98 a,B	0.40 a,A	3.86 a,A	0.12 a,A	33.36 a,B	0.20 a,A	2.17 a,A	16.33 a,A	7.98 a,A	0.30 a,A
	10-15	27.74 a,B	0.30 b,AB	4.09 a,A	0.15 a,A	32.28 a,B	0.18 a,A	1.84 b,A	15.65 a,A	8.09 a,A	0.29 a,A
	Mean	28.23	0.37	3.89	0.13	32.62	0.19	2.04	16.02	8.01	0.30
Bas Cange	0-5	18.13 na	0.51 na	2.01 na	0.06 na	20.71 na	0.26 na	2.32 na	13.77 na	8.20 na	0.29 na
	5-10	19.22 na	0.46 na	2.12 na	0.10 na	21.90 na	0.25 na	1.96 na	12.03 na	8.19 na	0.28 na
	10-15	18.68 na	0.41 na	2.04 na	0.11 na	21.24 na	0.23 na	1.59 na	10.77 na	8.23 na	0.27 na
	Mean	18.68	0.46	2.06	0.09	21.28	0.25	1.96	12.19	8.21	0.28
Grand Mean		28.77	0.38	2.26	0.10	31.50	0.19	1.74	14.21	8.09	0.29
	sd	13.28	0.12	1.10	0.04	13.63	0.04	0.36	1.660	0.09	0.04

[†] Cation Exchange Capacity
[‡] Electrical Conductivity
[§] Values within a location across depths followed by the same lowercase letter are not significantly different at $P<0.05$
[¶] Values within a depth interval across locations followed by the same capital letter are not significantly different at $P<0.05$
na - not applicable

Table 2.2. Analysis of variance among sampling depth increments for soil chemical and physical parameters by location from four selected crop fields in the Central Plateau of Haiti sampled in 2011.

Location	Ca	K	Mg	Na	CEC[†]	N	C	C/N	pH	EC[‡]
	-----	-----	-----	-----	-----	Pr>F	-----	-----	-----	-----
Bas Cange	na	na	na	na	na	na	na	na	na	na
Corporant	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Lachateau	ns	**	**	**	ns	**	**	ns	*	*
Maissade	ns	*	ns	ns	ns	ns	*	ns	ns	ns

*,** - significant at the 0.05 and 0.01 level, respectively

na - not applicable

ns - not significant

[†] Cation Exchange Capacity

[‡] Electrical Conductivity

Table 2.3. Sand, silt, and clay fractions from four selected crop fields in the Central Plateau of Haiti sampled in 2011.

Location	Depth	Sand	Silt	Clay
	cm	---------------	%	---------------
Corporant	0-5	51	24	24
	5-10	51	25	24
	10-15	52	24	24
	Mean	51	24	24
Lachateau	0-5	29	21	49
	5-10	30	19	51
	10-15	27	19	54
	Mean	29	20	51
Maïssade	0-5	18	35	47
	5-10	25	32	43
	10-15	22	31	47
	Mean	22	33	46
Bas Cange	0-5	12	57	31
	5-10	14	54	33
	10-15	8	56	36
	Mean	11	56	33
	Grand Mean	28	33	39
	sd	15	15	11

Table 2.4. Soil bulk density by depth at Corporant, Lachateau, and Maissade.

	Location					
Depth	Corporant		Lachateau		Maissade	
cm	----------g cm^{-3}----------					
0-2.5	0.91	a[†]	1.11	a	1.10	a
2.5-5	0.87	a	1.09	a	1.09	a
5-10	1.15	b	1.24	ab	1.08	a
10-15	1.66	c	1.41	b	1.12	a
Mean, 0-15 cm	1.15		1.21		1.10	

[†] Within a location, values followed by the same lowercase letter are not significantly different at $P<0.05$

Table 2.5. Macroaggregate organic matter fraction (250µm-8mm) weights, C and N content, and percentage of bulk soil at four selected crop fields in the Central Plateau of Haiti sampled in 2011.

				cPOM[†]										Ms+c[‡]						
Location	Depth			Mass		Carbon			Nitrogen				Mass		Carbon			Nitrogen		
	cm	% bulk soil		% of M[§] fraction		g kg^{-1} fraction		% total C	g kg^{-1} fraction		% total N		% of M fraction		g kg^{-1} fraction		% total C	g kg^{-1} fraction		% total N
Corporant	0-5	62	a[¶],B[#]	59.92	a,A	5.2528	a,B	22.23	1.3404	a,A	37.93		40.08	a,C	12.466	a,B	35.29	1.3829	a,B	26.181
	5-10	66.4	a,B	56.089	a,A	3.7307	a,B	12.97	1.6905	ab,A	28.03		43.912	a,C	12.153	a,A	33.07	1.361	a,A	17.664
	10-15	65.1	a,C	57.509	a,A	3.9562	a,B	18.03	2.0341	b,B	49.07		42.491	a,C	12.141	a,A	40.89	1.3617	a,B	24.27
	Mean	64.5		57.839		4.3132		17.75	1.6883		38.34		42.161		12.253		36.63	1.369		22.705
Lachateau	0-5	80.1	a,A	37.917	a,A	23.361	a,A	48.1	3.9197	a,A	61.32		62.083	a,B	11.946	a,AB	40.27	1.1055	a,B	28.312
	5-10	82.5	a,A	39.651	a,A	18.164	ab,A	47.16	3.0049	a,A	61.3		60.349	a,B	10.331	a,A	40.83	0.9054	a,A	28.114
	10-15	80.6	a,B	41.792	a,A	14.552	b,A	40.7	4.5544	a,A	76.91		58.208	a,B	12.478	b,A	48.61	0.6581	a,C	15.479
	Mean	81.1		39.787		18.692		45.31	3.826		66.51		60.213		11.585		43.24	0.887		23.968
Maïssade	0-5	89.6	a,A	30.876	a,A	24.918	a,A	44.01	3.563	a,A	49.74		69.124	a,A	12.218	a,A	48.3	1.4138	a,A	44.177
	5-10	90	a,A	32.628	a,A	26.497	a,A	47.54	3.5207	a,A	50.26		67.372	a,A	11.954	a,A	44.28	1.4789	a,A	43.584
	10-15	89.3	a,A	29.436	a,B	23.073	a,A	43.46	4.5793	b,B	53.71		70.564	a,A	9.7103	a,A	43.84	1.2311	a,A	34.608
	Mean	89.6		30.98		24.829		45	3.8877		51.24		69.02		11.294		45.47	1.3746		40.79
Bas Cange	0-5	81.9	na	9.6813	na	49.419	na	16.4	4.7018	na	22.67		90.319	na	24.04	na	74.45	1.4214	na	63.931
	5-10	87.6	na	10.221	na	73.224	na	24.65	5.9728	na	27.96		89.779	na	23.301	na	68.9	1.52	na	62.506
	10-15	84.6	na	5.4356	na	61.122	na	13.92	5.2282	na	15.58		94.564	na	19.574	na	77.49	1.3628	na	70.609
	Mean	84.7		8.446		61.255		18.32	5.3009		22.07		91.554		22.305		73.62	1.4347		65.682
	Grand Mean	80		34.263		27.272		31.6	3.6757		44.54		65.737		14.359		49.65	1.2663		38.286
	sd	9.99		18.647		22.592		14.64	1.4449		18.3		18.647		4.9709		15.23	0.2565		18.725

[†] Coarse particulate organic matter fraction

[‡] Macroaggregate silt + clay fraction

[§] Macroaggregate fraction

[¶] Values within a location, followed by the same lowercase letter are not significantly different at P<0.05

[#] Values within a depth interval, followed by the same capital letter are not significantly different at P<0.05

na - not applicable

Table 2.6. Microaggregate organic matter fraction (53-250µm) weights, C and N content, and percentage of bulk soil at four selected crop fields in the Central Plateau of Haiti sampled in 2011.

				Microaggregate																
				LF†									HF‡							
Location	Depth			Mass		Carbon			Nitrogen				Mass		Carbon			Nitrogen		
	cm	% bulk soil		% of M§ fraction		g kg^{-1} fraction		% total C	g kg^{-1} fraction		% total N		% of M fraction		g kg^{-1} fraction		% total C	g kg^{-1} fraction		% total N
Corporant	0-5	29.7	a[#],A[††]	0.1972	a,A	262.12		1.776	13.967		0.633		99.803	a,A	7.0322	a,A	23.77	0.9871	a,A	22.312
	5-10	25.8	a,A	0.1393	a,A			0.883			0.225		99.861	a,A	16.795	a,A	40.37	4.1315	a,A	47.363
	10-15	27	a,A	0.1094	a,A			0.946			0.267		99.891	a,A	7.4732	a,A	24.49	1.0077	a,A	17.478
	Mean	27.5		0.1486		262.12		1.202	13.967		0.375		99.852		10.433		29.54	2.0421		29.051
Lachateau	0-5	11.3	a,B	0.1913	a,A	335.55		0.489	16.843		0.186		99.809	a,B	5.0658	a,B	3.875	0.7614	a,A	4.4247
	5-10	9.84	a,B	0.2297	a,B			0.603			0.238		99.77	a,B	6.3077	a,A	4.916	0.8726	a,A	5.343
	10-15	10.5	a,B	0.0473	a,B			0.146			0.044		99.953	a,A	5.0764	a,B	4.405	0.7397	a,A	3.8746
	Mean	10.5		0.1561		335.55		0.412	16.843		0.156		99.844		5.483		4.399	0.7912		4.5474
Maïssade	0-5	4.24	a,B	0.2821	a,A	307.16		0.233	20.205		0.121		99.718	a,B	5.8366	a,B	1.576	0.8274	a,A	1.7661
	5-10	3.77	a,C	0.308	a,B			0.219			0.115		99.692	a,C	7.7433	a,A	1.778	0.994	a,A	1.8162
	10-15	4.47	a,C	0.1553	b,B			0.157			0.065		99.845	b,B	18.617	a,B	5.952	3.9004	a,A	7.766
	Mean	4.16		0.2485		307.16		0.203	20.205		0.1		99.752		10.732		3.102	1.9073		3.7828
Bas Cange	0-5	8.4	na	0.2039	na	348.95	na	0.246	22.165		0.226		99.796	na	8.6744	na	3.045	1.0178	na	5.1885
	5-10	5.74	na	0.6687	na			0.504			0.446		99.331	na	9.9482	na	2.132	1.4187	na	4.2276
	10-15	7.68	na	0.176	na			0.239			0.199		99.824	na	8.3206	na	3.157	1.2631	na	6.2725
	Mean	7.27		0.3495		348.95		0.33	22.165		0.29		99.65		8.9811		2.778	1.2332		5.2295
	Grand Mean	12.4		0.2258		313.45		0.537	18.295		0.23		99.775		8.9073		9.955	1.4935		10.6527
	sd	9.49		0.1564		38.397		0.48	3.627		0.165		0.1565		4.3748		12.54	1.1952		13.138

[†] Light fraction

[‡] Heavy fraction

[§] Microaggregate fraction

[¶] LF samples were combined by depth due to the small amount of sample for C and N analysis

[#] Values within a location, followed by the same lowercase letter are not significantly different at P<0.05

[††] Values within a depth interval followed by the same capital letter are not significantly different at P<0.05

na - not applicable

Table 2.7. Silt and clay organic matter fraction weights and C and N content and percentage of whole soil.

		S+C[†]							
Location	Depth	Mass		Carbon			Nitrogen		
	cm	% of bulk soil		g kg^{-1} fraction		% total C	g kg^{-1} fraction		% total N
Corporant	0-5	8.34	a[‡],AB[§]	17.81	a,A	16.93	2.04	a,A	12.94
	5-10	7.87	a,A	17.29	ab,A	12.71	1.92	ab,A	6.72
	10-15	7.91	a,A	16.25	b,A	15.64	1.75	b,A	8.92
	Mean	8.04		17.12		15.09	1.90		9.53
Lachateau	0-5	8.56	a,A	12.52	a,B	7.26	1.31	a,B	5.76
	5-10	7.67	a,A	10.66	b,AB	6.49	1.05	b,AB	5.01
	10-15	8.98	a,A	8.23	c,B	6.14	0.82	b,B	3.69
	Mean	8.40		10.47		6.63	1.06		4.82
Maissade	0-5	6.21	a,B	14.51	b,B	5.89	1.38	a,B	4.20
	5-10	6.26	a,A	16.16	a,B	6.19	1.48	a,B	4.23
	10-15	6.23	a,A	14.71	b,B	6.60	1.39	a,B	3.85
	Mean	6.23		15.13		6.23	1.42		4.09
Bas Cange	0-5	9.71	na	14.39	na	5.85	1.35	na	7.99
	5-10	6.62	na	15.33	na	3.81	1.41	na	4.86
	10-15	7.73	na	13.58	na	5.19	1.47	na	7.34
	Mean	8.02		14.43		4.95	1.41		6.73
	Grand Mean	7.67		14.29		8.23	1.45		6.29
	sd	1.15		2.76		4.32	0.34		2.71

[†] Silt + clay fraction

[‡] Values within a location followed by the same lowercase letter are not significantly different at $P<0.05$

[§] Values within a depth interval followed by the same capital letter are not significantly different at $P<0.05$

na - not applicable

REFERENCES

Adu, J., and J. Oades. 1977. Physical factors influencing decomposition of organic materials in soil aggregates. Soil Biology and Biochemistry 10:109-115.

Ayuke, F., L. Brussaard, B. Vanlauwe, J. Six, D. Lelei, C. Kibunja, and M. Pulleman. 2011. Soil fertility management: Impacts on soil macrofauna, soil aggregation and soil organic matter allocation. Applied Soil Ecology 48:53-62.

Boone, R. 1994. Light-fraction soil organic matter: Origin and contribution to net nitrogen mineralization. Soil Biology and Biochemistry 26(11):1459-1468.

Brady, N., and R. Weil. 2008. The nature and properties of soils. 14th ed. Pearson Prentice Hall, Columbus, OH.

Beldini, T., K. McNabb, B. Lockaby, F. Sanchez, and O. Navegantes-Cancio. 2010. The effect of Amazonian *Eucalyptus* plantations on soil aggregates and organic matter density fractions. Soil Use and Management 26:53-60.

Carter, M. 2002. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. Agonomy Journal 94:38-47.

Christensen, B. 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. European Journal of Soil Science 52:345-353.

Del Galdo, I., J. Six, A. Peressotti, and M. Cotrufo. 2003. Assessing the impact of land-use change on soil C sequestration in agricultural soils by means of organic matter fractionation and stable C isotopes. Global Change Biology 9:1204-1213.

Elliott, E. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Science Society of America Journal 50:627-633.

Gee, G., and J. Bauder. 1986. Particle-size analysis, in: Klute (Ed.), Methods of Soil Analysis Part 1, Soil Science Society of America Inc., Madison, Wisconsin

Golchin, A., J. Oades, J. Skjemstad, and P. Clarke. 1994. Study of free and occluded particulate organic matter in soils by solid state 13C CP/MAS NMR spectroscopy and scanning electron microscopy. Soil Biology and Biochemistry 32:285-309.

Gregorich, E., M. Beare, U. McKim, and J. Skjemstad. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Science Society of America Journal 70:975-985.

Gulde, S., H. Chung, W. Amelung, C. Change, and J. Six. 2008. Soil carbon saturation controls labile and stable carbon pool dynamics. Soil Science Society of America Journal 72:605-612.

Guthrie, R., and D. Shannon. 2004. Soil profile descriptions for steeplands research sites in Haiti, Auburn University. Auburn, Al. 24 pp.

Jacobs, A., M. Helfrich, S. Hanisch, U. Quendt, R. Rauber, B. Ludwig. 2010. Effect of conventional and minimum tillage on physical and biochemical stabilization of soil organic matter. Biology and Fertility of Soils 46:671-680.

Loeppert, R., and D. Suarez. 1996. Carbonate and gypsum, in: Klute (Ed.), Methods of Soil Analysis Part 1, Soil Science Society of America Inc., Madison, Wisconsin

Marin-Spiotta, E., W. Silver, C. Swanston, and R. Ostertag. 2008. Soil organic matter dynamics during 80 years of reforestation of tropical pastures. Global Change Biology 15:1584-1597.

McLauchlan, K., and S. Hobble. 2004. Comparison of labile soil organic matter fractionation techniques. Soil Science Society of America Journal 68:1616-1625.

Murage, E., P. Voroney, B. Kay, B. Deen, and R. Beyaert. 2006. Dynamics and turnover of soil organic matter as affected by tillage. Soil Science Society of America Journal 71:1363-1370.

Normandin, V., J. Kotuby-Amacher, and R. Miller. 1998. Modification of the ammonium acetate extractant for the determination of exchangeable cations in calcareous soils. Communications in Soil Science and Plant Analysis 29:11-14.

Posada, J., and E. Schuur. 2011. Relationships among precipitation regime, nutrient availability, and carbon turnover in tropical rain forests. Oecologia 165:783–795.

Pineiro, G., M. Oesterheld, W. Batista, and J. Paruelo. 2006. Opposite changes of whole-soil vs. pools C:N ratios: a case of Simpson's paradox with implications on nitrogen cycling. Global Change Biology 12:804-809.

SAS Institute Inc. 2008. SAS/STAT® 9.2 User’s Guide. Cary, NC: SAS Institute Inc.

Schepers, J., D. Francis, and M. Thompson. 1989. Simultaneous determination of total C total N and 15N on soil and plant material. Communications in Soil Science and Plant Analysis 20:949–959.

Sequeira, C., and M. Alley. 2011. Soil organic matter fractions as indices of soil quality changes. Soil Science Society of America Journal 75:1766-1773.

Six, J., E. Elliott, and K. Paustian. 1998a. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Science Society of America Journal 63:1350-1358.

Six, J., E. Elliott, K. Paustian, and J. Doran. 1998b. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Science Society of America Journal 62:1367-1377.

Smith, J., R. Papendick, D. Bezdicek, and J. Lynch. 1992. Soil microbial ecology: applications in agricultural and environmental management.

Sollins, P., G. Spycher, and C. Glassman. 1984. Net nitrogen mineralization from light- and heavy-fraction forest soil organic matter. Soil Biology and Biochemistry 16(1):31-37.

Sotomayor-Ramirez, D., Y. Espinoza, and R. Ramos-Santana. 2006. Short-term tillage practices on soil organic matter pools in a tropical Ultisol. Australian Journal of Soil Research 44:687–693.

Tan, Z., R. Lal, L. Owens, and R. Izaurralde. 2007. Distribution of light and heavy fractions of soil organic carbon as related to land use and tillage practice. Soil and Tillage Research 92:53-59.

Tiessen, H., and J. Stewart. 1983. Particle-size fractions and their use in studies of soil organic matter: Cultivation effects on organic matter composition in size fractions. Soil Science Society of America Journal 47:509-514.

Tisdall, J., and J. Oades. 1979. Stabilization of soil aggregates by the root systems of ryegrass. Australian Journal of Soil Research 17:429-441.

Tisdall, J., and J. Oades. 1980. The management of ryegrass to stabilize aggregates of a red-brown earth. Australian Journal of Soil Research 18:(415-22).

Tisdall, J., and J. Oades. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33:141-163.

Wander, M. 2004. Soil organic matter fractions and their relevance to soil function, in: F. Magdoff and R.Weil (Ed.), Soil Organic Matter in Sustainable Agriculture, CRC Press, Boca Raton, FL.

Zotarelli, L., B. Alves, S. Urquiaga, R. Boddey, and J. Six. 2007. Impact of tillage and crop rotation of light fraction and intra-aggregate soil organic matter in two Oxisols. Soil and Tillage Research 95:196-206.

CHAPTER III - RHIZOSPHERE PHOSPHORUS SOLUBILITY AS AFFECTED BY CROP IN A CLAY SOIL FROM THE CENTRAL PLATEAU OF HAITI

INTRODUCTION

Phosphorus is a nutrient commonly present in forms that are not immediately available to plants. It is relatively immobile in the soil and moves slowly by diffusion over short distances (10^{-12} to 10^{-15} m^2 s^{-1}) (Schachtman et al., 1998; Rengel and Marschner, 2005). This slow diffusion rate often results in a zone of P-depletion around plant roots as P is absorbed faster than it can diffuse to replenish the soil around the root (Jungk and Claassen, 1986). Phosphorus is commonly a major limiting factor in tropical soils due to a high P-fixing capacity of the soil or the continual mining of available P through intensive agriculture (Kahm et al., 1999). Growing crops continuously without P fertilizer can result in a P-depleted soil that will have a large affinity for any subsequent P additions, binding the nutrient to mineral surfaces where it is not available to plants (Ahmed et al., 2008). During growth periods where P is in high demand, plants need to find ways to access P that would not otherwise be available to them in nutrient-depleted soils.

Plants exhibit mechanisms to increase access or availability of P and other nutrients when they are exposed to a low nutrient environment (Schachtman et al., 1998; Dakora and Phillips, 2001; Rengel and Marschner, 2005). Plants form symbioses with mycorrhizal fungi (Trolove et al., 1996) and grow longer root hairs (Jungk and Claassen, 1986) to increase the soil contact surface area from which they are able to access P. Certain bean varieties have been found to increase basal root hair length under stressed conditions, and are able to increase P absorption by several times (Dorcinvil et al., 2010). Plants exude protons (Rengel and Marschner, 2005) and organic compounds (Dakora and

Phillips, 2001) to acidify the rhizosphere, solubilizing P in Ca, aluminum, and iron phosphates and while this occurs in all soils, some plants are more proficient in calcareous soils. Plant roots can produce organic anions that occupy adsorption sites on mineral surfaces and block phosphate ions from adsorbing to these sites (Kulabako et al., 2008). The ability of a plant to solubilize P through plant exudates has been shown to vary considerably with species (Tremain et al., 1987; Trolove et al., 1996; Rengel and Marschner, 2005).

Phosphorus adsorption in soils has been described using empirical models, such as the Langmuir, Freundlich (Abou Nohra et al., 2006), and Temkin (Ahmed et al., 2008) isotherms from which maximum adsorption can be determined. Kulabako et al. (2008) found that maximum P adsorption was relatively high in an urban soil in Uganda at 499 mg P kg^{-1} soil. An investigation of various soils in Australia found that maximum adsorption occurred at 500 mg P kg^{-1} soil in the top 15 cm of a severely nutrient-depleted soil (Ahmed et al., 2008). Various factors affect P adsorption capacity of a soil, such as soil pH, organic matter content (Ohno and Amirbahman, 2010), and Ca content (Kulabako et al., 2008). A study by Said and Dakermanji (2008) in calcareous surface soils from Syria indicated that soil clay content is positively correlated with P adsorption.

MATERIALS AND METHODS

Growth Chamber Experiment

Surface (0-15 cm) soil was collected from a farm operated by Caritas Diocésaine de Hinche near the town of Maissade, Haiti (19° 9' N, 72° 06' W, 291.4 m elevation) in the Centre Department. The soil was air-dried, shipped to Virginia, and ground to pass a 2mm sieve. A pot experiment utilizing a completely randomized design with seven treatments and three replications was conducted in a controlled-environment chamber for 49 days. Treatments were black bean, chickpea (*Cicer arietinum* L.), cowpea, grain sorghum (*Sorghum bicolor* (L.) Moench), lablab, pigeon pea, and velvet bean. Pots with a volume of 2200 cm^3 were half-filled with soil from the Maissade farm (approx 1200g soil pot^{-1}) and five seeds of one species were planted in each pot giving an approximate seeding density of 50,000 seed ha^{-1}. The growth chamber was set to typical Haitian conditions and cycled to match diurnal variation (temperature 23.3 - 32.2°C, percent relative humidity 58 - 64, 228 µmol m^{-2} s^{-1} daylight intensity, and 10hr of daylight). De-ionized water was added to the pots every two days to ensure an adequate water supply to the plants, and each pot was placed on a plate to avoid soil nutrient loss through leaching and excess water re-added to pots. Plants were thinned to one per pot, approximately 10,000 plants ha^{-1}, at the two-leaf stage and the pots were rearranged weekly. There were no other additions to the experiment.

Harvest and Processing

Seven weeks after planting, plants were carefully uprooted and shaken gently to remove bulk soil from the roots per the method of Clemensson-Lindell and Persson (1993). The soil remaining on the roots was collected as rhizosphere soil. A portion of the bulk soil was also collected for comparison. The plant was separated into above-ground and below-ground portions and washed to remove soil and debris, then dried in a forced-air oven at 50°C. Wet and dry weights were taken to determine percent moisture content in both above- and below-ground portions, then the dried plant material was ground to pass a 1mm screen using a Wiley mill (Thomas Scientific, Swedesboro, NJ).

Bulk and Rhizosphere pH and P

Bulk and rhizosphere soil were air-dried. A 10g subsample of each was ground to pass a 2mm sieve and was extracted with 20mL DI water through a 45µm filter under vacuum, with the extract being analyzed for pH (2:1 water) (Fisher Scientific AR25 Dual Channel pH/Ion Meter). Plant available P was determined according to Olsen et al. (1954). Two grams of bulk or rhizosphere soil were ground to pass a 2mm sieve and placed in a 50mL centrifuge tube with 40mL 0.5M $NaHCO_3$ adjusted to pH 8.5. The tubes were shaken for 30min at 180rpm and the contents extracted through a 45µm filter under vacuum, with the extract analyzed for P by ICP. Additionally, total P analysis was performed on bulk soil using EPA method 6010c to assess total organic and inorganic P.

Plant Tissue P

A wet digest was performed according to the procedure described in Thomas et al. (1967) with slight modification. A 0.2g subsample of root or shoot tissue was placed in a digestion tube with 2mL 30% H_2O_2 for 10min. Then 2mL H_2SO_4 was added and left for 5min, then placed on a pre-heated digestion block (200°C) for 30min. The process was repeated to ensure complete digestion. The contents of the digestion tube were diluted to 100mL with DI water and analyzed for P by ICP analysis.

P adsorption isotherm

A P sorption isotherm was evaluated for the soil before the growth chamber experiment took place. Thirty mL standard solutions of KH_2PO_4 containing between 15 and 400mg P L^{-1} were added to 3g soil and shaken for 2hrs at 180rpm according to the procedure from Vanlauwe et al. (2000). The mixture was then filtered through a 45µm filter and the extract was analyzed for P by ICP analysis.

Analyses

Analysis of variance was performed using the GLM procedure of the SAS software package 9.2 (SAS Institute, 2008). Data were analyzed separately by plant part (root or shoot) and by soil (bulk or rhizosphere). Mean separations were carried out by Tukey’s multiple comparison test at the 0.05 level of probability unless otherwise stated. Simple correlation analysis was performed between plant or soil fractions with SAS PROC CORR. Pearson correlation coefficients were considered significant at $r<0.05$.

RESULTS AND DISCUSSION

Soil pH and P

Bulk soil pH was determined to be 8.0. Total P and Olsen extractable P were 131 and 4mg kg^{-1}, respectively (Table 3.1). These P values are low compared to results obtained in other studies on calcareous soils (1700-2900mg kg^{-1} and 11-19mg kg^{-1} respectively [Gamboa et al., 2010] and 700-1900mg kg^{-1} and 5-103mg kg^{-1} respectively [Mathews et al., 2011]). Total Kjeldahl N was 2200mg kg^{-1}, which is typical for intensively cultivated tropical soils (McGrath et al., 2001; Navarrete and Tsutsuki, 2008; Ortiz-Escobar and Hue, 2011). Soil texture was determined to be clay and CEC was 32.6 cmol$_c$ kg^{-1} soil (Table 3.1).

Analysis between rhizosphere and bulk soil by species indicated that pigeon pea significantly reduced pH in its rhizosphere (Figure 3.1a). The treatment with the lowest rhizosphere pH was pigeon pea (8.10), while the highest was grain sorghum (8.39) with an average of 8.24 across all treatments (Figure 3.1a and Table 3.1). No significant difference between rhizosphere and bulk soil P among treatments was detected when using Tukey’s means separation ($P<0.10$) (Figure 3.1b). This could have resulted from a combination of low inherent plant-available P and the small differences in absolute P value or from the particular method used to isolate the rhizosphere soil. The treatment with the minimum rhizosphere P was pigeon pea (3.15mg L^{-1}) and the largest was velvet bean (4.46mg L^{-1}), with an average of 3.81mg L^{-1} P for all treatments. Similar results were obtained by Kamh et al. (1999), who observed that pigeon pea was able to solubilize more soil P than other species studied and they found that its biomass was not diminished much in a low P soil. This may indicate that pigeon pea may be an efficient scavenger of P in low P situations. Bulk soil P did not differ significantly among species likely due to the slow rate of P diffusion through soils and the fact that plant roots should not have explored, and subsequently removed P from, this entire soil volume.

Plant P uptake, biomass percent P, and dry weight

Both root and shoot dry weight was observed to vary among species (Figure 3.2a). Velvet bean produced significantly more aboveground biomass than all of the other treatments at 4.99g, while pigeon pea produced the smallest amount, at 0.57g (Figure 3.2a). The average shoot dry weight was 1.57g for all treatments. Similar results for velvet bean and cowpea were obtained by Wang et al. (2005), who found that velvet bean produced 30% more biomass than cowpea during a 10wk greenhouse pot experiment in a soil with 31mg kg^{-1} plant available P and pH 8.2. In a field experiment in Nigeria, Carsky et al. (1999) found that velvet bean produced twice as much biomass as lablab and 19% more than cowpea 70 days after planting. Root dry weight differed significantly among species, with grain sorghum producing the most biomass (0.80g) and cowpea producing the least amount (0.15g), with an average of 0.46g. Vanlauwe et al. (2000) found similar results in comparing lablab and velvet bean root biomass.

Plant shoot P uptake did vary significantly by species (Figure 3.2b), from grain sorghum at 0.0007mg kg^{-1} to velvet bean at 0.0041mg kg^{-1} (Figure 3.2b). Velvet bean took up more P in the shoot than all other crops by far: 94% more than the next highest treatment, lablab, and 490% more than the crop with the least shoot P uptake, grain sorghum. Based on the P concentration data, this is obviously a reflection of the greater biomass production by velvet bean. Means separation analyses indicated that black bean, cowpea, grain sorghum, and pigeon pea had less P in shoot tissue compared with velvetbean (Figure 3.2b). Correlation between shoot P uptake and rhizosphere P indicated that the two variables are positively correlated at the $r<0.01$ level of significance (Table 3.2). Root P uptake was less for cowpea than all other treatments except pigeon pea (Figure 3.2b). Grain sorghum was the only species in this experiment to produce more root than shoot biomass (38% more). Grain sorghum did not produce much aboveground material because of the short duration of the experiment (7wks) and the comparatively slow-growing nature of the species.

Percent P in shoot tissue was highest for black bean (0.16%) and minimum for velvet bean (0.08%), with an average of 0.13% over all treatments (Figure 3.2c). Velvet bean had significantly lower shoot P %, compared to all other species. Abarchi et al. (2009) found a higher P content in lablab and velvet bean in a P-limited system, about 0.15 and 0.10% respectively. Root P percentage also varies among species: black bean, lablab, pigeon pea, and velvet bean had significantly larger root P percentage compared with grain sorghum (94%, 97%, 86%, and 81% greater respectively). The treatment with the highest root P percentage was lablab (0.14%) but this was only significantly higher than the crop with the lowest root P, grain sorghum at 0.07%.

Results from the P isotherm show that the soil at the Maissade farm is able to adsorb a large amount of inorganic P, more than the largest standard that was used in the experiment (Figure 3.3). Even at 400mg L^{-1} of added P, only 14% of the added P was extractable, while the soil bound the remainder. Calculating the Langmuir maximum adsorption within the linear data range gave a value of 2000mg P kg^{-1} soil, which is very large compared to the values reported by other authors (500mg kg^{-1} [Ahmed et al., 2008] and 499mg kg^{-1} [Kulabako et al., 2008]). A study by Carreira and Lajtha (1997), which investigated calcareous soils, found P sorption capacity was positively correlated with Al- and Fe-oxide and carbonate content, and work by Guo et al. (2008) found pH was positively correlated with maximum P adsorption. The large clay content (55%) in the Maissade soil, the presence of carbonates (data not shown), and the high pH may explain the large P adsorption value obtained. However, the isotherm may reflect some precipitation occurring even at low equilibrium solution concentrations. All this indicates that relatively large amounts of P addition may be required in this soil before soil binding capacity is overcome and plant available P is increased. Alternatively, P additions, either through compost or fertilizer may need to be banded or concentrated to reduce the potential for P to react with bulk soil.

CONCLUSION

Though velvet bean took up the most P of all the evaluated species, soil pH results show that pigeon pea significantly decreased the soil pH in the rhizosphere. Grain sorghum did not produce much root or shoot biomass and had one of the lowest P uptake values for shoot and root biomass among the treatments. Some parameters varied greatly by species, such as shoot and root dry weight, shoot P uptake, and root percent P, while others did not (bulk and rhizosphere pH and P content, root P uptake, and shoot percent P). Velvet bean produced the most aboveground biomass and took up the largest amount of P of all the species, though lablab took in comparable amounts of P. This study suggests that velvet bean and lablab have potential to be effective cover crops in the Central Plateau. However, other factors not addressed in this study that may affect a small-holder's decision of cover crop species include seed availability and expense, disease tolerance, manageability, and ability to scavenge for other nutrients. Future research should include a seeding rate study, which could determine if the species competes well with itself, and a runoff simulation, which could quantify cover crop ability to reduce erosion. Biomass has been associated with erosion control, which would indicate that velvet bean is superior to the other species in this study in this regard. Grain sorghum would not be recommended as a cover crop due to its small shoot and root biomass in early stages of growth. High rates of P fertilizer would need to be applied to the Maissade soil in order to see an increase in plant available P due to the soil's large P sorption capacity.

Table 3.1. Physical and chemical parameters of Maissade soil used in P solubilization pot studies.

pH[†]	C:N	TKN[‡]	Total P[§]	Extractable P[¶]	Ca	K	Mg	Na	CEC[#]	EC[††]	Sand	Silt	Clay
		----------mg kg^{-1}----------			————cmol$_c$ kg^{-1} soil————					mS cm^{-1}	--------%--------		
8.24	10.5	2200	131.0	3.9	28.2	0.37	3.89	0.13	32.6	0.30	20	25	55

[†] 2:1 soil:water

[‡] Total Kjeldahl N

[§] Total soil P

[¶] NaHCO3 extractable P

[#] Cation exchange capacity

[††] Electrical conductivity

Table 3.2. Correlation coefficients (Pearson's r) comparing various measured soil and plant parameters.

	Bulk Soil pH	Bulk P	Rhizosphere pH	Rhizosphere P	Shoot Dry Weight	Shoot P Uptake	Root Dry Weight
Bulk P	ns						
Rhizosphere pH	ns	*, –					
Rhizosphere P	ns	ns	ns				
Shoot Dry Weight	ns	ns	ns	*, +			
Shoot P Uptake	ns	ns	ns	**, +	***, +		
Root Dry Weight	ns	ns	ns	ns	ns	ns	
Root P Uptake	ns	na	ns	*, +	ns	*,+	***, +

ns - not significant

*,**,*** - significance at 0.05, 0.01, and 0.001 respectively

–,+ - a negative and positive correlation, respectively

Figure 3.1. Comparison of pH (a) and plant available P (b) in rhizosphere and bulk soil as affected by seven crop species. BB=black bean, ChP=chickpea, CwP=cowpea, GS=grain sorghum, LL=lablab, PP=pigeon pea, VB=velvet bean. Columns representing mean values for a crop species with the same letter do not differ significantly at the 0.10 level of probability.

a.

b.

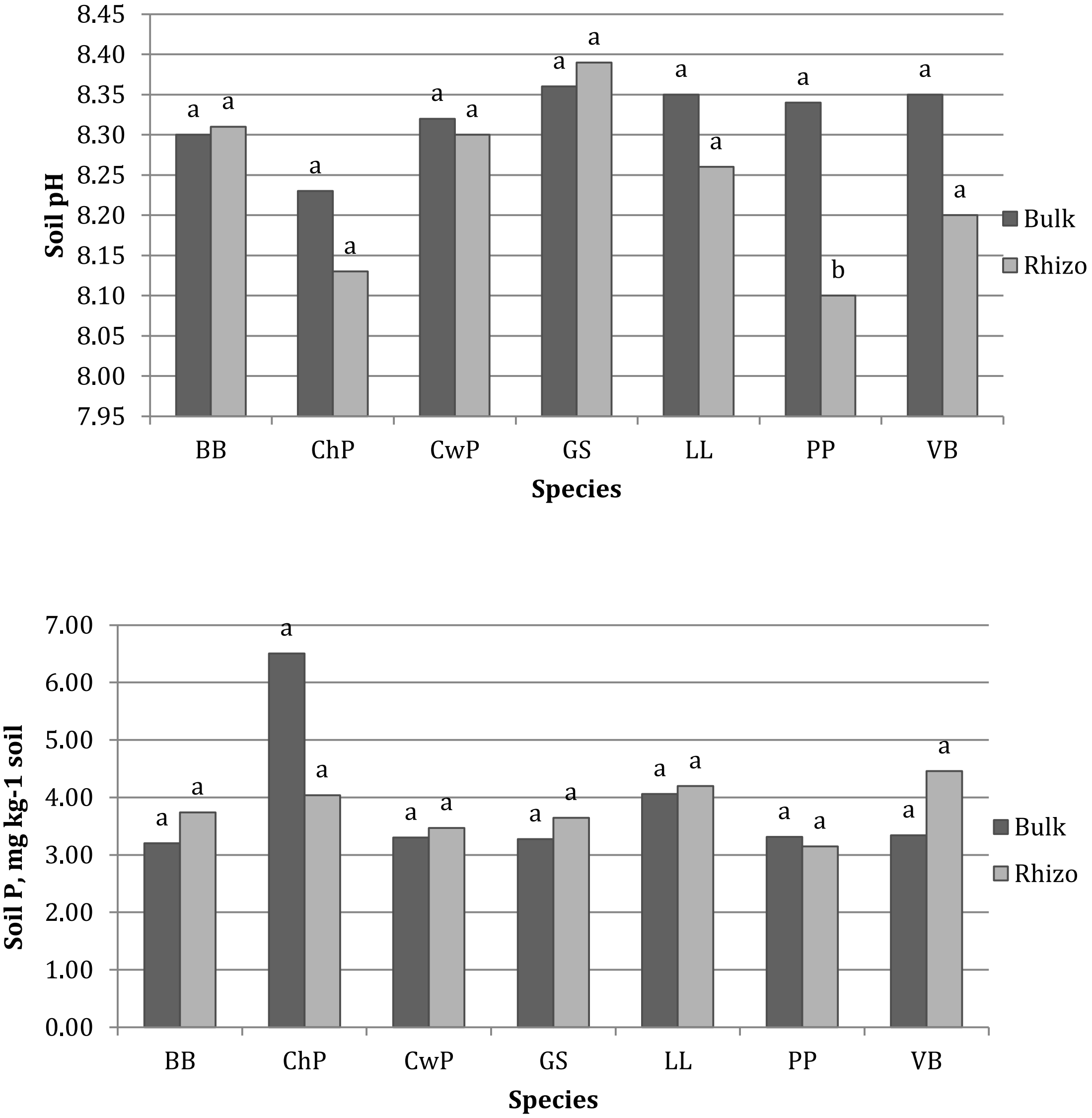


Figure 3.2. Comparison of plant dry weight (a), P uptake (b), and percent P (c) in the root and shoot portions of seven crop species. BB=black bean, ChP=chickpea, CwP=cowpea, GS=grain sorghum, LL=lablab, PP=pigeon pea, VB=velvet bean, na=not applicable. Columns of mean values by plant part with the same letter do not differ significantly at the 0.10 level of probability.

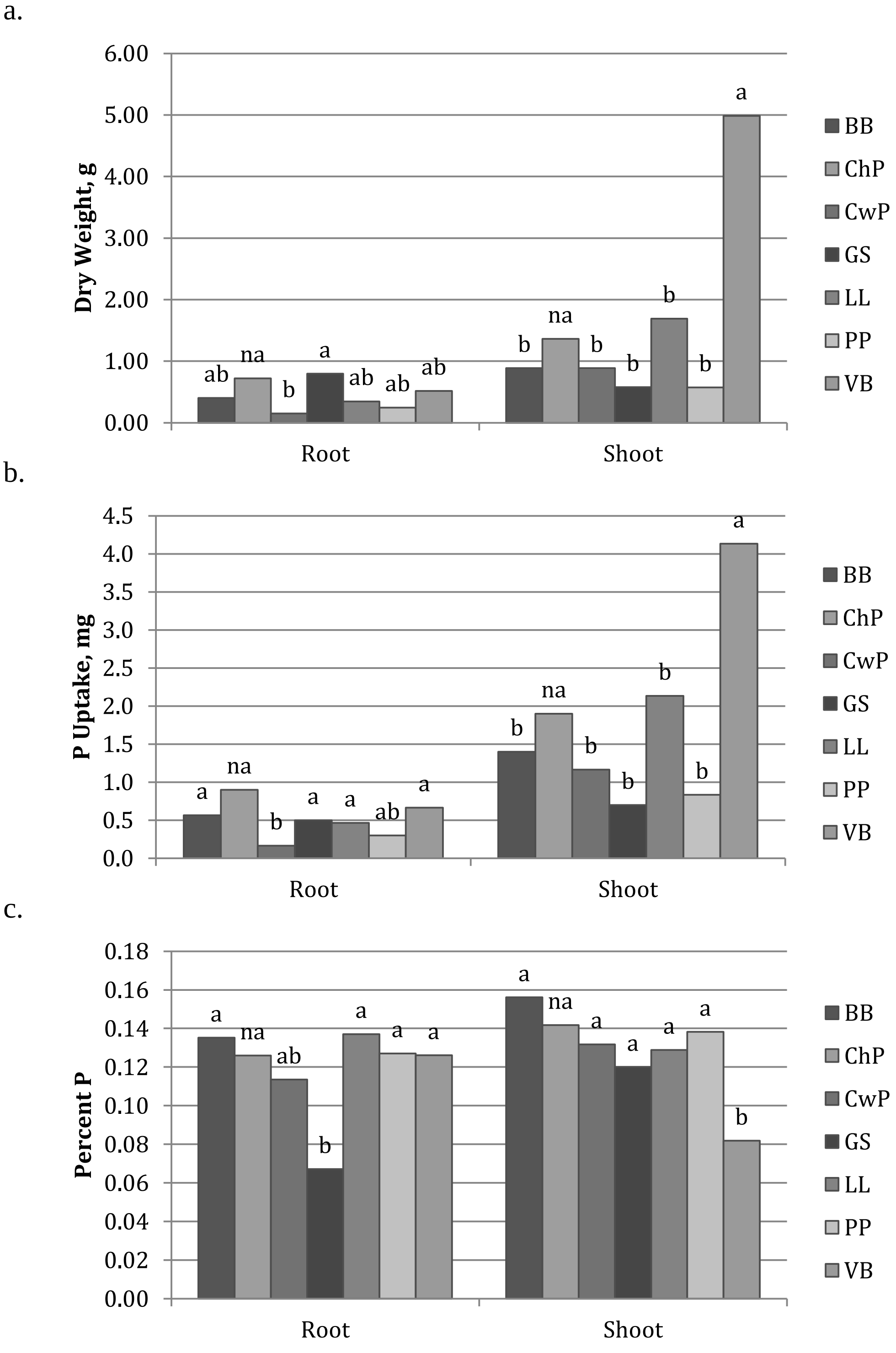
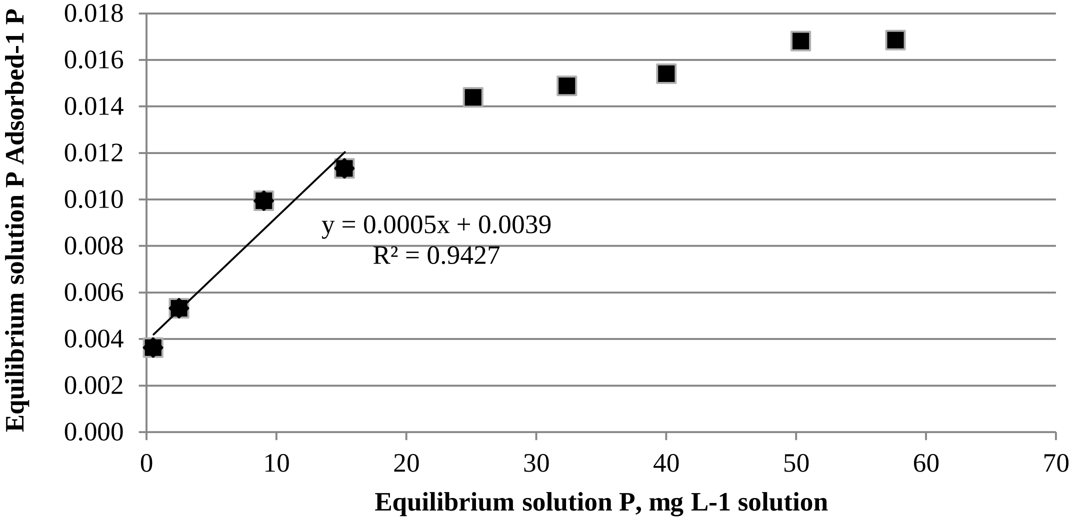


Figure 3.3. Phosphorus adsorption isotherm for soil at the Maissade farm.



REFERENCES

Abarchi, I., Z. Zhang, B. Vanlauwe, X. Guo, W. Wang, B. Ong'or, et al. 2009. Effects of plant age and rock phosphate on quality and nutrient release of legume residue. Pedosphere 19(1):78-85.

Ahmed, M., I. Kennedy, A. Choudhury, M. Kecskes, and R. Deaker. 2008. Phosphorus adsorption in some Australian soils and influence of bacteria on the desorption of phosphorus. Communications in Soil Science and Plant Analysis 39:1269-1294.

Abou Nohra, J., C. Madramootoo, and W. Hendershot. (2006). Modelling phosphate adsorption to the soil: Application of the non-ideal competitive adsorption model. Environmental Pollution 149:1-9.

Carreira, J., and K. Lajtha. 1997. Factors affecting phosphate sorption along a Mediterranean dolomitic soil and vegetation chronosequence. European Journal of Soil Science 48:139-149.

Carsky, R., B. Oyewole, and G. Tian. 1999. Integrated soil management for the savanna zone of W. Africa: legume rotation and fertilizer N. Nutrient Cycling in Agroecosystems 55:95-105.

Clemensson-Lindell, A., and H. Persson. 1992. Effects of freezing on rhizosphere and root nutrient content using two soil sampling methods. Plant and Soil 139:39-45.

Dakora, F., and D. Phillips. 2001. Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant and Soil 245:35-47.

Dorcinvil, R., D. Sotomayor-Ramirez, and J. Beaver. 2010. Agronomic performance of common bean (*Phaseolus vulgaris* L.) lines in an Oxisol. Field Crops Research 118:264-272.

Gamboa, A., C. Hidalgo, F. Leon, J. Etchevers, J. Gallardo, and J. Campo. 2010. Nutrient addition differentially affects soil carbon sequestration in secondary tropical dry forests: Early- versus late-succession stages. Restoration Ecology 18(2):252-260.

Guo, S., T. Dang, and M. Hao. 2008. Phosphorus changes and sorption characteristics in a calcareous soil under long-term fertilization. Pedosphere 18(2):248-256.

Jungk, A., and N. Claassen. 1986. Availability of phosphate and potassium as the result of interactions between root and soil in the rhizosphere. Journal of Plant Nutrition and Soil Science 149:411-427.

Kamh, M., W. Horst, F. Amer, H. Mostafa, and P. Maier. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant and Soil 211:19-27

Kulabako, N., M. Nalubega, and R. Thunvik. 2008. Phosphorus transport in shallow groundwater in peri-urban Kampala, Uganda: results from field and laboratory measurements. Environmental Geology 53:1535-1551.

Mathews, B., J. Carpenter, L. Sollengerger, and W. Steiner. 2011. Macronutrients in Hawaii's coastal wetland pastures and potential phosphorus release to water. Agronomy Journal, 103(3):830-843.

McGrath, D., C. Smith, H. Gholz, and F. Oliveira. 2001. Effects of land-use change on soil nutrient dynamics in Amazonia. Ecosystems 4:625-645.

Navarrete, I., and K. Tsutsuki. 2008. Land-use impact on soil carbon, nitrogen, neutral sugar composition and related chemical properties in a degraded Ultisol in Leyte, Philippines. Soil Science and Plant Nutrition 54:321-331.

Ohno, T., and A. Amirbahman. 2010. Phosphorus availability in boreal forest soils: A geochemical and nutrient uptake modeling approach. Geoderma 155:46-54.

Olsen, S., C. Cole, E. Watanabe, and L. Dean. 1954. Estimation of extractable phosphorus in soils by extraction with sodium bicarbonate, in: U.S. Department of Agriculture (Ed.), Washington D.C.

Ortiz-Escobar, M. and N. Hue. 2011. Changes in soil properties and vegetable growth in preparation for organic farming in Hawaii. Communications in Soil Science and Plant Analysis 42:2064-2072.

Rengel, Z., and P. Marschner. 2005. Nutrient availability and management in the rhizosphere: exploiting genotypic differences. New Phytologist 168:305-312.

Said, M., and A. Dakermanji. Phosphate adsorption and desorption by calcareous soils of Syria. Communications in Soil Science and Plant Analysis 24(1-2):197-210.

SAS Institute Inc. 2008. SAS/STAT® 9.2 User's Guide. Cary, NC: SAS Institute Inc.

Schachtman, D., R. Reid, and S. Ayling. 1998. Phosphorus uptake by plants: From soil to cell. Plant Physiology 116:447-453.

Thomas, R., R. Sheard, and J. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agronomy Journal 59:240-243.

Tremain, P., P. Sale, and R. Jessop. 1987. Effect of solubility of applied phosphate on the growth of narrow-leafed Lupin (*Lupinus angustifolius* L.). Nutrient Cycling in Agroecosystems 13:117-125. DOI: 10.1007/BF01064825.

Trolove, S., M. Hedley, J. Caradus, and A. Mackay. 1996. Forms of phosphate utilised and acidification of the rhizosphere. Australian Journal of Soil Research 34:1027-1040.

Vanlauwe, B., O. Nwoke, J. Diels, N. Sanginga, R. Carsky, J. Deckers, and R. Merckx. 2000. Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by Mucuna pruriens, Lablab purpureus and maize. Soil Biology and Biochemistry, 32(14):2063-2077.

Wang, Q., Y. Li, and W. Klassen. 2005. Influence of summer cover crops on conservation of soil water and nutrients in a subtropical area. Journal of Soil and Water Conservation 60:58-63.