ROCK PHOSPHATE, MANURE AND COMPOST USE IN GARLIC AND POTATO SYSTEMS IN A HIGH INTERMONTANE VALLEY IN BOLIVIA

By

RENÉE MICHELLE LORION

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE IN SOIL SCIENCE

WASHINGTON STATE UNIVERSITY
Department of Crop and Soil Sciences

AUGUST 2004

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of RENÉE MICHELLE LORION find it satisfactory and recommend that it be accepted.

Chair

ACKNOWLEDGMENTS

I would like to acknowledge my committee members, Bill Pan, Alan Busacca, and Bruce Frazier for supporting this research endeavor. I would also like to acknowledge Sally Burkhart of the International Programs Office, Dr. Pepe Salinas, and Peace Corps Bolivia. Doña Erlinda Fernandez, the women of the Club de Madres de Alta Gracia, and the people of Iscayachi made this research possible. Kim Glick had the foresight and ambition to set up the project. Ron Bolton, Margaret Davies, and Eric Harwood in the NCRE lab were extremely helpful with my lab work. My fellow Peace Corps Volunteers, Susan Appe, Alex Aurilia, Jennifer Gilland, Brigid Ryan, and Greg Verkamp all pitched in one way or another. Mary, Sean and Ted Monahan gave me coffee and a quiet place to live and write. My parents let me go off to Bolivia for two years and wrote to me faithfully.

Finally, my brother, Chris Lorion, was instrumental in setting up the experiment, and hauled wheelbarrows of manure in the pouring rain with a smile on his face.

ROCK PHOSPHATE , MANURE, AND COMPOST USE IN
GARLIC AND POTATO SYSTEMS IN A HIGH
INTERMONTANE VALLEY IN BOLIVIA

Abstract

by Renée Michelle Lorion, M.S.
Washington State University
August 2004

Chair: William L. Pan

A two-year field experiment on high valley Vertic Haplustolls in Bolivia was undertaken to study the effects of rock phosphate, manure, and rock phosphate composted with manure on yields of potato and garlic. While satisfactory yields were obtained from all plots, the results showed that none of the treatments significantly increased yields or available soil phosphorus with respect to the control. High nitrate levels in some areas of the field may have delayed potato tuberization. Adequate levels of background phosphorus in the study area soils, in combination with alkaline conditions and low application rates of the amendments, may explain the lack of treatment response. However, yields from the intensive organic system were comparable to those achieved by local farmers using synthetic fertilizers. Additional research is needed to explore the viability of rock phosphate as an alternative phosphorus source in small farming systems in Bolivia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Dedication

This thesis is dedicated to the people of Isacayachi, Bolivia

who welcomed me into their community

Chapter 1

Problem Statement

As costs of industrial phosphorus fertilizers rise in developing countries, it becomes necessary to look for alternative phosphorus sources for small farming operations. Developing nations that lack the raw materials or the industrial infrastructure to manufacture phosphorus fertilizers must import this commodity, making it relatively expensive for local farmers. While phosphorus needs vary between different soils and cropping systems, a lack of information about recommended application levels can lead to overuse of combination nitrogen and phosphorus chemical fertilizers. This is an unwarranted cost both in economic and environmental terms. Research into alternative phosphorus sources, along with extension at the local level, is needed to support small agricultural systems in the developing world.

Figure 1: *Map of Bolivia*

Background

Bolivia (Fig. 1) is one of the poorer nations in the world, ranking 114th out of 175 developing nations (FAO 2003). A landlocked nation in South America, it has a population of about 8.6 million people (FAO 2003). Table 1 documents several aspects of agriculture in Bolivia, including production statistics on potato and garlic, which are the subject of this thesis. Roughly one half of the population is directly involved in agricultural production (Salinas 2002). Major crops include wheat, corn, potatoes, rice, soybeans, cotton and sugar cane (Salinas 2002, FAO 2003). Farmers in the rural areas, or *campo*, are generally resource poor but are able to grow sufficient crops for household use and for market. Per capita income is around US$900 a year (FAO 2003). Small farmers in Bolivia generally have very limited access to soil testing facilities, thus decisions about fertilizer application are based on a combination of local knowledge, recommendations from extension workers and trial and error.

Table 1: ***Agricultural Production in Bolivia (FAO 2003)***

Total Area	271,349,260 acres (418,700 sq. mi)
Arable Land	7,163,000 acres (2.6% of total)
Land under Irrigation	326,040 acres
Land under Potato Production	321,100 acres
Land under Garlic Production	4940 acres
Average Potato Yield	6634 lbs/acre
Average Garlic Yield	4358 lbs/acre
Tractors in Use	6000
Tractors in Use in the USA	4,800,000

There is no industrial production of chemical fertilizers in Bolivia. Fertilizers instead are imported from neighboring countries, resulting in elevated prices for farmers (Salinas 2002). A market study by Salinas (2002) found that fertilizer prices in Bolivia were two to three times higher than prices for the same products in Colombia. Additionally, the governments of the United States, Japan, and the European Union donate fertilizers as part of their foreign aid efforts. The difficultly of regulating these donated amendments results in some black market exchange.

Approximately seventeen deposits of rock phosphate have been identified in Bolivia. Only one of these, a large deposit near the town of Capinota in the Cochabamba region, has been studied to any extent. The Capinota deposit is easily accessible by a major road; and is estimated to contain 2.8 million tons of phosphate. The rock varies in P content. Preliminary investigations into the use of the rock have shown that it can be an effective amendment, both in its raw form and partially acidulated (Salinas 2002).

Potatoes were originally cultivated in the Andean regions of Peru and Bolivia and continue to be a staple crop in most areas of Bolivia. In the high plains, or *altiplano*, the high altitude and cold climate are unsuitable for most crops; however two crops that do grow well are potatoes and garlic. Potatoes need adequate phosphorus in the initial rooting stage and continue to absorb increasing amounts of P throughout maturation (Khasawneh 1980). Inceptisols, which are common across the *altiplano*, chemically fix phosphorus in forms unavailable for plant uptake. Phosphorus fertilizers are recommended for potato production in soils with less than 20 ppm bicarbonate-extractable P (Lang et al., 1999). Plant available P can be further limited in these soils by alkalinity and/or free lime. It is thus desirable to amend soils with phosphorus in these cropping systems.

Garlic is a relatively recent arrival in Bolivia, but has proven to be a successful market crop. Nutrient needs for garlic are not particularly high, as it has an ability to utilize nutrients and water even if they are relatively scarce (Engeland 1991). Garlic responds to nitrogen fertilization, but does not appear to increase in quality as nitrogen rates are increased (Tyler et al., 1988). It has been shown that garlic does not respond to phosphorus fertilization, even when initial soil values are below 8 ppm (Tyler et al., 1988). Thus, phosphorus amendments applied to potatoes in a rotation with garlic should provide sufficient levels of soil phosphorus for subsequent garlic production.

Study Area

The Iscayachi valley is a high, intermontane valley in southwestern Bolivia, in the department of Tarija. The elevation of the valley floor is approximately 3,500 m (11, 480 ft). It has an *altiplano*-like climate, with a mesic soil temperature regime that has annual average temperatures of about 50°F (10°C) (PERTT 1998). The area has an ustic moisture regime with rainfall occurring primarily between November and March, averaging 352 mm a year (PERTT 1998).

The primary crops are potatoes, garlic, broad beans, chamomile, wheat, peas, and forage crops for animal feed. Crops are planted twice a year: in winter (July or August) and late spring/early summer (November to January). Production usually consists of a three- to four-year rotation based around potatoes, garlic, and broad beans, with a forage crop used as a fallow crop. Soluble fertilizers used by local farmers include ammonium phosphate, urea, and NPK 18-40-0. Fertilizers in southern Bolivia generally come from Argentina due to the proximity of the border.

Rock Phosphate

Introduction

Rock phosphate, a naturally occurring mineral source of phosphate, could serve as an alternative source of phosphorus in developing countries. Low-grade rock phosphate occurs on every continent and is generally unsuitable for industrial fertilizer processes. It is much less expensive than soluble phosphorus fertilizers, and is an amendment that is allowed by organic certification bodies. Phosphate rocks generally are apatitic, containing varying percentages of P_2O_5 in a calcium matrix.

Field trials that compare directly applied rock phosphate to soluble fertilizers show mixed results. Whereas rock phosphate has been shown to be generally less effective in side-by-side direct application experiments with single superphospate (SSP), triple superphosphate (TSP) or diammonium phosphate (DAP), there are situations where it produces similar results to its synthetic counterparts. On phosphorus deficient, acid soils, rock phosphate can reach high relative agronomic efficiencies (RAE). In cropping systems where farmers can only afford to apply fertilizers every few years, rock phosphate may be more economically effective than TSP or SSP. Rock phosphate may also be effective for perennial crops, such as tree crops or pasture. Less phosphorus is available immediately upon application, but in acid soils with adequate rainfall the dissolution of rock phosphate can maintain recommended levels of P over time (Khasawneh et al., 1980, Bolan et al., 1990, Chien et al., 1990, Sanyal and Datta 1991, Chien and Menon 1995).

Comparisons of rock phosphate with soluble phosphorus fertilizers are based on a standard formula to express the effectiveness of using rock phosphate (RP) under specified conditions. The standard, Relative Agronomic Effectiveness (RAE), is calculated as:

$$RAE = \frac{\text{yield with RP—yield of the control}}{\text{yield with soluble fertilizer—yield of the control}} \quad x\ 100$$

When comparing RAE values, it is important to note that they are dependent on application rates. Application rates are generally calculated based on the amount of phosphorus in a given phosphate rock, in order to supply an equal amount of phosphorus across treatments. An RAE value is only valid for a particular rock phosphate at a given application rate for the particular crop in the particular soil environment in which the experiment was carried out. While RAE values give an idea of how rock phosphate compares in a given situation, using them to predict the performance of rock phosphates in different situations can be problematic (Chien et al., 1990).

Properties of Rock Phosphate

Important factors in the effective use of rock phosphate include the solubility and fineness of the material. Substitution of carbonate for phosphate in the apatite structure is the principle characteristic influencing solubility (Chien and Menon 1995). Solvents such as citric acid and formic acid are used, often in conjunction with x-ray diffraction, infrared spectroscopy, or electron microscopy to evaluate solubility (Chien and Menon 1995). Different sources of rock phosphate can thus be compared using relative solubility indexes (Khasawneh 1980). Hammond et al. (1986b) ranked the relative agronomic potential of rock phosphate sources from throughout the world based on ranges of percent soluble P. Citrate soluble P fraction is correlated to plant P uptake during the cropping season (Chien et al., 1990).

Yield responses to applications of different rock phosphates for the same crop on the same soil directly correlate with increasing solubility of the rock phosphates. This correlation can be extrapolated to show that the relative agronomic effectiveness is an almost direct result of solubility for the first crop planted after application (Engelstad et al., 1974). A study of phosphate rocks on an acid soil in Venezuela showed that North Carolina rock phosphate, with 3.1% citrate soluble P, was not significantly different than TSP for improving yields, while three other phosphate rocks with citrate soluble P percentages ranging from 1.0-2.2 raised yields but were not as effective (Casanova and Solorzano 1994).

Concentrations of total P can also be compared among rock phosphate sources (Casanova 1995). A study of a rock phosphate from Tanzania with only 6.46% total P and 0.23% citrate soluble P showed that it was highly ineffective compared to TSP on an alkaline soil (Mnkeni et al., 2000). Phosphate rocks with such low P content are probably not appropriate for direct application. However, in the same study, compacted pellets of a 50/50 TSP/rock phosphate mixture had RAE's of 75%, so it is possible that these sources may be utilized in other ways (Mnkeni et al., 2000). Decreasing particle size and increasing surface area increase the reactivity of rock phosphate in soils. Particle sizes of 100 mesh or smaller are recommended (Khasawneh 1980, Sanyal and De Datta 1991). However, a finely ground dust is not particularly conducive to broadcast application. Compacting rock phosphate into pellets or granules has been found to be effective in several studies (Adediran and Sobulo1998, Mnkeni et al., 2000, Casanova and Solorzano 1994).

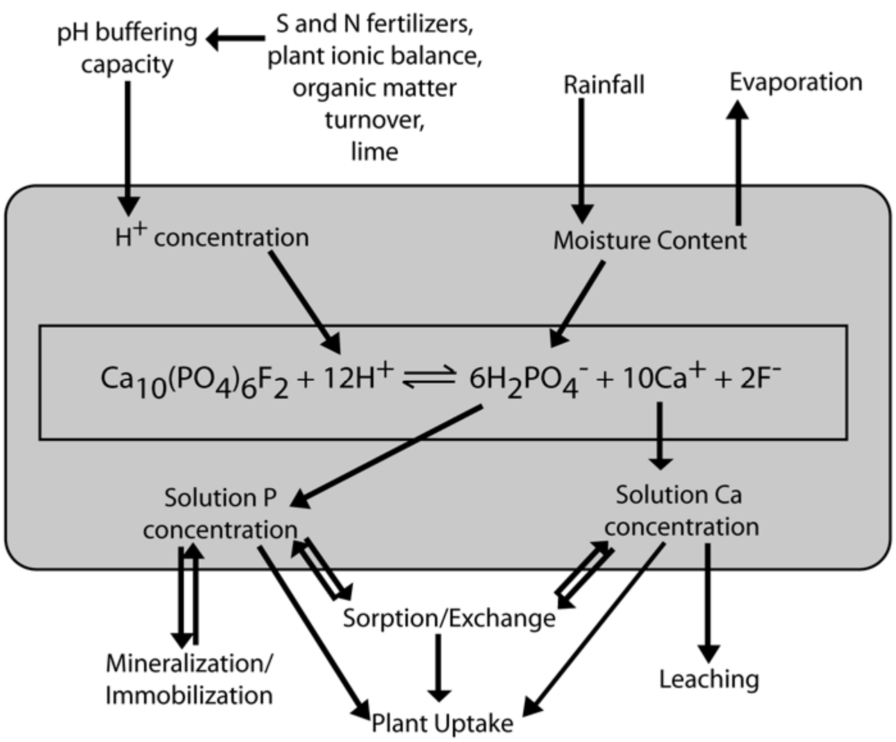

Figure 2: *Rock phosphate dissolution in soils, with rate limiting factors in gray (Adapted from Bolan et al., 1990)*

Soil Properties

Soil properties can affect the suitability of rock phosphate for direct application. Figure 2 shows the factors influencing the dissolution of rock phosphate in soil. Phosphate rocks are less effective in soils with high Ca content, low organic matter, and/or a low cation exchange capacity (CEC), due to the release of Ca ions during dissolution. Wilson and Ellis (1984) dissolved several different sources of rock phosphate in solutions with varying concentrations of Ca^{2+} and found an inverse relationship between the solubility of each rock phosphate and the concentration of Ca^{2+} in solution. Low CEC may limit a soil's ability to sorb Ca^{2+}, especially if exchange sites are occupied by existing exchangeable Ca^{2+}, resulting in decreased dissolution (Bolan et al., 1990).

The effectiveness of phosphate rocks in soils with high P-sorption capacities may be low due to formation of P-compounds that are unavailable for plant uptake (Hammond et al., 1986a). However, some studies indicate that the slow dissolution of rock phosphate in soils with high P-sorption capacities actually improves its efficiency because it is taken up as it dissolves, rather than being transformed into unavailable forms as can occur with excess P from soluble sources (Medhi and De Datta 1997, Smyth and Sanchez 1982). Slow dissolution rates may also be an advantage over soluble fertilizers in soils with very low P-fixing capabilities, as P is less likely to be lost to leaching (Sanyal and De Datta 1991). High soil organic matter can promote dissolution of rock phosphate by forming complexes with Ca^{2+} ions. A study of the effect of rock phosphate on maize yields on two soils equal with respect to pH, exchangeable Ca^{2+} and P-sorption capacities showed that yields were significantly higher in the soil with higher organic matter content (Chien et al., 1990).

The dissolution reaction of fluorapatite rock phosphate in acid soils is as follows:

$$Ca_{10}(PO_4)_6F_2 + 12H^+ = 6H_2PO_4^{--} + 10Ca^{2+} + 2F^{--}$$

Related reactions include:

$H_2PO_4^{-} + \text{HO-soil} \rightarrow H_2PO_4\text{-soil} + OH^{-}$

$F^{-} + \text{HO-soil} \rightarrow \text{F-soil} + OH^{-}$

$2F^{-} + Ca^{2+} \rightarrow CaF_2$ (Sanyal and De Datta 1991, Hong-Qing et al., 1997)

As rock phosphate releases P through dissolution, it is largely held in insoluble forms dominated by Ca-P. Forms of Fe-P and Al-P represent considerably smaller fractions (Muchovej et al., 1989). Concentration of calcium in solution has been shown to be inversely related to dissolution of rock phosphate (Wilson and Ellis 1984). Mutuo et al. (1999) studied the release of P from TSP and rock phosphate and found that while TSP samples had considerably more extractable P at one week, the levels were close to equal at seven months, and were equal at eighteen months. Extractable P levels increased slightly in the rock phosphate samples between one week and seven months, while dropping by more than half in the TSP samples in the same time period. In an incubation study, He et al. (1996) found that 30% of North Carolina phosphate rock was dissolved after thirty days. In a separate kinetics study, He et al. (1999a) found that addition of urea and zeolite increased average rock phosphate dissolution due to acidification by urea and removal of Ca^{2+} as it was exchanged with Na in zeolite..

Soil Management

Soil management practices can increase or decrease the effectiveness of rock phosphate. Comparisons between the effectiveness of rock phosphate amendments in acid and slightly basic soils show that yields are not significantly increased in slightly basic conditions, whereas yields from soils with pH levels between 4 and 6 show marked increases (Chien and Menon 1995**,** Kisitu 1991, Kumar et al., 1992). Increasing the pH of a soil through liming has been shown to decrease the levels of extractable P (He et al., 1999b, Mnkeni et al., 2000, Kanabo and Gilkes 1987). Several studies have found a direct correlation between increasing lime application rates and decreasing RAE values of rock phosphate (Habib et al., 1999, Akintokun et al., 2003). It has been suggested that applying rock phosphate several months before liming would allow for the dissolution of the material at a lower pH (Khasawneh 1980), although in a soil with a high P-sorption capacity this might reduce plant-available phosphorus at the time of planting. In a soil with high P-sorption capacity, maize yields from plots amended with rock phosphate six weeks before planting were lower than yields from plots amended at the time of planting, while the same comparison on a soil with low P-sorption capacity showed no significant difference in yields (Chien et al., 1990). Broadcasting of rock phosphate and incorporation into the soil increases dissolution through increased surface contact (Chien and Menon 1995). Incorporation also increases the chance that rock phosphate particles will encounter rhizosphere acidity, increasing dissolution (Sanyal and De Datta 1991).

Application rates for rock phosphate vary with the properties of the rock phosphate in question. It is necessary to know the soluble P content of the rock phosphate in order to calculate application rates. For comparison studies with soluble fertilizers, application rates for rock phosphate are determined by soluble P applied, or by the amount required to achieve equivalent yields (Bolan et al., 1990, Chien et al., 1990). By comparing the uptake of isotope-tagged P in dried plant material, Ankomah et al. (1995) determined the application rates for rock phosphate and TSP to supply P in equal amounts for cowpea grown in an acid soil in Ghana.

Other benefits of using rock phosphate include the reduction of exchangeable Al in soil. In soils with Al toxicity, rock phosphate has been shown to reduce exchangeable Al to a greater extent than TSP (Hong-Qing et al., 1997). Another advantage is that macronutrients such as Ca, Mg, and K can become more available through the dissolution of rock phosphate. Application of fungi can also influence uptake of P from rock phosphate sources. Uptake of P by maize amended by directly applied rock phosphate and mycorrhizal fungus was shown to be greater than uptake with rock phosphate alone, and levels of available micronutrients also increased in a greater extent in the fungus-treated samples (Alloush and Clark 2001). Although rock phosphate did not produce a significant yield response compared to SSP in a pasture, wheat and rye study, it did maintain levels of mycorrhizal fungi that were depleted in the SSP treated plots (Dann et al., 1996).

Mixing soluble fertilizers with rock phosphate has proven effective under certain circumstances, and is a way to reduce fertilizer costs without taking on as much risk. It has been proposed that plants are able to use P from TSP initially, when they are in the early development stages. As the root system develops, more contact is made with particles of rock phosphate, and dissolution is increased (Habib et al., 1999). In this way, the two fertilizers are utilized at different stages, with one leading to the increased efficiency of the other. Singaram et al. (1995) found that a 2:1 mixture of rock phosphate to SSP was 68% as effective initially and 73% as effective residually compared to SSP, and much higher than RP alone. Mixtures of compacted phosphate rock with TSP in 60/40 and 70/30 ratios were found to be equally effective as TSP on acid soils for soybeans (Casanova and Solorzano 1994).

Crop Considerations

Use on responsive crop species can improve the agronomic effectiveness of rock phosphate. It may be more effective for pasture and tea, for tree crops such as fruit, rubber or oil palm, and for crops with lower phosphate needs. Kumar et al. (1992) found that residual rock phosphate improved yields in maize, wheat, and lettuce, in decreasing order of increasing phosphate demands. Crops that absorb higher amounts of Ca may increase the dissolution of rock phosphate by absorbing the Ca ions released in the dissolution reaction. Higher P uptake from rock phosphate by certain crops has also been attributed to higher root density (Chien et al., 1990, Bolan et al., 1990, Ramirez et al., 2001). Rhizosphere acidity is increased by organic acids and protons released by roots, and rock phosphate particles are more likely to encounter rhizosphere chemistry as root density increases (Ramirez et al., 2001). Acidification in the rhizosphere may also be caused by plant species whose roots absorb more anions than cations at the root, resulting in increased dissolution and subsequent uptake of rock phosphate (Chien and Menon 1995, Scholefield et al., 1999). Organic exudates released by roots and metabolized by soil microorganisms may produce anions that complex Fe^{+} and Al^{+}, reducing P-sorption (Scholefield et al., 1999).

Legumes may be able to liberate more P from rock phosphate with rhizosphere acidification during N_2 fixation, converting it into available forms in the soil as well as incorporating it as biomass (Vanlauwe et al., 2000a). If residues are left in the field, a subsequent crop can access the P in legume residues as they decompose over the course of the growing season. Vanlauwe et al. (2000a) found that maize yields in a legume-maize rotation following a legume crop were significantly greater in rock phosphate amended plots than maize yields following a previous maize crop, even when the maize-maize plots were amended with TSP. Maize yields from plots with previous legume crops that were not amended with rock phosphate did not show the same improvement, implying that legumes alone do not greatly improve available soil P. In a companion study, Vanlauwe et al. (2000b) found that the addition of rock phosphate to legumes increased mycorrhizal fungi and root density to an extent not seen in similarly treated maize. Cowpea was found to more effectively take up P from rock phosphate than sorghum and maize in semi-arid conditions, both initially and residually, with RAE values of 82-101%. Sorghum yields were shown to improve when sorghum was planted after a rock phosphate fertilized cowpea crop in an acid soil in West Africa (Muleba and Coulibaly 1999). Uptake of phosphorus has been shown to be greater in a rice crop that follows a forage crop amended by rock phosphate than when rock phosphate is directly applied to the rice (Medhi and De Datta 1997).

Experiments comparing different cultivars of a crop could be used to determine which are more efficient at P uptake from rock phosphate, and could also indicate what levels of rock phosphate should be applied to achieve sufficient uptake. A comparison of five cultivars of cowpea amended with rock phosphate showed that some cultivars were significantly better at using rock phosphate P than others, though the exact reasons for the differences between the cultivars were not straightforward. It was found that cultivars that were better able to absorb soil P were also better able to absorb P from rock phosphate (Ankomah et al., 1995). A similar study of six maize cultivars looked at rhizosphere chemistry and root systems, and found that total root surface as well as increased P and Ca uptake were factors contributing to increased uptake by some cultivars (Ramirez et al., 2001). This finding suggests that crops could be bred to exhibit certain qualities that would enhance their ability to utilize P from rock phosphate.

Site Considerations

Finally, climate and aspect can affect the efficiency of rock phosphate. In a toposequence study, Vanlauwe et al. (2000a) found that plots on a slope did not respond to P fertilizers like valley and plateau plots did, due to a higher initial P level. A study of local rock phosphate in Nigeria showed that directly-applied rock phosphate reached an initial RAE of 60% compared to SSP at a site that received 1200-1400mm of annual rainfall, and an RAE of 80% at a site that received 900-1100mm of annual rainfall, but reached only marginal RAE values at sites with annual rainfall between 600 and 800mm. Residually, rock phosphate had an RAE of nearly 150% at the high rainfall site (Adediran and Sobulo 1998). The poor results from the drier sites may be attributed to insufficient soil solution for effective dissolution of rock phosphate. It has been shown that temperature has no effect on the performance or solubility of rock phosphate (Hammond et al., 1986b).

Phosphocomposts

Phosphocomposts are phosphorus-enriched composts, made with rock phosphate and a range of organic materials. Phosphocomposts have been shown to be an effective way to incorporate rock phosphate with various organic nitrogen sources while improving soil structure. The mineralization of insoluble P forms by organic acids is the major advantage of composting rock phosphate. While organic inputs such as cow manure are beneficial on their own, inclusion of additional P may produce yields on par with inorganic fertilizers (Roy et al., 2001). Organic acids in the various organic materials used in the compost help break down the rock phosphate faster during the composting period by pushing the dissolution reaction to the right.

Organic matter may also complex Ca^{2+} ions in the soil solution, increasing the dissolution of rock phosphate (Sanyal and De Datta 1991). It has been shown that incorporation of rock phosphate with organic compost increases the amount of loosely bound P in soils and significantly decreases the fraction held as Ca-P compared to incorporation of rock phosphate alone (Singh and Amberger 1995). It must be considered that increased dissolution of rock phosphate does not necessarily translate directly into increased P uptake by plants, if soils have high P-retention. Organic matter can complex released P from rock phosphate, making it more available for plant uptake than insoluble P complexes formed in the soil. It is thought that the P released from rock phosphate and taken up by microorganisms is available over a longer period of time as they decompose (Singh 1985).

Addition of other mineral materials can enhance the overall agronomic value of compost. Solid waste materials, including agricultural and industrial waste products, have been studied in recent years as possible ingredients for composting. Materials used in composts may include animal manure, animal urine, kitchen wastes, legume crop residues, cereal crop residues, tree leaves, city rubbish, thermal power waste, sewage sludge, urea, and pyrite. Small amounts of soil or molasses are often added to introduce microbial activity, and in some cases P-solubilizing and/or cellulose decomposing organisms are added. Composts are mixed and left to decompose over periods ranging from one to six months. Generally it is preferable to allow sufficient time for organic acids to decompose so the compost will not be toxic to seeds or roots when applied.

Analysis of the levels of organic acids in phosphocomposts has shown that they are undetectable after 120 days of decomposition (Singh and Amberger 1997), but this can vary depending on the climate and materials used.

Pyrite is commonly added to compost due to its natural sulphur content. When pyrite is oxidized during composting, sulphuric acid is produced. The presence of sulphuric acid is thought to increase dissolution of rock phosphate in addition to preventing N losses through the volatilization of ammonia (Bangar et al., 1989). Comparisons of phosphocomposts with and without pyrite show that total N is higher in pyrite mixtures over periods of up to ninety days (Singh et al., 1992). However, Saha and Hajra (2001) found that addition of pyrite to compost consisting of rock phosphate and rice straw reduced water soluble P, possibly due to refixation by free Fe in the pyrite. Rock phosphate composted with paddy straw and a phosphorus solubilizing organism released more P during composting than a mixture of rock phosphate and pyrite, but the pyrite mixture was slightly more agronomically effective for rice (Misra et al., 2002).

Sulfur-oxidizing bacteria have been used in conjunction with organic matter to acidify the soil and increase rock phosphate dissolution, resulting in plant uptake efficiency equal or greater to that achieved with SSP (Muchovej 1989). In the same study, rock phosphate dissolution did not significantly change soil solution P, indicating that most or all of the released P had been sorbed onto Al or OM sites. If a soil is high in Al sesquioxides, this is the likely explanation. High fractions of Al-bound P have been shown to increase plant uptake of phosphorus from rock phosphate and subsequent crop yields in acid soils, especially if the pH is increased through liming (Muchovej et al., 1989).

Soil microbial biomass carbon (SMBC) has been shown to increase in soils amended with phosphocomposts more than in soils amended with soluble fertilizers (Manna et al., 2001). Greater increases in soil microbial biomass carbon were obtained with varying phosphocomposts made from soybean straw, mustard straw, chickpea straw, wheat straw and city garbage compared to soluble fertilizers (Manna and Ganguly 1998). Dehydrogenase, catalase, and phosphatase levels increased significantly in compost amended soils (Manna and Ganguly 1998). Nodules per plant were higher than control in groundnut crops amended with phosphocomposts and this has been attributed to improved growth of microbes in the rhizosphere (Saha and Hajra 2001).

Comparisons of phosphocomposts with single and triple-superphosphate have demonstrated that certain mixes of phosphocomposts are capable of producing similar or better yield results than the traditional phosphate fertilizers. A composted mixture of rock phosphate and millet straw did better than compost alone for millet yields, approaching the yield returned with chemical fertilizers applied at recommended levels (Badiane et al., 2001). Although yields of rye grass from directly applied rock phosphate did not compare to those from single superphosphate, wheat straw compost enriched with the same phosphate rocks slightly outperformed the SSP (Singh and Amberger 1995). Bangar et al. (1989) found that phosphocomposts made with organic material, rock phosphate, pyrite, and urea produced comparable yield results for wheat when compared with single superphosphate. Manna et al. (2001) showed that composts made using cereal and legume straws, rock phosphate, and cow manure produced soybean yields nearly equal to yields produced by applications of soluble N and P. Wheat was planted to examine the residual effects of the amendments, and all plots were amended with N, P and K, although the compost plots were amended at a rate of half the amount added to the soluble fertilizer plots. The experiment demonstrated that wheat biomass from the compost-amended plots was only slightly less than the plots amended with soluble N and P (Manna et al., 2001). N enriched phosphocomposts may be even more effective. The addition of urea to a phosphocompost, with pyrite to help retain the N, has been shown to produce wheat yields equal to single superphosphate (Singh et al., 1992).

A method of improving yields while saving resources in small-scale cropping systems may be to combine phosphocomposts with soluble fertilizers. Saha and Hajra (2001) found that phosphocomposts applied with 50 to 75% recommended NPK outperformed 100% recommended NPK for groundnut. Combinations of rock phosphate-enhanced soybean trash compost with SSP were shown to produce higher yields than SSP alone in an initial soybean crop and in a follow up wheat crop (Verma and Rawat 1999).

Economic Considerations

It is important to analyze farm budgets when looking at alternative fertilizers. For small scale cropping systems in developing nations, the use of cheap, local sources of nutrients is preferable, if not unavoidable due to a lack of other options. By subtracting the total net cost of production from the returns from a crop, a net profit number can be determined and used to compare different inputs. A simple analysis to determine the economic viability of rock phosphate is achieved by multiplying the relative agronomic effectiveness (RAE) by the ratio of the price of soluble fertilizers to the price of rock phosphate. The relationship can then be plotted to aid in evaluating the viability of rock phosphate (Engelstad et al., 1974).

Residual effects are an important consideration for resource-poor farmers. A greenhouse study analyzing soluble P fractions in soil showed that very little P had been released from rock phosphate after a month compared to SSP (Owusu-Bennoah and Acquaye 1996). However, slow dissolution over several cropping sequences can make the application of rock phosphate economically viable. Rock phosphate applied to an acid soil in Kenya produced better corn yields than TSP in an initial planting season, and reached 79% RAE in the following season (Mutuo et al., 1999). Rapeseed yields from rock phosphate treated plots had RAE's of 90-100% in an Ulitsol in an initial season, and were more effective than TSP for the following crop (Hong-Qing et al., 1997). Studies of a crop sequence on alkaline soils showed that rock phosphate was not nearly as effective as SSP in an initial millet crop, but surpassed SSP yields in subsequent maize and blackgram crops (Singaram et al., 1995).

An analysis of rock phosphate in a cropping sequence in India showed that while rock phosphate was not economically viable for one crop compared to SSP, over the course of the cropping sequence it had an equal return (Singaram et al., 1995). Badiane et al. (2001) compared several compost and fertilizer combinations for millet production in Senegal and found that the return from compost made with rock phosphate was better than the return from compost alone. Van den Berghe (1996) compared the net profits of three treatments, compost alone, compost with rock phosphate, and compost combined with diammonium phosphate, finding that although the latter two produced greater crop yields and subsequent financial returns, there were no significant differences between the three when input costs were subtracted from the returns. Clearly, the cost of the rock phosphate itself is the vital factor when considering its economic viability in terms of chemical fertilizers or other amendments. If it requires partial acidulation or other processing, the cost may be higher.

Statement of research objectives

The objectives of this investigation were: 1) to evaluate alternative phosphorus fertilizers in cropping systems in the Bolivian highlands, and 2) determine if composting rock phosphate with cow manure increased P solubility and improved potato and garlic yields. Agronomic effectiveness and economic viability were reviewed.

Chapter 2

Abstract

A two-year field experiment on high valley Vertic Haplustolls in Bolivia was undertaken to study the effects of rock phosphate, manure, and rock phosphate composted with manure on yields of potato and garlic. While satisfactory yields were obtained from all plots, the results showed that none of the treatments significantly increased yields or available soil phosphorus with respect to the control. High nitrate levels in some areas of the field may have delayed potato tuberization. Adequate levels of background phosphorus in the study area soils, in combination with alkaline conditions and low application rates of the amendments, may explain the lack of treatment response. However, yields from the intensive organic system were comparable to those achieved by local farmers using synthetic fertilizers. Additional research is needed to explore the viability of rock phosphate as an alternative phosphorus source in small farming systems in Bolivia.

Introduction

As demand for phosphorus fertilizers in the developing world rises, cheaper alternatives to soluble phosphorus fertilizers must be considered for resource-poor farmers. Rock phosphate, a naturally occurring source of phosphorus, may prove to be an effective amendment for small farm operations. Although the agronomic effectiveness of rock phosphate varies from site to site (Chien et al., 1990), under certain conditions it can provide P and produce yields equal to those achieved with soluble phosphorus fertilizers. Factors influencing the suitability of direct application of rock phosphate include solubility of the rocks, soil acidity, soil P-fixation capacity, soil organic matter content, and crop P requirements (Chien and Menon 1995, Sanyal and De Datta 1991, Hammond 1986a). When directly applied, rock phosphate requires no processing, and is much less expensive than soluble fertilizers. The slow release of P by rock phosphate may make it more efficient over time, which is important in cropping systems where farmers are not able to apply fertilizer every year. The economic advantage for subsistence farmers with little capital must be considered.

Incorporating rock phosphate into compost materials has been shown to be an effective method of improving available P and N to crops (Singh and Amberger 1997, Bangar et al., 1989, Manna et al., 2001, Misra et al., 2002). Rock phosphate may be dissolved more rapidly in the acid environment created by organic acids in various types of compost, and the application of organic materials improves overall soil quality. Materials for composting can include farmyard manure and crop residues, which are readily available and inexpensive.

Phosphorus deficiencies can occur in the high valleys of Bolivia, where the primary crops are potatoes, garlic, broad beans, and forage (Salinas 2002). Potatoes, a subsistence crop grown and consumed by most rural Bolivian farmers, require adequate levels of phosphorus throughout their growing season for healthy development (Khasawneh 1980). Application of phosphorus fertilizer for potato production is recommended in soils with less than 20 ppm bicarbonate-extractable P (Lang et. al. 1999). Garlic is a successful market crop in the study area that requires relatively low nutrient input. Minimal nitrogen application is recommended, but garlic does not respond to phosphorus or potassium amendments (Tyler et al, 1988). Alkaline or free-lime conditions can further reduce plant available P (Khasawneh 1980). Crop production in some areas may also be affected by salinity. A reactive rock phosphate, containing 22.2% P_2O_5, is available in the Cochabamba region of Bolivia and could be used for direct application.

The objective of this experiment was to evaluate the effect of manure, rock phosphate, and rock phosphate-enriched compost on P availability and crop yields. Agronomic effectiveness and economic viability will be reviewed.

Materials and Methods

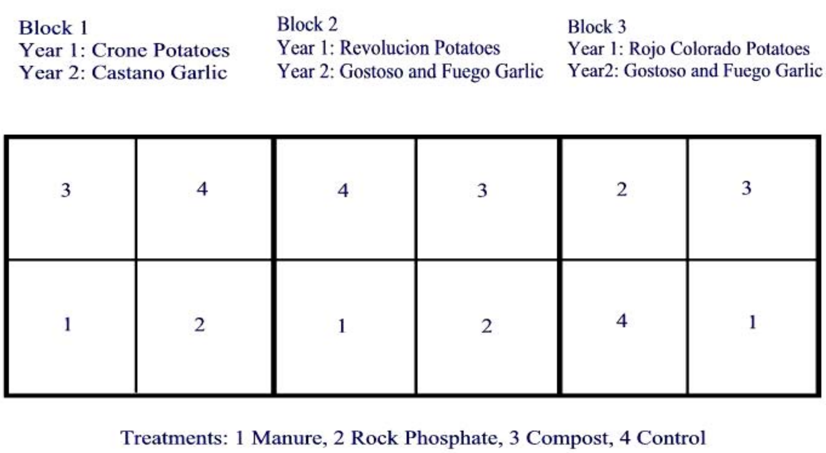

Figure 3. ***Experimental Design***

Table 2: ***Soil properties of Iscayachi valley bottom soil (before treatment, 0-10 cm)***

Property	Value
pH	7.96
OM (%)	5.41
EC (dS/m)	8.45
NO_3-N (mg/kg)	60
NH_4-N (mg/kg)	8.4
Olsen P (mg/kg)	15.4

A two-year field experiment was conducted on a valley bottom in the Iscayachi valley in the department of Tarija, Bolivia. The experimental design consisted of three fertilizer treatments and a control in a random block design. The block was replicated three times (Fig. 3). Each treatment plot was 80 square meters.

The soils were slightly basic, saline Mollisols. Some characteristics of the study area soils are given in Table 2.

Table 3. ***Properties of Capinota Rock Phosphate used for compost and direct application (Salinas 2002)***

Compound	Value (%)
Total P_2O_5	22.2
Citrate Soluble P	2.02
SiO_2	33.82
Al_2O_3	4.14
Fe_2O_3	6.93
CaO	32.39

Table 4. ***Properties of cow manure used for compost and direct application***

Property	Value
pH	7.6
EC(dS/m)	8.73
Olsen P (ppm)	55.6
OM (g/kg)	583.3
Total N (g/kg)	15.5

The compost was prepared by mixing manure with rock phosphate at a dry weight ratio of 9:1 (180 kg manure to 20 kg rock phosphate). Properties of the rock phosphate and manure are given in Tables 3 and 4. The pile was moistened to field capacity, thoroughly mixed, and covered with plastic. The compost was moistened and turned once a week for five weeks.

Amendments were applied once at the beginning of the experiment, a week prior to sowing the potato crop. The cow manure was applied at a rate of 910 kg/ha (7.28 kg/80 sq.m.). The rock phosphate application level was based on the application of 50kg/ha of P_2O_5 (1.74 kg/80 sq.m.). The compost was applied at a combined rate of 910kg/ha of manure plus 50kg/ha P_2O_5 (9.02 kg/80 sq. m.). All treatments were incorporated by two passes of a wooden plow to an approximate depth of 25 cm.

Cow urine diluted in a 1:2 ratio with water was applied as a pesticide twice each growing season. The field received row-by-row flood irrigation approximately every two weeks during production. The history of fertilizer use on the study area was limited to an application of sheep manure one year before the experiment, when the field was in garlic production. Prior to that it lay fallow for 5-6 years.

Potatoes were planted in the plots on November 27, 2002 and harvested on April 26, 2003 (151 days). Garlic was planted on August 3, 2003 and harvested in January 21, 2004 (171 days). Yields were determined for each plot after harvest of each crop. Potatoes were weighed in three size classes, small, medium, and large, according to local practice. The average yield for each treatment was calculated and analyzed for statistical significance.

Soil samples were taken from the tillage horizon of each plot before fertilizer application, between potato harvest and garlic planting, and after garlic harvest. Soils were air dried and bagged for transport. Particle size distribution was determined by a Malvern Mastersizer-S (Lilligren 2000). Soil pH was determined with a Orion 211 pH meter, EC was measured by an YSI Model 35 conductance meter. Olsen-P was extracted with 0.5M $NaHCO_3$ (pH 8.5) and measured with a Perkin-Elmer Lambda 2 UV-VIS spectrophotometer (Olsen et al., 1954). Total soil carbon and nitrogen were measured with a Leco CNS2000 dry combustion analyzer. Soil carbon was converted to organic matter by multiplying by a factor of 1.72. Nitrogen fractions were extracted with 1M KCL and measured by a Latchet Automated Ion Analyzer. The significance of treatment effects on soil properties and yield were tested with an analysis of variance (ANOVA) using SAS version 9.0.

Results and Discussion

Analysis of composting method

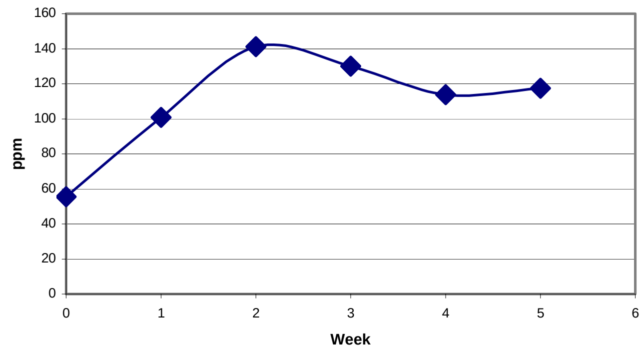

Figure 4. *Olsen-P in compost over time*

Five weeks of composting resulted in an increase in soluble P in the compost mixture (Fig. 4). Depending on the composition and materials of compost, Olsen-P levels typically range from 50-1850 ppm (Bezdicek and Fauci 1997). It is not clear whether the increase in soluble P is due to rock phosphate dissolution or decomposition of the manure. The compost pH (Fig. 5) did show a slight initial decrease, but was not lower than 7.57 at any point. Thus it is unlikely that rock phosphate dissolution was greatly increased by organic acids during composting. The compost pH is in the recommended range of 5-8.5 (US Composting Council 2000).

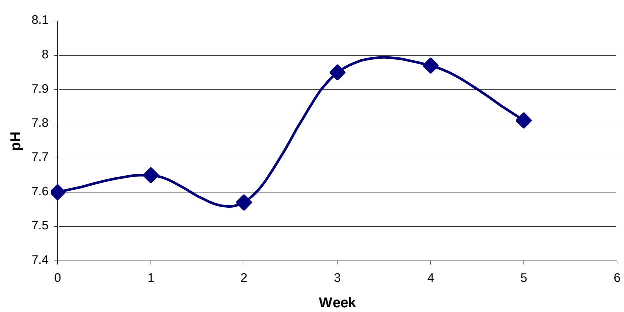

Figure 5. *pH in compost over time*

The effect of manure, rock phosphate and compost on soil properties

Soil pH values over the course of the experiment are presented in Figure 6. There were no significant differences as a function of treatment (F = 4.34, Pr > F 0.06). Conditions were alkaline throughout the experiment. Soil EC values are presented in Figure 7. The study area soils were found to be moderately saline (8-16 dsm/m2; Soil Survey Staff, 1993), corresponding with occasional observations of surface salt accumulation. A general reduction in salinity can be seen over the course of the experiment, which may be attributed to the removal of crop nutrients, or to the movement of salts down through the profile as a result of irrigation. There were no significant differences in EC due to the treatment applications (F = 1.22, Pr > F 0.38), although it appears that the manure and rock phosphate plots retained higher salinity levels at the second sampling date compared to the compost and control plots.

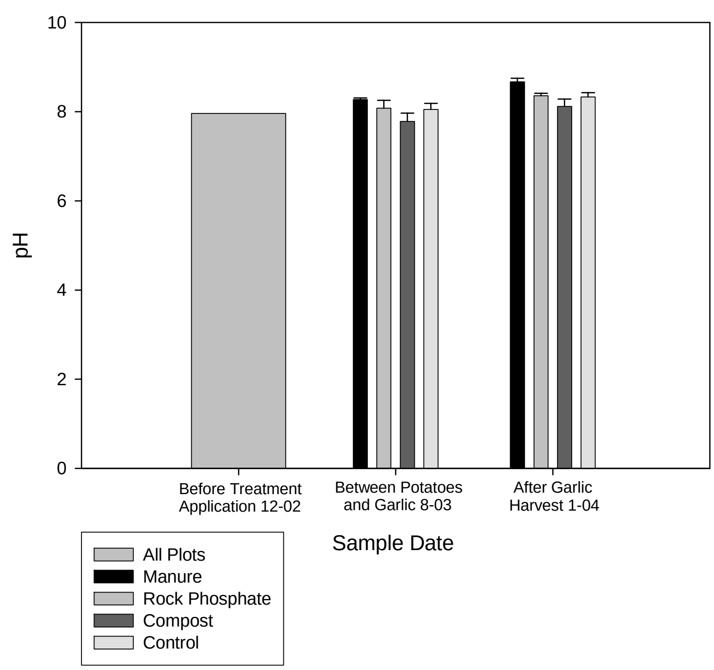

Figure 6: ***Soil pH by treatment at three sampling dates (sampling depth: 0-25cm), error bars represent standard error for each average***

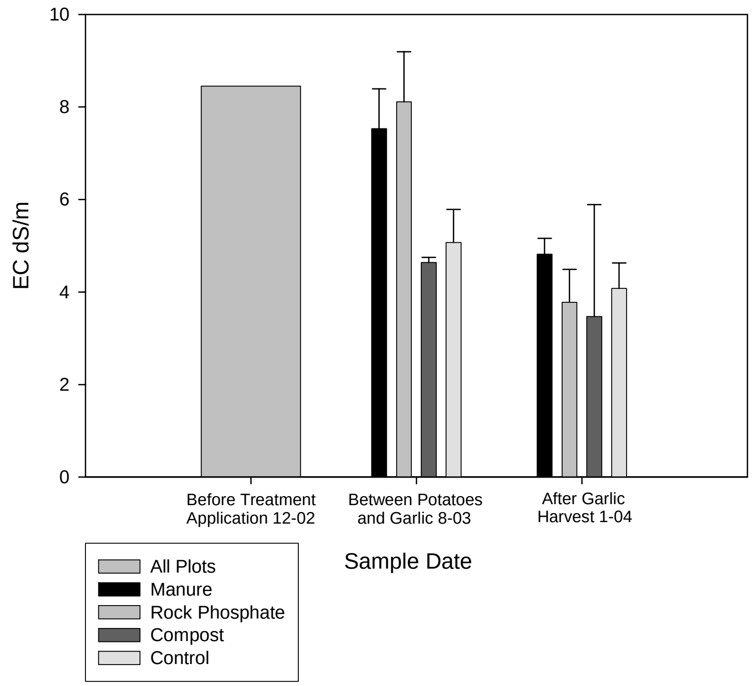

Figure <u>7</u>: ***Soil Electrical Conductivity (EC) by treatment at three sampling dates in units of dS/m (sampling depth: 0-25cm), error bars represent standard error for each average***

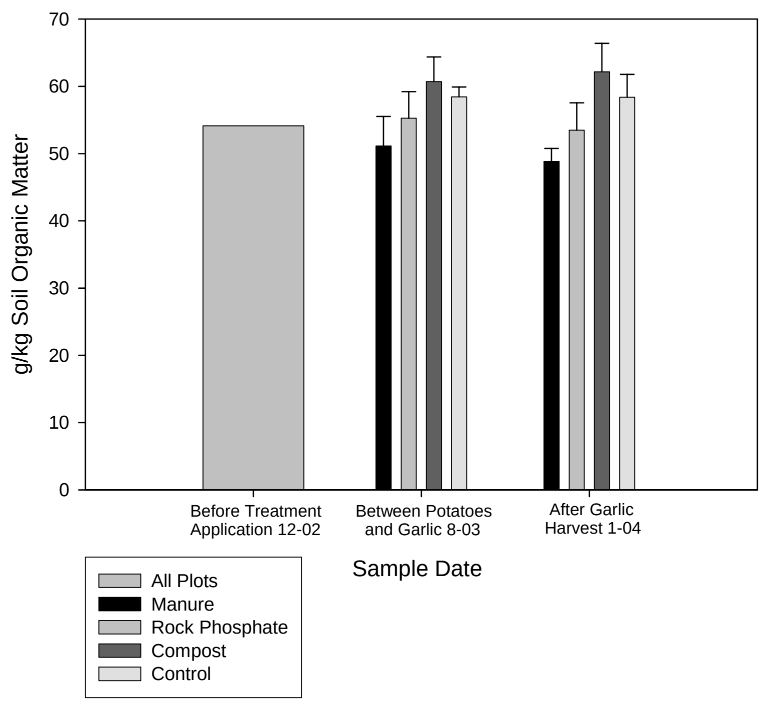

Figure <u>8</u>: ***Soil Organic Matter by treatment at three sampling dates in units of g/kg (sampling depth: 0-25cm), error bars represent standard error for each average***

Data for soil organic matter is presented in Figure 8. The soil before treatment had a relatively high amount of soil OM, and none of the treatments significantly increased OM over the control (F= 2.43, Pr > F 0.16). Total soil nitrogen is presented in Figure 9. Again, there was no significant treatment effect (F = 3.10, Pr > F 0.11). However, the compost treatments appeared to slightly increase both organic matter and total soil N.

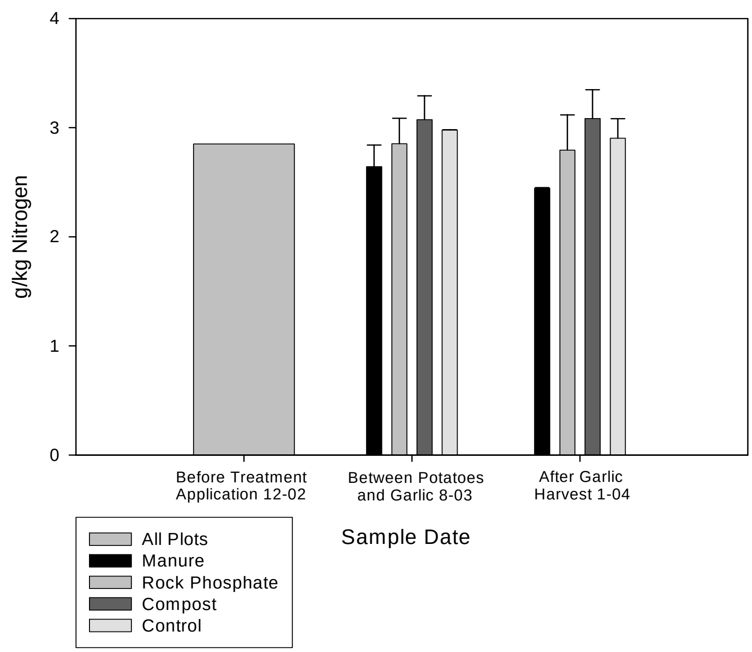

Figure 9: *Total Soil N by treatment at three sampling dates in units of g/kg (sampling depth: 0-25cm), error bars represent standard error for each average. Lack of error bar indicates low standard error.*

Values for ammonium-N and nitrate-N are given in Figures 10 and 11. Soil nitrogen was not a limiting factor for crop growth. There were no significant treatment effects on ammonia-N (F = 1.07, Pr > F 0.43) or nitrate-N (F = 0.82, Pr > F 0.53). Disproportionately high nitrate levels were tested in some areas of the field, particularly in the block that produced poor yields, resulting in high variability in the averages by treatment.

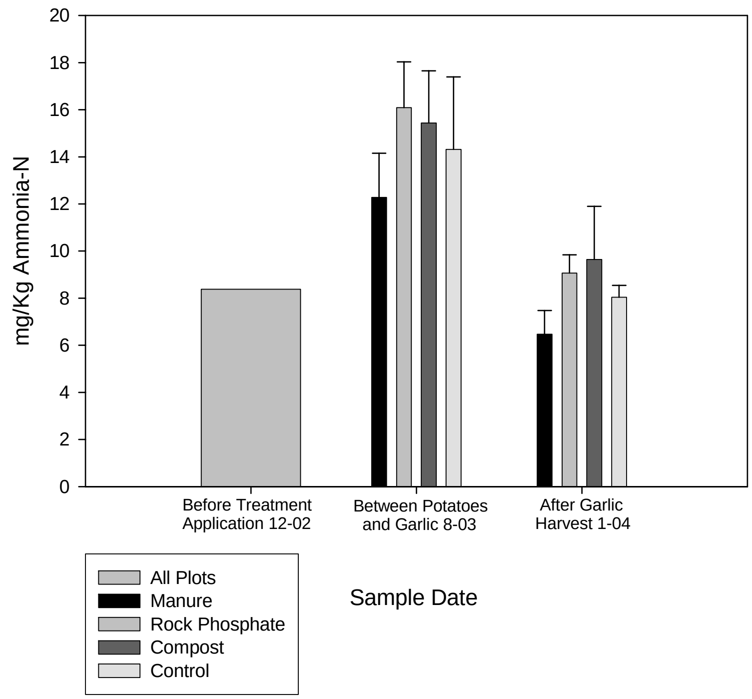

Figure 10: ***Soil Ammonium-N by treatment at three sampling dates in units of mg/kg (sampling depth: 0-25cm), error bars represent standard error for each average***

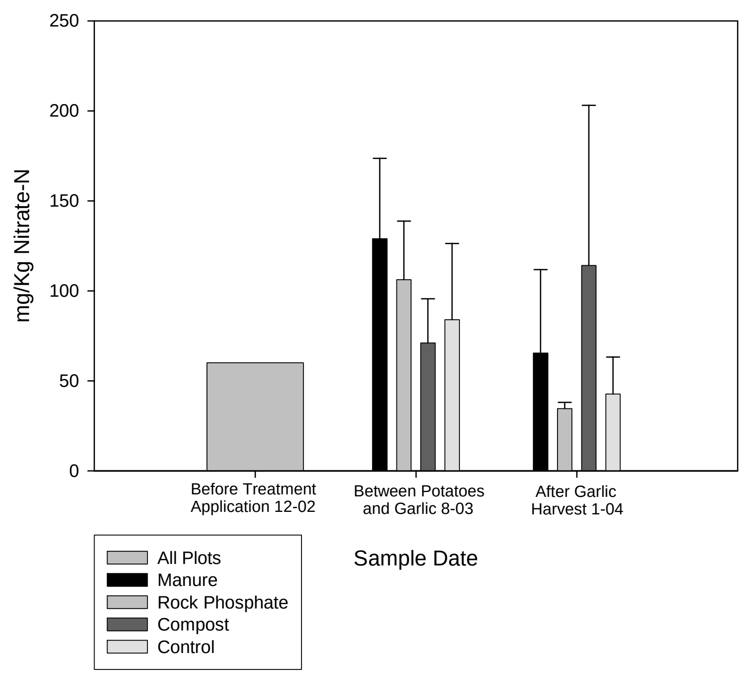

Figure 11: ***Soil Nitrate-N by treatment at three sampling dates in units of mg/kg (sampling depth: 0-25cm), error bars represent standard error for each average***

The effect of manure, rock phosphate, and compost on crop yield

Yield results for potatoes are presented in Figure 12. The poor performance of the Rojo variety in comparison to the other two varieties is attributed to a lower tolerance to several late freezes that occurred after planting. It should be noted that the Rojo block of the field produced poor garlic yields as well, and was found to have higher nitrate-N levels than the rest of the field. Analysis of average potato yields as a function of treatment showed that none of the three treatments significantly improved yield over the control ($F=0.11$, $Pr > F=0.95$). Further statistical analysis of yield data according to size class showed no significant treatment differences between the yields of large ($F = 1.83$, $Pr > F$ 0.24), medium ($F = 0.67$, $Pr > F$ 0.60), or small potatoes ($F = 1.37$, $Pr > F$ 0.34) (Fig. 13-15).

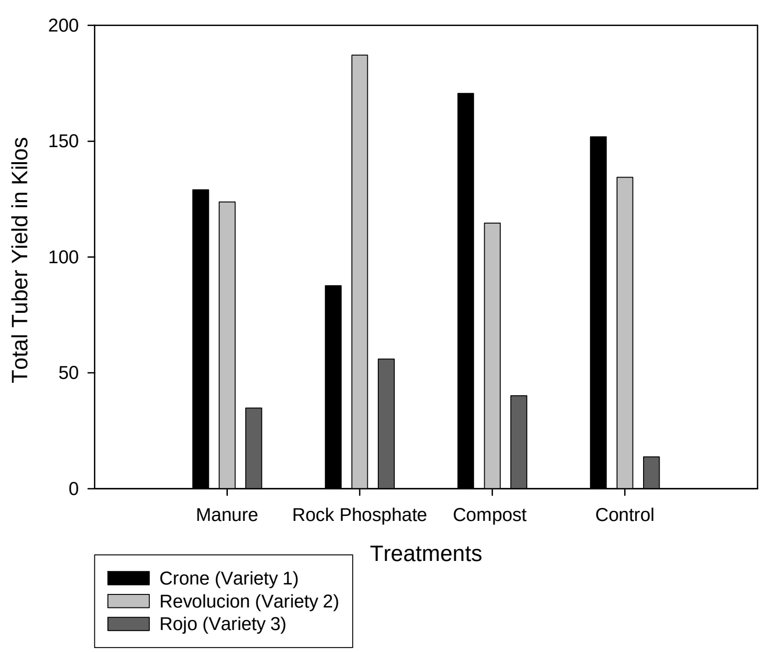

Figure <u>12</u>: ***Total potato yields by treatment (For each bar, n=1)***

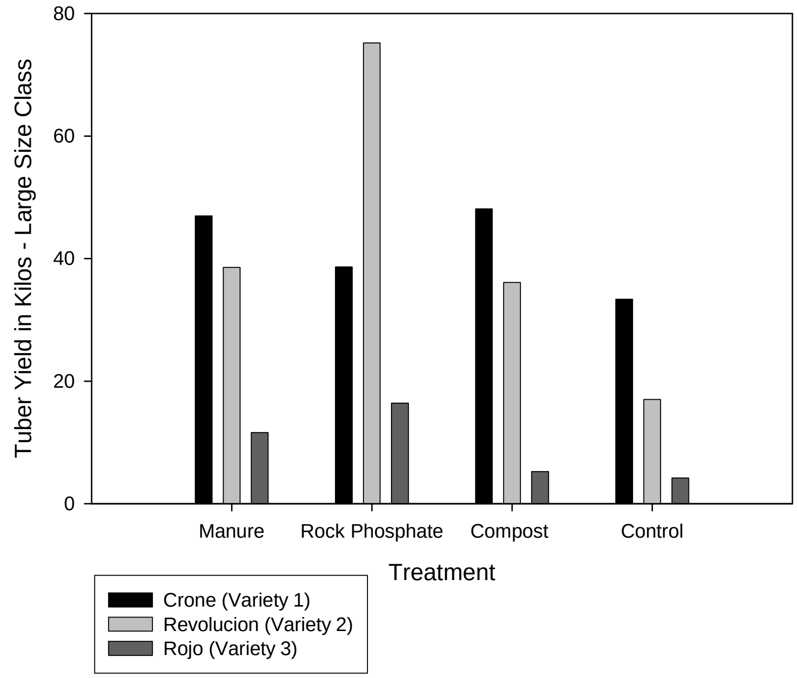

Figure <u>13</u>: ***Potato yields by treatment, Large size class (For each bar, n=1)***

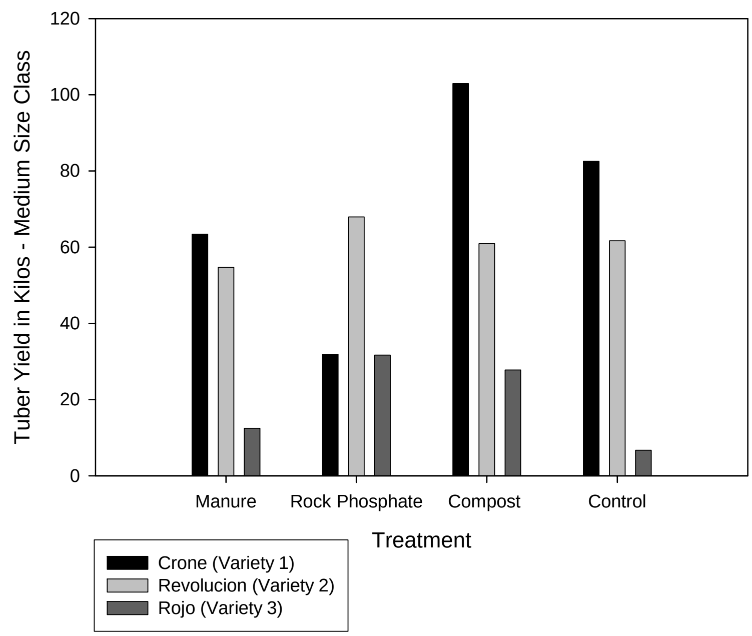

Figure <u>14</u>: ***Potato yields by treatment, Medium size class (For each bar, n=1)***

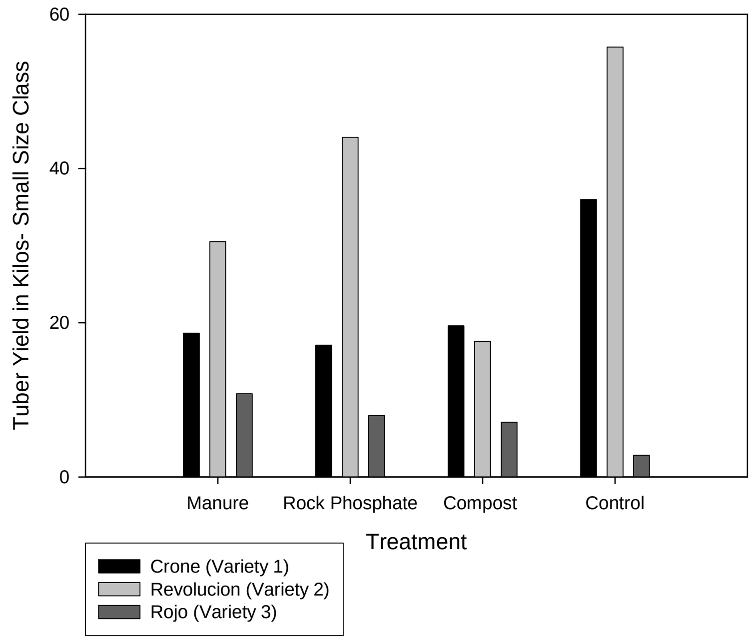

Figure <u>15</u>: ***Potato yields by treatment, Small size class (For each bar, n=1)***

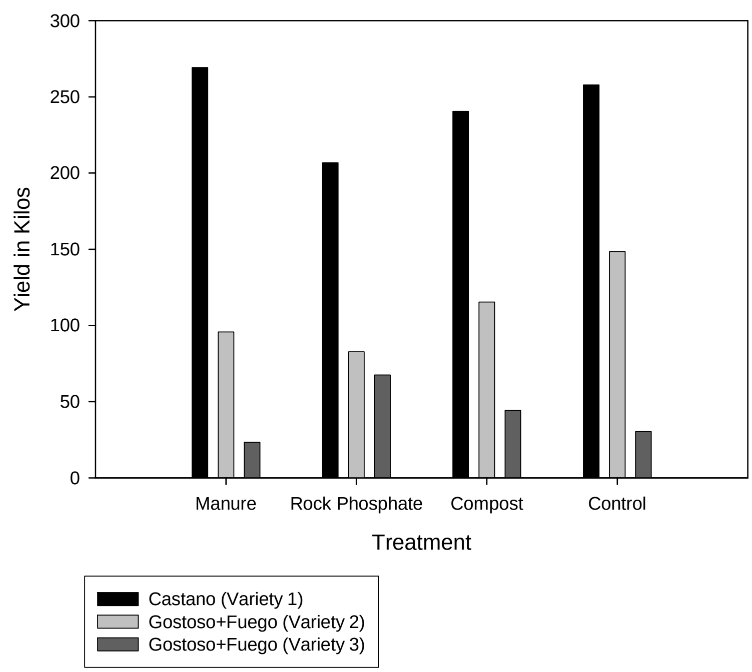

Figure <u>16</u>: ***Total garlic yields by treatment (For each bar, n=1)***

Yield results for garlic are presented in Figure 16. A large difference in yield according to variety is apparent. The Castaño variety outperformed the combination Gostoso-Fuego varieties greatly, and the third block did poorly even though it was the same variety as the middle block. High levels of nitrate-N were found in the samples from the third block. Treatment effects on garlic yields in the second year of the experiment were also shown to be insignificant ($F = 0.46$, $Pr > F = 0.72$). The treatments did not improve yield relative to the control. Thus, there was no apparent increased residual effect on the second crop due to slow dissolution of rock phosphate in the soil.

The effect of manure, rock phosphate and compost on available P levels

Olsen-P data from the plots is shown in Figure 17. There was a general increase in available P in all the plots, including the control, over the course of the experiment. The compost treatments appeared to have increased available P, although one high outlying value creates variability in the average. Data analysis indicated that none of the treatments, including the compost, significantly improved plant-available phosphorus over the control at either sampling date, between the two crops ($F = 0.01$, $Pr > F = 0.99$) or after garlic harvest ($F = 3.09$, $Pr > F = 0.11$). The lack of increased levels of available phosphorus during potato and garlic production corresponds with the lack of increased yields for both crops.

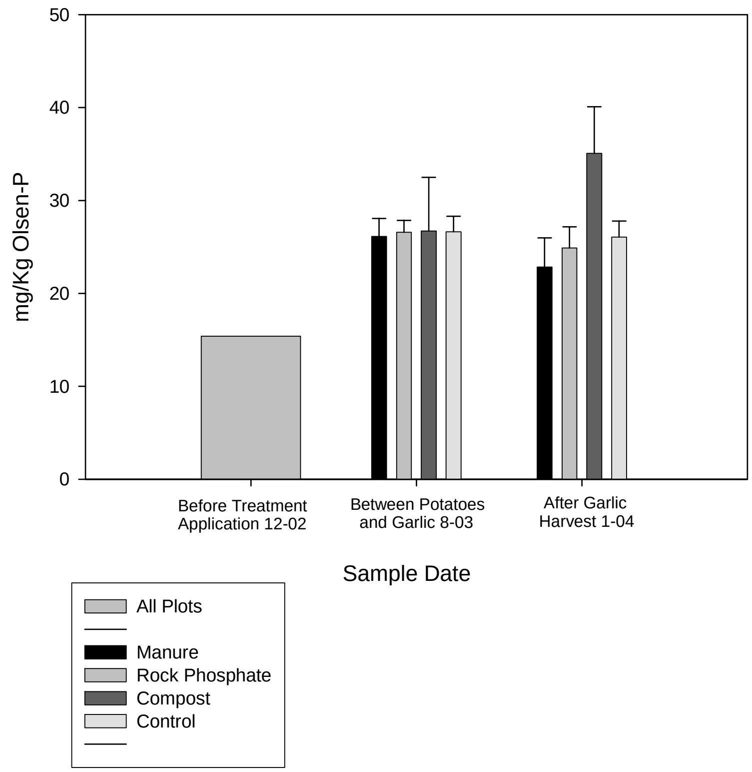

Figure 17: *Soil Olsen-P by treatment at three sampling dates (sampling depth: 0-25cm)*

Discussion

Economic Analysis of Rock Phosphate Use

Chemical fertilizer in the form of NPK 18-40-0 is widely used in the Iscayachi valley for garlic and potatoes. The annual cost of application for 200 kg of the chemical fertilizer, containing 80 kg of P_2O_5, is approximately US$94/ha. The cost of 348 kg of 23% P_2O_5 Capinota rock phosphate, containing 80 kg of P_2O_5, is approximately US$57/ha.

It must be considered that 36 kg of nitrogen is added with the 200 kg of chemical fertilizer. The cost of the manure used alone and in the compost, which presumably added nitrogen, is difficult to calculate. The manure used was obtained from a community member involved in the project. The previous year she received crop residues from the plot for her cattle, and subsequently owed the project whatever manure was produced. Most farmers have livestock that produce farmyard manure for use in their fields, thus it is problematic to put a price this on-farm resource. My own estimate, based on personal experience, puts the price of manure at an application rate of 910 kg/ha at about US$93/Ha. Care must be taken when considering this cost in direct comparisons, as most farmers would be able use their own on-farm manure without incurring additional out of pocket expenses.

The price of 20 kg of Capinota rock phosphate, the amount used to make the compost for this trial, was about US$3. The price of 180 kg of manure, the amount used in the compost, was about US$18. The combined cost of the additives at the rates applied, 910 kg/Ha of manure and 50 kg/Ha P_2O_5 of rock phosphate, brings the compost cost to about $128/Ha. Again, it is likely that farmers would use their own on-farm manure, making this a difficult direct comparison.

Potato yields from intensive systems in Washington state range from 30,000 lbs/acre up to as much as 70,000 lbs/acre (Lang et al., 1999). Farmers in the Iscayachi valley study area consider 15,000-20,000 lbs/acre a good yield range for potatoes. The average yield for the Crone and Revolución varieties from treatment plots in this experiment was within that range (16,500 lbs/acre). The highest yielding plot, amended with rock phosphate alone, was at the top of the range (19,500 lbs/acre). Thus, adequate to very good relative yields were obtained using these amendments.

Garlic yields from intensive systems in California range from 12,600 lbs/acre up to 30,300 lbs/acre (Tyler et al., 1988). Good yields for garlic in the Iscayachi valley study area range from 6300 to 7500 lbs/acre. The average yield for the Castaño variety was 19,800 lbs/acre, and the average yield for the Gostoso-Fuego variety mix was 7850 lbs/acre. Again, the experimental yields were comparatively high.

Evaluation of Results

The rate of application of rock phosphate was based on 50 kg/ha of P_2O_5, which may be slightly low. Although it produced yields on par with local production using soluble P at 80 kg/ha P_2O_5, it may be that a greater application rate was needed to produce a significant treatment response relative to the control. Experiments using Capinota rock phosphate at application rates of 120 kg/ha up to 200 kg/ha P_2O_5 have shown significant treatment responses on soils with similar pH values (Salinas 2002); however the trials took place under about twice as much rainfall. Higher soil moisture levels throughout the year could increase dissolution of rock phosphate over time.

A moderately alkaline soil pH likely inhibited the dissolution reaction for rock phosphate, resulting in a lack of significantly increased levels of soluble P in the rock phosphate-treated plots. The dissolution reaction, given below, is driven to the right in acid conditions. Neutral or slightly basic conditions retain P in relatively insoluble Ca complexes (Khasawneh 1980).

$$Ca_{10}(PO_4)_6F_2 + 12H^+ = 10Ca^{2+} + 6H_2PO_4^{--} + 2F^{—}$$

Although acid conditions in the compost increased soluble P over the course of composting, the levels of soluble P were perhaps not high enough upon application to create a treatment response in the compost-treated plots.

Adequate levels of background phosphorus in the study area soil are likely the main explanation for the lack of treatment response, and may have prevented a treatment response even at higher P_2O_5 application rates. Samples collected before treatment contained Olsen-P concentrations of 15 ppm, and levels as high as 21 ppm were measured in an adjacent field. Significant yield responses to P fertilizer application have been noted in soils with background Olsen-P levels of 12 ppm and below (Harris 1992). The recommended application rate for phosphorus for potato production in Washington State in soils with 12-20 ppm Olsen-P is 30 lb/acre (33 kg/Ha). For soils with Olsen-P concentrations above 20 ppm, no P application is necessary (Lang et al., 1999). Increases in soil-P past sufficient levels for plant growth do not produce further yield responses (Lang et al., 1999).

The lack of treatment response in the garlic crop can also be attributed to sufficient levels of background phosphorus. Garlic does not respond to P addition, even in soils with Olsen-P levels lower than 8 ppm, which would be considered deficient for other vegetable crops (Tyler et al., 1988). Garlic does respond to nitrogen amendments in soils with low nitrate-nitrogen, however the soils in the study area did not have particularly low levels of nitrate-N.

High nitrate levels in block 3 of the field may have resulted in stunted tuberization during potato production. Excess nitrogen in the early stages of potato development can delay tuberization in some potato varieties (Lang et al., 1999). Nitrate-N levels as high as 292 mg/kg were measured in the third block. There is a slight depression in this area of the field, and it is possible that poor drainage in the depression results in an accumulation of salts.

A possible explanation for the increase in Olsen-P and nitrogen in the control plots, which received no amendments, could be the open-water irrigation system used in the valley. The communal system collects water from the surrounding hills, stores it in ponds, and delivers it via open ditches to farmer's fields. It may be that this water is a source of nutrients, as the entire valley is used for sheep and cattle grazing. As the field lay fallow for several years preceding the experiment, it was not irrigated. The onset of production, and subsequent irrigation, may explain the increase in nutrients in the control plots. No samples of irrigation water were collected, however, to test this hypothesis.

Opportunities for Further Study

Analysis of the irrigation water in the Iscayachi valley would be beneficial in understanding its role in the nutrient cycling of this system. Another interesting angle would be to explore the differences between crop varieties to determine which are better able to utilize phosphorus from rock phosphate and why. The history of the Iscayachi area, along with anthropological evidence, may better explain the native fertility of the soils. A comparison of the subsoil of the study area with subsoils from other parts of the valley, where people were less likely to live and produce crops, might reveal variability in phosphorus levels that would indicate human interaction with the soil over time.

Further study is needed to determine the effectiveness of rock phosphate in small farming systems in Bolivia. Important factors to consider include application rates, soil acidity, and soil phosphorus levels. The cost of the material is low, making it an attractive alternative. Composting with farmyard manures to increase dissolution and add nitrogen to the soil may be a viable way to incorporate rock phosphate. Further exploration into appropriate composting materials, timing, and application rates is needed. Another relatively inexpensive, effective alternative may be to apply the rock in combination with fertilizer N sources such as urea. Partial acidulation of the rock phosphate to increase solubility is another possibility. More field trials are needed to determine the best use of this local resource.

Conclusion

Applications of rock phosphate, manure, and compost did not produce significant potato or garlic yield responses over the control. Available P in the soil was not significantly increased by the treatments. Moderately alkaline conditions may have slowed the dissolution of rock phosphate in the compost as well as the soil. The lack of treatment response may be attributed to a combination of low amendment application levels and adequate background levels of phosphorus in the study area soil. However, yields obtained with the intensive organic system were comparable to those obtained by local farmers using synthetic fertilizers. Further study is needed to explore the best use of rock phosphate as an alternative phosphorus source in small farming systems in Bolivia.

Chapter 3

Context of Research

The research was undertaken during the author's two-year service in the United States Peace Corps. The Peace Corps, started in 1961 by President John F. Kennedy, was designed to promote peace and cultural exchange throughout the world. Peace Corps Volunteers currently serve in 69 countries throughout the world. Volunteer experiences vary greatly, but generally volunteers live in rural villages and work at a grassroots level with host country nationals. A small monthly stipend is provided, comparable to the income of the local population. The author's monthly income was US$200. The Masters International Program, a cooperative program through Washington State University and Peace Corps, allowed for the author to complete coursework at the university in 2001 and the research project in Bolivia from 2002-2004.

My Peace Corps Experience

Upon arriving in Bolivia for Peace Corps, I began 11 weeks of training in language, culture, and technical skills. I lived with a family and intensively studied Spanish. I was one of 10 agriculture volunteers in my training group. At the end of training, we were assigned to the villages where we would live and work for the next two years. My background in soils led to a placement in the town of Iscayachi, in the department of Tarija.

Iscayachi is a Quechua word meaning 'two roads'. The town lies at the crossing of the north-south route from the Argentinean border to Potosi and the turnoff to the southern city of Tarija. The volunteer who served in Iscayachi before I arrived, Kim Glick, lived and worked there for three years. She applied for a grant through USAID's

Small Project Assistance program for Peace Corps Volunteers and received US$2000 to start a communal farming project with the Mother's Club. Her idea was to bring high quality garlic seed into the community and start a kind of seed bank, run by the women. Certified garlic seed was purchased in Argentina. The women were given a plot of land by the municipal government, and began growing garlic, as well as potatoes, chamomile, and a broad green bean called *haba*. The production was completely organic.

I replaced Kim in 2002, the second year of the project. The women had decided to divide the first year's harvest between them rather than sell it. The garlic was of seed quality, and each of the 45 women was able to take her share and plant it the next year in her family plot, selling the harvest for family income. We reserved a portion of the best seed to plant again in the communal plot. I proposed my experimental design to the women and they approved my use of their communal land to apply and compare alternative fertilizers. We planted again according to the rotation that Kim had designed.

Available resources were a limiting factor in the experimental design. Three varieties of potato and garlic seed had been purchased for the project. There was not enough of any one variety to plant all the experimental plots, so each variety was planted in one block of the experiment. This was not an ideal replication, due to large differences in yield between the varieties, but it was what we had to work with. Another experimental design I considered, direct comparison with synthetic fertilizers, was ruled out because the goal of the project was to use only organic inputs on the communal plots. Other designs, such as increasing rates of compost and rock phosphate, were ruled out by time and resource restrictions.

Women in the Bolivian *campo* generally help their husbands in the fields and know a great deal about agriculture, although they are not the decision makers in terms of what to grow or how to grow it. They work primarily in their homes, preparing food, rearing children, cleaning, and sometimes running a small store or selling empanadas to supplement the household income. They have a strong and respected role in the family, as well as in the greater community. It was not uncommon for the women in Iscayachi to participate in politics at the local level.

Mother's Clubs exist in most communities and are the primary way for the women to meet and organize. The local government uses the monthly Mother's Clubs meetings to disseminate information about local issues, and non-governmental organizations (NGO's) work with the Mother's Clubs in areas such as health and education. The communal farming project was organized through the Mother's Club, with only those who wanted to participate putting in the work and sharing the harvest. While we had the help of many supportive husbands, the women did the decision-making and most of the labor.

The president was in charge of overseeing the production. We worked together to organize workdays, troubleshoot and plan. Sometimes I would decide on a workday, only to discover it was conflicting with a school dance performance or other community event. Flexibility was vital to the success of the project. Work in the field was so carefully divided that it messed up the system if I weeded a row. It was very important to the women that everyone did her equal share. Other jobs, like cooking, were determined by turn. When we planted or harvested, a small group of women would prepare lunch and bring it to the field so everyone could eat together.

In *campo* communities, tradition dictates certain rituals to ensure a good harvest. Most of these rituals date from pre-Colombian times. The Quechua people, descendants of the Incas, still worship Pachamama, the mother earth figure, as well as different forms of a male mountain god. When crops are planted, it is important to give small offerings to Pachamama and ask for her blessings of fertility. Coca leaves, which are usually chewed by people while working, are planted in the soil and pure grain alcohol is sprinkled over the ground. It is also customary to drink wine, pouring a portion on the ground before drinking as an offering to Pachamama.

Conveying the ideas and design of the experiment and getting everyone on the same page was an interesting experience. I had marked out the plots with stakes and string in order to apply the fertilizer treatments several days before the women came to plant potatoes. The president had asked everyone to come at eight-thirty that morning. Around nine-fifteen we had about half the group. The plow, or *yunta*, a traditional wooden wedge pulled by two yoked bulls, showed up a few minutes later and we started. The rest of the women trickled in, until we had almost everyone. The plow made a long trench down the field, and women standing all along it placed seed potatoes down in the furrow. The plow made another pass close to the first one, covering the seeds, and turned to make another row. Planting the field, about 1000 square meters, took about three hours. When we finished, we poured wine and sprinkled coca on the field, passed the wine around, and went to eat lunch.

It was impossible to have absolute control, and I had to give up the idea of a tightly managed field experiment. It was enough to make sure the right varieties of potatoes and garlic were planted in the right plots, and to convey the idea that I was trying to weigh and measure the yields for comparison. When we were harvesting potatoes, some of the women who were leaving to prepare lunch started to take potatoes from inside one of the treatment plots. I had to ask them to take from a different pile, outside the treatment area. I explained that we couldn't eat the potatoes until I had weighed them, and they had a good laugh at me. I borrowed a scale from my neighbors, who sold meat, and weighed the bags by hanging the scale from a broomstick held by two helpers.

When it was time to harvest the garlic, it rained for a week straight. Then it was postponed for a two-day soccer tournament, then it rained for a few more days. Finally the sun came out. Everyone showed up between eight and nine and we started digging. The field was muddy, but the garlic was beautiful, big, fat, healthy heads. The women laughed and made fun of each other, joked about the mud, about how we were going to have to give the garlic a bath. At the end of the long day, a borrowed truck came to take the harvest to the house where it would be stored and dried, and we all helped load it up. It had to make two trips, and on the return to the field some of the women rode in the empty bed. We were pitching and swerving all over the old road to the field, and the women in the back were screaming and laughing. We unloaded the last of the garlic at 8pm. We carried it in our arms and stacked it in piles in the patio of one of the women's houses. We bumped into each other in the dark and they joked that we looked like ants. As we were sweeping out the empty truck, the first few drops of rain fell.

While this was not a typical field experiment, in the sense that I had only limited control over the variables, it was a true 'field test'. All of the outcomes were unknowns. I had a plot of land, some seed, and a group of people. I wanted to demonstrate the idea of a side-by-side field trial, and give the women a sense of accomplishment by including them as active participants in the research.

In two years of working with this group of women, I learned more than could ever be contained in a classroom. Their sense of community and ways of working together to accomplish goals are remarkable. I watched them develop leadership and organizational skills, I saw them solve problems and work out compromises. While we got a lot of work done, there was a lot of socializing and laughter. I feel immensely privileged to have been able to work with these incredible women, and the experience far outweighs any data I collected.

Bibliography

Adediran JA and Sobulo RA (1998) Agronomic evaluation of phosphorus fertilizers developed from Sokoto rock phosphate in Nigeria. Communications in Soil Science and Plant Analysis 29: 2415-2428.

Akintokun OO, Adetunji MT, and Akintokun PO (2003) Phosphorus availability to soyabean from an indigenous phosphate rock sample in soils from southwest Nigeria. Nutrient Cycling in Agroecosystems 65: 35-41.

Alloush GA and Clark RB (2001) Maize response to phosphate rock and arbuscular mycorrhizal fungi in acidic soil. Communications in Soil Science and Plant Analysis 32: 231-254.

Ankomah AB, Zapata F, Danso SKA and Axmann H (1995) Cowpea varietal differences in uptake of phosphorus from Gafsa phosphate rock in a low-P Ultisol. Fertilizer Research 41: 219-225.

Badiane A, Faye A, Yamoah CF, and Dick RP (2001) Use of compost and mineral fertilizers for millet production by farmers in the semiarid region of Senegal. Biological Agriculture and Horticulture 19: 219-229.

Bangar KC, Shanker S, Kapoor KK, Kukreja K, and Mishra MM (1989) Preparation of nitrogen and phosphorus-enriched paddy straw compost and its effect on yield and nutrient uptake by wheat (Triticum aestivum L.). Biology and Fertility of Soils 8: 339-342.

Bezdicek D and Fauci M (1997) Nutrient aspects of compost. Compost Connection No. 3, Washington State University Cooperative Extension and Center for Sustaining Agriculture and Natural Resources.

Bolan NS, White RE and Hedley MJ (1990) A review of the use of phosphate rocks as fertilizers for direct application in Australia and New Zealand. Australian Journal of Experimental Agriculture 30: 297-313.

Casanova EF (1995) Agronomic evaluation of fertilizers with special reference to natural and modified phosphate rock. Fertilizer Research 41: 211-218.

Casanova E and Solorzano PR (1994) Sorghum and soybean response to natural and modified phosphate rock on acid soils in Venezuela. Communications in Soil Science and Plant Analysis 25: 215-224.

Chien SH and Menon RG (1995) Factors affecting the agronomic effectiveness of phosphate rock for direct application. Fertilizer Research 41: 227-234.

Chien SH, Sale PWG and Hammond LL (1990) Comparison of the effectiveness of phosphorus fertilizer products. In: Proceedings of the Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania: 143-156. International Rice Research Institute, Manila, Philippines.

Dann PR, Derrick JW, Dumaresq DC, and Ryan MH (1996) The response of organic and conventionally grown wheat to superphosphate and reactive phosphate rock. Australian Journal of Experimental Agriculture 36: 71-78.

Engeland, RL (1991) Growing Great Garlic: The definitive guide for organic gardeners and small farmers. Filaree Productions, Okanogan, WA.

Engelstad OP, Jugsujinda A and De Datta SK (1974) Response by flooded rice to phosphate rocks varying in citrate solubility. Soil Science Society of America Proceedings 38: 524-529.

Food and Agriculture Organization of the United Nations (2003) FAO Yearbook: Production 2002. Vol. 56. Rome.

Gaind S and Gaur AC (2003) Quality assessment of compost prepared from fly ash and crop residue. Bioresource Technology 87: 125-127.

Habib L, Chien SH, Carmona G, and Henao J (1999) Rape response to a Syrian phosphate rock and its mixture with triple superphosphate on a limed alkaline soil. Communications in Soil Science and Plant Analysis 30: 449-456.

Hammond LL, Chien SH and Easterwood GW (1986a) Agronomic effectiveness of Bayovar Phosphate Rock in Soil with Induced Phosphorus Retention. Soil Science Society of America Journal 50: 1601-1606.

Hammond LL, Chien SH and Mokwunye AU (1986b) Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. Advances in Agronomy 40: 89-140.

Harris PM ed. (1992) The Potato Crop: The scientific basis for improvement. Chapman and Hall, London.

He ZL, Baligar VC, Martens DC, Ritchey KD and Elrashidi MA (1999a) Effect of byproduct, nitrogen fertilizer, and zeolite on phosphate rock dissolution and extractable phosphorus in acid soil. Plant and Soil 208: 199-207.

He ZL, Baligar VC, Martens DC, Ritchey KD and Elrashidi MA (1999b) Relationship of ryegrass growth to extractable phosphorus in acidic soil amended with phosphate rock, coal combustion by-product, limestone and cellulose. Communications in Soil Science and Plant Analysis 30: 457-470.

He ZL, Baligar VC, Martens DC, Ritchey KD and Kemper WD (1996) Kinetics of phosphate rock dissolution in acidic soil amended with liming materials and cellulose. Soil Science Society of America Journal 60: 1589-1595.

Hong-Qing H, Xue-Yuan L, Jing-Fu L, Feng-Lin X, Jing L, and Fan L (1997) The effect of direct application of phosphate rock on increasing crop yield and improving properties of red soil. Nutrient Cycling in Agroecosystems 46: 235-239.

Kanabo IAK and Gilkes RJ (1987) The role of soil pH in the dissolution of phosphate rock fertilizers. Fertilizer Research 12: 165-174.

Khasawneh, FE ed. (1980) The Role of Phosphorus in Agriculture. American Society of Agronomy-Crop Science Society of America-Soil Science Society of America. Madison, WI.

Kisitu VB (1991) Some aspects of using rock phosphate as direct application fertilizers. Fertilizer Research 30: 191-192.

Kumar V, Gilkes RJ, and Bolland MDA (1992) The residual value of rock phosphate and superphosphate from field sites assessed by glasshouse bioassay using three plant species with different external P requirements. Fertilizer Research 32: 195-207.

Lang, NS, Stevens, RG, Thornton RE, Pan WL, and Victory, S. (1999) Nutrient Management Guide: Central Washington Irrigated Potatoes. Washington State University Cooperative Extension EB 1882.

Lilligren S (2000) Malvern Mastersizer-S Protocol for Particle Size Analysis. Unpublished Washington State University Crop and Soil Science laboratory protocol.

Manna MC and Ganguly TK (1998) Influence of inorganic and in situ phosphocompost on soil microbial biomass activity in Typic Halustert under rice (Oryza sativa)—wheat (Triticum aestivum) system. Indian Journal of Agricultural Sciences 68: 732-733.

Manna MC, Ghosh PK, Ghosh BN, and Singh KN (2001) Comparative effectiveness of phosphate-enriched compost and single superphosphate on yield, uptake of nutrients and soil quality under soybean-wheat rotation. Journal of Agricultural Science 137: 45-54.

Medhi DN, De Datta SK (1997) Phosphorus availability to irrigated lowland rice as affected by sources, application level, and green manure. Nutrient Cycling in Agroecosystems 46: 195-203.

Misra UK, Das N and Pattanayak SK (2002) Fertilizer value of indigenous phosphate rock modified by mixing with pyrite and composting with paddy straw. Journal of the Indian Society of Soil Science 50: 259-264.

Mnkeni PNS, Chien SH and Carmona G (2000) Effectiveness of Panda Hills phosphate rock compacted with triple superphosphate as source of phosphorus for rape, wheat, maize and soybean. Communications in Soil Science and Plant Analysis 31: 3163-3175.

Muchovej RM, Muchovej JJ, and Alvarez VH (1989) Temporal relations of phosphorus fractions in an oxisol amended with rock phosphate and *Thiobacillus thiooxidans*. Soil Science Society of America Journal 53: 1096-1100.

Muleba N and Coulibaly M (1999) Effects of phosphorus fertilizer sources on cowpea and subsequent cereal crop productivity in semi-arid West Africa. Journal of Agricultural Science 132: 45-60.

Mutuo PK, Smithson PC, Buresh RJ, and Okalebo RJ (1999) Comparison of phosphate rock and triple superphosphate on a phosphorus-deficient Kenyan soil. Communications in Soil Science and Plant Analysis 30: 1091-1103.

Owusu-Bennoah E and Acquaye DK (1996) Greenhouse evaluation of agronomic potential of different sources of phosphate fertilizer in a typical concretionary soil of Northern Ghana. Fertilizer Research 44: 101-106.

Programa Ejecutivo de Rehabilitacion de Tierras Tarija PERTT (1998) Reporte Annual de Climatologia del Departamento de Tarija.

Ramirez R, Fernandez SM, and Lizaso JI (2001) Changes of pH and available phosphorus and calcium in rhizosphere of aluminum-tolerant maize germplasm fertilized with phosphate rock. Communications in Soil Science and Plant Analysis 32: 1551-1565.

Roy SK, Sharma RC and Trehan SP (2001) Integrated nutrient management by using farmyard manure and fertilizers in potato-sunflower-paddy rice rotation in the Punjab. Journal of Agricultural Science 137: 271-278.

Saha H and Hajra JN (2001) Preparation of phosphocompost from rice straw and response of groundnut. Journal of the Indian Society of Soil Science 49: 144-149.

Salinas, JG (2002) Uso Potencial de la Roca Fosfórica de Capinota como Fertilizante. Presented at the First National Congress of Agronomy, September 10-13, 2002 Cochabamba, Bolivia.

Sanyal SK and De Datta SK (1991) Chemistry of phosphorus transformations in soil. Advances in Soil Science 16: 37-55.

Scholefield D, Sheldrick RD, Martyn TM and Lavender RH (1999) A comparison of triple superphosphate and Gafsa ground rock phosphate fertilizers as P-sources for grass-clover swards on a poorly-drained acid clay soil. Nutrient cycling in Agroecosystems 53: 147-155.

Singaram P, Rajan SS, and Kothandaraman (1995) Phosphate rock and a phosphate rock/superphosphate mixture as fertilizers for crops grown on a calcareous soil. Communications in Soil Science and Plant Analysis 26: 1571-1593.

Singh CP (1985) Preparation of phospho-compost and its effect on the yield of moong bean and wheat. Biological Agriculture and Horticulture 2: 223-229.

Singh CP and Amberger A (1995) The effect of rock phosphate-enriched compost on the yield and phosphorus nutrition of rye grass. American Journal of Alternative Agriculture 10: 82-87.

Singh CP and Amberger A (1997) Organic acids and phosphorus solubilization in straw composted with rock phosphate. Bioresource Technology 63: 13-16.

Singh S, Mishra MM, Goyal S, and Kapoor KK (1992) Preparation of nitrogen and phosphorus-enriched compost and its effect on wheat (Triticum aestivum). Indian Journal of Agricultural Sciences 62: 810-814.

Smyth TJ and Sanchez PA (1982) Phosphate rock dissolution and availability in Cerrado soils as affected by phosphorus sorption capacity. Soil Science Society of America Journal 46: 339-345.

Soil Survey Division Staff. 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Tyler KB, May DM, Guerard JP, Ririe D and Hatakeda JJ (1988) Diagnosing nutrient needs of garlic. California Agriculture 42: 28-29.

Van den Berghe CH (1996) The effect of Matongo rock phosphate and urea as compared to di-ammonium phosphate in the composting process and the yield of potatoes in the Mugamba region in Burundi. Fertilizer Research 45: 51-59.

Vanlauwe B, Diels J, Sanginga N, Carsky RJ, Deckers J and Merckx R (2000a) Utilization of rock phosphate by crops on a representative toposequence in the Northern Guinea savanna zone of Nigeria: response by maize to previous herbaceous legume cropping and rock phosphate treatments. Soil Biology and Biochemistry 32: 2079-2090.

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

Verma LN and Rawat AK (1999) Low grade rockphosphate: a complimentary phosphorus source in soybean (Glycine max)-wheat (Triticum aestivum) cropping system. Indian Journal of Agricultural Sciences 69: 297-299.

Wilson MA and Ellis BG (1984) Influence of calcium solution activity and surface area on the solubility of selected rock phosphates. Soil Science 138: 354-359.

APPENDIX A
Soil Profile Description and Particle Size Data

<u>Site Description</u>: Sample area is in an alluvial plain with low relief. Drainage is moderate, all horizons below the A are moist during the rainy season. This site is in the depositional toe of an alluvial fan complex where it meets the valley axis and is subject to infrequent deposition of new alluvial materials. The elevation is approximately 3,500 meters. Mean annual precipitation is 352mm and mean annual temperature is 50° F. The location is 21° 38' South, 64°59' West, Mendez Province, Department of Tarija, Bolivia.

Taxonomic Class: Vertic Haplustoll.

Ap—0-10cm; grayish brown (10YR 5/2) silt loam, very dark grayish brown (10YR 3/2); moist; weak fine subangular blocky structure parting to strong very fine to fine granular; extremely hard, slightly sticky, non-plastic; few fine roots throughout; common very fine tubular pores throughout; clear wavy boundary.

A1—10-34cm; gray (10YR 5/1) silt loam, very dark gray (10YR 3/1); moist; moderate fine to medium subangular blocky structure parting to strong very fine to fine granular; slightly hard, moderately sticky, moderately plastic; few very fine roots throughout; very few very fine tubular pores throughout; clear wavy boundary.

A2—34-60cm; gray (10YR 5/1) silt loam, very dark gray (10YR 3/1); moist; moderate fine to medium subangular blocky; slightly hard, moderately sticky, moderately plastic; few very fine roots throughout; very few very fine tubular pores throughout; common, fine, prominent, soft, moist, spherical reddish brown (5YR 4/4) iron masses in the matrix with clear boundaries; clear wavy boundary.

Bw—60-66cm; grayish brown (10YR 5/2) silt loam, dark grayish brown (10YR 4/2); moist; moderate very fine to medium subangular blocky; slightly hard, moderately sticky, moderately plastic; few very fine roots throughout; very few very fine tubular pores throughout; common, fine, prominent, soft, moist spherical reddish brown (5YR 4/4) iron masses in the matrix with clear boundaries; abrupt smooth boundary.

Ab—66-71cm; dark gray (10YR 4/1) silt loam, very dark gray (10YR 3/1); moist; moderate very fine to medium subangular blocky structure with pockets of strong fine to medium granular; slightly hard, very sticky, moderately plastic; few very fine roots throughout; very few very fine tubular pores throughout; common, fine, prominent, soft, moist spherical reddish brown (5YR 4/4) iron masses in the matrix with clear boundaries; common, fine, distinct, soft, moist, spherical black (10YR 2/1) manganese concretions in the matrix with clear boundaries; common, medium, faint, grayish brown (10YR 5/2) moist irregular mottles; abrupt smooth boundary.

Ab'—71-80cm; very dark gray (10YR 3/1) silt loam, black (10YR 2/1); moist; strong fine to coarse subangular blocky structure with pockets of strong fine to medium granular; moderately hard, very sticky, very plastic; few very fine roots throughout; very few very fine tubular pores throughout; common, fine, prominent, soft, moist spherical reddish brown (5YR 4/4) iron masses in the matrix with clear boundaries; common, fine, distinct, soft, moist, spherical black (10YR 2/1) manganese concretions in the matrix with clear boundaries; common, medium, faint, grayish brown (10YR 5/2) moist irregular mottles.

Table 5: ***Profile Particle Size and Chemical Data***

Horizon	**Depth**	**% Clay**	**% Silt**	**% Sand**	**Texture Class**	**pH**	**EC (dS/m)**	**% OM**	**Total $N0_3^-$, NH_4^- (ppm)**	**Olsen-P (ppm)**
Ap	0-10cm	14.47	61.58	23.95	Silt Loam	8.47	4.47	4.94	49.53	24.45
A1	10-34cm	21.74	70.9	7.36	Silt Loam	8.13	1.91	2.82	9.06	19.28
A2	34-60cm	24.47	67.1	8.43	Silt Loam	7.81	1.01	3.68	8.45	18.63
Bw	60-66cm	20.03	73.49	6.48	Silt Loam	7.2	0.86	1.68	5.47	14.1
Ab	66-71cm	22.97	65.89	11.14	Silt Loam	6.93	0.77	4.41	8.16	22.77
Ab’	71-80cm	25.62	66.12	8.26	Silt Loam	6.84	0.62	4.8	8.07	10.16

APPENDIX B
Iscayachi Climate Data

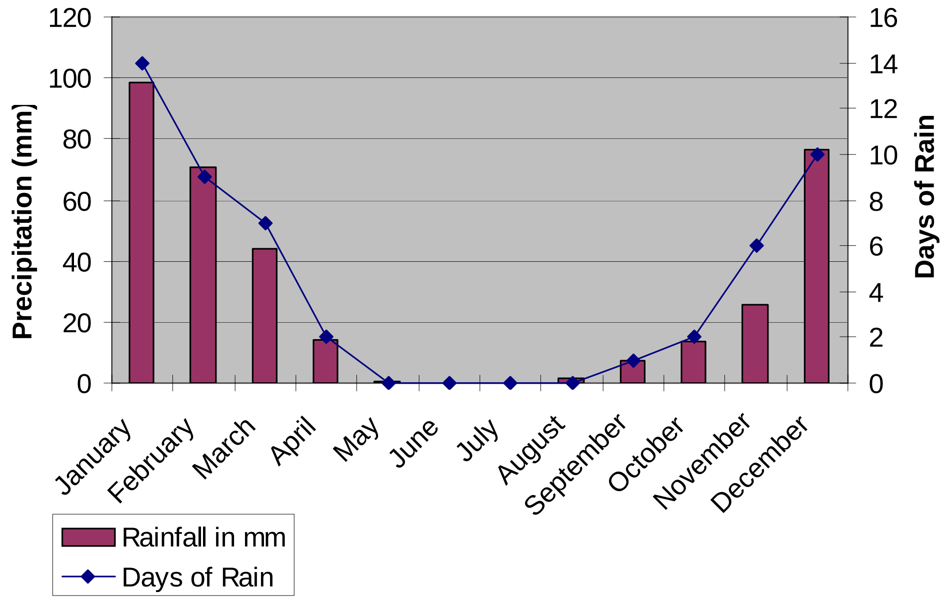

Figure 18: ***Average Precipitation by Month, Iscayachi Valley***

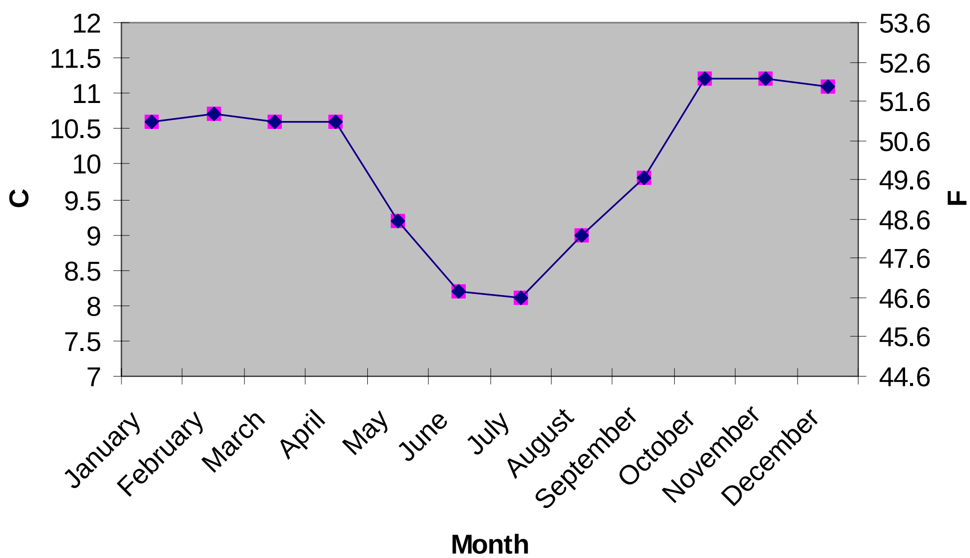

Figure 19: ***Average Air Temperatures by Month, Iscayachi Valley***