Soil Fertility in an Acidic Andisol: An Analysis of Acidity Management Practices in Vara Blanca, Costa Rica

Dane Brizzolara

Point Loma Nazarene University

Abstract

In Costa Rica's Vara Blanca district farmers are faced with the challenge of cultivating soil on the slopes of the Poás Volcano. Emissions of sulfur dioxide from the crater of Poás cause levels of rainwater acidity high enough to lower the pH of surrounding soils to an extent that compromises the fertility of the soil, resulting in stunted crop growth. The traditional method used in the region to ameliorate soil acidity and prevent stunted crop growth is the application of agricultural lime. Residents of Vara Blanca have observed that many farmers using this method, while successful in maintaining soil fertility in early years of cultivation, have experienced declining soil fertility and even crop failure after cultivating the soil for more than 5 to 10 years. Amidst this trend, however, one farmer has emerged as a positive deviant. The farm managed by this farmer relies entirely on organic material-rich soil amendments including compost, vermicompost, and manure to ameliorate soil acidity. A visit to this farm, in which highly fertile soil and a variety of vigorous crops were observed, in addition to an analysis of studies which show the value of organic material as a soil acidity ameliorant, led to the prediction that farmers supplementing lime applications with significant quantities of organic material will observe superior trends in soil fertility and yields than farmers solely using lime. To test this prediction, and to gain a better understanding of the acidity management decisions made by farmers in the region, interviews were conducted with 18 farmers in the region. The prediction, however, was not testable because almost all respondents reported applying significant quantities of amendments rich in organic material in addition to lime. Despite this, the survey responses did confirm an association between consistent applications of lime and declining long-term soil fertility and crop health. Therefore, this study explores possible explanations for this correlation

and assesses the viability of normalizing soil pH in Vara Blanca entirely through the use of organic material-rich amendments.

Soil Fertility in a Highly Acidic Andisol: An Analysis of Acidity Management Practices in Vara Blanca, Costa Rica

The agricultural potential of the soils on the slopes of volcanoes such as Poás, Barba, Irazú, and Turrialba has led to much of the development of cities in and around Costa Rica's Central Valley region. The characteristics of soils in this region, however, are far from consistent throughout. The highly variable elevation profile correlates with a wide range of average temperatures, levels of humidity, and levels of microbial activity in the soil. Equally important are the differences in soil characteristics caused by proximity to the aforementioned volcanoes (Hernández, 2001). Differences in the parent materials of these soils and the frequency and intensity of periodic ash depositions from past eruptions causes unique mineralogical profiles. Furthermore, constant fumarolic activity from some of these volcanoes can have significant effects on soils on their slopes. This is certainly the case for soils on the slopes of the Poás Volcano. Near constant emissions of sulfur dioxide from the volcano result in the deposition of highly acidic rainwater to the surrounding soils, with rainwater pH being measured as low as 2.4 near the crater (Martinez et al., 2000, as cited in Herre et al., 2007). For farmers in Vara Blanca, a small district about 7.5 kilometers East of the Poás crater, this leads to the challenge of cultivating highly acidic soils.

The most common practice used to neutralize the harmful effects of these highly acidic soils is the application of agricultural lime. This is a common practice in acidic soils across the globe, yet, in Vara Blanca, community members have expressed concern surrounding the tendency of farmers, most of whom use heavy application of lime, to experience significant decreases in soil fertility after five to ten years of cultivation. Interestingly, there is some evidence which points to organic material inputs as an alternative to lime as a method of soil acidity neutralization in the acid soils of Vara Blanca. This evidence came from a visit to one farmer in the region who was observed to be maintaining fertile soil and producing high yields without the use of lime. Instead, this farmer uses a mix of various organic material amendments such as compost and vermicompost to maintain satisfactory pH conditions.

Questions still remain, however, regarding the potential of widespread adoption of this alternative strategy across the region and its long-term sustainability for farmers. Additionally, there is need for research surrounding potential explanations for the crop failure that some of the lime-reliant farmers in the region are experiencing. Thus, this paper analyzes these questions through a review of relevant literature and through a survey used to collect information from farmers in Vara Blanca.

The survey was specifically designed with the aim of better understanding land use history, organic material soil amendments, liming practices, fertilizer and pesticide use, and changes in soil fertility and crop response among these farms. All of these factors were included in the survey to attempt to address any confounding variables that may have important influences on any connections between the practices used by farmers and the varying success of lime and alternative acidity-neutralization strategies in the region. It was predicted that the survey will reveal a negative trend in soil fertility and crop yield among farmers using large applications of lime with little to no supplemented organic material.

Literature Review

Soil on the Slopes of the Poás Volcano

Soils existing in areas surrounding volcanoes in Costa Rica’s central valley such as Poás are classified as andisols (Herre et al., 2007; Hernández, 2001). Andisols, one of the 12 soil orders designated by the USDA system of soil taxonomy, occupy only 1.2% of tropical regions globally. Tropical andisols, being geologically young soils derived from volcanic parent materials, are usually considered to be very fertile (Sanchez, 2019).

The andisols on the slopes of Poás have a very inconsistent profile. A review of the area by Macey (1975) describes each layer as "vary[ing] in depth and show[ing] no regular profile" (p. 240). Past eruptions have led to the creation of a number of distinct layers of soil. The variable development of each layer is "hindered by periodic ash coverings, lack of vegetation cover, and low temperatures which reduce microbial activity" (p. 240). The soil surrounding the volcano, in areas such as Vara Blanca, is also very susceptible to erosion. The soil tends to have a high total porosity, which leads to the creation of stable microaggregates and high filtration rates. This characteristic of the soil makes it especially susceptible to erosion during periods of intense rain (Hernández, 2001). Furthermore, around 1945, much of the forest in areas surrounding the volcano was cleared of trees in order to provide pasture for dairy cattle (Macey, 1975). This has also increased vulnerability to soil erosion throughout the region.

The volcanic parent material of the soil on the slopes of Poás is considered to be potentially deficient in magnesium, an issue less associated with soils derived from other volcanoes in the central valley (Mata & Alvarado-Hernandez, 2016). Additionally, phosphorus deficiencies are a concern in Costa Rican andisols in the central valley due to the high propensity of these soils to retain both in situ phosphorus and phosphorus added through fertilizers (Hernández, 2001).

Another unique attribute of soils surrounding Poás is the soil acidification caused by the release of sulfur dioxide from the crater, resulting in highly acidic rain. "Since 1955 the Poás Volcano has shown fumarolic activity of varying magnitude, emitting SO_2, HCl and HF, with SO_2 being the dominant acid-generating component of the gas plume" (Rowe et al., 1992, as cited in Herre et al., p. 433). As described in a study conducted by Delmelle, Delfosse, and Delvaux (2003), the Masaya Volcano in Nicaragua, which is also emitting significant quantities of sulfur dioxide, has led to "continuous acid inputs" which have "decreased the pH of both the vitric and eutric andisols" downwind of the volcano (p. 455). This finding is important to consider because it was noted in both the vitric and eutric andisols surrounding the volcano. Vitric andisols, which are the type of andisols surrounding Poás, differ from eutric andisols in that they are not known to contain allophane minerals (Herre et al., 2007). Due to the tendency of sulfates to complex with allophane minerals, the "capacity of the eutric andisols to buffer elevated sulfur inputs is expected to be higher than that of the vitric andisols" (Delmelle et al., 2003, p. 455). Thus, Poás andisols can be considered to be at more risk of the acidifying effects of SO_2 deposition than other regions because of their non-allophanic nature.

Aluminum Toxicity

One issue that can arise from high levels of soil acidity in andisols is aluminum toxicity. Levels of aluminum toxic to crops may occur in soils with high enough levels of acidifying cations in the soil solution. Aluminum cations (Al^{3+}) and hydrogen cations (H^{+}) are the primary acidifying cations present in soil solutions. Sanchez (2019) describes the quantity of these cations as being the level of exchangeable acidity in the soil. Sanchez also explains that most processes causing soil acidification result in the formation of hydrogen cations, but that most of these hydrogen cations quickly react with aluminum compounds in the soil to create exchangeable aluminum (Al^{3+}). Generally, the precipitation of Al^{3+} occurs only at pH values below 5.5. Thus, "little or no exchangeable Al^{3+} is found at higher soil pH values" (p. 213).

Different crops have varying levels of resilience to exchangeable aluminum in the soil, but a general rule is that an aluminum saturation of over 60% will be harmful to crops (Sanchez, 2019). Aluminum saturation refers to the percentage of the cation exchange capacity that is comprised of Al^{3+}, as opposed to other cations such as Ca^{2+}, Mg^{2+}, and K^{+}. This is particularly relevant for soils in Vara Blanca because “the exchangeable cation composition in Poás soils is dominated by aluminum” (Herre et al., 2007). The primary effects of toxic levels of aluminum for crops is “direct injury to the root system.” Root growth is stunted, and roots may appear stubby with dead spots (Sanchez, 2019, p. 216). Additionally, “aluminum tends to accumulate in the roots and impede the uptake and translocation of calcium and phosphorus to the plants tops” (Foy, 1974, as seen in Sanchez, 2019, p. 216).

The use of nitrogen fertilizers can be a potential concern in soils already vulnerable to aluminum toxicity. Ammonium (NH_4^{+}), for example, a commonly used source of nitrogen in fertilizers, produces acidifying hydrogen cations once it creates nitrates (NO_3^{-}) through nitrification. “Two hydrogen ions are produced for every ammonium ion converted to nitrate” (Harter, 2007, p. 2). These hydrogen cations can then react with various aluminum compounds in the soil to create exchangeable aluminum cations, which can contribute to aluminum toxicity. These aluminum cations will also “compete with the Ca^{2+} and Mg^{2+} for binding sites resulting in greater leaching of these ions from the soil” (Price & Berkelaar, 2001, p. 2). It also needs to be considered that the use of organic materials to provide nitrogen can cause the same nitrification process and can result in increased acidification (Hernández, 2001). Therefore, the use of nitrogen fertilizers in areas with potentially high levels of Al^{3+} in the soil, such as the slopes of Poás, should be managed carefully in efforts to avoid risking both aluminum toxicity and leaching of important nutrients.

A final variable that needs to be considered in the conversation surrounding aluminum toxicity is the types of crops that are grown in the potentially at-risk soils. A review conducted by Sanchez and Salinas (1982) describes numerous crops that are known to be resilient against highly acidic soils and potentially toxic levels of soil aluminum, such as cassava, plantains, soybeans, and coffee. It should be considered, however, that some crops which show aluminum tolerance may have high requirements for nutrients such as calcium, magnesium, or phosphorus, which are nutrients known to be lacking in certain aluminum-dominated acid soils. Additionally, many crops have a variety of different cultivars with varying levels of aluminum tolerance. Thus, there are many variables to consider when selecting crops to grow in soil with potentially toxic levels of aluminum.

Aluminum toxicity in andisols. Non-allophanic andisols, andisols with a mineralogical profile largely devoid of allophane, such as the soils surrounding Poás, “often show an aluminum toxicity to aluminum-sensitive plant roots” whereas “typical allophanic andisols rarely show any aluminum toxicity to plant roots” (Dahlgren et al., 2004; Nanzyo et al., 1993, as seen in Yamada et al., 2011, p. 491). The reason for this toxicity has to do with the weathering process of the volcanic ash from which the soil is born. Nanzyo’s (2002) review of volcanic ash soils stated the following:

> The unique chemical properties of andisols are basically due to their aluminum-rich elemental composition, the highly reactive nature of their colloidal fractions and their high surface area. The aluminum-rich elemental composition of these soils is obtained after leaching of Si, Na, Ca and so on during andisol formation (p. 99).

This demonstrates how the aluminum-rich composition of many andisols, in addition to being caused by aluminum rich parent materials, is caused by highly reactive minerals that tend to have a preference towards binding with aluminum cations while other cations are leached out (Nanzyo, 2002). Therefore, despite a typically high humus content and weathering reactions that lead to a highly reactive mineralogical profile, both of which contribute to a large cation exchange capacity (CEC), the majority of the exchange sites in the soil may be occupied by hydrogen and aluminum cations (Nadkarni & Wheelwright, 2000). This phenomenon can lead soils to become deficient in important nutrients as a result of getting displaced by Al^{3+} and H^{+} at exchange sites and leached out of the soil, in addition to potentially bringing the aluminum saturation to levels toxic to plants.

When considering the potential of aluminum toxicity in andisols on the slopes of Poás specifically, the deposition of sulfur dioxide and the resulting acidic inputs into these soils is another important variable to consider. Interestingly, in the study conducted by Herre et al. (2007), areas with greater sulfur dioxide inputs from Poás were observed to have less aluminum complexation capacity than areas with less sulfur dioxide inputs from Poás. “A smaller complexation capacity at sites with larger H^{+} deposition may be due to smaller humus content and differences in organic material quality” (p. 438). This is logical because the complexation of aluminum by organic acids is an important process by which potentially toxic aluminum is rendered unavailable to crops. As a result, soils less rich in quality organic matter naturally form less compounds between organic acids and aluminum, resulting in less aluminum complexed with organic material. Thus, the study conducted by Herre et al. (2007) suggests that consistent deposition of volcanogenic sulfur dioxide in soils surrounding Poás is more likely to lead to aluminum toxicity in areas where soil is lacking in soil organic matter (SOM).

Liming

Most commonly agricultural lime refers to calcium carbonate ($CaCO_3$), referred to as calcitic lime, or a combination of magnesium carbonate ($Mg(CO_3)_2$) and calcium carbonate, which is referred to as dolomitic lime. Using these compounds as soil amendments is “the most widely used long-term method of soil acidity amelioration, and its success is well documented" (Conyers et al., 1991; Haynes, 1982; Kaitibie et al., 2002; Scott et al., 2001; as seen in Fageria & Baligar, 2008, p. 353). The neutralization of exchangeable aluminum cations and the provision of calcium and magnesium are the primary benefits of using lime in acid soils (Sanchez, 2019).

Liming decreases plant-available aluminum through the following process: $CaCO_3$ or $Mg(CO_3)_2$ disassociates in the soil once in contact with water, releasing Ca^{2+} or Mg^{2+} as nutrients that increase the base saturation of calcium and magnesium in the soil. Hydroxide anions (OH^-) are also released by this disassociation. Hydroxide may complex with either Al^{3+} or H^+, two acidifying cations. Water molecules are formed when OH^- is complexed with H^+. Additionally, Aluminum hydroxide, a form of Aluminum that is not toxic to plants, is formed when $3OH^-$ is complexed with Al^{3+}. Thus, exchangeable aluminum can be rendered unavailable to plants through this process (Harter, 2007). Furthermore, by decreasing the amount of exchangeable aluminum in the soil, liming also has the potential to decrease the amount of phosphorus in the soil that is locked up by exchangeable aluminum cations, thus allowing plants to access more phosphorus (Fageria & Baligar, 2008).

When applying lime to soil, it is very important to consider the quantity of lime being applied. This is because under-liming can fail to sufficiently neutralize aluminum toxicity and over-liming can introduce a myriad of various soil toxicities and deficiencies. Harter (2007) describes potential problems associated with liming soil to a pH of above 6.0 in the tropics:

> Continued increase in pH, however, can cause molybdenum to become toxic. In addition, plants can become deficient in nutrients such as copper, zinc, boron, and manganese. This is both a result of these nutrients being less soluble at higher pH levels and decreased acid weathering of the few nutrient containing minerals still in the soil (p. 9).

These detrimental effects of over-liming demonstrate the need for controlled and measured applications of lime. Although liming to pH levels of 5.0 to 5.5 in the tropics is a common general recommendation, measurements of a soil's aluminum saturation can be used to more accurately calculate the proper amount of lime needed to prevent aluminum toxicity without over-liming. This process will be discussed further in the following section.

Calculating lime requirements in andisols. In many tropical soils that are vulnerable to aluminum toxicity at low enough levels of soil pH, soil testing needs to be done to calculate the amount of lime required to raise the pH to a level that will neutralize the toxicity. The most common method for making this calculation in the tropics is through identifying the amount of exchangeable aluminum in the soil (Espinosa, 1996). This is a test that needs to be done in a soil laboratory, as opposed to on-site. As described by Sanchez (2019), the calculation is done by multiplying the centimoles of charge per kilogram of exchangeable aluminum by a factor between 1.5 and 3. The factor is chosen based on the level of soil organic matter (SOM) in the soil and the aluminum tolerance of the crops being grown. The figure created by this calculation will provide the adequate amount of lime to be applied in tons per hectare.

Andisols, however, present a unique challenge for those attempting to calculate the correct amount of lime to apply. The mineralogical profile of many andisols gives soil a very high buffering capacity, which is the extent to which a soil resists or "buffers against" changes in soil pH. A high buffering capacity can cause farmers applying lime to see minimal changes in pH despite significant applications of lime (H. Osorno & L. Osorno, 2010). The buffering capacity of andisols tends to be high because the clay particles that result from the weathering of the volcanic ash have highly reactive surfaces. "When lime is applied to these soils it reacts with the clay surfaces, creating charge while failing to increase pH or to precipitate Al" (Espinosa, 1996, p. 31). Espinosa and Molina (2015) elaborate further on this phenomenon. They explain that the hydroxides created by the hydrolysis of lime react with the surface of the clay particles in a reaction that creates a negative charge on the clay surface, thereby increasing the cation exchange capacity (CEC) without actually changing the pH of the soil. Thus, in some andisols liming may not be able to raise the pH enough to be able to neutralize aluminum toxicity unless it is applied in very large quantities, quantities that may be uneconomical for farmers (H. Osorno & L. Osorno, 2010).

In addition to having high buffering capacities, it is the variable nature of these buffering capacities across regions that makes liming calculations difficult for andisols. Espinosa and Molina (2015), H. Osorno and L. Osorno (2010), and Espinosa (1996) all point to the inconsistent weathering and age of volcanic ash as the principle cause of varying buffering capacities across regions with andisols. Interestingly, for this reason, Espinosa (1996) references "simple field trials" as being the only way to "indicate precisely the amount of lime needed at a specific site" (31). This is certainly applicable to farmers in Vara Blanca, seeing as differences in altitude, humidity, and proximity to Poás can cause variable age and weathering of the volcanic ash in the soil. Therefore, farmers in Vara Blanca may be risking over-liming or under-liming their soil unless they conduct field trials with the specific crops they plan to grow, which is a time and resource-consuming endeavor.

Liming to release phosphorus. Some soils have high phosphorus sorption capacities, meaning much of the phosphorus in the soil is retained in the soil and is unavailable to crops. This is often the case for andisols, which have clay particles with surfaces that have a high affinity for phosphorus (Espinosa & Molina, 2015). In fact, Mata & Alvarado-Hernandez (2016) explain that crops grown in andisols generally need to receive large fertilizer applications of soluble phosphorus. Interestingly, it is often recommended that andisols with high levels of exchangeable Al^{3+} are to be given lime applications not only to reduce aluminum toxicity, but also to decrease phosphorus sorption in the soil, thereby decreasing the need for phosphorus fertilizer. Liming can lead to decreased phosphorus sorption because the resulting decrease in exchangeable aluminum will allow for less phosphorus to be rendered unavailable to crops through complexation with Al^{3+} cations (Sanchez, 2019).

There is considerable controversy, however, surrounding the ability of lime to actually make more phosphorus available to crops (Amarasiri & Olsen, 1973; Pearson, 1975; as seen in Sanchez & Salinas, 1982). This controversy exists because the aluminum hydroxides that are precipitated by the liming process can also complex with phosphorus in the soil (Sanchez & Salinas, 1982; Espinosa & Molina, 2015). There is evidence that suggests that this may lead to unchanged levels of phosphorus sorption. For example, Pearson (1975) references a study by Fassbender (1969) which found levels of available soil phosphorus to be unchanged after liming an andisol in Costa Rica.

The possibility of lime being ineffective in reducing phosphorus sorption, as well as the high affinity that clay particles in andisols tend to have for phosphorus, presents a concern for farmers in Vara Blanca and other areas of Costa Rica’s central valley. Even though phosphorus is likely present in sufficient quantity in these geologically young soils, much of it may be locked up in the soil. This may lead to phosphorus deficiencies in crops unless phosphorus fertilizers are applied in sufficient quantities. It is also important to consider that phosphorus requirements vary based on the crop being grown, as do the symptoms of a phosphorus deficiency, although general stunting of the crop during early growth is a symptom in most crops (Silva & Uchida, 2000).

Effects of liming on microbial activity and soil organic carbon (SOC). Fageria and Baligar (2008) explain that liming is known to increase microbial biomass and activity in acid soils. Seeing as most soil bacteria, including nitrogen-fixing rhizobium, are neutrophiles (bacteria adapted to neutral soil conditions), it is logical that "acidic pH ranges are detrimental to bacterial activities" (p. 357). Nanzyo (2002), in a review of volcanic ash soils, also refers to this idea, stating that "microbial activity is not very high in unameliorated andisols due to…acidic to weakly acidic pH" (108). Thus, liming in acidic andisols, if successful in raising soil pH to near-neutral levels, can be assumed to have a positive effect on nutrient mineralization by soil bacteria, making more nutrients, particularly N, available to crops.

This increased nutrient mineralization caused by increased microbial activity, however, can impact soil organic carbon (SOC) levels in the long term. This is important to consider because the percent of SOC in the soil is an important determinant of soil fertility and soil structure (Aye et al., 2016). Interestingly, some studies have shown liming to have a neutral or positive effect on SOC content, while others have shown a decrease in SOC content (Paradelo et al, 2015). When liming is shown to decrease SOC content, it is "mainly attributed to enhanced carbon mineralization following increased carbon solubility, microbial activity, or both" (Ahmad et al., 2013; as seen in Wang et al. 2015, p. 301).

Furthermore, most studies that have shown decreased SOC after liming link this result to insufficient carbon inputs into the system, which fail to balance out the losses of soil carbon from increased mineralization (Paradelo et al, 2015). In their study of the long-term effects of liming a sodosol in Australia, Aye, Tang, & Sale (2016) observed decreased SOC content in a limed soil after 34 thirty-four years of low organic matter inputs. Similarly, a study of an acidic tenosol in Australia done by Wang et al (2015) found unlimed plots to have higher SOC content than the limed plots after five years. It was concluded that "the additional carbon inputs…were too low to counter the carbon losses from enhanced decomposition [in the limed plots]" (p. 303). These two studies show that crop residue retention, significant organic material inputs, reduced tillage, and other strategies aimed at enhancing soil carbon may be necessary to maintain or increase levels of SOC in limed soils.

Although research is lacking surrounding the effects on liming on SOC in non-allophanic andisols such as those in Vara Blanca, the available literature still suggests that there is reason to suspect that farmers in Vara Blanca may be experiencing losses in SOC. This is more likely to be the case if farmers are applying enough lime to create significant increases in soil pH while amending their soil with little to no organic material. The initial years of success cultivating crops after liming could, in part, be caused by "short-term stimulating effects on soil biological activity" and the resulting increased organic matter mineralization (Paradelo et al, 2015, p. 99). Furthermore, the rapid decrease in soil fertility that farmers in Vara Blanca experience after five to ten years could be, at least in part, due to resulting long-term decreases in SOC stocks. This phenomenon could also play a part in contributing to aluminum toxicity, which becomes more of a concern with decreasing organic material content in andisols (Herre et al., 2007).

Effects of liming on mycorrhizal fungi. Arbuscular mycorrhizal fungi (AMF) are the predominant category of soil fungi that engage in symbiotic relationships with plant roots. They are critical in agricultural systems for their ability to access nutrients beyond what plant roots can access as well as their ability to suppress bacterial diseases and certain nematodes. Seeing as environmental conditions can have a significant effect on their growth and viability, their response to liming is important to consider (Tahat & Sijam, 2012).

There is research suggesting that liming soil can compromise the ability of AMF to form symbioses with plant roots and ultimately support healthy plant growth (Siqueira et al., 1984). Weyman-Kaczmarkowa & Pedziwilk (2000) conducted two studies that showed a decrease in fungal biomass after lime application. In their discussion of the results they noted that “in agricultural practice, soil liming may presumably bring about even stronger inhibition of fungal growth than that which we found in our studies” (p. 110). Similarly, Siqueira et al. (1990) conducted a study on a Brazilian inceptisol that demonstrated that AMF isolated from acidic soil “sporulated more abundantly and showed a higher symbiotic effectiveness…when no lime was applied” (p. 70). This study in particular demonstrates how native acid-adapted fungi can be highly vulnerable to lime-induced increases in pH.

In acidic tropical andisols the presence of AMF may be particular important due to their ability to alleviate aluminum toxicity and increase access to soil phosphorus. Clark et al. (1999) explain that “AMF alleviation of toxicity symptoms and/or reduced acquisition of toxic elements has been reported for Al.” This alleviation of toxicity is likely due to the secretion of organic acids which result from the AMF-root symbiosis (p. 174). Additionally, AMF can “increase nutrient uptake from the soil solution and can counteract, at least partially, the adverse effects of acidity on plant growth” (Siqueira et al., 1990, p. 70). Much of this beneficial effect is attributed to the ability of AMF to increase uptake of phosphorus by the host plant (Casierra-Posada & Aguilar-Avendaño, 2007; Clark et al., 1999).

The importance of AMF in acidic tropical soils and their potential vulnerability to liming has important implications for farmers in Vara Blanca. Their large applications of lime may be limiting the ability of native acid-adapted mycorrhizae to suppress aluminum toxicity and increase phosphorus availability. It is also interesting to consider that the farmer in Vara Blanca who has relied on various composting and vermiculture strategies to enhance soil fertility was observed to be adding leaf litter and forest floor cover from the rain forest to a compost system. This was done with the intention of inoculating the soil with native mycorrhizal fungi. The success found using this strategy, as opposed to relying on lime, serves as anecdotal evidence implicating the importance of preserving and enhancing AMF growth in acidic andisols such as those in Vara Blanca.

Organic Material Inputs as Lime Alternatives

While prior sections explore literature that points to potential reasons for crop failure among farmers in and around Vara Blanca, it is also imperative to explore literature supporting possible explanations for organic material-intensive strategies as alternatives to lime heavy approaches. The farmer in Vara Blanca who was observed to be practicing organic material-intensive methods is an outlier in the region. This farmer was observed using an extensive compost system and a vermiculture system, as well as bokashi, an anaerobic compost system, as means of enriching his soil with nutrients. The majority of the organic material inputs for these systems are sourced on-site and lime is not applied. Evidence for this farmer's success in farming highly acidic soils without reliance on lime may provide reason for more farmers in the region to begin practicing organic material-intensive strategies.

A study completed by Bougnom et al. (2009) observed the effects of compost applications on a variety of soil fertility indicators in a humid region of Cameroon. The soils studied were oxisols and ultisols. Communal biowaste and tree-bush cuttings were used to create the compost used in the study and results were compared against the same compost amended with wood ash and an untreated control. Results showed both compost types to be effective in decreasing exchangeable aluminum, increasing available phosphorus, and increasing the concentration of other important elements such as Ca, Mg, K, Na, Cu, and Zn. The study did not compare the results against plots amended with lime, but concluded that compost, particularly when amended with wood ash, "could alleviate problems of soil infertility…where lime is often not affordable for resource-poor farmers." (406). The reason for the effectiveness of compost and organic residues in decreasing exchangeable aluminum, among other benefits, is described in a review of the topic conducted by Haynes & Mokolobate (2000):

> The complexation of Al by soluble organic materials produced during residue decomposition is a particularly important mechanism of detoxification of Al. Indeed, addition of organic residues to soils typically decreases the proportion of Al present in soil solution…regardless of whether soil pH has been increased or not (p. 54).

Another relevant study conducted by Yagi et al. (2003) compared the effectiveness of vermicompost amendments against lime in an acidic typic hapludox in Brazil. Results showed significant pH increases after organic fertilization with vermicompost. For example, 40 t/ha of vermicompost raised the pH from 4.03 to 4.95, an increase that the study also observed with an application of 2.5 t/ha of lime. The largest increases in pH, however, was observed when lime and vermicompost were both applied to the soil. Interesting, a study by Oluwatoyinbo et al. (2009) also found best results on a variety of soil fertility indicators in a Nigerian ultisol when combining compost and lime. The combined application resulted in the greatest increase in available P, K, Mg, and Ca. Additionally, "the highest yield was obtained when lime was combined with 5 t/ha [of] compost" (p. 859). These studies point to the value of supplementing lime with compost fertilization. This is not only because both amendments can serve to increase soil and pH and increase nutrient availability, but also because compost applications can compensate for the long-term losses in organic material and SOC associated with liming (Curtin et al., 1998, as seen in Yagi et al., 2003)

Survey of Farmers in Vara Blanca

During a May 2019 visit to Vara Blanca a visit was made to the farmer employing organic-material intensive strategies instead of relying on lime. It was clear that the farmer had found success growing a variety of food crops without relying on lime to neutralize soil acidity. Instead, the farmer was observed using compost systems and vermiculture to create high-quality and nutrient-rich soil to apply to his cropland. This farmer’s success starkly contrasted the abandoned farmland and dilapidated greenhouses which once belonged to farmers reliant on lime in the cultivation of the soil. This contrast pointed to the need for a more in-depth look into the acidity neutralization strategies of farmers in the region.

After the May 2019 visit to Vara Blanca a survey was designed for farmers in Vara Blanca. The survey was created with the intent of gaining a better understanding of the management practices used to neutralize soil acidity in the region. In addition to quantitative questions regarding agricultural inputs, changes in yield, and effects on crop health, free-form response questions were included to ask farmers about their reasoning behind their management decisions. Although the survey was primarily designed with the intent of identifying trends in the application of lime and organic material inputs to see how these factors may influence long term farm success in the region, a number of other variables were included in the survey. These variables, which include land use history, fertilizer use, use of chemical controls, and types of crops grown can all have significant effects on the bioavailability of nutrients in the soil and ultimately the profitability of the farm. Thus, they were included in the survey in an effort to avoid making conclusions without addressing confounding variables.

Survey Methods

Surveys were completed in February 2020 by members of the Association for Development through Education (ADE), a local nonprofit organization in Vara Blanca. Field visits were made to each farmer given the survey so that the surveys could be completed as in-person interviews. The responses of each farmer were recorded by ADE members in an electronic form. In-person interviews were chosen over physical or electronic submission of survey responses by the farmers in an effort to assure that each question was understood and given a complete answer. A total of eighteen interviews were conducted with farmers throughout the Vara Blanca district. Three of these farmers are ranchers that grow pasture and the other fifteen are farmers growing various food crops. The number of interviews conducted limited the scope of the survey analysis, as the sample size was not deemed large enough to conduct certain statistical analyses. The survey did still demonstrate trends, however, in understanding the implications of management decisions made by farmers.

Survey Results

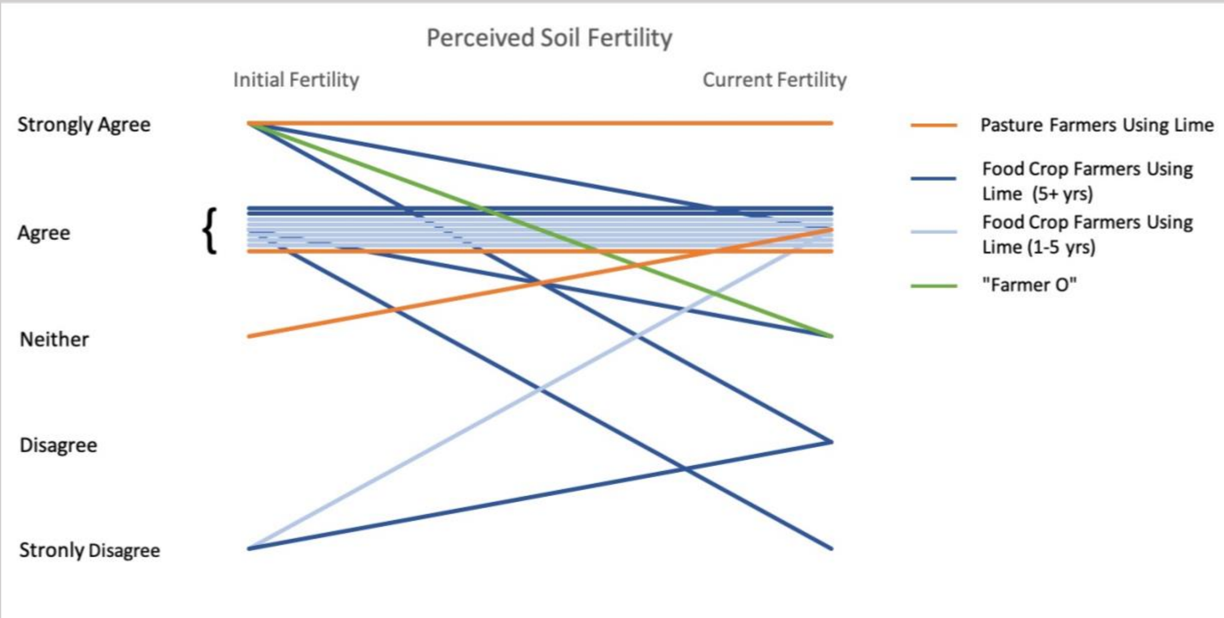
Questions regarding the perceived fertility of the farmers' soil were asked to determine any trends in soil fertility that may exist among farmers with different management decision histories. Although their responses are subjective and vulnerable to bias, changes in their perception of overall soil fertility during their first year of cultivation compared to their current perception of fertility provides insight into important changes that may be occurring in their soil. For example, Figure 1 shows that 4 of the 7 food crop farmers who have used lime for more than 5 years have observed a decline in soil fertility since they began cultivating their soil, whereas none of the 7 food crop farmers who have used lime for less than five years reported a decline in soil fertility. In fact, 6 of these 7 farmers agreed that their soil was fertile when they began cultivating it and was still fertile at the time of their interview.

Only one farmer using organic material inputs and no lime was interviewed. This farmer, referred to as “Farmer O,” who is the same farmer discussed in the Introduction and Literature Review for his observed success with this approach, reported strongly agreeing that his soil was fertile 4 years ago when he began cultivating it, but that he neither views his soil as fertile or infertile currently.

Among the 18 farmers that participated in the survey 3 were ranchers who grow pasture grass for their cattle. These ranchers face the challenge of maintaining healthy grass for the cattle in highly acidic soils, just as food crop farmers in the region do. Ranchers in the region also generally use lime to manage the acidity of their soil. In contrast to farmers growing food crops in the region, Figure 1 shows that the three ranchers who responded to the survey reported no declines in their perception of soil fertility. 2 of the 3 ranchers surveyed supplemented their lime applications with organic material, but despite this difference all of the ranchers reported no significant changes in soil fertility.

Figure 1

Changes in Farmers' Perceptions of Soil Fertility

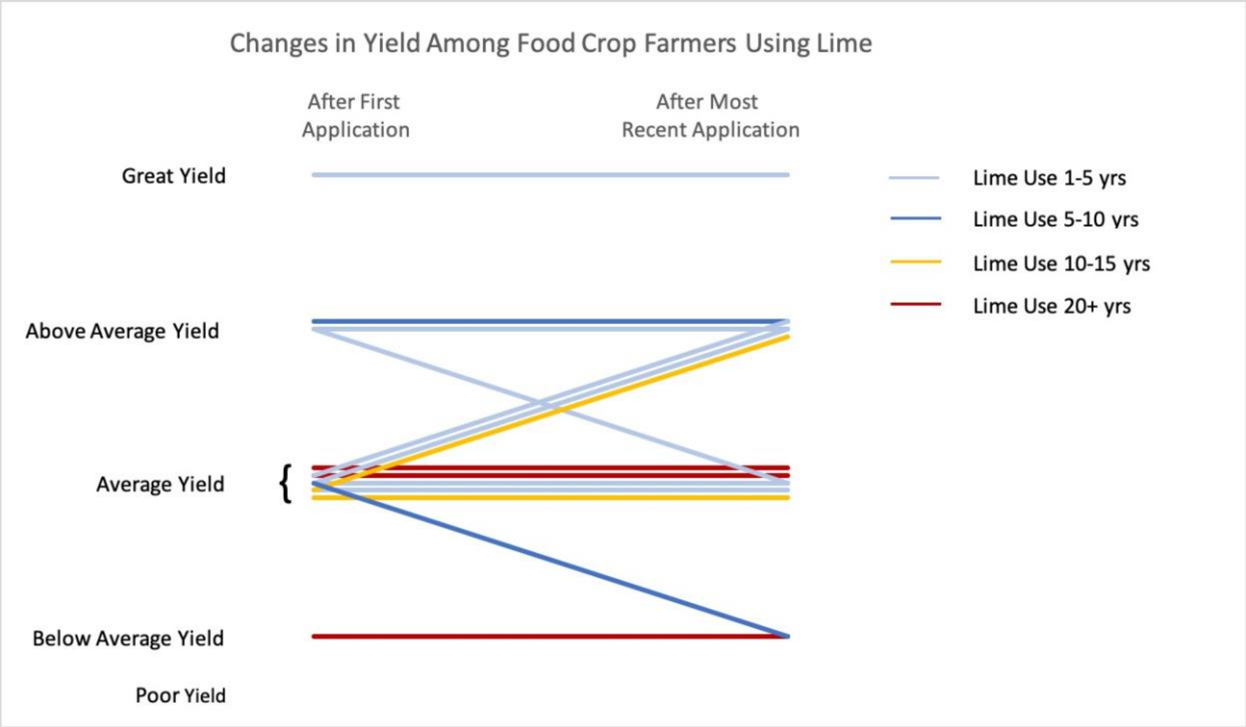


Note. Farmers' perception of soil fertility is based on their level of agreeance with a prompt stating that their soil was fertile when they initially began cultivating it and a prompt stating that their soil is currently fertile.

The food crop farmers' perceptions of changes in yield over time, in contrast to their perceptions of soil fertility, do not suggest a connection between lime use and declining returns. Figure 2 shows that none of the 3 farmers who have used lime for more than 20 years reported declines in yield. 1 of the 2 farmers using lime for between 10 and 20 years reported a decline. Among the 7 farmers that had started using lime in the last five years, 1 reported a decline in yield while 2 actually reported an increase in yield. This data suggests no clear correlation between lime use and changes in yield. It is conceivable, however, that other factors, such as increased fertilizer use, could be compensating for declines in soil fertility in order to maintain the same yields for the farmers who have been using lime for more than five years.

Figure 2

Changes in Perceived Yield Among Food Crop Farmers Using Lime

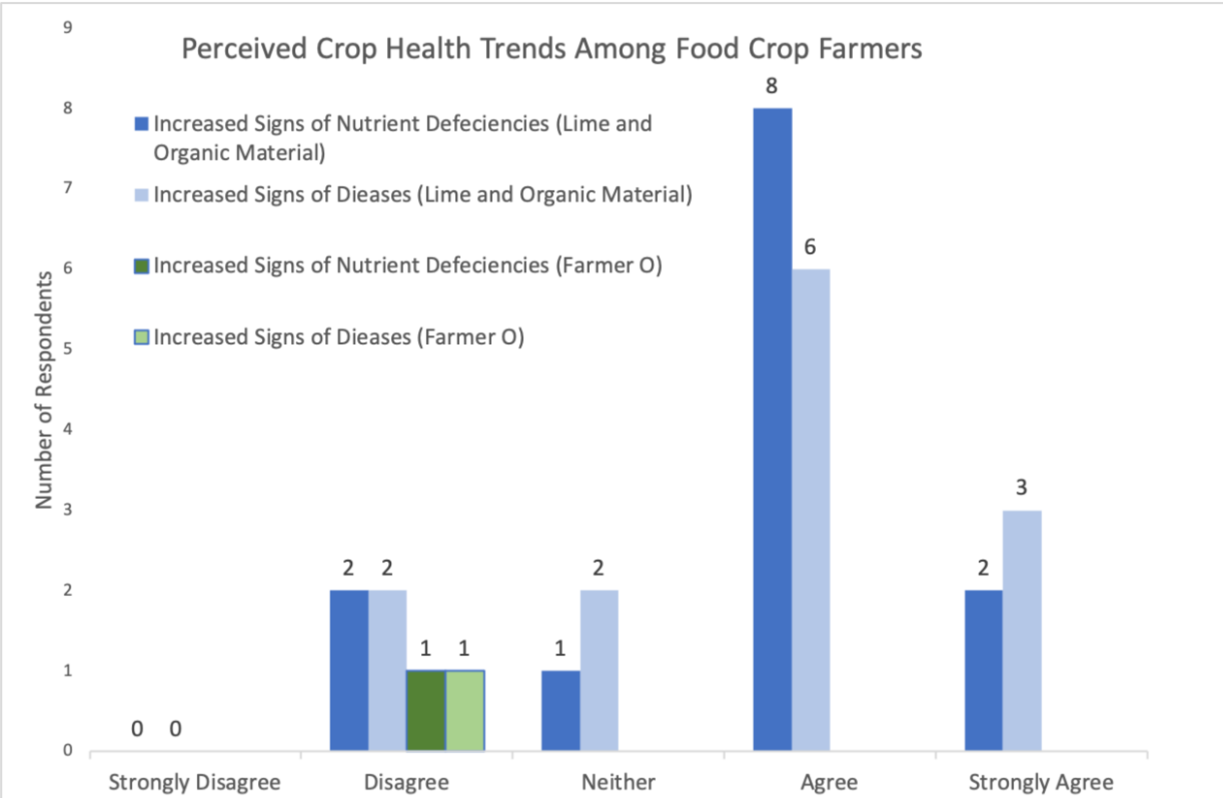


Note. Farmers' perception of yield after their first application of lime and after their most recent application of lime is subdivided into categories based on the number of years that each farmer has been applying lime regularly.

Yield, however, is not the only indicator related to crop response that farmers provided in their interviews. Farmers were also asked about their level of agreeance with two prompts, one stating that the number of crops showing signs of nutrient deficiencies has increased over time and the other stating that increasing signs of diseases have been observed over time. Their responses are shown in Figure 3. In contrast to Farmer O, who disagreed with both of these statements, 77% of the farmers using a combination of lime and organic material either agreed or strongly agreed that their crops show increasing signs of nutrient deficiencies and 69% agreed or strongly agreed that their crops showing increasing signs of diseases. Only 15% of these farmers disagreed with each of these statements.

Figure 3

Trends in Perceived Crop Health

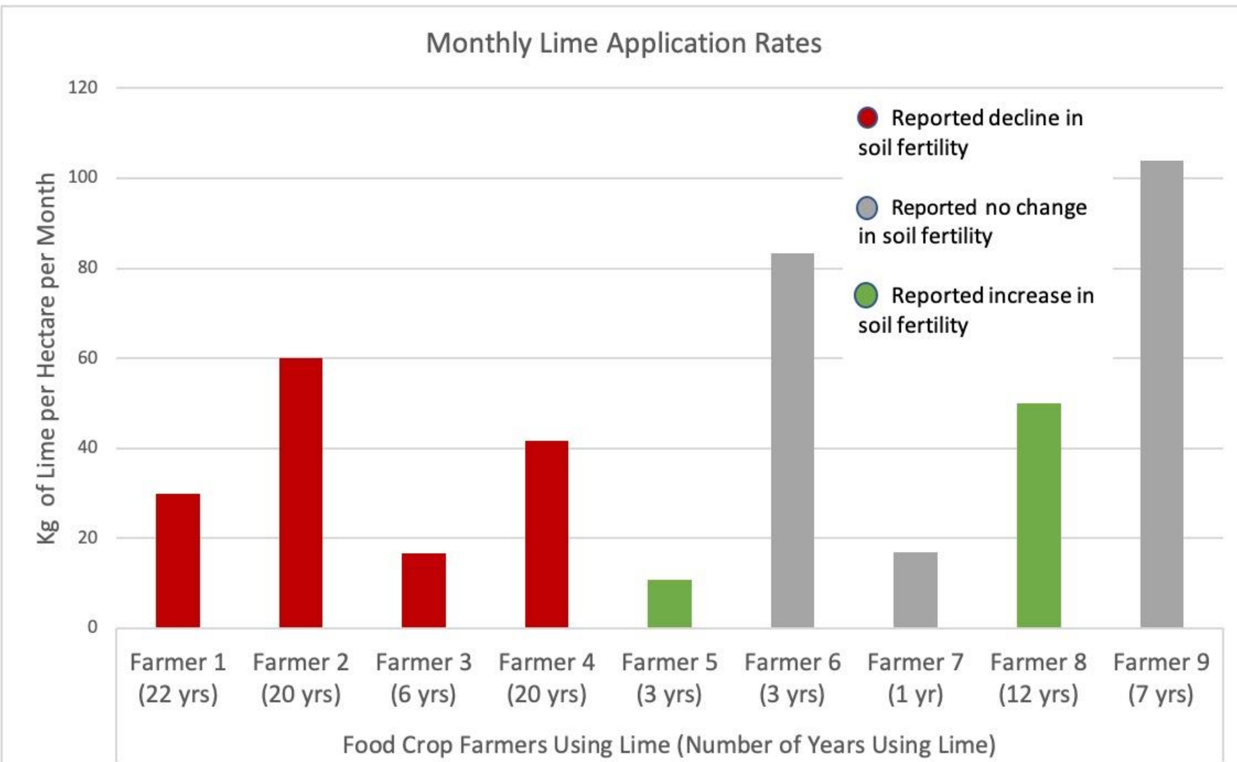


Note. Farmers' perception of crop health trends is based on their level of agreeance with prompts stating that their crops increasingly shows signs of nutrient deficiencies and diseases. The green bars show the response of the single farmer interviewed that applies only organic material for acidity neutralization. The light and dark blue bars show the responses of the 14 other food crop farmers who apply a combination of lime and organic material.

Another important factor to consider when assessing the effect of lime on outcomes that farmers observe over the course of multiple years of applications is the rate at which lime is applied to the soil. Figure 4 shows that reported application rates are highly variable, ranging from 15 to 105 kg per hectare per month. The results do not suggest that either high, moderate, or low application rates correlate with better trends in soil fertility. A larger sample size, ideally with farmers organized by the crops that they grow, may reveal trends in outcomes related to lime application rates, but the variability of soil conditions on different farms in the region and the ideal pH ranges of different crops grown by the farmers still introduces a number of confounding variables.

Figure 4

Variances in Lime Application Rates Among Food Crop Farmers Using Lime



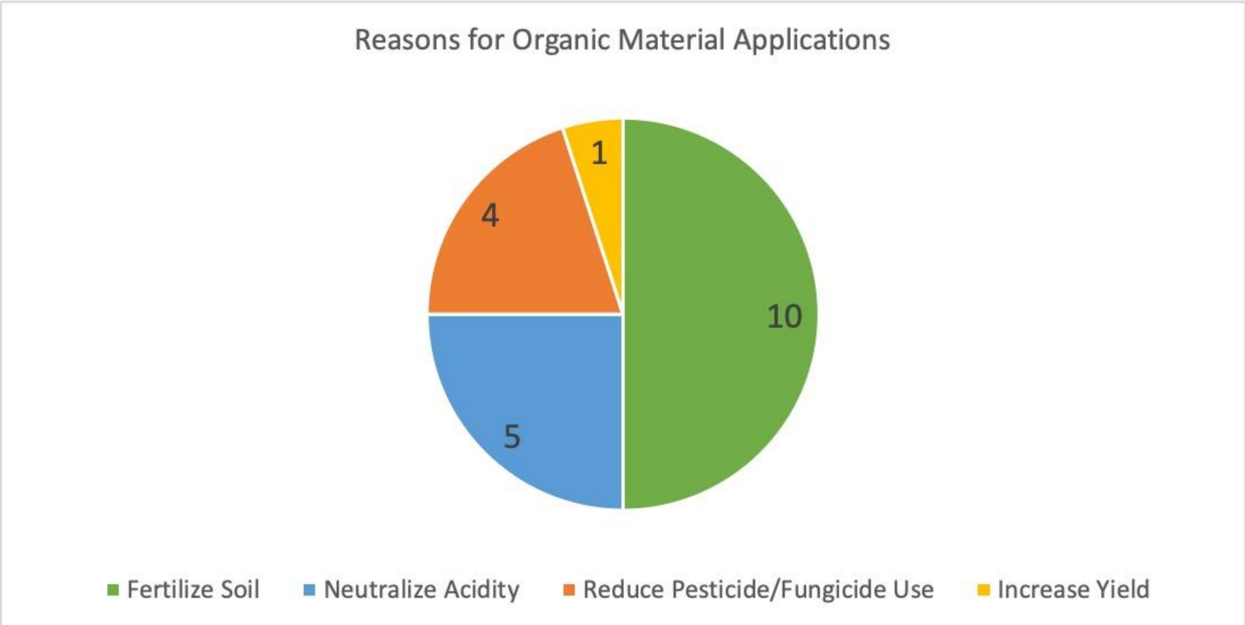
Note. Farmers apply lime at frequencies ranging from weekly to annually but are adjusted to monthly rates in this figure. Only 9 of the 14 food crop farmers using lime provided application rate figures in their interviews. Appendix C lists crops grown by Farmers 1 through 9.

13 of the 14 food crop farmers using lime reported also applying significant quantities of amendments rich in organic material to their soil. Figure 5 shows that 10 of these farmers apply

various types of organic material due to its ability to act as a fertilizer. Additionally, 5 of these farmers see the value of organic material in its ability to neutralize soil acidity. It can be inferred that these five farmers view a combination of lime and organic material as being most effective in neutralizing acidity. It is also relevant to consider that 9 of these 14 farmers reported solely purchasing their organic material, 4 reported sourcing all of their organic material on-site, and 1 reported doing both. This serves to demonstrate the value that the majority of the farmers see in organic material as an amendment, seeing as many of them are willing to go out of their way to pay for organic material sourced from off-site locations.

Figure 5

Reasons for Organic Material Applications



Note. Data includes responses from interviews with 14 food crop farmers applying various types of organic material to their soil. Some farmers responded with multiple reasons. Appendix A shows the types of organic material used by the farmers.

Discussion

The goal of analyzing the survey responses was to identify any trends that provide evidence supporting explanations for declining long-term fertility among farmers using lime. In addition, any contrasts in long-term outcomes between farmers using solely lime, farmers using lime and organic material amendments, and farmers using organic material amendments and no lime were analyzed to identify any evidence that supports alternative acidity neutralization strategies that are only partially reliant or not reliant on lime at all.

The decline in perceived soil fertility among 4 of the 7 farmers who have used lime in their food crop systems for over five years was expected based on anecdotal evidence prior to disbursing the survey. Despite the survey results showing no significant trend in yield changes over time, the reported declines in perceived soil fertility show that there may indeed be a connection between long-term lime use and declining fertility in the soils of Vara Blanca. The use of chemical controls and fertilizers, the types of crops grown, and land use history are all other variables that affect the bioavailability of nutrients, but the application of lime, particularly at the high levels, is one uniquely evident common denominator that needs to considered as a contributor to declining soil fertility.

It was predicted before the survey was disbursed to farmers in Vara Blanca that farmers using lime and little to no organic material amendments would report worse trends in soil fertility and yields than farmers who regularly apply significant quantities of organic material. This prediction was made due to the findings of multiple studies which found optimal returns on soil fertility and crop health when lime was supplemented with organic material in tropical acidic soils (Oluwatoyinbo et al., 2009; Yagi et al., 2003). The prediction was also made because of research from Herre et al. (2007), which studied soil on the slopes of Poás and concluded that soil with higher levels of soil organic matter is more effective in buffering against the acidifying effects of sulfur dioxide deposition from Poás. The responses provided by the farmers in their interviews did not allow for this prediction to be tested because only one farmer using lime reported no significant applications of organic material.

Figures 1 and 3 do show that farmers who have been using lime for more than five years, despite also applying significant amounts of organic material to their soil, have faced downturns in fertility, as well as increasing signs of nutrient deficiencies and diseases. This trend could point to several different explanations. One explanation is that another variable, such as chemical controls, which are used by the majority of the food crop farmers, are limiting crop performance due to harmful effects on soil biota (See Appendix B). Another such variable is fertilizers. All eighteen farmers reported applying some sort of fertilizer to supply phosphorus to their soil. The need for phosphorus in acidic andisols, as described in the literature review, can be very high, however. It is possible that certain food crops grown in the region are phosphorus deficient even when given phosphorus fertilizers, particularly if high levels of soil aluminum are complexing with added phosphorus and rendering it unavailable to crops. Further, heavy use of either synthetic or non-synthetic nitrogen fertilizers could be contributing to soil acidity and cancelling out the acidity-neutralizing effects of both the lime and the organic amendments. Sixteen of the eighteen farmers reported applying fertilizers that supply nitrogen.

Another potential explanation for declining soil fertility and crop health despite the supplementation of lime with organic material is due to the direct effects of heavy lime applications on soil biota. Declining SOC stocks as a result of increased mineralization caused by lime-induced increases in microbial activity could be a concern despite 14 of the 15 food crop farmers applying organic material to their soil. The quantity of these applications was not reported by respondents, so it is possible that their applications may not be large enough to balance losses in SOC caused by lime-induced increased mineralization (Paradelo et al, 2015). Additionally, years of heavy liming may be injurious to native populations of mycorrhizal fungi, which in combination with the use of chemical controls, may drastically reduce the ability of mycorrhizae to increase the availability of nutrients and limit aluminum toxicity (Siqueira et al., 1990).

One final concern related to lime use, as described in the literature review, is the risk of over-liming and under-liming. This risk is particularly high in acidic andisols due to their highly variable buffering capacity and the resulting difficulty in calculating the proper application rate (Espinosa, 1996). Figure 4 does not show any clear trend between application rate and soil fertility. It does show, however, that some of the farmers have applied large quantities of lime for over 20 years and have seen the health of their soil decline. It is conceivable that these farmers have applied lime at rates high enough to introduce some of the negative effects of over-liming, such as Molybdenum toxicity and various micronutrient deficiencies (Harter, 2007). This is a possibility because making effective lime application rate calculations on a site-by-site basis, which is necessary in soils with highly variable characteristics across short distances, requires tests done in a soil lab or time-intensive field tests. For farmers in Vara Blanca these are expensive endeavors, so they are more likely to have to rely on their best judgement or advice from other farmers to decide how much lime to apply.

Further, without an accurate basis to make decisions about the quantity of lime applications it is also possible that farmers may not be ameliorating enough soil acidity. Aluminum saturation may still be high enough to affect crop health after liming and application of organic materials, particularly if crops with low tolerance to aluminum toxicity are being grown. As seen in Appendix C, all but two of the interviewed food crops farmers are growing strawberries, and eight of them grow exclusively strawberries. Strawberries generally do prefer slightly acidic soil (Davis, 2009). Thus, under-liming may be seen as less of a concern, but it is still something that should be considered given the potential for soils in Vara Blanca to have very high pH buffering capacities against lime applications.

Despite these concerns, the reasons for the use of lime by farmers in Vara Blanca are clear. It has been proven to be effective in altering soil chemistry in such a way that the farmers see good returns initially, so from the perspective of the farmer there is no reason to stop applying it. Figures 1 and 2 show that the majority of the farmers who have begun using lime in the last five years have observed steady or even increasing soil fertility and yields. Thus, if soil fertility and yields decline after roughly five years, lime is unlikely to be seen as the culprit because of its association with soil fertility in early years of cultivation. When, in reality, the decline in fertility and yields may be due to one or several of the aforementioned potentially negative effects of liming, most of which would likely take at least several years of heavy applications on the same soil to develop. Further, farmers are likely to be hesitant to switch to an alternative method such as complete reliance on organic material due to the inherent perceived risk of switching to a different approach. In the face of poverty, many of the farmers in Vara Blanca do not have the luxury of experimenting with new methods simply because the potential costs of failure are too high. Additionally, 11 of the 14 respondents who apply lime reported that they did not consider lime to be an expensive amendment, so cost-reduction does not seem to be a strong incentive to stop or reduce lime application.

Figure 5 shows that many of the surveyed farmers are motivated to apply organic material for reasons beyond its use as a fertilizer, such as its ability to neutralize the acidity of the soil. The survey also revealed that the majority of the farmers are willing to pay for this capability through sourcing the material off-site. While most studies do point to compost, vermicompost, manure, and other organic material inputs as being effective alternatives to lime, the availability of the inputs and the quality of these inputs are two of the primary variables affecting their level of cost-effectiveness in comparison to lime. The ability to create sufficient quantities of compost through organic material sourced on-site will increase the cost-effectiveness of this approach. On the other hand, if compost needs to be purchased off-site, the cost-effectiveness of this approach will markedly decrease in comparison to lime, particularly in places like Vara Blanca where lime is readily available at a low cost. For farmers in Vara Blanca, the scale of each farm and its access to organic waste will be a key factor affecting decisions to utilize compost or lime supplemented with compost in the future. Evidence discussed in the Literature Review does show, however, that a switch from lime to compost applications and other organic material-intensive strategies can have benefits that go beyond the immediate cost-effectiveness of the approach in comparison to liming. For farmers in Vara Blanca specifically, there is potential for these strategies to present a longer-term solution to issues associated with soil acidity in andisols, such as aluminum toxicity and phosphorus sorption, while simultaneously enhancing soil carbon levels and maintaining a strong presence of mycorrhizal fungi.

The success of “Farmer O” presents a case study which supports this decision to rely completely on organic material as a source of acidity amelioration. Although Farmer O has only been cultivating the soil on the farm for 4 years, the fertility of the soil and health of the crops reported in the survey and observed during the May 2019 visit provide evidence suggesting that this approach could present a more sustainable long-term approach than reliance on lime. This is because the use of compost, vermicompost, “bokashi” compost, manure, wood ash, and material from the rainforest floor, all of which are used by Farmer O, support healthy populations of soil bacteria and fungi in the same way that these populations are supported and kept productive in the natural tropical ecosystems of this region. It should be considered, however, that Farmer O was the only survey respondent that uses this approach. Evidence of long-term success of this approach on farms across a variety of microhabitats in the Vara Blanca district is needed in order to make conclusions about its effectiveness in comparison to lime. Further, there are a number of other variables that are likely contributing to the health of the soil on the farmland that Farmer O cultivates, such as the use of organic repellants as opposed to chemical pest controls, the diversity of crops grown, and the practice of crop rotation.

Conclusion

Evidence from relevant literature, in addition to the results of the conducted survey, point to consistent heavy lime applications as being a contributing factor to long-term declining soil fertility among food crop farmers cultivating the acidic andisols in Vara Blanca. Further, the success of Farmer O serves as a case study which points to the ability of compost, manure, and other organic material-rich soil amendments to be used as an alternative approach to acidity management in the region with a myriad of added benefits. Despite these conclusions, further research is needed to determine specific soil characteristics in Vara Blanca. Testing soil from various sites from farms across the region will allow researchers to determine levels of aluminum toxicity, soil organic matter, available phosphorus, and other important characteristics under different soil management systems. Data from these tests has the potential to lead to more specific conclusions regarding the implications of lime and organic material as different acidity management strategies and their long-term impacts on important soil characteristics.

As farmers in Vara Blanca continue to face the challenge of cultivating highly acidic soil, this study can serve as a resource for farmers making decisions aimed at ensuring longstanding soil fertility. Additionally, future studies that sample soils from Vara Blanca and analyze them in soil laboratories have the potential to build upon this study and develop a more comprehensive resource for farmers. Granted, as in any agricultural system, soil fertility in Vara Blanca is affected by countless environmental factors and numerous management decisions made by the farmers. Explanations for trends in soil fertility cannot be curtailed to a singular factor such as lime use or organic matter inputs but must instead recognize the complexity of the numerous interactions taking place in the soil and how an assortment of inputs, ranging from acid rain to vermicompost to synthetic fungicides, affects all of these interactions.

Works Cited

Andrade, D. S., Murphy, P. J., & Giller, K. E. (2002). Effects of liming and legume/cereal cropping on populations of indigenous rhizobia in an acid Brazilian Oxisol. *Soil Biology and Biochemistry*, *34*(4), 477–485. doi: 10.1016/s0038-0717(01)00206-1

Arshad, M. A., Soon, Y. K., Azooz, R. H., Lupwayi, N. Z., & Chang, S. X. (2012). Soil and crop response to wood ash and lime application in acidic soils. *Agronomy Journal*, *104*(3), 715. doi: 10.2134/agronj2011.0355

Aye, N. S., Sale, P. W. G., & Tang, C. (2016). The impact of long-term liming on soil organic carbon and aggregate stability in low-input acid soils. *Biology and Fertility of Soils*, *52*(5), 697–709. doi: 10.1007/s00374-016-1111-y

Bougnom, B. P., Mair, J., Etoa, F. X., & Insam, H. (2009). Composts with wood ash addition: A risk or a chance for ameliorating acid tropical soils? *Geoderma*, *153*(3-4), 402–407. doi: 10.1016/j.geoderma.2009.09.003

Casierra-Posada, F., Aguilar-Avendaño, O.E. (2007). Estrés por aluminio en plantas: reacciones en el suelo, síntomas en vegetales y posibilidades de corrección: una revisión [Stress for aluminum in plants: reactions in the soil, symptoms in plants and amelioration possibilities: a review]. *Revista Colombiana de Ciencias Hortícolas, 1*(2), 246-257. doi: 10.17584/rcch.2007v1i2.8701

Clark, R. B., Zobel, R. W., & Zeto, S. K. (1999). Effects of mycorrhizal fungus isolates on mineral acquisition by Panicum virgatum in acidic soil. *Mycorrhiza*, *9*(3), 167–176. doi: 10.1007/s005720050302

Davis, J. B. (2009). Strawberry Success. *Organic Gardening*, *56*(5), 52–56.

Delmelle, P., Delfosse, T., & Delvaux, B. (2003). Sulfate, chloride and fluoride retention in andosols exposed to volcanic acid emissions. *Environmental Pollution*, *126*(3), 445–457. doi: 10.1016/s0269-7491(03)00196-9

Espinosa, J. (1996). Liming tropical soils: A management challenge. *Better Crops*, *80*, 28–31.

Espinosa, J. & Molina, E. (2015). *Acidez y encalado de los suelos* [Soil acidity and liming]. Quito, Ecuador: International Plant Nutrition Institute.

Fageria, N. K. & Baligar, V. C. (2008). Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production. In D. L. Sparks, *Advances in Agronomy* (345-399). Cambridge, MA: Academic Press.

Harter, R. D. (2007). Acid soils of the tropics. *ECHO*, North Fort Myers, FL.

Haynes, R. J., & Mokolobate, M. S. (n.d.). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems*, *59*, 47–63.

Hernández, A. A. (2001). Manejo de suelos derivados de cenizas volcánicas [Soil management in soils derived from volcanic ash]. In Meléndez, G. & Molina, E., *Fertilidad de Suelos y Manejo de la Nutrición de Cultivos en Costa Rica* [Soil fertility and management of nutrition for crops in Costa Rica] (pp. 11-26). San Pedro de Montes de Oca, Costa Rica: Universidad de Costa Rica Centro de Investigaciones Agronómicas.

Herre, A., Lang, F., Siebe, C., Dohrmann, R., & Kaupenjohann, M. (2007). Mechanisms of acid buffering and formation of secondary minerals in vitric Andosols. *European Journal of Soil Science*, *58*(2), 431–444. doi: 10.1111/j.1365-2389.2007.00890.x

Latifah, O., Ahmed, O. H., & Majid, N. M. A. (2017). Soil pH buffering capacity and nitrogen availability following compost application in a tropical acid soil. *Compost Science & Utilization*, *26*(1), 1–15. doi: 10.1080/1065657x.2017.1329039

Macey, A. (1975). The vegetation of Volcán Poás National Park, Costa Rica. *Revista De Biología Tropical*, *23*(2), 239–255.

Mata, Rafael & Alvarado-Hernandez, Alfredo. (2016). *An Agroecological Approach.* San Pedro de Montes de Oca, Costa Rica: Universidad de Costa Rica Centro de Investigaciones Agronómicas.

Mosse, B., & Hayman, D. S. (1970). Plant growth responses to vesicular-arbuscular mycorrhiza: growth of endogone-inoculated plants in phosphate-deficient soils. *New Phytologist*, *70*(1), 19–27. doi: 10.1111/j.1469-8137.1971.tb02505.x

Nadkarni, N. T., & Wheelwright, N. T. (2000). *Monteverde: Ecology and Conservation of a Tropical Cloud Forest*. New York: Oxford University Press.

Nanzyo, M., 2002. Unique properties of volcanic ash soils. *Global Environmental Research, 6*(2), 99–112.

Naramabuye, F. X., Haynes, R. J., & Modi, A. T. (2008). Cattle manure and grass residues as liming materials in a semi-subsistence farming system. *Agriculture, Ecosystems & Environment*, *124*(1-2), 136–141. doi: 10.1016/j.agee.2007.08.005

Oluwatoyinbo, F. I., Akande, M. O., Makinde, E. A., & Adediran, J. A. (2009). Growth and yield response of okra to lime and compost on an acid soil in the humid tropics. *Research Journal of Agriculture and Biological Sciences*, *5*(5), 858–863.

Osorno, H. H., & Osorno L. B. (2010). Determinacion de los requerimientos de cal [How to determine lime requirements for cultivated soils]. *Suelos Ecuatoriales 41*(1), 29-35.

Paradelo, R., Virto, I., & Chenu, C. (2015). Net effect of liming on soil organic carbon stocks: A review. *Agriculture, Ecosystems & Environment*, *202*, 98–107. doi: 10.1016/j.agee.2015.01.005

Pearson, R. W. (1975). *Soil Acidity and Liming in the Humid Tropics*. Ithaca: New York State College of Agriculture and Life Sciences, Cornell University.

Price, M., & Berkelaar, D. (2001). The effect of aluminum in acidic soils on plant growth. *ECHO*, North Fort Myers, FL.

Sánchez, P. A. (2019). *Properties and Management of Soils in the Tropics*. Cambridge, United Kingdom: Cambridge University Press.

Sánchez, P. A., & Salinas, J. G. (1981). Low-Input technology for managing oxisols and ultisols in tropical America. *Advances in Agronomy*, 279–406. doi: 10.1016/s0065-2113(08)60889-5

Silva, J. A., & Uchida, R. S. (2000). *Plant Nutrient Management in Hawaii's Soils: Approaches for Tropical and Subtropical Agriculture*. Honolulu, HI: College of Tropical Agriculture & Human Resources, University of Hawaii at Manoa.

Siqueira, J. O., Hubbell, D. H., & Mahmud, A. W. (1984). Effect of liming on spore germination, germ tube growth and root colonization by vesicular-arbuscular mycorrhizal fungi. *Biological Processes and Soil Fertility*, 115–124. doi: 10.1007/978-94-009-6101-2_10

Siqueira, J. O., Rocha, W. F., Oliveira, E., & Colozzi-Filho, A. (1990). The relationship between vesicular-arbuscular mycorrhiza and lime: Associated effects on the growth and nutrition of brachiaria grass (Brachiaria decumbens). *Biology and Fertility of Soils*, *10*, 65–71. doi: 10.1007/BF00336127

Tahat, M. M., & Sijam, K. (2012). Mycorrhizal fungi and abiotic environmental conditions relationship. *Research Journal of Environmental Sciences*, *6*(4), 125–133. doi: 10.3923/rjes.2012.125.133

Valarini, P. J., Curaqueo, G., Seguel, A., Manzano, K., Rubio, R., Cornejo, P., & Borie, F. (2009). Effect of compost application on some properties of a volcanic soil from central south chile. *Chilean Journal of Agricultural Research*, *69*(3), 416–425. doi: 10.4067/s0718-58392009000300015

Wang, X., Tang, C., Baldock, J. A., Butterly, C. R., & Gazey, C. (2015). Long-term effect of lime application on the chemical composition of soil organic carbon in acid soils varying in texture and liming history. *Biology and Fertility of Soils*, *52*(3), 295–306. doi: 10.1007/s00374-015-1076-2

Weyman-Kaczmarkowa, W., & Pędziwilk, Z. (2000). The development of fungi as affected by pH and type of soil, in relation to the occurrence of bacteria and soil fungistatic activity. *Microbiological Research*, *155*(2), 107–112. doi: 10.1016/s0944-5013(00)80045-2

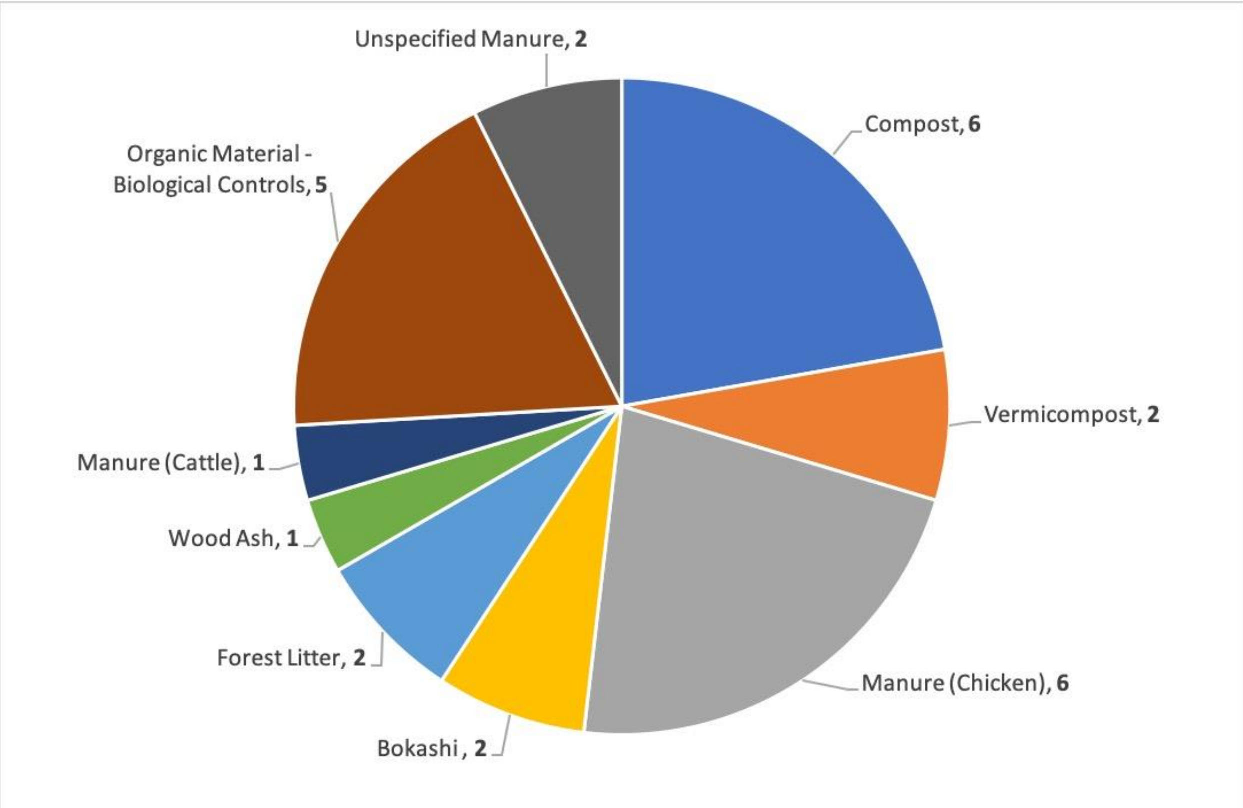
Yagi, R., Ferreira, M. E., Cruz, M. C. P. D., & Barbosa, J. C. (2003). Organic matter fractions and soil fertility under the influence of liming, vermicompost and cattle manure. *Scientia Agricola*, *60*(3), 549–557. doi: 10.1590/s0103-90162003000300021

Yamada, K., Ito, K., Takahashi, T., Kanno, H., & Nanzyo, M. (2011). Inhibitory effect of acid Andosols on plants – is aluminum toxicity true for allophanic Andosols? *Soil Science and Plant Nutrition*, *57*(4), 491–499. doi: 10.1080/00380768.2011.595360

Additional Figures

Appendix A

Types of Organic Material Applied



Note. Bolded numbers refer to the number of respondents who reported using each type of organic material input.

Appendix B

Controls Used

	Controls (x) A type of chemical control applied regularly or when needed (o) Non-synthetic control applied regularly or when needed		
Food Crop Farmers Using Lime	**Pesticide**	**Fungicide**	**Herbicide**
Farmer 1	x	x	x
Farmer 2	x	x	

Farmer 3	x	x	x
Farmer 4	x	x	x
Farmer 5	o	x	x
Farmer 6	x	x	x
Farmer 7	x	x	x
Farmer 8	o	x	o
Farmer 9	o		
Farmer 10	x	x	
Farmer 11	x	x	x
Farmer 12	x		o
Farmer 13	x		
Farmer 14	x		
Farmer O	o	o	

Note. Non-synthetic controls refer to biological controls such as plants and fungi that have properties which suppress various pests and weeds.

Appendix C

Types of Crops Grown

Food Crop Farmers Using Lime	Crops Grown
Farmer 1	Strawberries, Celery, Coriander
Farmer 2	Strawberries
Farmer 3	Strawberries, Chiles
Farmer 4	Strawberries, Lettuce
Farmer 5	Strawberries
Farmer 6	Strawberries
Farmer 7	Strawberries
Farmer 8	Strawberries
Farmer 9	Strawberries, Chiles, Cilantro, Spinach, Radishes, Cauliflower, Cabbage
Farmer 10	Strawberries, Peruvian ground cherry
Farmer 11	Strawberries
Farmer 12	Strawberries
Farmer 13	Lettuce, Beets, Garlic
Farmer 14	Strawberries

Farmer O	Onions, Carrots, Lettuce, Broccoli, Turnips, Spinach, Kale, Arugula, Cabbage, Garlic, Asparagus

Appendix D: List of Frequently Used Terms

Andisol. An order of soil characterized by a volcanic-ash parent material. They account for less than one percent of nonpolar land area globally.

Acidity Neutralization/Amelioration. The neutralization or amelioration of acidity refers to a decrease in the concentration of acidifying cations (Al^{3+} and H^{+}) in the soil solution, resulting in the soil pH becoming more basic.

Arbuscular Mycorrhizal Fungi (AMF). AMF are a specific type of fungi present in most soils. They form a mutualistic relationship with plants by attaching to roots and receiving in sugars from the plant. They benefit plants in allowing the plant to access greater quantities of nutrients and nutrients existing in forms that would otherwise be inaccessible to the plant. They also often allow the plant to persist in a wider range of environmental conditions and provide defense against some nematodes.

Aluminum Saturation. Aluminum saturation refers to the percentage of a soil's cation exchange capacity that are occupied by exchangeable aluminum cations.

Bioavailability. In the context of this paper bioavailability refers to amount of a nutrient present in the soil that is accessible by a crop. A greater amount of a nutrient than is actually accessible by the plant in likely to exist in the soil.

Cation Exchange Capacity (CEC). CEC is a key defining feature of any soil and is difficult to alter significantly. Essentially it refers to the total capacity that a soil has to hold exchangeable cations, which are cations that plants can access. Many essentially plant nutrients are accessed as cations, such as calcium, magnesium, and potassium.

<u>Exchangeable Aluminum.</u> Exchangeable aluminum refers to aluminum existing as cations, which can be accessed by plants and can be toxic to plants at high enough concentrations.

<u>Nutrient Mineralization.</u> The mineralization of nutrients refers to the conversion of nutrients from an organic form to an inorganic form. This process is the result of the decomposition of organic matter by soil microbes and is key in allowing the nutritive value of organic matter to be transformed into forms that are accessible by plants.

<u>Soil Organic Carbon (SOC).</u> SOC is the carbon component of everything within a soil that qualifies as soil organic matter. SOC enters the soil as plant and animal residues and is the main food source for micro-organisms. High levels of SOC are generally a determinant of soil fertility. Net increases in SOC result in increased carbon sequestration.

<u>Soil Organic Matter (SOM).</u> SOM is a phrase used to describe all hydrocarbon compounds in soil that are at various stages of decomposition. SOM is key in contributing to nutrient retention, quality soil structure development, and moisture retention.

<u>Soil Buffering Capacity.</u> The buffering capacity of a soil is the capacity that a soil has to resist against a change caused by an input. In the context of soil acidity, a soil's buffering capacity is the extent to which the soil is able to resist against changes in its pH. For example, if lime is added to a soil with a strong buffering capacity, which is often the result of a high aluminum saturation, much of the exchangeable aluminum removed by the lime is likely to be replaced by other aluminum cations, resulting in little change in soil pH.

<u>Sorption.</u> Sorption is a term that describes the adherence or incorporation of one substance with another substance. In soil, the sorption of a substance results in the retention of that substance in soil. Oftentimes the sorption of a nutrient, such as phosphorus, results in the phosphorus being

rendered unavailable to plants. For example, phosphorus often complexes with aluminum and iron hydroxides, making it unavailable for plant roots to access.