CHAPTER 1. SOIL FERTILITY IN CALCAREOUS TROPICAL SOILS: THE CASES OF YUCATAN, MEXICO, AND VILLA CLARA, CUBA.

1.1. INTRODUCTION

Soil fertility studies in the semiarid tropics, and particularly of calcareous tropical soils, are limited. Specifically, in semiarid regions exist an increasing pressure due to the population increase and the impacts of economic policies on land tenure. The assessment of the nutritional conditions of these soils may contribute to improve soil management. Suitable and sensitive techniques, which combine the influence of climatic factors and biochemical processes in the soil, permit a better understanding of these semiarid ecosystems.

This thesis deals with the problematic of semiarid calcareous soils from Yucatan, Mexico and Villa Clara, Cuba, which have low productivity. Problems related to phosphorus availability, cation imbalances, and water availability, have been reported in the literature as probable limiting factors in these soils (Weisbach et al., 2002, Vargas et al., 2003).

The aim is to establish the main chemical indicators of soil quality for these calcareous soils and evaluate the effect of management on soil fertility. More specifically, the work in this thesis focuses on the following points:

- Determine soil carbon and nitrogen contents, as well as the amounts of exchangeable calcium (Ca), magnesium (Mg), and potassium (K), in these calcareous soils under three different land uses from the semiarid tropic.
- Characterize phosphorus (P) in these soils based on its bioavailability to plants and microbes in these soils under contrasting managements.

- Evaluate the influence of soil moisture on the availability of five main nutrient ions (Ca, Mg, K, nitrate (NO_3^--N) and phosphate (PO_4^{2-}-P)) in these calcareous soils with different agricultural uses through incubation studies with ion exchange membranes.

1.2. LITERATURE OVERVIEW

1.2.1. Environmental concerns of calcareous soils in the semiarid tropics

The warm arid and semiarid tropics encompass very large areas of sub-Saharan Africa, Asia, and Latin America and the Caribbean, where populations are often relatively high (Sivakumar and Valentin, 1997). Semiarid ecosystems have soils that are considered to be problem soils, being highly susceptible to degradation. The phenomenon of land degradation involves an unfavorable alteration in one or all of soil's physical, chemical and biological properties and processes leading to loss of sustainable use (Abubakar, 1997), such as loss of organic matter, erosion, crust formation, structural decline, and sometimes salinity. Together they may be more significant than decreases in rainfall (Sivakumar and Valentin, 1997). Syers et al. (2002) considered soil degradation is an important factor affecting the sustainability of agricultural systems and remarked that nutrient depletion is one of the most important chemical processes involved in it, because nutrient supply is vitally important for crop production. A decreasing nutritional status of the soil has major implication for the sustainability of agriculture systems and future food supplies.

Calcareous soils are common in semiarid and arid climates, and occur as inclusions in more humid areas. The total extent of Calcisols is estimated at 800 million hectares worldwide, mainly concentrated in arid or Mediterranean climates. However, the total area of calcareous soils is difficult to estimate because many are salinized and do not key out as Calcisols (FAO, 2000).

Limestone soils are identified by the presence of the mineral calcium carbonate in the parent material, accumulation of lime, pH usually above 7 and may as high as 8.5. When these soils contain sodium carbonate, the pH may exceed 9. In some soils, $CaCO_3$ can concentrate into very hard layers, termed caliche (hardpan), that are impermeable to water and plant roots (Leytem and Mikkelsen, 2005). They are also characterized by high concentrations of bicarbonate ions in the soil solution and almost no exchangeable H^+ (Misra and Tyler, 1999).

The presence of free carbonates may cause nutrient deficiencies, excess nutrients, and nutrient imbalances resulting in losses of productivity (Kishchuk et al., 1999). High pH results in unavailability of phosphate, frequently the most limiting nutrient in these soils, and also reduces micronutrient availability, e.g. boron, manganese, zinc and iron. Availability of phosphorus is often the most limiting factor for plant growth in these soils (Leytem and Mikkelsen, 2005). The amount, nature and reactivity of carbonate minerals affect phosphate reactions in calcareous soils. Phosphorus is geochemically fixed in soils through its interactions with Ca, Al, and Fe, to form phosphate minerals or surface complexes. In arid ecosystems carbonate controls P retention and fixation in calcic horizons (Carreira et al., 2006).

Not only phosphorus is a limiting nutrient in calcareous soils, potassium and magnesium nutrition may be also problems as a result of the nutritional imbalance between these elements and calcium (Kishchuk et al., 1999 and FAO, 2000). Available Mg and K are sometimes in inadequate supply due to an imbalance between plant available Ca, Mg, and K ions. In these soils, the proportion of Ca to other exchangeable cations exceeds 80% and a low proportion of exchangeable Mg (less than 4%) and low exchangeable K, may lead to Mg and/or K deficiencies in crops (Hagin and Tucker, 1982 and Marschner, 1995 in Imas, 2000). In tropical soils, exchangeable K accounts for a variable percentage (0.5 - 50%) of total K of the soil (Baligar and Bennett, 1986).

The land use of calcareous soils is highly variable; ranging from deserts to intensively cultivated irrigation areas (FAO, 2000). They can be extremely productive for agricultural purpose when they are managed properly (Leytem and Mikkelsen, 2005). However, land management practices can also affect ecosystem function mainly due to their effects on microbial population or by temporal changes of chemical properties of the soils. For instance, slash-and-burn agriculture can induce an increase in plant-available nutrients through release from biomass and transfer into the soil environment with the ashes (Juo and Manu, 1996; Twosend et al., 2002). The quantities of the nutrient elements gained by the soil after burning depend not only upon the amount of each element in the ash but also the capacity of the soil to retain and store these nutrients in forms that are readily available to plants (Juo and Manu, 1996). Soil heating is a secondary mechanism of nutrient release in soils that experience slash-and-burn processes (Giardina et al., 2000). The heat can induce pyromineralization of the organic bound soil P causing the transformation of more resistant forms into plant available forms (Saa et al., 1993 in Lawrence and Schlesinger, 2001). Other studies have shown the effect of contrasting land-use systems on soil P fractions. Buehler et al. (2002) assessed P in a Colombian Oxisol under four treatments (two of them with fertilizer additions), and found that all fractions were strongly dependent on total P content of the soil, which was affected by the amount of P added as fertilizer and removed by plant uptake. In the two P-fertilized treatments most of the P was stored in the resin-Pi, Bicarbonate-Pi, and NaOH-Pi fractions, whereas in the two unfertilized the transfer of labeled ^{33}P into these inorganic pools was less clear suggesting that the soil Pi was much less exchangeable and the transference of labeled P into organic fractions was more important. Guo et al. (2000) reported the effect of exhaustive cropping on P fractions in eight Hawaiian soils. Their results suggest that resin Pi and $NaHCO_3$-Pi were the most sensitive fractions to plant removal in all soils. NaOH-Pi was the dominant fraction in the highly weathered soils, and also declined with plant removal. In contrast, residual P in the highly weathered soils is accumulated with plant removal, suggesting that it was unavailable to plants.

The erratic nature of the rainfall exerts a direct effect on soil moisture, and subsequently on nutrient availability. Limestone soils are commonly found in semiarid and arid regions, so, supplemental irrigation water is often the first barrier for crop production (Leytem and Mikkelsen, 2005). There are many recent studies on the relationships between precipitation and ecosystem processes in the semiarid tropics.

Phosphorus uptake by plants is influenced by soil moisture, being largely controlled by diffusion rates and P depletion in the rhizosphere (Gahoonia et al., 1994 in Misra and Tyler, 1999). Because phosphorus diffusion occurs in water-filled pore spaces within the soil, the volumetric soil water content is an important factor controlling diffusive flux (Kovar and Claassen, 2005), so the diffusive flux of phosphorus increase significantly as the soil moisture increases. Misra and Tyler (1999) studied the influence of soil moisture on soil solution chemistry in a limestone soil (Rendzic leptosol) and reported that phosphate concentrations increased with soil moisture, but most of this increase occurred above 70% water holding capacity (WHC). At low soil water content, the diffusion path is impeded, making phosphorus less available to plants, which was reflected also in nutrient content in biomass of calcicole plants according to the results obtained in this research.

Carbon (C) and N mineralization rates are highly susceptible to changes in soil moisture and drying-rewetting cycles (Fierer and Schimel, 2002). Schwinning et al. (2004) summarized the experimental approaches used to examine the implications of the seasonality in the semiarid tropics and its erratic rainfall in land degradation and nutrient cycling. They explained that soil moisture regimes regulate the mechanism of nutrient gain and losses in these environments where mineral and organic substrates tend to accumulate during dry periods. In these conditions, there is little nutrient demand, whereas the onset of the wet season leads to an excess of mineralization and denitrification increasing the losses of carbon and nitrogen from soil pools.

1.2.2. Climate, land uses, and soil fertility studies from Yucatan, Mexico and Villa Clara, Cuba

Yucatan, Mexico

The Yucatan peninsula, in southeastern Mexico, is completely south of the Tropic of Cancer. Throughout the peninsula a range of climatic vegetation complexes can be distinguished by the Köppen system, but the majority of the peninsula is considered a tropical dry forest (Aw) due to long periods of little to no precipitation. Annual precipitation ranges from 500-1500 mm (Benjamin, 2000), with the lower values in the North-West coast of the peninsula and values above 1200 mm in the South-East (Duch, 1988). Temperature in some moths may reach more than 40 ºC (Benjamin, 2000). The annual mean temperature is 26ºC (Duch, 1988).

The Yucatan peninsula, due to its physical and geographic characteristics, differs from the rest of Mexico because its biogeographycal relationships with the Antilles and the Caribbean region (Chiappy and Gama, 2004). The landscape of the peninsula can be described as unusual due to the dominant limestone bedrock found underneath a shallow soil surface layer, the lack of surface water and the presence of underground caves and rivers, but also sinkholes or cenotes, which are formed when limestone shelf collapses due to the dissolving process and expose the water below, throughout the peninsula (Benjamin, 2000).

The Yucatecan soils are formed from tertiary limestone on a typical karstic landscape of flat rocks outcrops and shallow depressions, giving a mosaic of black lithosols, which occur mainly on slightly elevated areas (<0.5m), and red rendzinas, which occur in depressions and are deeper (>20 cm) with a low gravel content. The differences in depth, stone content and high calcium carbonate content are closely related to their chemical properties (Weisbach et al., 2002).

Since pre-Columbian times, an assortment of agricultural and forestry systems have been used and adapted by Mayan settlements throughout the peninsula. Current Maya production systems include milpa farming, a shifting agriculture that co-exists with secondary forest, and homegardens (Benjamin, 2000). In Yucatan, one third of the soils (800 000 ha) is dedicated to the milpa, the traditional agriculture for maize associated with sweet potato, pumpkins, beans, and other legumes, and usually are cultivated for two years. Most of the areas need fallow periods between 15 and 25 years for restoration of soil fertility, but increasing population, changes in land tenure, and limited allocation has reduced fallow periods from around 20 years to less than 7, threatening the sustainability of the milpa ecosystems (Moya et al., 2003; Benjamin, 2000; and Weisbach et al., 2002).

Homegardens have been important to Maya cultivation for centuries. Nowadays, in the Maya villages in Yucatan, houses are surrounded by homegardens that mimic a complex structure of a mature forest with plants growing in multiple strata, and often, animals for household use. This ecosystem has been shown to be a productive use of the areas that surround people’s houses, providing fruits and vegetables for household consumption and also, for sale at a market (Benjamin, 2000). The constant inputs of resources in form of food, manure, “rich” soil “tierra de sarteneja” from the secondary forest, and human dwellings, and also, water management enrich the system as a site for plant growth. For this reason, Yucatecan homegardens could be described as a trap of nutrients (Andrist, 2003).

Soil fertility studies in Yucatan are limited mainly focused on the decline of soil fertility by cropping, but most of them present analytical problems and the quality of data is negatively influenced by the high heterogeneity of the soils (Weisbach et al., 2002).

Total soil carbon and nitrogen are very high in Yucatecan soils (Benjamin, 2000; Weisbach et al., 2002). Soil organic matter in Yucatecan forests averaged over 20%, which is higher than values (0.5 to 5%) for other tropical regions, and also N and P are much higher than those of other tropical dry forests (Ceccon et al., 2002). Weisbach et al. (2002) reported higher C and N content, and also a much greater accretion of soil organic matter in black soils, about twice that in red soils, even when both soils were under similar plant residue inputs explaining that this can be caused by a delayed decomposition of the plant residues or its concentration in the thin soil layer of the black soils. Higher organic matter content in black soils has been also reported by Bautista et al. (2003). These soils also differ in carbonate content, effective cation exchange capacity, primary P mineral and total P content. Red soils present lower content of all nutrients, indicating a more advance development (Weisbach et al., 2002).

Villa Clara, Cuba

The climate is tropical with a humid summer (Aw), prevailing in nearly the whole island with an alternating moisture regime. The rainy season starts in April-May and ends in November. Annual rainfall varies between 1000 and 1200 mm. Mean temperature is about 25 degrees and the hottest months are July and August and the coldest is January. Relative humidity is usually about 80% and can be near to 90% (Diaz Cisneros, 1989 cited by Villegas et al., 1994; CITMA, 2004).

Cuba, the largest island in the Greater Antilles, presented a complex geomorphology derived of its geological history (Russel et al., 2000; Soza et al., 2004; Kerr et al., 1999). The big island, where a limestone plain cover almost three quarter of its total surface (UNIDO et al., 2004), is part of a limestone platform related to the limestone areas of Florida, the Bahamas and the Yucatán (Chiappy et al, 2001).

In Cuba, agricultural surface is 62.7 % of all lands in the country, of which 76.8 % have diminished their fertility to very low levels. This has reduced potential crop yields at least in 30%. At the same time, desertification affects 14% of the country, principally in coastal areas (CITMA, 2004). Soil fertility is affected by erosion, sodicity, salinity and acidity problems, bad drainage and losses of organic matter (García and Perera, 1997; CITMA, 2004; Urquiza, 2002).

Brown calcareous soils [Orthi-Calcaric Cambisol in the FAO/UNESCO system according to Villegas et al. (1994) and Aleman et al. (2002)] account for 16% of the area of soils in Cuba (Urquiza, 2002). They have a great importance in Cuban agriculture and economy, because they cover a large area well distributed all over the island, and frequently have been used for sugarcane production; e.g. in Villa Clara they represented 32% of the area dedicated to sugarcane monoculture (Villegas et al., 1994).

The parent materials of these soils are calcareous rocks and sedimentary rocks with different carbonate content. In Santa Clara region, brown calcareous soils are developed from soft limestone and tend to contain residual carbonates and the presence of dolomite, differing from others developed in dryer areas of the country (east part), which present secondary carbonates (Cairo and Fundora, 1994). There are also serpentine minerals in the Santa Clara valley, which is surrounded by serpentinitic low hills with fersialitic soils developed over this serpentine rocks (Fundora, 1979; Torrecilla, 2005). Serpentine soils are characterized by the