UNIVERSIDAD DE LA FRONTERA

Facultad de Ingeniería y Ciencias

Doctorado en Ciencias de Recursos Naturales

"EFFECT OF TILLAGE, FERTILIZER APPLICATION AND CROP ROTATION ON SOIL PHYSICAL-CHEMICAL CHARACTERISTICS AND SOIL CARBON ACCUMULATION ON AN ANDEAN SOIL FROM ECUADOR"

DOCTORAL THESIS IN FULFILLMENT OF THE REQUERIMENTS FOR THE DEGREE DOCTOR OF SCIENCES IN NATURAL RESOURCES

Fabián Homero Salomón Montesdeoca Montesdeoca

TEMUCO-CHILE

2022

Esta tesis fue realizada bajo la supervisión del Director de tesis, Dr. Fernando Borie B. perteneciente al Departamento de Ciencias Químicas y Recursos Naturales, Facultad de Ingeniería y Ciencias de la Universidad de La Frontera y ha sido aprobada por los miembros de la comisión examinadora.

"EFFECT OF TILLAGE, FERTILIZER APPLICATION AND CROP ROTATION ON SOIL PHYSICAL-CHEMICAL CHARACTERISTICS AND SOIL CARBON ACCUMULATION ON AN ANDEAN SOIL FROM ECUADOR"

……………………………………….

Dr. Andrés Quiroz D.

DIRECTOR DEL PROGRAMA DE DOCTORADO EN CIENCIAS DE RECURSOS NATURALES

………………………………………………

Dr. Fernando Borie Borie

…………………………………………….

Dr. Roberto Godoy

……………………………………………

Dra. Claudia Castillo

....

Dra. Mónica Rubilar A.

DIRECTOR ACADEMICO DE POSTGRADO

UNIVERSIDAD DE LA FRONTERA

……………………………………………

Dr. Rolando Demanet

…………………………………………..

Dra. Paula Aguilera

Dedico esta tesis a mi esposa Gladys Beatriz, a mi hija Sara Alejandra, a mis nietos Ezequiel Alejandro y Paula Sofía.

Agradecimientos/Acknowledgments (en español o inglés)

En primer lugar, agradezco al Dr. Fernando Borie B. y al Dr. Pablo Cornejo R. por su constante apoyo durante mis estudios en el doctorado.

A la Profesora Victoria Ferrada.

Al personal directivo, docentes y secretarias del Doctorado en Ciencias de Recursos Naturales de la UFRO.

Al personal del Centro de Investigación CIMYSA.

Expreso mi gratitud para todas las autoridades de la Universidad Central del Ecuador y de la Facultad de Ciencias Agrícolas por apoyar la capacitación del personal docente.

Gracias al Dr, José Espinosa M., por su apoyo incondicional, consejos sabios y oportunos.

Al Ing. Jorge Caicedo por su apoyo en el análisis estadístico.

A la Dra. Soraya Alvarado y al personal del laboratorio de Química Agrícola y Suelos de la Facultad de Ciencias Agrícolas de la Universidad Central del Ecuador.

A mi colega María Eugenia Ávila-Salem.

Este estudio se hizo posible gracias al convenio de colaboración para estudios de doctorado UCE-UFRO 2014-2019, a través de la beca de doctorado N° 304.

Summary and thesis outline

In **Chapter I**, general introduction, hypothe**sis**, and the proposal of general and specific objectives are presented. The general objective of this Doctoral Thesis was "To compare the effect of No tillage (NT) and Conventional tillage (CT) on soil physical and chemical properties and on soil organic matter (SOM) accumulation and stabilization in an Andean soil of the northern Ecuadorian highlands cultivated with *Phaseolus vulgaris* L. - *Amaranthus caudatus* L. - *Phaseolus vulgaris* L. and *Phaseolus vulgaris* L. - *Zea mays* L. - *Phaseolus vulgaris* L. rotations under different fertilization rates*"*. A comprehensive description is also given to establish the conceptual and methodological framework of this Thesis.

In **Chapter II**, a review with the title: *No tillage, organic matter and sustainable agriculture in intertropical zones,* is presented to describe the consequences that the implementation of CT has brought to intensive soil degradation; no tillage (NT) being a alternative to CT, which consists on direct sowing without soil disturbance leaving on the surface the residues of the previous crop. NT produces positive effects on soil biological, chemical and physical characteristics, represents a net increase in SOM, better water infiltration, therefore preventing erosion; the SOM is the source of plant nutrients and food and energy for soil microorganisms, influences the microbial community composition especially arbuscular mycorrhizal fungi that produces glomalin, a glycoprotein that protects hyphae during transport of nutrients from the plant to the end of the hypha, and from the soil to the plant. To expand the efforts to promote NT, particularly on small farmers´ fields from the tropics, it is urgent to develop a package of three agronomic practices: absence of soil disturbance, retention of sufficient crop residue to provide surface coverage, and diversified rotations that include legumes.

The **Chapter III** corresponds to the published article entitled "*Early changes in the transition from conventional to no-tillage in a volcanic soil cultivated with beans (Phaseolus vulgaris L.)".* Small farmers in the Ecuadorian highlands normally use CT that consist in the remotion of the soil during seedbed preparation to eliminate weeds, improve soil aeration, avoid compaction, and develop an adequate rooting space; however, this tillage system promotes deep changes in some physical, chemical, and biology soil properties which in time have negative effects on crop performance. Most of these effects can be avoided using no-tillage (NT), but nevertheless, this tillage system is not utilized by farmers in the Ecuadorian highlands, then it was justified to compare two different tillage systems with two rotation schemes: bean - corn - bean, and bean - amaranth - bean, applying four rates of nitrogen fertilization. This report presents the initial changes on yield and some soil properties promoted by the transition from CT to NT after the cultivation of bean, the first crop in the rotation. Bean yield under NT was 42% higher than CT suggesting that the soil improvements promoted by NT were also conductive to the difference in crop yield; although in the physicochemical characteristics, only the changes in pH and gravimetric water content presented significant differences; changes in other measured soil parameters like soil organic matter, total N, available P, and bulk density were not significant, in spite of the lack of statistical significance the trend was always favorable to NT indicating that the elimination of soil movement begins to improve soil conditions for plant growth even with no fertilizers applied in such a way that these results constitute an incentive for farmers to adopt this conservation tillage system.

The **Chapter IV** corresponds to the manuscript entitled "*Effect of tillage, fertilizer rates, and crop rotations on yield, soil physical-chemical characteristics, and accumulated carbon in Ecuadorian highlands*". The objective of this report was to contrast the effects of the application of both tillage systems with different rates of nitrogen (N) on crop yield and soil physicochemical properties after three planting cycles, having completed the two proposed rotations. Bean yield in Beans-Maize-Beans (BMB) rotation with NT was 26.2% higher compared with CT and in the second rotation cycle NT cob maize yield was 75% higher than CT. However, no differences in bean yield were observed at third cycle. On the other hand, organic C and N were also higher under NT in both rotations being more evident with Beans-Amaranthus- Beans (BAB), but no differences were observed for particulate organic matter (POM). A minor E_4/E_6 ratio was only observed in BAB rotation suggesting higher SOM humification. Soil pH, available P, and K, Ca and Mg ions were variable depending on rotation and tillage systems. In general, main overall effects of tillage on bulk density and water content were higher under NT than CT but the contrary was observed with soil aggregation. Results obtained are encouraging in terms of the trend of improved soil physicochemical characteristics under NT will lead to a better crop yield, with the inclusion of amaranth crop it should be the more important factor for NT adoption by small farmers in the Ecuadorian highlands.

In the **Chapter V** it is presented ***"General discussion, conclusions, and future trends"***. At the middle of the previous century when the increase in the world population represented a great daring to increase the production of food so permitted the applied "Green Revolution" allowing the production of high crop yield and the expansion of the agricultural frontier, what has led deterioration of soil, water, and the environmental crisis that humanity currently faces; a method to produce more food without damaging the environment is the one that was tested in the present work; the findings here shown strongly suggests that both tillage management and rotation schemes have beneficial effects over the main chemical and physical soil properties of the volcanic soil used, which represent almost all the northern highlands soils from Ecuador. The fertilization rates used in this study did not have significantly influence on such properties possibly due to the relative high nutrients levels of the original soil; moreover, the novelty of this research relies mainly in the rotation scheme used; this is the first time that amaranth, an interesting highly profitable crop used in sustainable agriculture, is included in this type of studies; the amaranth rotation had a much lower E_4/E_6 ratio suggesting a faster humification rate compared with corn residues which are degraded at a slower rate. This information permitted to accept the hypothesis for this work in the sense that NT management of crop rotations, including amaranth implemented on soils from the small farmers' areas of the Ecuadorian northern highlands, improved soil physical and chemical characteristics as well as the quantity and SOM stability in comparison to CT, even in the short time. When identifying the future tasks that we should undertake to complement this research, the following emerge: evaluation of agronomic practices to improve the amaranth cultivation techniques, evaluation of the efficiency of nitrogen and phosphorus use of in corn and amaranth crops, research replication with the use of other rotation schemes under NT, and using relevant results to generate a process of technology transfer, impact, and finally it adoption.

TABLE OF CONTENTS

CHAPTER I

“General Introduction”

1.1 General Introduction

During the last century, the demographic explosion of the world population was evident, so thinkers like Malthus predicted the scourge of famines because the growth rate of the world population exceeded the growth of food production, however, thanks to the work approach of the "Green Revolution" led by Norman Borlaug, wheat varieties with higher yields were developed that spread rapidly in countries such as Pakistan and Sri Lanka, the same happened with corn in Mexico and with rice in the Philippines. This approach sits over four general pillars: 1) use of modern farm machinery, 2) food transportation from distant and disperse production fields to big consumer centres (cities with high population), 3) intensive use of agrochemical, biotechnology and genetic engineering, and 4) installation and use of sophisticated irrigation systems. Green revolution increased yields significantly, but, on the other hand, promoted the utilization of fossil fuels, the indiscriminate use of pesticides and fertilizers, the intensive soil use of the land with monoculture, the elimination of plant species considered of low interest, and sometimes inefficient water use. As a consequence, this approach stimulated the degradation of renewable resources such as soil, air and water (Glaeser, 2010; Horlings and Marsden, 2011; Kerr, 2012). Soil has been perhaps the most affected natural resource by the intensive crop production. The constant soil movement with CT has promoted radical changes of soil physical, chemical and biological properties, which in turn had negative effects on crop yields and environmental quality (Subbulakshmi, et al., 2009; Su, et al., 2021). Continuous soil movement disturbs soil porosity and upsets the water, gasses and nutrient movement, oxidizes SOM and reduces organic carbon (OC) content; processes that expose to erosion and decreases soil fertility and resilience (Lal, 2011).

An alternative to CT has been developed over the last decades, as the tillage practice known as NT, which places crop seeds in the ground without soil movement, leaving on the surface the residues of the preceding crop (Franchini, et al., 2012; Espinosa, et al., 2016; Khan, et al., 2017). This is a soil management system utilized in extensive areas of North America, and in the plains of Argentina and Brazil in South America, that has produced sustained high yields without soil movement (Wingeyer, *et al.*, 2015). In spite of NT success in extensive areas of the world, this tillage practice has not been adopted in production areas cultivated by small farmers in Central and South America. No-till could become a viable soil management alternative for most crops grown by small farmers in the condition of the highlands of Ecuador characterized by steep and long slopes, land tenure problems, and population growth which has increased land pressure forcing farmers to use marginal land in even steeper areas (Espinosa, 2014). Population growth has forced farmers to divide the land among family descendants creating a complicated network of smallholdings intensively used where agricultural production is limited by the scarce investment capital and by the adverse location and disposition of the plots on the slope which promotes severe soil erosion (Espinosa and Moreno, 2018).

There have been few attempts to implement NT on small farmer fields in the Ecuadorian highlands, apparently due to the difficulty of implementing the system on small intensively used plots (Boada and Espinosa, 2017). For this reason, there exist ample possibilities to conduct research on tillage systems in the same volcanic soils utilized by smallholders to document the effect of tillage management on soil properties and carbon dynamics. With all of the above in mind, this research project proposal aimed to compare the effects of CT and NT management on soil physical and chemical properties, carbon sequestration and SOM quality in rotation systems and fertilization schemes common to smallholders of the northern Ecuadorian highlands. Crop rotations will include alternated crops of beans - corn and bean - amaranth in five consecutive cycles. It's expected that the accumulated information will serve a support to develop more applied research and to help shaping agricultural public policies that encourage the use of NT by small farmers. Additionally, the development of information about amaranth will promote the expansion of the planted area and the utilization of a crop catalogued as super food for its unusual nutrient content (Alvarez-Jubete, *et al.*, 2010; Peralta, *et al.*, 2014) as a diverse and profitable source of income for small farmers.

1.1.1 Land tenure in the highlands of Ecuador

Changes in land tenure in the highlands of Ecuador over the last 60 years have promoted the expansion of a large group of landholders of small plots (minifundio) that use the land to develop what is known now as subsistence or family agriculture (Carrión and Herrera, 2012; Nieto and Vicuña, 2015). Analysing the land reform laws that shaped land tenure in Ecuador it can be concluded that they transformed the big land holdings (haciendas) in more efficient production units, however, they also promoted the access to the land to a high number of individuals, situation that derived in the development of extensive areas under smallholdings. Statistical data from the 1964 to 1994 period indicates that the total area affected by land reform was of 9,024 km^2, 3.4 % of the total area of the country. The extension of this area is low compared with the effect of colonization of available land, mainly in the Amazonia, also promoted by the same land reform, which incorporated 63,631 km^2 to agricultural use, 23 % of the national territory (Brassel, *et al.*, 2008; Carrión and Herrera, 2012) argue that, in spite of these changes, the basic structure of the country land tenure has not changed over the last 50 years, situation which clearly surfaced from the analysis of the 1954, 1974 and 2000 national census. Data indicate that there has been a 138 % increment in the number of holdings, and that the total agricultural land has expanded in 106 %; however, these changes have not affected land tenure patterns characterized by extensive holdings in the hand of a few land owners. In fact, data from the 1954 agricultural census indicates that 71.1 % of the production units with less than five hectares comprise only 7.2 % of the total land under agriculture and livestock, and the landholding with more than 100 hectares covered 64.4 % of the country agricultural land. In spite of the significant country increment of land under agriculture and livestock use (5´999,700 hectares in 1954 to 12´355,830 in 2000 (Brassel *et al.*, 2008), the situation in 2000, in percentage terms, is similar to that one in 1954. Land holdings with less than five hectares represented 63.5 % of the total number of holdings occupying only

6.3 % of the land under agriculture and livestock, while the holding with more than 100 hectares represented only 2.3 %, but they covered 42.6 % of the agricultural land (Brassel *et al*., 2008).

A consequence of the prevalent Ecuadorian land tenure structure has been the projection of a large group of holders of small farming plots generating a sector of the economy known as family agriculture as a synonymous of peasant agriculture or subsistence agriculture. This economic model maintains its productive rationality associated to use of the family hand labour, but it does not sustain itself in time from agricultural production along, depending on the income generated out of the farm as hired hand labour or in services to make ends meet (Brassel, *et al.*, 2008; Nieto and Vicuña, 2015). Regardless of the restrictions imposed by this production model, family agriculture not only produces for self-consumption, but also generates surplus to satisfy the demand of local markets, helps agro diversity and environment conservation, and is one of the main tools to revitalize the economy, fight poverty and provides the basis more a more just society (Carrión and Herrera, 2012).

1.1.2 Soils from the highlands of Ecuador

The Andes divides Ecuador in three natural regions: Costal Plane, Highlands and Amazonia, each one a varied system of climate, landscapes, soils and biodiversity product of the equatorial conditions of the country and the altitude. For these reasons, sunshine is not uniform in all areas of the country promoting the presence of anarchic winds and distinct pluvial regimes that control soil development and shape the unique set of soils in these distinct regions of the country (Moreno, *et al.*, 2018).

The Andean Highlands are made of the western and eastern cordilleras arranged in a north-south direction, with very steep outer slopes characterized by a gradual decline in altitude as they diffuse into the Coastal Plane or the Amazonia, and a decreasing massiveness also from north to south. Highlands are divided into three regions: Northern, Central and Southern Highlands. The Northern part received recent contributions of volcanic projections (ash and lapilli) over which diverse fertile and generally deep Andisols have been developed, characteristics closely linked to climate and parent material. The Central Highlands do not have active volcanoes or recent pyroclastic projections and parent material consists of old volcanic and metamorphic rocks in a monotonous relief. Southern Highlands are characterized by a more rugged relief over granites, metamorphic formations, tertiary sediments and glacis of colluvial deposits (Moreno, *et al.*, 2018).

As a consequence of the prevailing parental material, soil from the Northern Highlands are characterized by the presence of allophane, imogolite and humus-Al complexes clay materials which have promoted the presence of dark coloured soils, medium texture, medium fertility and slightly acid classified as Andisols, Mollisols and Inceptisols in the upper and mid sections of the internal and external flanks of the cordillera, while the bottom of the internal valleys are in part characterized by coarse textured soils classified as Inceptisols and Entisols (Moreno, *et al.*, 2018). The Central highlands developed ferralitic-fersalitic soils in the upper sectors which are moderately evolved with mollic or vertic features, but in the middle sectors and in the lowland the soils are poorly developed Inceptisols and Entisols. The Southern Highlands are characterized by ferriallitic saturated soils rich in minerals 2:1, along with desaturated ferralitic Paleosols in the upper part, but in the lower part soils are mainly Vertisoles, often surrounded by the ferriallitic Paleosols (Moreno, *et al.*, 2018).

The highlands of Ecuador have a dense concentration of rural population, promoted by the benign climate and fertile soils, which places a high pressure over the land resulting in easily observed land degradation problems, mainly soil erosion. Altitude modifies radically local climate, and this is an evident fact on the highlands of Ecuador, where a diversity of microclimates can certainly be present in relative short distances. This is the reason why a wide variety of crops is possible in tropical areas of the world like the highlands of Ecuador, particularly if water is available, facilitating continuous production all year around since climate seasons are almost imperceptible (Espinosa, 2014; Espinosa and Moreno, 2018).

1.1.3 Tillage systems

The traditional tillage system used by small farmers in the highlands removes completely the soil to prepare seed bed for planting. This traditional continuous soil movement has promoted profound changes in soil physical, chemical and biological properties with negative effects on crop yields and the environment. Farmers argue that soil disturbance is necessary to control undesirable weeds, to allow better air movement through the soil profile, to avoid soil compaction, and to develop a suitable medium for root growth (Espinosa, 2014). However, the constant soil alteration destroys soil pores, particularly macro pores, affecting the movement of water, gases and nutrients as a result of soil structure alteration. Soil movement also oxidizes OC and significantly reduces its content in the soil (Al-Kaisi and Yin, 2005; Bronick and Lal, 2005). All of these conditions upset crop growth because they decrease soil resistance to compaction and erosion and they affect soil resilience to stress conditions (Craswell and Lefroy, 2001; Wingeyer, *et al.*, 2015). There is limited information about the effects of soil disturbance through tillage on the highlands of Ecuador, but land degradation problems are evident on most of the landscapes (Alwang, *et al.*, 2013; Espinosa, 2014).

The introduction of mechanized soil movement using tractors on the highlands of Ecuador encouraged land degradation in occasions revealed as dramatic losses of huge amounts of soils when tractors are driven down the slope to prepare the soil, leaving the ground in the most open condition to erosion. Tractors are common and freely owned or leased among the farmer communities in the highlands. In the absence of tractors, soil removal is conducted by team of oxen or simply using hand tools with almost the same damage to the soil (Espinosa, 2008; Espinosa, 2014; Boada and Espinosa, 2017). As a consequence of land management, erosion is perhaps the more severe environmental problem of Ecuador affecting more than 50 % of cultivated land of the country (Alvarado, *et al.*, 2011; Espinosa and Moreno, 2018). No matter the way soil is tilled, the practice leaves no residue on the ground condition which becomes even worst because any residue left on the ground is either burned on site or used by the farmers as firewood or to feed animals (Dercon, *et al.*, 2007; Espinosa, 2014). Erosion has reduced soil fertility of farmers' fields and the lack economic resources make it difficult to replenish nutrients to maintain crop yields. As a consequence, crop growth is limited and not uniform and biomass accumulation is not enough to cover the ground during the crop cycle, and crop yields are constantly lower over the time. Unprotected bare soils are common all over the highlands of Ecuador. As erosion advances, top soil is eliminated and poor hard sub soil appears as an unproductive matrix of hardened material known as cangahua (Espinosa and Moreno, 2018).

Erosion control methods aimed to protect soil surface and to reduce the volume and speed of water runoff are not unknown or difficult to implement. However, small farmers in the highlands see these practices rather as a nuisance because they force them to manage the plots in a different way. Apparently, traditional land management is simpler and quicker, however, this simplification does not take in account social and economic factors that also influence farmer management decisions and that should analyse to propose changes in soil management (Carrión and Herrera, 2012; Alwang, *et al.*, 2013; Espinosa and Moreno, 2018).

No till is one of the soil conservations practices that effectively control soil erosion. This practice does not remove the soil to localize the seed on the ground and leaves on the surface the residues from the preceding crop (Six, et al., 2002; Bronick and Lal, 2005; Soracco, et al., 2010; Lal, 2011; Derpsch, et al., 2014; de Moraes, et al., 2016). This tillage system is widely used in extensive agricultural areas form North America and in the plains of Argentina and Brazil with an intensive use of farm machinery which has stimulated the production of high sustainable yields without soil removal (Kassam, *et al.*, 2010; Wingeyer, *et al.*, 2015). Regardless of its success in extended areas of the world, NT has not been adopted in the agricultural areas in the hands of small farmers in Central and South America. No till is ideal for crops like open pollinated corn and beans common for the highlands and their crop management could be easily adapted to this tillage system (Boada and Espinosa, 2017).

There is scarce published information about NT adoption in Ecuador, particularly in the volcanic highlands of the country. The scanty research work conducted during the past few years reported no difference in soil properties and crop yields when comparing NT with CT. In this context, the first documented NT experimental work was conducted on the coastal plane from 1985 to 1990 at the INIAP Pichilingue Experiment Station; data from the experiments demonstrated that NT can control erosion and maintain soil productive capacity by increasing residual soil moisture, however, this study does not report the effect of NT adoption on soil properties (INIAP, 1990). Subsequently, Estrada and Calvache (2004) working with a bean-corn association under NT, minimum tillage (MT), and CT found that NT increased soil compaction, but no changes were reported in soil chemical properties or crop yield. Studies conducted by Vinueza and Calvache (2004) using open pollinated maize to evaluate the effects of NT, MT, and CT, reported no differences in soil physical-chemical properties or crop yield in response to tillage management. The lack of response in the three previously mentioned studies is probably due to the short duration of the field work (one crop cycle). Research conducted by Acosta y Galárraga (2011) in Santo Domingo de los Tsáchilas evaluating the effect of NT on two consecutive cycles of hybrid corn found a slight increment in SOM content compared to CT, but no change was found in chemical soil properties. Too experimental work conducted by Alvarado, *et al.* (2011) in small farmers fields in the provinces of Pichincha and Bolivar demonstrated not only that NT was feasible in these conditions, but also that it was possible to attain open pollinated corn grain yields as high as those obtained with CT (5.2 t ha^{-1} for Bolivar and 7.1 t ha^{-1} for Pichincha). On the other hand, Arevalo (2011) and Alwang, et al. (2013) studying the response of NT, MT, and CT introduced a crop rotations component (barley, broad beans, and a mixture of oats-vetch) in the experiment, prolonging the evaluation to three continuous crop cycles. Reported results indicate that, in general, crop yields were slightly higher with NT, but they exceeded in 10 % the rate of return because the cost reduction and productivity improvement when tillage was avoided. At the same time increments in SOM and water holding capacity were reported for the NT treatment.

It has been widely demonstrated the beneficial effect of NT adoption on soil properties. For example, continuous soil management with NT on poor, acid Oxisols from Brazil have improved physical soil characteristics in the upper strata of the soil profile (<10 cm) attaining higher water retention in comparison with CT (Derpsch, *et al.*, 2010; Soracco, *et al.*, 2012; de Moraes, *et al.*, 2016). Similar behaviour is expected in volcanic soils from the highlands of Ecuador. Mechanisms of improved water retention are directly related to the effect of soil management on structure, expressed as aggregate stability. Aggregation is the result of flocculation and cementation of soil particles as SOM content increases (Six, *et al.*, 2002; Six, *et al.*, 2002). Soil structure can be significantly modified by NT management which increases the content of SOM and soil microorganisms' activity especially fungal hyphal action through entangling and enmeshing soil particles and aggregates due to their filamentous growth from hyphae (Six, *et al.*, 2002; Bronick and Lal, 2005; Lal, 2006; Borie, *et al.*, 2008; Lal, 2011).

No till also modifies chemical soil characteristics situation that has been documented in wide arrange of soil types in the world. Nine years of continuous NT in semiarid zones of Australia increased the content of SOM, nitrogen (N) and exchangeable cations in the upper 10 cm of the soil profile (Thomas, *et al.*, 2007). The effect adoption and continuous implementation of NT for more than 20 years in Mollisols from the USA and Uruguay, Oxisols from Brazil and Andisols from Chile increased SOM and N content. These studies also demonstrated the stratification of the NT effect in the soil profile showing that SOM and N were concentrated in the upper 10 cm from the soil surface, mainly due to the absence of soil movement (Borie, *et al.*, 2006; Salvo, *et al.*, 2014; Wingeyer, *et al.*, 2015).

Residue accumulation on the soil surface and the consequent increment of soil organic carbon (SOC) after eliminating soil movement is perhaps the most important product of NT adoption; however, it's interesting to emphasize the stratification of SOC content in the profile once NT has been stabilized completely after several years of adoption. There exists abundant information on SOC stratification which document that SOC accumulates in the first 5 cm of the profile which then gradually decreases in the 5-10 and 10-30 cm layers (Green, *et al.*, 2007; González-Barrios, *et al.*, 2011; He, *et al.*, 2011). The stratification also has brought the consequent segregation of the physical, chemical and biological properties in the same soil layers (Lupwayi, *et al.*, 2006; He, *et al.*, 2011). It has been clearly demonstrated that CT liberates CO_2 to the atmosphere, contributing to the greenhouse effect, and that the adoption of NT significantly reduced CO_2 evolution, however, it has also has been demonstrated that NT promotes the liberation of N_2O, a strong greenhouse gas, due to processes associated to the increase of nitrification in soils under NT (Muñoz, *et al.*, 2011; Dendooven, *et al.*, 2012; Abdalla, *et al.*, 2013).

1.1.4 Crop rotations

No till is the best alternative for soil conservation, but to optimize its performance the adoption of a good crop rotation system is needed. Crop yields and soil performance depend upon the crop sequence over time because rotations control SOM accumulation, nutrient balance, and water use, and have an inhibitory effect on diverse soil pathogens (insects and diseases) and weeds. Crop rotations and a dense soil biomass protective layer regulate water and nutrient cycles which promote high crop yield and an efficient use of agricultural inputs (Fan, *et al.*, 2012; Castilla, 2013; Plaza-Bonilla, et al., 2016; Raphael, et al., 2016; Kazula, *et al.*, 2017) It advisable to use crop rotations with a high capacity to produce root biomass to prevent the formation of compacted strata and to improve soil physical quality (Munkholm, *et al.*, 2013).

Crop rotations that include legumes and cereals reduce mineral N application and nitrate leaching losses. The alternate use of these crops improves biomass accumulation in the root zone and the quality and quantity of root exudates, increases microorganisms' population and soil aggregation which protects SOM and N mineralization (Six, and Paustian, 2014; Cates, *et al.*, 2016; Plaza-Bonilla, *et al.*, 2016).

The inclusion of amaranth in the rotation scheme of this project proposal surges as a new, social, economic and dietary alternative for small farmers from the highlands of Ecuador. For its nutritional quality, amaranth is catalogued as the best food of vegetal origin for human consumption (National Research Council, 1984; Mlakar, *et al.*, 2009; Vega-Gálvez, *et al.*, 2010). Amaranth can be easily industrialized in a series of widely accepted gluten free and protein and fiber rich products such as snacks, baby foods and breakfast cereals (Raja, *et al.*, 2012; Diaz, *et al.*, 2013). Amaranth production and industrialization can open an economic perspective for familiar agriculture operating at northern Ecuadorian highlands (Diaz, *et al.*, 2013; Peralta, *et al.*, 2014).

Amaranth can fit in the NT systems due to its high biomass production which can leave large amounts of residues on the ground. This crop grows better in the climatic altitudinal range of 1500 and 2800 m above the sea level, so it grows well on the inner lower valleys of the highlands where the mean annual temperatures are around 15° C, however, its susceptible to low temperatures and places susceptible to frost are to be avoided (Peralta, *et al.*, 2014).

1.1.5 Nutrients management

Crop nutrition enhances the effect of NT on soil properties and yields of the crops included in the rotations (Mazzoncini, *et al.*, 2011; de Moraes, *et al.*, 2016). Nutrient output of accumulated nutrients in harvested portion of the crops reduces soil nutrient content and should replenished to maintain soil fertility and sustain crop productivity (Mazzoncini, *et al.*, 2011; El-Ramady, *et al.*, 2014; Havlin, *et al.*, 2014). Small farmers' fields from the highlands usually are nutrient deficient due to high output and limited input from external sources and even from internal sources due to the use of plant residues for other purposes. The situation leads to poor crop harvests which only accentuates poverty and keeps degrading soil resources (Espinosa, 2014; Boada and Espinosa, 2017). Research conducted in volcanic soils from the northern highlands of Ecuador demonstrated that main nutrients that limit crop yields are N and phosphorus (P) (Alvarado, *et al.*, 2011; Gallager, *et al.*, 2017). For these reasons, it makes only sense to study nutrient response to inorganic and organic sources in NT systems established in common rotation from highlands.

1.2 Hypothesis

No-till management of crop rotations, including amaranth, implemented on soils from the small farmer's areas of the Ecuadorian northern highlands will improve soil physical and chemical characteristics and the quantity and quality of SOM, in comparison to conventional tillage (CT) even in the short time.

1.3 General objective:

To compare the effects of NT and CT on soil physical and chemical properties and on the accumulation of stabilized SOM in an Andean soil of the northern Ecuadorian highlands cultivated with beans - corn and bean - amaranth rotations under different fertilization rates.

1.4 Specific objectives:

- To establish a benchmark data base of soil physical and chemical characteristics of the soil utilized in this study which was previously utilized to grow corn, potato and pastures.
- To compare, on the medium term, the effect of NT and CT systems over the main soil physical and chemical characteristics, as well as, on the quantity and quality of SOM.
- To evaluate the agronomic development and productive performance of the beans – corn and beans – amaranth rotations under the two tillage systems as individual crops and as a part of the rotation and tillage scheme.

CHAPTER II

"No Tillage, Organic Matter and Sustainable Agriculture in Intertropical Zones: A Review"

NO TILLAGE, ORGANIC MATTER AND SUSTAINABLE AGRICULTURE IN INTERTROPICAL ZONES: A REVIEW

Abstract

Conventional tillage (CT) is the soil physical conditioning by removal to facilitate the uniform and rapid plantlet emergence after seed germination that also promotes plant establishment and deep root penetration, facilitates fertilizer and agricultural residue incorporation and controls weed germination; however, continuous CT utilization has produced negative effects leading to intensive soil degradation. No tillage (NT) is an alternative to CT, which consists on direct sowing without soil disturbance leaving on the surface the residues of the previous crop. With NT adoption there is a net increase in soil organic matter (SOM), better water infiltration, therefore preventing erosion. Besides, NT produces positive effects on soil biological, chemical and physical characteristics. Soil organic matter consists of unrecognizable partially decayed plant residues, soil microorganisms, soil fauna, and the byproducts from the decomposition/synthesis of carbonaceous compounds that lead to the production of stable compounds in the soil called humic substances (HS). It has been argued that the accumulation of soil humic substances is not relevant in agricultural systems and the practice to increase the stable soil humus content through agricultural practices based on the humification model seem contradictory since soil organic carbon (SOC) is most important when soil organic substances decompose releasing nutrients and energy, and the process of continuum decomposition is more important that the nonproductive organic carbon deposits. Consequently, the easily decomposable active fraction of the SOM is more relevant in terms of biological and chemical activity. This fraction, named particulate organic matter (POM), is made of particles of < 2 mm and > 0.053 mm in size and is the source of plant nutrients and food and energy for soil microorganisms, increases pH buffering and cation exchange capacity and binds pollutants like pesticides and heavy metals. No till noticeably increases soil aggregation since the increment on SOM content has profound effects on soil particle clumping. Aggregation physically protects SOM, influences size and structure of the microbial community, promotes oxygen diffusion and regulates water flow. In addition to the tillage system, the formation, persistence and size of soil aggregates are influenced by the roots that develop and decompose in the soil. No till influences the microbial community composition especially arbuscular mycorrhizal fungi that produces glomalin, a glycoprotein that protects hyphae during transport of nutrients from the plant to the end of the hypha, and from the soil to the plant. Good farming practices, such as NT, favor ecosystem services. The main ecosystem services provided by NT are climate regulation, air pollution reduction, soil carbon accumulation, reduced greenhouse gas emission, improved water cycle, soil quality improvement and preservation, soil nutrient provision, wind and water erosion control, better control of pests (insects and diseases) and, fundamentally, sustainable food production. To expand the efforts to promote NT, particularly on small farmers´ fields from the tropics, it is necessary to develop a package of three agronomic practices: absence of soil disturbance, retention of sufficient crop residue to provide surface coverage, and diversified rotations that include legumes. This review summarizes the current knowledge about no-till technology and its impacts on soil properties related to carbon dynamics and explores the potential role of tillage practices in mitigating climate change in zones of under tropical influence.

Keywords: No tillage, soil organic matter, aggregates, arbuscular mycorrhizal fungi, glomalin.

2.1 Introduction

Agriculture developed around 13,000 years ago, being the human activity that produced the most important changes in the conformation of present civilization. The growth of human nucleus with large individual concentrations would not have been possible without a sufficient surplus of food (Lal, *et al.*, 2007). Agriculture adopted a number of practices as crop production developed in established fields, situation which finally led to the adoption of soil turn over or tillage as a common practice for soil preparation for seed bed. During the last century, agricultural production increased substantially taking advantage, among other things, of the development of improved varieties of agricultural plant species, availability of pesticides and fungicides, intensive use of water and agricultural machinery, condition which stimulated high productivity per unit of area, bringing, on the other hand, an intensive degradation of natural resources such as soil and water (Cooper, *et al.*, 2016; Lal, *et al.*, 2007). Soil has been perhaps the most affected natural resource by the intensive crop production. The constant soil movement with conventional tillage (CT) has promoted radical changes of the soil physical, chemical and biological properties, which in turn produce negative effects on crop yields and environmental quality (Martínez, *et al.*, 2008). Continuous soil movement disturbs soil porosity and upsets water, gasses and nutrient movement, oxidizes SOM and reduces organic carbon (OC) content; processes that expose to erosion decreasing soil fertility and resilience (Lal, 2011).

The tropical areas of world are located between 23° to the north and the south of the equatorial line limited by the circle marking the tropics of Cancer and Capricorn, respectively. A variety of soils are present in this land strip, among them the volcanic ash derived soils. Approximately 60 % of volcanic soils are present in tropical areas in countries such Bolivia, Colombia, Ecuador, Panama, Costa Rica, Guatemala, México, Sudan, Nigeria, Somalia, Etiopía, Omán, India, Myanmar, Vietnam, Indonesia, Papua, Nueva Guinea (Takahashi and Shoji, 2002). In the case of Ecuador, more than 30 % of its soils are of volcanic origin, most of them located in important agricultural areas. In Ecuador, the Andean Highlands are made of the western and eastern cordilleras arranged in a north-south direction, with very steep outer slopes characterized by a gradual decline in altitude as they diffuse into the Coastal Plane or the Amazonia, and a decreasing massiveness also from north to south. Highlands are divided into three regions: Northern, Central and Southern Highlands. The Northern part received recent contributions of volcanic projections (ash and lapilli) over which diverse fertile and generally deep Andisols have developed, characteristics closely linked to climate and parent material. The Central Highlands do not have active volcanoes or recent pyroclastic projections and parent material consists of old volcanic and metamorphic rocks in a monotonous relief. Southern Highlands are characterized by a more rugged relief over granites, metamorphic formations, tertiary sediments and glacis of colluvial deposits (Moreno, *et al.*, 2018).

As a consequence of the prevailing parental material, soil from the Northern Highlands are characterized by the presence of allophane, imogolite and humus-Al complexes clay materials which have promoted the presence of dark colored soils, medium texture, medium fertility and slightly acid classified as Andisols, Mollisols and Inceptisols in the upper and mid sections of the internal and external flanks of the cordillera, while the bottom of the internal valleys are in part characterized by coarse textured soils classified as Inceptisols and Entisols (Zehetner, *et al.*, 2003; Moreno, *et al.*, 2018). The Central highlands developed ferralitic-fersiallitic soils in the upper sectors are moderately evolved with mollic or vertic features, but in the middle sectors and in the lowland the soils are poorly developed Inceptisols and Entisols. The Southern Highlands are characterized by fersiallitic saturated soils rich in minerals 2: 1, along with desaturated ferralitic Paleosols in the upper part, but in the lower part soils are mainly Vertisoles, often surrounded by the fersiallitic Paleosols (Moreno, *et al.*, 2018).

The highlands of Ecuador have a dense concentration of rural population, promoted by the benign climate and fertile soils, which places a high pressure over the land resulting in easily observed land degradation problems, mainly soil erosion. Altitude modifies radically local climate, and this is an evident fact on the highlands of Ecuador, where a diversity of microclimates can certainly be present in relative short distances. This is the reason why a wide variety of crops is possible in tropical areas of the world like the highlands of Ecuador, particularly if water is available, facilitating continuous production all year around since climate seasons are almost imperceptible (Espinosa, 2014; Espinosa and Moreno, 2018).

As in other regions of the world, plowing has also been used in the tropical areas as an important soil management practice, having the same consequences in land degradation, especially on soil erosion (Lal, 2006; Lal, *et al.*, 2007; Cooper, *et al.*, 2016). The processes of erosion and degradation are accelerated when agriculture is conducted on steep slopes as in the case of the Andean highlands of Ecuador (Espinosa, 2014; Espinosa and Moreno, 2018). Additionally, both water and wind erosion is exacerbated by plowing soil removal which loosens the soil, buries crop residues and exposes the soil to high intensity rainfall and high wind speed conditions that that lead to severe erosion (Lal, *et al.*, 2007; Derpsch, *et al.*, 2010). Intensive tillage systems promote the rapids degradation of crop residues leaving a bare soil surface which can easily be affected by rain drops leading to surface sealing and crusting that may prevent seed germination. Constant soil alteration destroys soil pores, particularly macro pores, affecting the movement of water, gases and nutrients as a result of soil structure alteration. Soil movement also oxidases OC and significantly reduces its content in the soil (Al-Kaisi and

Yin, 2005; Bronick and Lal, 2005). All of these conditions upset crop growth because they decrease soil resistance to compaction and erosion and they affect soil resilience to stress conditions (Wingeyer, *et al.*, 2015; de Moraes, *et al.*, 2016; Indoria, *et al.*, 2017; Khan, *et al.*, 2017). Sediments originated from erosion fills streams, rivers, reservoirs, lakes and roadside ditches, reducing their useful life and producing other deleterious effects as eutrophication. Others important forms of soil degradation originated by plowing are soil compaction, acidification, and salinization (Acevedo, 2003; Lal, *et al.*, 2007; Cooper, *et al.*, 2016).

Conservation tillage can address some of the issues generated by CT and provides alternatives that are environmentally and economically compatible while maintaining a high degree of social acceptability. Conservation tillage practices include, amongst others, strip tillage, cover cropping, contour farming, mulch tillage, reduced tillage, and no-tillage (NT) which have the ultimate objective of reducing or eliminating soil removal (Blanco-Canqui and Lal, 2004; Tormena, *et al.*, 2017). Agricultural practices which allow the transition from reduced soil removal to the complete elimination of plowing (NT) have significant implications for environmental quality due to their effectiveness in controlling soil erosion and runoff, increasing water infiltration, enhancing soil organic matter (SOM) concentration, increasing soil biological activity, and saving energy. The transition to NT also has technical implications for farmers in determining crop rotations and cover crops, selecting suitable soil type, managing residues, selecting crop varieties and seeding rate, controlling pests, managing soil fertility and pH, and choosing the right equipment, as a holistic way to implement a sustainable-high-yield agriculture (Acevedo, 2003; Crovetto, 2006; Derpsch, *et al.*, 2010; Huang, *et al.*, 2012).

In general, NT can provide most of the above beneficial functions, also improving some other ecological services in agroecosystems. For example, diverse studies show that

NT also increases water accumulation, storage and management, provides storm protection and flood control, strengthens nutrient cycling and C and N fixation, increases C sequestration in soils and trees, promotes the presence of farm wildlife which helps pest and disease control, increases biodiversity, cleans water and air, increases aesthetic value, provides recreation and other amenities, and provides jobs contributing to the local economy (Derpsch, *et al.*, 2010; Huang, *et al.*, 2012). However, among the most important factors in determining soil quality appears SOM accumulation and reduction of carbon dioxide (CO_2), nitrous oxide (N2O) and methane (CH_4) emissions, which are greenhouse gases (GHG) and some of the most important contributors to global climate change. Based on the above, this review is aimed to compile updated information on the effects of the main agricultural management practices on soil physical and chemical characteristics in zones under tropical influence. We hope that this information can facilitate the design, validation and implementation of sustainable agricultural systems in tropical soils under a context of intense land pressure and climate change.

2.1 Tillage Systems: definitions and classification

Tillage is the physical conditioning of the soil by removal to facilitate the easy emergence of the plantlet after seed germination and to promote plant establishment and deep root penetration, but also facilitates the incorporation of fertilizers and agricultural residues from the previous crop into the soil and controls weed germination (Derpsch, *et al.*, 2014; Lopez-Bellido, *et al.*, 2017).

There are different types of soil tillage, but the most contrasting are conventional tillage (CT) and NT. Conventional tillage accomplishes disturbance using machinery (plowing) that partially or totally cuts or reverses the first 15 - 20 cm soil layer. As a consequence, soil loosens, aerates and mixes facilitating water penetration, nutrient mineralization and reduction of animal and plant pests (Acevedo, 2003; Lal, *et al.*, 2007; Cooper, *et al.*, 2016). In general, the principle aim of CT is the inversion of the soil to control weeds, which is followed by several other operations for soil preparation and planting. However, continuous application of intensive CT produces other deleterious effects such as bare and compact soils, which in fact facilitate soil erosion and prevent proper development of roots, having ultimately an important impact on the soil quality and plant growth (Acevedo, 2003; Martínez, *et al.*, 2008).

In contrast, NT is an alternative to CT or mechanized tillage, which consists on the direct sowing without soil disturbance leaving on the surface, totally or partially, the residues of the previous crop depending on their amount and quality. Some studies have shown that after certain time of NT adoption there is a net increase in soil organic matter (SOM) and better water infiltration, because residue accumulation reduces surface sealing caused by the impact of raindrops, improving water infiltration and reducing runoff speed, therefore preventing erosion, maintaining soil moisture, reducing weed germination, and finally lowering production costs due to less use of machinery (Acevedo, 2003; Baker, *et al.*, 2006; Martínez, *et al.*, 2008; Derpsch, *et al.*, 2010).

2.3 Beneficial effects of No Till

No till produces positive effects on the soil biological, chemical and physical characteristics (Sapkota, et al., 2012; Margenot, et al, 2017; Tormena, et al., 2017) (**Annexed 1 and 2**). Regarding to the improvement of soil biological conditions, it has been demonstrated that NT increases the quantity of soil bacterial and fungal communities including arbuscular mycorrhizal fungi (AMF) which regulates soil structure by diverse mechanisms when associated with plant roots (Borie, *et al.*, 2008; Brito, *et al.*, 2012; Hu, *et al.*, 2014; Dai, *et al.*, 2015; Santander, *et al.*, 2019; Avila- Salem et al, 2020).

A product of AMF is glomalin, a glycoprotein, which forms part of fungi hyphae the cell wall, however, its effect on soil aggregation is not entirely clear (Rillig and Mummey, 2006), but it has been proposed that glomalin is operationally related to soil proteins (Glomalin-Related Soil Protein, GRSP) which act as a hydrophobic adhesive of the elementary particles helping the formation of soil aggregates (Driver, *et al.*, 2005; Rillig and Mummey, 2006). Since glomalin is a recalcitrant compound, this glycoprotein cannot be used as a signature molecule for living AMF (Borie et al., 2008; Grumberg, *et al.*, 2010; Hu, *et al.*, 2014; Dai, *et al.*, 2015).

Considering the importance of soil organic compounds, their quantity, composition, persistence and role played in soil C sequestration, they deserve a in depth characterization, in especial regarding to the main agricultural management practices such as soil tillage and crop rotation. Soil organic matter consists of unrecognizable partially decayed plant residues, soil microorganisms, soil fauna, and the by products from the decomposition of carbonaceous compounds that lead to the production of stable compounds (Havlin, *et al.*, 2014). It have been proposed by many authors that the majority of organic stable components in the soil correspond to humic substances (HS) (Baldock and Broos, 2012; Kachari, *et al.*, 2015) which affect colour, increases soil aggregation and its water stability, increases cation exchange capacity and liberates nitrogen (N), phosphorus (P) and other nutrients during its slow mineralization/decomposition (Lassaleta, *et al.*, 2014; Margenot, *et al.*, 2017; Ranaivoson, *et al.*, 2017; Houlton, *et al.*, 2019). Humus is formed by complex humic substances (fulvic acids, humic acids and humins), compounds that remain in the soil after the decomposition of the residues. The functional groups are primarily -COOH groups, -OH groups from phenols and alcohols, and a small amount of ketone oxygen. Humic acids (HA) are the largest of the HS having a molecular weight comprised from

10,000 to 100,000 Daltons, and, in general, contain 56 % C, 5.5 % H, 4 % N, and 33% O. Compared to fulvic acids (FA), HA contain more S and P. The high oxygen content of the FA relative to the HA is a result of much higher -COOH and -OH content. Both FA and HA are adsorbed to clay minerals and hydrous oxides by polyvalent cations such as Ca^{2+} and Fe^{3+}. Humins fraction (Hu) is more strongly bound to minerals and have a C content in excess of 60 % (Piccolo, 2001; Canellas and Façanha, 2004).

The identification of HA and FA has been achieved through visible ultraviolet electroscopy using the light of the visible, ultraviolet (UV) and near infrared region of a wavelength ranging 380 to 780 nm. The radiation absorbed by the molecules from this region of the spectrum produces quantifiable electronic transitions. UV-visible spectroscopy is used to identify some functional groups of molecules and to determine the content and strength of a substance. The absorbance ratio of 465 and 665 nm, commonly called the E_4 / E_6 ratio, is used to characterize the humification time, the degree of condensation, the relative molecular weight, the aromaticity of the humic acids and fulvic acids. It was been found that this ratio is less than 5 for HS, while for AF it ranges from 6 to 8.5. It is also suggested that aromatic substances give a lower ratio and a longer residence time, whereas aliphatic substances result in a higher ratio and a shorter residence time (Bonometo, 2010; de Moura Luz, 2013; Kachari, et al., 2015).

On the other hand, Lehmann and Kleber (2015) argue that accumulation of soil humic substances is not relevant in agricultural systems and suggests that the humification model of soil carbon accumulation should be abandoned. The practice to increase the stable soil humus content through agricultural practices based on the humification model seem contradictory since soil organic carbon is most important when soil organic substances decompose releasing nutrients and energy, and the process of continuum decomposition is more important that the nonproductive organic carbon deposits. Few studies evaluating the relation among SOM and crop productivity have reported positive results, however, several studies have demonstrated that the biological and chemically active fraction of the SOM is easily decomposable. This fraction, named particulate organic matter (POM), is made of particles of less than 2 mm and greater than 0.053 mm in size. The POM is a source of plant nutrients, food, and energy for soil microorganisms, increases pH buffering and cation exchange capacity and binds pollutants; this fraction organic matter also influences the dynamics of diseases present on the soil (Pikul, *et al.*, 2009). The determination of POM in the lab, as a management tool, is strongly suggested (Galantini, *et al.*, 2007; Bongiovanni and Degioanni, 2012; Six and Paustian, 2014).

2.4 Soils protection and its relation to soil aggregation and structure

No till noticeably increases the soil aggregation since the increment on SOM content (Tivet, et al., 2013; Gupta, and Germida, 2015; Margenot, et al, 2017) has profound effects on soil particles clumping, and soil aggregation influences the dynamics of soil processes (Six and Paustian, 2014; Gupta and Germida, 2015). This way, aggregation physically protect SOM (Six, *et al.*, 2000; Six, *et al.*, 2002; Martínez, *et al.*, 2008), influences microbial community in terms of size and structure (Riley, *et al.*, 2008; Sapkota, *et al.*, 2012; Gupta and Germida, 2015), promotes oxygen diffusion and regulates water flow (Blanco-Canqui and Lal, 2004; Lal, 2006; Strudley, *et al.*, 2008; Six and Paustian, 2014), determines nutrient adsorption and desorption form exchange sites (Crovetto, 2006; Thomas, *et al.*, 2007; Derpsch, *et al.*, 2010; Divito, *et al.*, 2011), and strongly reduce run-off and erosion (Lal, 2006; Lal, 2011), among others.

Particles in the soil are not present as individual entities, with the exception of sandy soils, but they are usually united resulting in discrete clumps, resulting in composite or aggregate structural units. An aggregate is a three dimensional unit of soil structure that results from the union of individual particles formed by natural processes and the internal cohesion is due to the presence of various forces acting between soil particles (Porta-Casanellas, *et al.*, 2011; Asano and Wagai, 2014). The aggregates (secondary level of structural complexity) are composed of mineral associated OM and POM, together with microorganisms and microbial products (Six, *et al.*, 2000; Six, *et al.*, 2002; Salvo, *et al.*, 2010; Sapkota, *et al.*, 2012). A soil with good structure is easy to cultivate, water and the air circulate effectively through soil profile, roots of the cultivated plants develop well and it stands rain or wind erosion (Lal, 2006; Porta-Casanellas, *et al.*, 2011; Asano and Wagai, 2014).

According to their size, aggregates can be large macro-aggregates (>2000 μm), small macro-aggregates (250–2000 μm), and micro-aggregates (53–250 μm), complemented by silt and clay fractions (<53 μm) (Hurisso, *et al.*, 2013). The size and stability of the soil aggregates is strongly influenced by the type of cementing agents, clay particles bonded through ionic charges, rootlets and hyphal fungi (Blanco Canqui, 2012; Torres-Guerrero, *et al.*, 2013).

In order to understand the relationship between soil fertility, formation and stability of soil aggregates and soil management systems its necessary to address the subjects of aggregates hierarchy, the role of plant roots in the formation of aggregates, the quality of SOM, the size of the aggregates and finally the relation of them with tillage systems. The classical models of soil aggregation state that the aggregate organization involves organic binding of primary soil particles into micro-aggregates that encapsulate SOC forming macro-aggregates. Modern models propose instead that micro-aggregates occluding SOC are actually formed within the macro-aggregates rather than vice versa (Blanco Canqui, 2012; Six and Paustian, 2014; Lehmann and Kleber, 2015). Micro-aggregates, in interaction with decomposed organic materials develop within macro-aggregates before releasing new micro-aggregates for the next cycle of macro-aggregation. Both models recognize that C rich fresh plant residues are responsible for the formation and stabilization of macro-aggregates (Six, *et al.*, 2000; Blanco Canqui, 2012; Asano and Wagai, 2014; Six and Paustian, 2014).

Two sets of observations can be used to identify the existence of aggregate hierarchy in a soil: (1) an increase in C concentration with increasing aggregate size; and (2) a higher content of new and more labile C (having a higher C:N ratio) in macro-aggregates than in micro-aggregates (Six et al, 2014). Thus, NT can be used as a way of C accumulation in soil surface. It's well known that there is an excess atmospheric CO_2, while it is scarce in soils; therefore, NT is a good alternative practice to harvest the CO_2 from the air and store it in the soil (Crovetto, 2006; Power, 2010; Palm, *et al.*, 2014; Stevenson, *et al.*, 2014).

The other hand, SOM is in a continuous state of transformation with no defined limits and theoretically it is possible to define several discrete compartments with a negative relation between size and rate of decomposition, realizing that the most abundant fractions decompose slowly (Six, *et al.*, 2002). The ability to decompose (lability) of each of these compartments will depend on the chemical composition, C: N ratio, state of humification and its position within the soil matrix and on microbial activity (Six, *et al.*, 2002). Two fractions with different characteristics, composition and functions can be distinguished: the stabilized SOM associated to the soil mineral fraction and the young or POM (Galantini, *et al.*, 2007; Bongiovanni and Degioanni, 2012; Six and Paustian, 2014).

Particulate organic matter is the active pool of SOM comprised mostly of coarse and fine but unstable organic detritus in various stages of decomposition and constitutes between 10–20% of the total SOM. It differs from the passive organic pool because it is readily decomposable. Free POM from coarse residues in contact with the soil adsorbs soil particles through microbial colonization, forming clusters of macro-aggregates. The POM fraction within micro-aggregates is protected from microbial decomposition (Six and Paustian, 2014; Lehmann and Kleber, 2015). In this sense, it is noticeable that residence time of C increases with decreasing aggregate size. Losses of SOC from macro-aggregates are faster and larger than those from micro-aggregates (Blanco-Canqui and Lal, 2004). Oorts, *et al.* (2007) report than most of the surplus C and N stocks under NT, compared with CT, was situated in aggregates larger than 250 µm. This supports the initial idea of physical protection of OM by soil aggregates and is consistent with Blanco-Canqui and Lal (2004) and Six and Paustian (2014), who reported that micro-aggregates (< 250 µm) are less sensitive to management systems than macro-aggregates (> 250 µm). Some authors found that the increase in C concentration was mainly due to considerably greater POM concentrations.

Lehmann and Kleber (2015) favor a soil continuum model that focuses on the ability of decomposer organisms to access SOM and on the protection of SOM from decomposition provided by soil minerals. In the continuum model concept, OM exists as a continuum of organic fragments that are uninterruptedly transformed by the decomposer community towards smaller molecular size. The breakdown of large molecules leads to a decrease in the size of primary plant material with concurrent increases in polar and ionizable groups, and thus to increased solubility in water. At the same time, the opportunity for protection against further decomposition increases through greater reactivity towards mineral surfaces and incorporation into aggregates.

2.5 The roots and soil aggregates

In addition to the tillage system, the formation, persistence and size of soil aggregates are influenced by the roots that develop and decompose in the soil. Some crops generate meso and macro-aggregates as a result of the penetration of their radical systems and their subsequent decomposition, releasing MO that serves as the aggregating material (Micucci and Taboada, 2006; Gregory, 2010; Lipiec, *et al.*, 2012;). This process triggers a synergistic effect between root penetration and the activity of soil fauna, especially earthworms, which in their wake create galleries that can be used by the roots for their growth. Worms help stabilize the soil structure by ingesting soil and mulch particles form the OM nuclei, mucus and minerals. Root penetration into the aggregates decreases the relative proportions of unstable macro-aggregates and increases the proportion of stable micro-aggregates with high C content. The C of the stable micro-aggregates is not available for soil biota and acts as a C store (Singh, and Singh, 2018, Muniyandi, 2019).

Roots exert pressures on the soil, expand the existing pores and create new ones, generate a greater particle and micro-aggregates packing modifying the arrangement of the clay particles (Gregory, *et al.*, 2010; Torres-Guerrero, *et al.*, 2013). Bulk density increases in the range of 12 to 35 % near the zone of root influence with respect to soil bulk density (Torres-Guerrero, *et al.*, 2013). The modifications occur at a distance of 50-200 μm around the roots increasing the stability of soil aggregates within the rhizosphere (Caravaca, *et al.*, 2002; Gregory, *et al.*, 2010; Chen, *et al.*, 2014). This condition promotes water flow through the macropores and directly affects the wetting and drying cycles of the soil, but also affects indirectly the soil aggregation (Gregory, *et al.*, 2010; Gupta and Germida, 2015; Jat, *et al.*, 2019).

Soil water conditions are modified with the presence of roots because they generate three concomitant water processes: 1) specific areas are dried and the clays are united with the organic root exudates forming aggregates due to water absorption (Bais, *et al.*, 2006; Torres-Guerrero, *et al.*, 2013); 2) the exudates clog the pores reducing wetting and breaking of previously formed aggregates (Hinsinger, *et al.*, 2009; Gupta and Germida, 2015); and 3) water flows freely through the pores created by live roots (Rasse, *et al.*, 2000; Hinsinger, *et al.*, 2009), modifying rhizosphere ionic and osmotic balance through nutrient uptake and rhizo-deposition (Bronick and Lal, 2005). Thus, where conservation agriculture techniques are applied, the amount of available water for crop growth increases (Rasse, *et al.*, 2000; Fuentes, *et al.*, 2009; Verhulst, *et al.*, 2011; Huang, *et al.*, 2012) allowing optimum root growth (Muñoz-Romero, *et al.*, 2010), and increasing its density and length in the superficial soil strata (Qin, *et al.*, 2006; Hinsinger, *et al.*, 2009).

On the other hand, in agronomic systems where tillage is reduced and residues are incorporated, the water potential of roots and leaves undergoes changes that are directly related to transport and nutrient availability (Grzesiak, *et al.*, 2013). Root decomposition contribute with POM that acts as cementing agent of the soil particles and as a source of C for the microorganisms that produce excretions, which act as glue for the formation of aggregates (Gregory, 2006; Grzesiak, *et al.*, 2013).

Through root exudates, plants can increase or decrease soil nutrient availability by altering soil chemistry and soil biological processes. These effects can in turn influence the outcome of resource competition between plants. Effects of root exudates on soil resource availability may most often be strongest in the rhizosphere of the plants that produce them, providing a competitive advantage over neighboring plants that lack the same abilities. The most important exudates are phytosiderophores and organic acids (Hinsinger, *et al.*, 2009). Therefore, it is important to choose the most appropriate crops that promote this availability of nutrients through their excretions when implementing NT systems (Bais*, et al.*, 2006).

With soil removal, accomplished with CT, soil loosens apparently facilitating root penetration; however, with the repeated use of machinery compact the soil, promoting compaction over time that prevents root penetration to the proper depth, due to the plants need to explore the soil to find water and nutrients necessary for their growth. In 40 % of the world's soils, crop growth is limited by the scarcity of available P for plants, and it is projected that the world's reserves of this nutrient will be limited within 60-80 years (Miller*, et al.*, 2001; Cooper*, et al.*, 2011; Heckenmüller*, et al.*, 2014). Several investigations present data in the sense that NT favors the availability of P for plants that participate in a crop rotation process (Acevedo, et al., 2003; Redel, et al., 2011; Margenot, et al., 2017) (**Annexed 3**). For example, P as well as iron, are relatively abundant in soils, but in unavailable forms. In particular, P is often bound as insoluble ferric, aluminum, and calcium phosphates, especially in soils with high pH. Organic acids such as citric, malic, and oxalic acid can form complexes with iron or aluminum in ferric and aluminum phosphates, thus releasing plant available phosphate-into the soil (Lombi*, et al.*, 2004; Van Raij*, et al.*, 2010; Balemi and Negisho, 2012; Noack*, et al.*, 2012).

Organic acids may also increase P availability by blocking P absorption sites on soil particles or by forming complexes with cations on soil mineral surfaces (Jones*, et al.*, 2004). Several plants substantially increase organic acid root exudation in response to P deficiencies, including *Lupinus alb*us (Hinsinger, 2001; Bais*, et al.*, 2006), and *Medicago sativa* (Hinsinger, *et al.*, 2009). In response to P deficiency, lupines form clusters of specialized root structures, termed proteoid roots, which excrete organic acids. Mature roots appear both to increase organic acid production and decrease organic acid metabolism compared to non proteoid roots, resulting in much higher levels of organic acid exudation. As a result, P uptake can be as much as 50 % greater in proteoid than non proteoid lupine roots (Hinsinger, 2001; Hinsinger, *et al.*, 2009).

Residue accumulation on the soil surface and the consequent increment of soil organic carbon (SOC) after eliminating soil movement is perhaps the most important product of NT adoption; however, it's interesting to emphasize the stratification of SOC content in the profile once NT has been stabilized completely after several years of adoption. There exists abundant information on SOC stratification which document that SOC accumulates in the first 5 cm of the profile which then gradually decreases in the 5-10 and 10-30 cm layers (Cooper, *et al.*, 2016). Stratification brings also the consequent segregation of the physical, chemical and biological properties in the same soil layers (Lupwayi, *et al.*, 2006; Grove, *et al.*, 2007; Cooper, *et al.*, 2016). At the same time, significant P stratification has also been documented in NT situations, with elevated P concentration in the superficial soil layer of the soil profile which can be explained by SOM accumulation and nutrient mobility (Mallarino and Borges, 2006; Grove, *et al.*, 2007; Galizzi, *et al.*, 2012).

Soils under NT usually have higher C and N concentrations than soils under CT. Rapidly decomposing residues enhance the formation of aggregates, but their action is transient, whereas slowly decomposing residues have a gradual impact on aggregation and their long-term effect on SOC sequestration is higher than rapidly decomposing residues. The decomposition of dead roots is related to soil aggregation by the time it takes for a full decomposition which in turn is influenced by C: N ratio and root lignin and phenolic compounds content (Bais, *et al.*, 2006).

The degree the effectiveness of organic materials for improving soil structure is function of the C:N ratio of plant residues and this ratio depends on the type of organic residues, being low in N rich materials (13 in freshly cut alfalfa), and high in carbon rich residues (80 in wheat straw, and 90 in fresh tree leaves) (Six, *et al.*, 2000; Marquez, 2001). Organic residues with higher C:N ratio persist for long time and improve soil aggregation (Hagedorn, *et al.*, 2003). Residues with low C:N ratios are rapidly decomposed and have reduced impact on soil structure improvement. The increase in atmospheric CO_2 augments microbial biomass in the soil, thus raising N uptake by plants (Hu, *et al.*, 2001; Stewart, *et al.*, 2018). The dynamics of C:N ratio is complex and varies between soils and within the same soil. The C:N ratio decreases with decreasing particle size and with increasing soil depth and depends on the tillage system (Blanco-Canqui and Lal, 2004; Stewart, *et al.*, 2018).

Polysaccharides are compounds that have a very high molecular weight, which depends on the number of monosaccharide units that participate and in their structure. Examples of polysaccharides are cellulose, hemicellulose or chitin. They come from the decomposition of the vegetable remains that cover the ground. Since there are many microorganisms that use them, these compounds, in general, do not last long in the soil. Microorganisms in turn synthesize most of the soil polysaccharides as they break down fresh waste (Blanco-Canqui and Lal, 2004).

As stated, polysaccharides mineralize easily in the soil and the main intervention in soil aggregation is that they initiate the process, but binding is not stable in the long term. Molecules of polysaccharides have strong affinity with mineral surfaces acting as bridges in aggregation. They are also present in form of glues like substances that stick aggregates together (Liu, *et al.*, 2005).

The effect of other organic residues (lignin, phenolic aromatic sterols and lipids compounds) on soil aggregation is a function of biochemical properties of the residues

(Blanco-Canqui and Lal, 2004). Lignin content and C:N ratio is residue parameters that affect the decomposition of SOM. Soil organic carbon concentration has a positive correlation with lignin content (Lamlom and Savidge, 2003). As indicated previously, physical decomposition of residues depends on the C:N ratio (Soto-Mora, *et al.*, 2016), but advanced or chemical decomposition of organic residues is controlled by lignin concentration (Martens, 2000). Mature organic materials with high lignin content are important to soil structure development. Lignin is mostly associated with the macro-aggregation and stabilizes and binds particles into aggregates (Six and Paustian, 2014; Stewart, *et al.*, 2018). Lignin at the surface of the aggregates is more decomposed than that within the them due to increased microbial activity outside of the clump (Arévalo, 2011; Stewart, *et al.*, 2018).

Phenolic compounds decompose at slower rates than polysaccharides and amino acids and can promote long-term aggregation (Lamlom and Savidge, 2003; Stewart, *et al.*, 2018). Indeed, Martens (2000) found that aggregate stabilization is highly correlated (r = 0.96) with phenolic acid concentration in native prairie and in corn–soybean rotation systems in a Haplaquoll from the USA, indicating also that tillage lowers the concentration of phenolic compounds, resulting in decreased aggregate stability.

2.6 Arbuscular mycorrhizal fungi and glomalin

No till leaves crop residues on soil surface, which decomposes in different periods depending on the soil type, humidity, temperature and the microorganisms' presence. Agricultural management practices such as NT influence the community composition of soil biota which in turn alter a number of ecosystem services (plant productivity, nutrient uptake) (Borie, *et al.*, 2006; Borie, *et al.*, 2008; Köhl, *et al.*, 2014). The observed differences in ecosystem functioning between NT and CT soil biotic communities imply that belowground soil biodiversity has to be taken into consideration when choosing a soil management system (Köhl, *et al.*, 2014). Fungi and bacteria are the principal microorganisms known as decomposers of SOM. Fungi are the most important agents involved in soil aggregation through polysaccharides and fungal mycelia network.

The role played by arbuscular mycorrhizal fungi (AMF) in soil aggregation relevant due to the physical network of hyphae maintaining soil particles together by the cementing capacity of the released extracellular compounds (Driver, *et al.*, 2005; Borie, *et al.*, 2008; Grumberg, *et al.*, 2010). Arbuscular mycorrhizal fungi appear to be the most important fungal mediator of soil aggregation due to: a) they represent a dominant soil component accounting for 30 % of whole of soil microbial biomass (Rillig and Mummey, 2006; Brito, *et al.*, 2012); b) carbon supply resources for survival comes from root photosynthates in comparison with saprobic fungi which depend on limited carbon substrates available in the bulk soil, and c) there is some evidence that grazers "prefer" saprobic than mycorrhizal hyphae (Gryndler, 2000) perhaps as a thing of taste which results in a longer AMF resilience in the soil due to the chitin content. As a consequence, AMF appear as one of the most important components in describing biotic influences on soil aggregation. However, AMF exert a strong influence at the scale of macro-aggregates (> 250 μm) in comparison with bacteria and archaea which would be expected to influence the formation and stabilization of micro-aggregates in a more direct way (Rillig and Mummey, 2006). Additionally, arbuscular mycorrhizal fungi produce glomalin, a glycoprotein that protects hyphae during transport of nutrients from the plant to the end of the hypha, and from the soil to the plant. Once the hyphae senesce and stop transporting nutrients, the glomalin contained in their cells is released and accumulated in the soil, representing 5 % of the edaphic carbon (C) and N contents (Treseder and Turner, 2007). There glomalin acts as a binder of minerals and organic matter, so it is in direct relation with the stability of aggregates and the structure of the soil (Borie *et al.*, 2000; Curaqueo *et al.*, 2010; Grumberg, *et al.*, 2010).

2.7 No till and ecosystem services

Ecosystem services are good for farmers and for society as a whole, because the idea that good agricultural productivity and farming practices that favor ecosystem services cannot coexist should discarded; nevertheless, farmers routinely manage for greater productivity by using inputs and practices to increase yields, but management practices can also enhance ecosystem services (Power, 2010). Many farmers and agronomists are reluctant to conservation agriculture practices because they believe that their adoption will decrease crop yields, especially in tropical countries (Boada and Espinosa, 2017; Palm, *et al.*, 2014). It is worth mentioning that regarding NT adoption by small farmers, published information is contradictory in terms of crop yields, since some authors report increases and others reductions (Derpsch, *et al.*, 2010; Palm, *et al.*, 2014); in any case, it seems that in the transition stage the productive and physical variables decrease, but, once the NT system is established results are positive. The main ecosystem services provided by NT are climate regulation, air pollution reduction, soil carbon accumulation, reduced greenhouse gas emission, improved water cycle, soil quality improvement and preservation, soil nutrient provision, wind and water erosion control, better control of pests (insects and diseases) and, fundamentally, sustainable food production (Palm, *et al.*, 2014; Power, 2010; Stevenson, *et al.*, 2014).

Climate regulation refers to the processes that contribute or mitigate the global warm through of greenhouse gasses emission (GHG) to the atmosphere, other factors that contribute to GHG depend on magnitude soil C changes, nitrous oxide (N_2O) and methane (CH_4) emissions associated with the implementation NT, compared to conventional practices (Palm, *et al.*, 2014). Soil C sequestration refers to the increase in C stored in the soil by capturing atmospheric CO_2 as a result of changes in land use or management (Palm, *et al.*, 2014; Powlson, *et al.*, 2011). Many study reports increase in C reserves in soils where NT has been implemented (Six, *et al.*, 2002; Govaerts, *et al.*, 2009; Grace, *et al.*, 2010; Gattinger, *et al.*, 2011; Lal, 2011; Corsi, *et al.*, 2012; Ogle, *et al.*, 2012;). Factors influencing the C storing in the soils are climate, soil type, and nutrient and water availability, these being the primary determinants of biomass production and decomposition rates. Crop rotations complemented with the practice of leaving on the soil the residues of the previous crops are utilized to increase C inputs (Palm, *et al.*, 2014). Another effect of NT adoption is that it increases of soil C in the topsoil (0 to 10 cm), but it does not in deeper layers (Grove, *et al.*, 2007; Govaerts, *et al.*, 2009; Luo, *et al.*, 2010). Soil C storage is affected more by quantity than by the type or quality of organic inputs (West and Post, 2002).

It is estimated that agricultural activities are responsible for 12–14 % of global anthropogenic emissions of greenhouse gases. After fossil fuel combustion, land use change is the second largest global cause of CO_2 emissions, and some of this change is driven by land conversion to agriculture (Power, 2010). Approximately 49 % of global anthropogenic emissions CH_4 and 66 % of global annual emissions of N_2O, both greenhouse gases, are attributed to agriculture (Forte, *et al.*, 2017; Krauss, *et al.*, 2017), although there is a wide range of uncertainty in the estimates of both the agricultural contribution and the anthropogenic total (Power, 2010).

There is no a clear response to the effects of NT compared to CT on N_2O emissions (Snyder, *et al.*, 2009). With NT, residues are returned to the soil resulting in surface mulches which may lower evaporation rates and hence increase soil moisture and increase labile organic C and consequently increase N_2O emissions compared to CT. Decreased bulk density with NT, compared to CT, may also increase emissions (Galbally, *et al.*, 2005). On the other hand, lower soil temperatures and better soil structure under NT may reduce the incidence of soil saturation and reduce emissions of N_2O, NT only increased N_2O emissions in poorly aerated soils (Palm, *et al.*, 2014).

On the other hand, in the case of CH_4, agricultural soils contribute to emissions as a result of methanogenic processes in waterlogged conditions (Palm, *et al.*, 2014). Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on their C:N ratio; residues with a high C:N ratio have little effect on oxidation while residues with a narrow C:N ratio seem to inhibit oxidation (Hütsch, 2001).

Soil quality refers to the soil properties and functions that improve plant productivity and is assessed by soil biological, physical, and chemical means. Many soil quality properties are determined, in part, by soil texture and mineralogy, but can be modified by SOM content and composition and the activities of soil biota, both of which are affected by management practices; hence, reducing runoff and water erosion with NT should result in lower transport of sediments, nutrients and pesticides/herbicides and higher water quality (Palm, *et al.*, 2014).

Trapping of sediments and erosion are controlled by the architecture of plants at or below the soil surface, the amount of surface litter and litter decomposition rate. Invertebrates that move between the soil and litter layer influence water movement within soil, as well as the relative amounts of infiltration and runoff (Swift, *et al.*, 2004). Modifying the tillage regime or mulching can reduce soil evaporation by 35–50 % (Power, 2010). Inputs for agriculture through irrigation are indispensable in some parts of the world, and 80 % of agricultural water use comes from rainfall stored in soil moisture (Molden, 2007). Water storage in soil is regulated by plant cover, SOM and the soil biotic community (Power, 2010).

The two nutrients that are most limiting in agricultural systems are N and P. Nitrogen and phosphorus fertilizers have greatly increased the amount of new N and P in the biosphere and have had complex, often harmful, effects on natural ecosystems (Snyder, *et al.*, 2007; Snyder, *et al.*, 2009). These mobilized nutrients have entered both groundwater and surface waters, resulting in many negative consequences for human health and the environment. Approximately 20 % of N fertilizer applied in agricultural systems moves into aquatic ecosystems (Galloway and Sahagian, 2004; Smith and Schindler, 2009). Impacts of nutrient loss from agroecosystems include groundwater pollution and increased nitrate levels in drinking water, eutrophication, increased frequency and severity of algal blooms, hypoxia and fish kills, and dead zones in coastal marine ecosystems (Smith and Schindler, 2009).

No till and other soil conservation measures can maintain soil fertility by minimizing the loss of nutrients and keeping them available to crops. Cover crops facilitate on-farm retention of soil and nutrients between crop cycles, while hedgerows and riparian vegetation reduce erosion and runoff among fields. Incorporation of crop residues can maintain SOM, which assists in water retention and nutrient provision to crops (Power, 2010).

Good management practices which include diversifying nutrient sources, legume intensification for biological N fixation and P solubilization, and diversifying rotations are needed to reduce the requirement for surplus nutrient additions in agriculture (Drinkwater and Snapp, 2007).

Erosion severity depends on soil type, topography, climate, and rainfall (duration and intensity); repeated studies have shown significant erosion reductions with the adoption of NT practices compared to CT (Montgomery, 2007; Meijer, *et al.*, 2013). Erosion control is one of the main objectives of NT and residue retention, contributing to both to agriculture productivity and ecosystem services. No till and surface applied residues directly reduce erosion by minimizing the time that the soil remain bare and exposed to wind, rainfall and runoff (Verhulst, *et al.*, 2011).

In complex landscapes, natural enemies and pollinators move among natural and semi-natural habitats that provide them with refuge and resources that may be scarce in crop fields (Coll, 2009). Natural enemies with the ability to disperse long distances or that have large home ranges are better able to survive in disturbed agricultural landscapes with few or more distant patches of natural habitat. Not so disturbed environments where NT is practiced provide the habitat and diverse food resources required for arthropod predators and parasitoids, insectivorous birds and bats, and microbial pathogens that act as natural enemies to agricultural pests and provide biological control services in agroecosystems. These biological control services can reduce populations of pest insects and weeds in agriculture, thereby reducing the need for pesticides (Power, 2010).

Evidence suggests that management systems that emphasize crop diversity through the use of polycultures, cover crops, crop rotations and agroforestry can often reduce the insect abundance that specialize on a particular crop, while providing refuge and alternative prey for natural enemies (Fan, , *et al.*, 2012; Zotarelli, , *et al.*, 2012; Kazula, *et al.*, 2017).

2.8 Perspectives

To expand the efforts to promote NT, particularly on small farmers´ fields from the tropics, it is necessary to develop a package of three agronomic practices: zero soil disturbance, retention of sufficient crop residue to provide surface coverage, and diversified cropping patterns (rotations) that include at least three plant species including one legume.

Energies should be expended for understanding and quantifying the tradeoffs between the benefits of avoiding soil removal and residue retention for future crop productivity and soil quality, versus the value of soil a residue for other uses.

Promote participatory on-farm research to identify biophysical and socioeconomic constraints to increase crop production, and to guide farmers in finding solutions from a broader range of sound agronomic practices to achieve the fundamental goals of conservation agriculture.

To present relevant research data to local governments to raise awareness and obtain financing for the payment of incentives to farmers who adopt these technologies that provide ecosystem service).

CHAPTER III

"Early Changes in The Transition from Conventional to No-Tillage in a Volcanic Soil Cropped with Beans (Phaseolus vulgaris L.)"

Published in Chilean Journal of Agricultural & Animal Sciences (ex Agro-Ciencia), 36, 181-189

EARLY CHANGES IN THE TRANSITION FROM CONVENTIONAL TO NO-TILLAGE IN A VOLCANIC SOIL CROPPED WITH BEANS (*Phaseolus vulgaris* L.)

Fabián Montesdeoca[1, 2*], María Ávila[1, 2], Janeth Quishpe[1], Fernando Borie [2, 3], Pablo Cornejo[2], Paula Aguilera[2], Soraya Alvarado[1], José Espinosa[1]

1 Universidad Central del Ecuador, Av. América, Ciudadela Universitaria, Quito, Ecuador.

2 Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile

3 Universidad Católica de Temuco, Av. Manuel Montt 56, Temuco, Chile

* Corresponding author: fmontesdeoca@uce.edu.ec

Abstract

Conventional tillage (CT), soil management system commonly used by small farmers in the Ecuadorian highlands, removes the soil during seedbed preparation to eliminate weeds, improve soil aeration, avoid compaction, and develop an adequate rooting space. Removal promotes deep changes in some physical, chemical, and biological soil properties which in time have negative effects on crop performance. Most of these effects can be avoided using no-tillage (NT); however, this tillage system is rarely utilized by farmers in the Ecuadorian highlands. A long-term field experiment was designed to investigate the contrasting soil changes promoted by CT and NT systems in a volcanic soil from the slopping highlands which was cultivated with the following crop rotation schemes: beans (*Phaseolus vulgaris* L.)-corn (*Zea mays* L.)-beans and beans-amaranth (*Amaranthus caudatus* L.)-beans. This study presents the initial changes on yield and some soil properties promoted by the transition from CT to NT after the cultivation of

bean, the first crop in the rotation. Beans yield under NT was 42% higher than CT suggesting that the soil improvements promoted by NT were also conductive to the difference in crop yield; however, only the changes in pH and gravimetric water content presented significant differences. Changes in other measured soil variables like soil organic matter, total N, available P, and bulk density were not significant; though, data shows an initial trend of improvements under NT suggesting that these changes are responsible for the higher initial crop performance and conductive to better rotation performance in the medium to long term.

Key words: Ecuadorian highlands, tillage, beans, crop rotation.

3.1 Introduction

Ecuador is crossed by the Andean Mountain range which divides the country in three natural continental regions: Coastal plane, Highlands, and Amazonia. The Highlands inter Andean basins are narrow and long depressions (1.4 million ha) at an altitude from 1600 to 3000 meters, are suitable for agricultural use with a wide range of temperate climate crops (Moreno, et al., 2018). Spaces devoted to agriculture have a rugged topography that, for the most part, do not meet the conditions for intensive agriculture. Furthermore, land tenure is characterized by a high percentage of small productive units, with less than 5 ha, which promotes intensive land use. Soils remain uncovered and subject to erosion, because farmers use crop stubble to feed livestock, and they lack of alternatives to produce without soil removal (Espinosa and Moreno, 2018).

No-tillage (NT) is one of the soil conservation practices that effectively controls soil erosion with other widely recognized beneficial effects (Khan, et al., 2017). There is scarce published information about the application of this practice in Ecuador, but the scanty research work conducted during the past few years indicate a tendency of better yields with NT in volcanic highlands soils. In general, only one crop cycle has been reported and the effects of NT in respect to conventional tillage (CT) in soil properties was partially reported or not consistent (Alvarado, et al., 2011).

It has been reported that NT and crop rotations are complementary to maintain medium and long-term soil quality (Munkholm, et al., 2013); however, at national level, there is not enough information on the contribution of crop rotations, particularly in small farmers fields. Thence, it is mandatory to document the effects of NT and rotation schemes on soil properties and carbon dynamics, which is especially relevant in the framework of the current global climate change.

The objective of this study was to report the initial effects of NT, fertilization rates and depth of sampling on yield and selected soil chemical and physical properties after the first crop cycle of two common rotation schemes.

3.2 Materials and Methods

3.2.1 Experimental site

This research project was conducted at the Experimental and Teaching Farm La Tola, Universidad Central del Ecuador, situated at La Morita, Pichincha province. The site is located at 78°21´18´´ W and 00°13´49´´ S, with an altitude of 2505 masl, a mean annual rainfall of 868 mm, temperature of 17°C and relative humidity of 73.9%. The soil is a Mollisol of volcanic origin classified as Entic Durustolls of sandy loam texture, pH-H_2O 6.9, organic carbon (OC) 1.89 %, total nitrogen (TN) 0.22 %, available-P (Olsen) 140 mg kg^{-1}, exchangeable K^+ 1.27 cmol kg^{-1}, Mg^{2+} 5.12 cmol kg^{-1}, and Ca^{2+} 9.5 cmol kg^{-1}. Two rotation schemes were implemented under NT and CT. The first rotation scheme was alternating crops of common beans and maize, and the second one alternating crops of common beans and amaranth; common beans was used for its expected N contribution to the second crop.

The experimental design utilized was a complete random block design in a split plot arrangement with eight replications. The experimental site was previously cropped with oats for homogenizing its fertility, and its residues were discarded. After three months of fallow period, oat regrowth and weeds were treated with glyphosate herbicide. The main plot was the tillage systems (CT and NT) and the subplots were the treatments based on the following fertilizer rates: N_1, N_2, and N_3, with 11, 22, and 33 kg N ha^{-1} as urea, and P_1, P_2, and P_3, with 22, 44, and 66 kg P ha^{-1} as Triple Superphosphate, respectively. A control plot with no fertilizer application was also included.

Plots under NT were treated with herbicide to control weeds avoiding soil movement. All plots were manually planted under the same agronomic management throughout the cropping season. Experimental plots were seeded with common beans at the middle of the rainy season and fertilizer rates were applied 21 days after planting. The seed rate used was 90 kg ha^{-1} in plots of 12 x 7 m (84 m^2), with 0.70 m between planting rows and 0.30 m between planting sites. Beans were harvested at maturity after 4 months growing cycle. Soil sampling and analysis were performed immediately after harvest.

Subsequently, for the second cycle, the large plots of NT and CT were divided into two subplots each where Corn (C) in the ones and Amaranth (A) in the others was sown, each with four fertilization rates and three repetitions, so that the two rotation schemes were configured: the first: beans-corn-beans and the second beans-amaranth-beans.

The results show in this paper belong to the first crop cycle.

3.2.2 Measurements. After harvest, bean grain was classified, cleaned, and dried at 12% moisture. The harvested grain was weighed and expressed in kg ha^{-1}. Measured soil properties were as follows: bulk density (Grossman and Reinsch, 2002); water storage capacity (Gardner, 1996), soil pH-H_2O (Peech, 1996); total nitrogen (TN) using Kjeldhal method (Bremner, 1996); phosphorus (P) Olsen (Sims, 2000); potassium (K), calcium (Ca) and magnesium (Mg) (Heald, 1996; Pratt, 1996); soil organic matter (SOM) was calculated using the soil organic carbon (SOC) procedure proposed by Nelson and Sommers (1996) utilizing 1.892 as conversion factor.

3.2.3 Statistics. The factorial ANOVA analysis and mean comparison (DMS 0.05 and post hoc multiple range test of Tukey) were conducted using Infostat (Di Rienzo, et al., 2018). The described ANOVA was utilized for each of the proposed sampling depths. Soil core samples were taken at two sampling depths (0-5 and 5-20 cm).

3.3 Results and Discussion

3.3.1 Effects of tillage systems and fertilizer rates on bean yields

There were significant differences in grain yield and weight of 100 seeds when contrasting both tillage systems at all fertilizer rates (**Table 1**). NT yield was greater than CT, suggesting that the elimination of soil disturbance improves the general conditions for crop growth. Most reports on the effect on yield in the transition from CT to NT indicate that NT grain production is, in most cases, higher or at least equal to CT (Derpsch, et al., 2010), condition which could lead to NT adoption by small farmers. These results indicate that there is potential for successful production of dry beans using NT cropping systems. There is no information related to tillage disturbance on bean yields in the highlands of Ecuador, but land degradation problems on beans fields are evident on most of the landscapes (Espinosa and Moreno, 2018); however, recent experiments have been conducted reporting that NT yields of different crops are as high or higher than yields obtained under CT (Alvarado, et al., 2011; Quichimbo, et al., 2012; Gallager, et al., 2017). The study conducted by Alvarado et al. (2011) with open pollinated corn for human consumption, common in the Highlands of Ecuador, reported a grain yield of 5.2 t ha^{-1} for NT and 4.3 for CT.

Table 1. Grain yield of common beans (*Phaseolus vulgaris* L.) cultivated in a volcanic Mollisol under two contrasting tillage systems at four fertilizer rates.

Tillage system	**Fertilizer rates**	**Yield (kg ha^{-1})**	**Weight of 100 seed (g)**
NT[1]	N_0P_0	2518.7 a	56.6 a
	N_1P_1	2464.5 ab	56.5 a
	N_2P_2	2559.9 a	57.2 a
	N_3P_3	2547.2 a	57.7 a
CT	N_0P_0	2028.4 bc	50.1 c
	N_1P_1	1524.5 d	51.2 bc
	N_2P_2	1753.4 cd	52.1 bc
	N_3P_3	1786.4 cd	52.7 b
ANOVA			
Tillage		31.27***	84.74***
Fertilization		0.74	1.97 ns
Tillage*Fertilization		0.49 ns	0.35 ns

[1]NT = No-till; CT = Conventional tillage

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Different letters in a column indicate statistical differences according to Tukey's multiple range test at $p < 0.05$.

Higher yield obtained in the check plot (N_0P_0) with NT and CT could be due to the effect of the experimental site conditions prior to our experiment where different potato fertilization experiments were conducted over time and despite the batch actions taken to homogenize the fertility of the site some historical memory was dragged to the plots.

3.3.2 Effects of tillage systems and fertilizer rates on soil physical characteristics

Although conservation tillage effects on crop yields have been extensively investigated in the long term (Derpsch et al., 2010), there is limited information concerning tillage-induced changes on soil properties in the first years of transition from CT to NT. Thereby, the comparison of both tillage systems should result in soils having different soil physical and chemical properties, due to soil matrix undergoes less disturbance and such differences can be greater with time under NT (Blanco Canqui, 2012; Lal, 2015). However, the changes occurring on soil physical properties are expected to develop slowly after the initiation of NT (de Moraes, et al., 2015).

In this study, changes in bulk density and water storage capacity were evaluated at two soil layers, 0-5 and 5-20 cm from the soil surface. Data analysis (**Table 2**) shows that beneficial effects of NT on these soil physical characteristics is more noticeable in the surface 0–5 cm layer than in the deeper layer. As plowing involves the breaking of soil aggregates changing soil structure and promoting SOM losses by C mineralization due to rootlets and fungal hyphae crushing, it is expected to observe lower densities in undisturbed soils (Blanco-Canqui, et al., 2009; Wingeyer, et al., 2015). Bulk density is usually highly correlated with clay content and tillage in the upper soil layer (Bronick & Lal, 2005; Alvarez, et al., 2009), and NT helps to reduce soil compaction (Singh, et al., 2014). In our study, conducted in a volcanic Mollisol, no statistical significance was found for the effect of tillage on bulk density (1.34 and 1.39 g cm^{-3} for NT and CT, respectively), at the 0-5 cm soil layer, the same trend was observed at the 5-20 cm layer (**Table 2**). However, the literature contains conflicting information regarding the effect of NT on bulk density. Data collected by Li et al. (2007) in a Cambisol from China cropped with a wheat monoculture for 15 years indicated a higher bulk density in NT plots during the first six years probably due to tractor traffic. Furthermore, an experiment conducted by Roldan, et al. (2007) in a high clay Vertisol from Mexico cultivated with a maize - bean rotation documented a higher bulk density in NT compared with CT at the end of a four year period. In addition, these authors reported a higher percentage of soil macroaggregates in the NT soils at 0-20 depth. Additionally, in our study the interaction of tillage and fertilizer rates on bulk density was highly significant ($p < 0.01$) at both sampling depths (**Table 2**) suggesting a synergism of these two factors in the performance of bulk density as an indirect effect of fertilizer application on SOM accumulation promoted by increased root biomass (Sainju, et al., 2005).

Water storage capacity is of great importance in soil fertility because it is useful to describe water availability and usually predicts its incidence on plant root growth and crop production (Morison, et al., 2008). The increment of SOM promoted by NT also increases soil macroaggregates, soil aeration and the number of small channels which are filled with water and dissolved nutrients affecting plant growth, and soil root ability and workability (Dexter, 2004). In this study, water storage capacity is higher in NT contrasted with CT at both depths being more evident in the upper layer **(Table 2)**. The greater water storage capacity in the NT bean (20.01 %) compared to CT (15.57 %) indicates a condition which can be explained by the protective effect produced by the plant residues on the soil surface, such residue accumulation also prevents soil exposure to sun light and wind promoting a greater water storage capacity for the growing crop (Vidal, et al., 2002; Crovetto, 2006). The changes in water storage capacity values for NT and CT were not significant at the 5-20 cm soil layer, but the interaction tillage and fertilizer rates were highly significant ($p < 0.01$), suggesting again a tight process of synergy among these two factors. When comparing the effects of NT and CT on bulk density and water storage capacity content it is evident that these two parameters are negatively correlated showing that plots with lower density have higher water storage capacity (- 0.04 ns). Data also show that the NT treatment with the highest N and P fertilization (N_3P_3) presents a low bulk density value (1.31 g cm^{-3}) and a high water storage capacity (22.17 %) compared to the CT- N_3P_3 which presents a higher bulk density value (1.41 g cm^{-3}) and a lower water storage capacity (15.29%), although, in our case, without statistical differences. This trend has been well documented in other research sites (Khan, et al., 2017; Tormena, et al., 2017).

3.3.3 Effects of tillage systems and fertilizer rates on soil chemical characteristics

Changes in main soil chemical characteristics due to tillage and fertilizer rate were more evident at 0-5 cm compared to 5-20 cm depth layer. Soil pH in the control plot was significantly lower for NT compared to CT at both depths, such differences were higher at 5-20 cm depth (**Table 2**). It has been reported that pH tends to be lower in NT compared to CT, condition which has been attributed to plant detritus accumulation and decomposition in the soil upper few centimeters which enhances microbial biomass activity increasing C and N mineralization, producing phenolic organic acids and promoting changes in chemical soil characteristics including soil pH (Balota, et al., 2004; Rahman, et al., 2008).

Soil management, particularly ammoniacal N fertilizers use, can produce acidification that can lead to negative soil conditions for crop growth (Bloom & Skyllberg, 2012; Havlin, et al., 2014). Initially the N content of the original plant materials together the urea hydrolysis causes an increase of pH associated with the formation of ammonium carbonate but protons are further released by nitrification processes producing a moderate soil acidification. In any case, the pH changes are small and tend to modify the acidity towards values close to neutrality due to MOS buffer capacity. However, a better pH buffering condition is expected under NT due to higher SOM content (Singh, et al., 2014; Jat, et al., 2019), but these changes usually require more than one crop cycle to be evident (Díaz-Zorita, et al., 2004). The main effect of fertilizer rates on soil pH was significant ($p < 0.05$) at both sampling depths suggesting a trend of acidification with increasing N fertilization.

As it was expected, at this point in the experiment (first cycle), the effects of tillage and fertilizer rate application on SOM and TN were not statistically significant **(Table 2)** but small differences were more noticeable in the upper soil layer. The SOM build up is quantitatively more evident only when consecutive cycles of NT and crop rotation are applied (Blanco-Moure, et al., 2011; Basanta, et al., 2012).

On the other hand, initial soil available P at the beginning of this experiment was 140 mg kg^{-1}, but after harvesting, the soil P in the NT and CT control plots decreased to 124 and 93 mg P kg^{-1}, respectively, suggesting that the P use efficiency was higher in NT than CT, given the higher yields and lower soil P consumption of the NT control plot. The same behavior was observed with K. There was not a significant difference for the main effect of tillage but the differences in soil P promoted by the fertilizer application were highly significant ($p < 0.01$) at both tillage systems with a constant P buildup in the 0-5 cm soil layer but an important and significant decrease in P concentration was observed at 5-20 cm soil layer ($p < 0.05$). The lack of soil movement with the consequent residue accumulation on the surface of NT soils, as well as the low P mobility, promotes the stratification of plant nutrients, particularly P, resulting in the P accumulation in the 0-5 cm soil layer which gradually decreases with soil depth (Lupwayi, et al., 2006; Grove, et al., 2007).

Table 2. Physical and chemical characteristics of a Mollisol cultivated with common beans (*Phaseolus vulgaris* L.) under two contrasting tillage systems at four fertilization rates.

Tillage system	Fertilizer rates	Bulk density ($g\ cm^{-3}$)		Water storage capacity (%)		pH		SOM (%)		TN (%)		P ($mg\ kg^{-1}$)		K ($cmol\ kg^{-1}$)		Sum of Bases ($cmol\ kg^{-1}$)	
		Soil depth (cm)															
		0-5	5-20	0-5	5-20	0-5	5-20	0-5	5-20	0-5	5-20	0-5	5-20	0-5	5-20	0-5	5-20
NT[1]	N_0P_0	1.18 b	1.45 bc	19.90 ab	18.41 abc	7.1 b	6.4 bc	4.1 abc	3.1 a	0.20 abc	0.16 a	124 bc	64 b	1.68 a	0.64 a	18.7 e	13.93 a
	N_1P_1	1.42 a	1.43 bc	19.14 b	18.10 abc	7.2 b	6.7 ab	4.0 abc	3.0 a	0.20 abc	0.15 a	127 abc	81 b	1.42 ab	0.80 a	27.7 ab	14.13 a
	N_2P_2	1.43 a	1.39 cd	18.81 bc	17.94 abc	7.1 b	6.6 ab	3.7 bc	3.0 a	0.18 bc	0.15 a	149 ab	91 b	1.28 b	0.88 a	27.3 abc	14.25 a
	N_3P_3	1.31 ab	1.51 b	22.17 a	20.48 a	6.6 c	6.5 bc	4.6 a	2.9 a	0.23 a	0.14 a	181 a	112 ab	1.17 b	0.66 a	30.1 a	14.55 a
CT	N_0P_0	1.41 ab	1.62 a	13.65 e	16.32 c	7.4 a	6.9 a	3.5 c	2.9 a	0.18 c	0.15 a	93 c	68 b	1.12 b	0.66 a	17.3 e	13.57 a
	N_1P_1	1.33 ab	1.50 bc	17.44 bcd	19.23 ab	7.0 b	6.6 abc	4.3 ab	3.1 a	0.21 abc	0.16 a	128 abc	109 ab	1.17 b	0.74 a	25.8 bcd	14.66 a
	N_2P_2	1.40 a	1.47 bc	15.89 cde	17.13 bc	7.2 b	6.7 ab	4.2 ab	3.2 a	0.21 abc	0.16 a	145 abc	92 b	1.27 b	0.84 a	24.5 cd	14.78 a
	N_3P_3	1.41 a	1.32 d	15.29 de	20.29 a	7.2 ab	6.3 c	4.3 ab	3.1 a	0.22 ab	0.15 a	171 ab	154 a	1.33 b	0.95 a	23.9 d	14.32 a
ANOVA																	
Tillage		3.25 ns	1.13 ns	44.7***	0.53 ns	12.64 **	0.30 ns	0.03 ns	0.10 ns	0.00 ns	0.13 ns	0.60 ns	1.77 ns	4.02*	0.42 ns	22.15***	0.07 ns
Fertilization		3.35*	3.55*	1.79 ns	4.19*	3.76*	2.81*	1.63 ns	0.04 ns	1.68 ns	0.05 ns	4.28**	3.91*	0.61 ns	1.23 ns	43.51***	0.63 ns
Tillage * Fertilization		6.98**	6.86**	3.60*	0.97 ns	6.17* **	3.46*	1.48 ns	0.22 ns	1.28 ns	0.18 ns	0.25 ns	0.50 ns	3.57*	0.99 ns	0.68 ns	0.30 ns

[1]NT = No-till; CT = Conventional tillage

*p < 0.05; **p < 0.01; ***p < 0.001. Different letters in a column indicate statistical differences according to Tukey's multiple range test at p < 0.05.

The differences in the main effect of tillage on soil K and sum of cations (K, Ca and Mg) were statistically significant ($p < 0.05$) in the 0-5 cm soil layer suggesting again a trend of nutrient accumulation in NT plots (**Table 2**) compared with CT plots. The lack of expected SOM accumulation in NT over CT is probably due to the fact that the crop initiating the rotation scheme is a legume with a low C/N ratio which favors residue mineralization delaying organic carbon accumulation in the soil profile (Zotarelli, et al., 2012; Raphael, et al., 2016).

The correlation for interdependency of the principal components presented in **Figure 1** discriminates the effects of NT and CT and suggests that there is a strong association among total grain yield and weight of 100 grains with bulk density, gravimetric water content, soil P and fertilizer rates in the NT system supporting the observed total trend of the data which indicates that NT provides better soil conditions for bean yields.

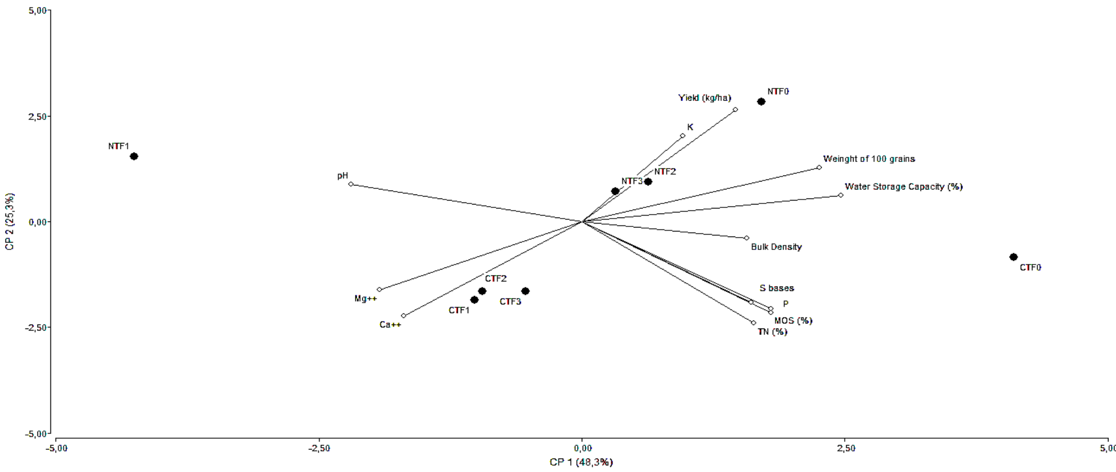


Figure 1. Grouping of the main chemical and physical variables as effect by tillage, and N rates after the first cycle of beans of two crop rotation schemes. CTF = conventional till N rate; NTF no till N rate.

The clustering analysis of the data in **Figure 2** provides and insight over the impact of the measured variables on bean yield. Clustering collected the NT-N_2P_2 100 and NT-N_3P_3 150 treatments as one main group and CT-N_2P_2 100 and CT-N_3P_3 150 as a different group suggesting that NT soil conditions provide a better ambient for yield response to fertilizer application.

This study complements biological results recently obtained by Avila-Salem, et al. (2020) in the same soils allowing us to conclude that at this initial point in the transition from CT to NT, common bean yields are higher for NT, which represent an important technical argument for promoting farmer adoption of this conservation tillage system in the highlands of Ecuador.

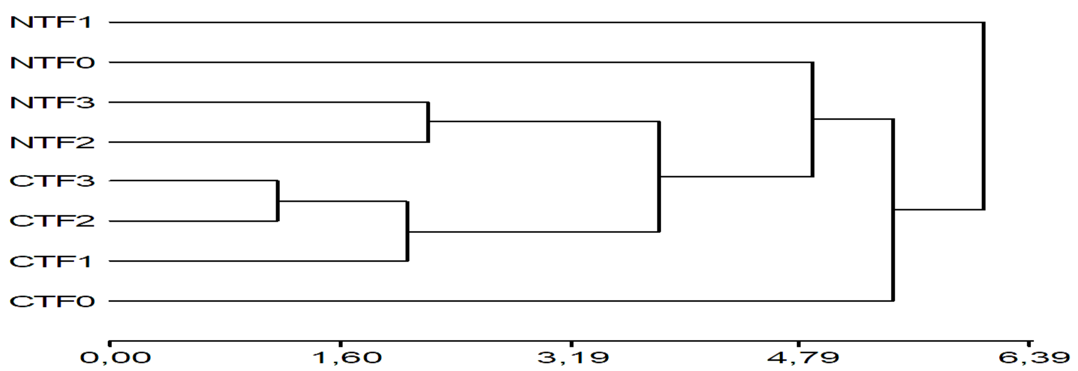


Figure 2. Analysis of non-hierarchical conglomerates of experimental units considering all response variables studied for two tillage systems and nitrogen rates after the first cycle of beans of two crop rotation schemes. CTF = conventional till N rate; NTF no till N rate.

3.4 Conclusions

The common beans yield, initial crop of the proposed long term rotation schemes, was significantly higher under no tillage (NT) than the one obtained with conventional tillage (CT), suggesting that the former develops a more adequate set of soil physical and chemical quality characteristics that are conductive to obtain better crop yields. The only soil properties that showed a significant difference in favor of NT in the 0-5 cm soil layer were soil moisture, pH, soil P and K. In spite of the lack of significance for the other measured variables (SOM, TN) the trend of higher values for NT is evident indicating that the elimination of soil movement begins to improve soil conditions for plant growth even with no fertilizers applied.

CHAPTER IV

"Effect of Tillage, Fertilizer Rates, and Crop Rotations on Yield, Soil Physical-Chemical Characteristics, and Accumulated Carbon in Ecuadorian Highlands"

Article under revision in Journal of Soil Science and Plant Nutrition.

EFFECT OF TILLAGE, FERTILIZER RATES, AND CROP ROTATIONS ON YIELD, SOIL PHYSICAL-CHEMICAL CHARACTERISTICS, AND ACCUMULATED CARBON IN ECUADORIAN HIGHLANDS

Montesdeoca, F.[1, 2*], Ávila-Salem, M.[1, 2], Espinosa, J.[1], Oña, J.[1], Chamorro, F[1], Rosero, J.[1], Herrera, M.[1], Alvarado, S.[1], Cornejo, P.[2], Aguilera, P.[2], Borie, F.[2, 3].

[1]Universidad Central del Ecuador, Av. América, Ciudadela Universitaria, Quito, Ecuador.

[2]Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile

[3]Universidad Católica de Temuco, Av. Manuel Montt 56, Temuco, Chile

* Corresponding author: fmontesdeoca@uce.edu.ec

Abstract

Conventional tillage (CT) is a soil management system commonly used by small farmers in the Ecuadorian highlands which, in the long run, has negative effects on crop performance. These effects can be avoided by using no-till (NT). The objective of this study was to contrast the effects of the application of both tillage systems with different nitrogen (N) rates on crop yield and some soil physicochemical properties after implementing the following crop rotation schemes: beans (*Phaseolus vulgaris* L.)-maize (*Zea mays* L.)-beans (BMB) and beans-amaranth (*Amaranthus caudatus* L.)-beans (BAB). Crop yields were recorded for each crop cycle and soil was sampled and analyzed at two depths (0 - 5 and 5 - 20 cm) after harvesting the third crop. Averaged bean yields in the BMB rotation under NT was 26.2 % higher compared with CT, and in the second rotation cycle under NT cob maize yield was 75 % higher than under CT. However, no differences in bean yields were observed at the third cycle. Additionally, organic C and N were also higher under NT in both rotations, being more evident in MAB, although no

differences were observed for particulate organic matter (POM). A lower E_4/E_6 ratio was observed in BAB rotation suggesting higher SOM humification. Soil pH, available P, and K, Ca and Mg ions were variable depending on the rotation and tillage systems. In general, effects of tillage on bulk density and water content were higher under NT than under CT, however the contrary was observed for soil aggregation. To the best of our knowledge, this is the first study including amaranth in rotation systems including tillage in Andean soils. Results obtained are encouraging in terms of the trend for improved soil physicochemical characteristics under NT, which will lead to better and sustainable crop yields, being the most motivating factor for NT adoption by small farmers in the Ecuadorian highlands.

Key words: Smallholders, no-till, conventional till, amaranth, maize, beans.

4.1 Introduction

Soil physicochemical properties are a consequence of climate, vegetation, parent material, topography, and time, but rapid changes in these properties in agricultural soils are promoted by land management intensity. One of the most influential factors affecting such properties is the type of tillage used to prepare a seedbed for planting, nutrient incorporation, and crop residue management to provide a proper environment for seed germination and root growth. During the last sixty years, many studies have been conducted to compare the effects of minimum or no-tillage (NT) and conventional tillage (CT) on soil physical, chemical and biological properties (Subbulakshmi, et al., 2009; Su, et al., 2021); however, the most of such studies has been carried out in flat lands (Derpsch, et al., 2014).

No-till is one of the conservation practices soil that effectively controls soil erosion (Franchini, et al., 2012; Espinosa, et al., 2016; Khan, et al., 2017), and the beneficial effect of NT adoption on several soil properties has been widely demonstrated

(Soracco, et al., 2012; Derpsch, et al., 2014; de Moraes, et al., 2015). NT significantly increases SOM content, perhaps the most relevant of all soil properties in terms of crop production and soil environmental services (Six, et al., 2002; Bronick and Lal, 2005; Soracco, et al., 2010; Lal, 2011; Derpsch, et al., 2014; de Moraes, et al., 2015) even in volcanic (Avila-Salem, et al., 2020) and granitic soils (Crovetto, 2006).

Agricultural production in the Ecuadorian highland soils occur under a very rugged topography which usually does not meet the appropriate conditions for intensive agriculture, particularly if these practices include soil tillage. Furthermore, land tenure structure is characterized by a high percentage of small agricultural production units (< 5 ha), which promotes intensive land use, while forcing the agricultural frontier towards unsuitable areas for farming purposes (Espinosa, 2014). The lack of reforestation can sharpen this problem, since Ecuador has one of the lowest rates of forest recuperation in South America (Mosandl, et al., 2008).

There is scarce published information about NT adoption in Ecuador, particularly in the volcanic highlands of the country. The scanty research work conducted during the past few years reported no difference in soil properties and crop yields when comparing NT with CT. In this context, Estrada and Calvache (2004) working with a bean-corn association under NT, minimum tillage (MT), and CT found that NT increased soil compaction, but no changes were reported in soil chemical properties or crop yield. Studies conducted by Vinueza and Calvache (2004) and Arévalo (2011) using open pollinated maize to evaluate the effects of NT, MT, and CT, reported no differences in soil physical-chemical properties or crop yield in response to tillage management. The lack of response in the three previously mentioned studies is probably due to the short duration of the field work (one crop cycle). On the other hand, Alwang, et al. (2013) studying the response of NT, MT, and CT in similar soils as those utilized by Arevalo

(2011) introduced a crop rotations component (barley, broad beans, and a mixture of oats-vetch) in the experiment, prolonging the evaluation to three continuous crop cycles. Reported results indicate that, in general, crop yields were slightly higher with NT, but they exceeded in 10 % the rate of return because the cost reduction and productivity improvement when tillage was avoided. At the same time increments in SOM and water holding capacity were reported for the NT treatment.

Cultivation of beans-maize-beans (BMB) is one of the most used crop rotation schemes by Ecuadorian smallholders, rotation which is implemented for food security purposes and to maintain soil fertility because include a legume. Amaranth, a valuable annual crop due to its nutritional properties (Raja, et al., 2012; Montellano, 2014) is used for self-consumption and for the export market, and it can be viewed as a novel and good alternative to be included in the rotation with beans, becoming a beans-amaranth-beans (BAB) rotation scheme. From the agronomic point of view, and facing the actual climatic change scenario, amaranth is a C4 plant which adapts well to various environments, especially because it is resistant to drought conditions, consumes between 60 to 75 % less water in relation to cereals (such as wheat or oats), and grows well at temperature range of 10 to 24°C (Hernánez, et al., 2014; Montellano, 2014).

Based on the above, it was hypothesized that the inclusion of amaranth in the NT crop rotation schemes will improve soil physical and chemical characteristics and will enhance crop yield in comparison to CT, even in the short term, in soils like those prevalent in the small farmer's areas of the Ecuadorian northern highlands.

4.2 Materials and Methods

4.2.1 Characteristics of the experimental site: This study was conducted at La Tola Experimental and Teaching Farm, Universidad Central del Ecuador (CADET), which is geographically located at 78°21´18´´W and 00°13´49´´S, at an altitude of 2555 m a.s.l. Local climate is characterized by an average annual rainfall of 868 mm, mean annual temperatures of 17° C, and 73.9 % mean annual relative humidity. The soil of the site is classified as Entic Durustolls, a Mollisol of volcanic origin (Moreno, et al., 2017) with the following initial characteristics: sandy loam texture, pH: 6.9, SOC: 2.1 %, total N: 0.22 %, available-P (Olsen): 68 mg kg^{-1}, K, Ca, Mg, and BS: 0.91, 8.50, 4.43 and 13.83 $cmol^{(+)}$ kg^{-1}, respectively. Two rotation schemes were implemented under CT and NT. The first rotation scheme was alternating crops of common beans-maize-beans (BMB), and the second one was beans-amaranth-beans (BAB); the following cultivars were used, beans: I-Centenario, maize: I-Chaucho Mejorado, amaranth: I-Alegría. Common beans were used for its expected N contribution to the next crop.

4.2.2 Experimental design: The study experimental design was a complete randomized block design in a split plot arrangement with eight replications. To homogenize soil fertility, the experimental site was previously planted with oats and cut periodically discarding the residues. After three months of fallow period, oat regrowth and weeds were treated with glyphosate herbicide. The main plots in the layout of the experiments were the tillage systems (CT and NT), the subplots the fertilization rates, and three replicates were used in the first bean cropping cycle. To initiate the second crop cycle (after beans), the CT and NT large plots were divided in two to accommodate the intermediate crops (maize and amaranth) configuring the two rotation schemes: beans-maize-beans (BMB), and beans-amaranth-beans (BAB), leaving a total of eight replications.

4.2.3 Experiment management: Nitrogen (N) rates for the first beans and third cycles were 0, 11, 22, and 33 kg N ha^{-1} as ammonium nitrate with a complementary blank application of 32 kg P ha^{-1} as triple superphosphate. The N rates for maize in the second crop rotation cycle were 0, 40, 80, 120 kg N ha^{-1}, and 0, 50, 100, 150 kg of N ha^{-1} for amaranth. It was not necessary to apply complementary blank application of P and K because soil analysis indicated there was no need of such application for the second crop cycle. Fertilizer was applied in two parts, half between 21 to 28 days after sowing (DAS), and half between 45 to 60 DAS. Seed rate for beans was 90 kg ha^{-1}, 120 kg ha^{-1} for maize and 10 kg ha^{-1} for amaranth. Sowing distance for beans was 0.70 m between rows and 0.30 m between plants, 0.70 m between row and 0.20 m between plants for maize, and 0.70 m between rows and 0.25 m between plants for amaranth. Beans were harvested at 120 DAS, corn was harvested between 200 to 210 DAS, and amaranth at 180 to 190 DAS. The precipitation and average temperature during the crops were as follows, in the first cycle (May/2016 – September/2016), the amount of rainfall was 127.2 mm and the average temperature was 16.2°C, in the second cycle (October/2017 – February/2018), the amount of rainfall was 472.8 mm and the average temperature was 16.2°C, in the third cycle (October/2018 – February/2019), the amount of rainfall was 469.7 mm and the average temperature was 16.8°C.

4.2.4 Soil sampling and analysis: Soil sampling was carried out after crop harvesting at two soil depths (0-5 and 5-20 cm) in all experimental units. Soil samples, each made of five subsamples**,** were transported to the laboratory, air/dried and subjected to the respective analysis.

4.2.5 Measurements: After harvesting, bean and amaranth grains were washed, dried at 12 % moisture, and weighed. Maize was harvested as fresh cobs which were counted and weighed. Values of the three crops were expressed in kg ha^{-1}. Analyzed soil chemical properties were as follows: organic carbon (SOC), by wet combustion using chromic acid digestion according to (Nelson and Sommers, 1996), using 1.892 as conversion factor**;** particulate organic matter (POM) by dispersing soil by sodium hexametaphosphate and passing it through a 0.53 um sieve according to Cambardella and Elliott (1992), Six, et al. (2002); HA extraction with NaOH according Kachari, et al., (2015), optical density determination (E_4: 465 nm and E_6: 665 nm) and E_4/E_6 ratio (Swift, 1996); soil pH in a 1:2 soil water ratio (Thomas, 1996); total nitrogen (TN) using Kjeldhal method (Bremner, 1996); phosphorus (P) (Sims, 2000): exchangeable cations (K; Ca, Mg) using the modified Olsen solution (Kuo 1996). Analyzed soil physical were bulk density (BD) (Grossman and Reinsch, 2002), and water storage capacity, water aggregate stability, and size distribution (Six, et al., 2002).

4.2.6 Statistics. The factorial ANOVA analysis and mean comparison (DMS 0.05 and post hoc multiple range test of Tukey) were conducted using Infostat (Di Rienzo et al., 2018). The described ANOVA was used for each of the sampling depths and each crop cycle of the proposed rotation schemes, with the exception of POM, E_4/E_6 ratio, aggregate stability and size distribution which were only analyzed for the second and third crop cycles.

4.3 Results

Because, in general, no significant differences on yields and soil chemical-physical characteristics with the application of fertilizer rates were observed in this study, only the average of all treatments appears in the following figures; however, in ANOVA (**Table 2**) and PCA (**Figure 6**) components the effect of fertilizer rates is included.

4.3.1 Effects of tillage and fertilizer rates over crop yields of the three crop cycles of two rotation schemes

The main effect of tillage on grain yields for each crop cycle in the rotation schemes [beans-maize-beans (BMB) and beans-amaranth-beans (BAB)] is presented in **Figure 1**. In the BMB rotation, the yield of the first bean crop cycle was 26.2 % higher than CT; in the second crop in the rotation, NT yield of cob corn was a 75 % higher than under CT, while no statistical differences were evident in the yields of beans in the third crop cycle of the rotation. On the other hand, the response in grain yield to tillage in the BAB rotation was not significant in all crop cycles, however in the first bean cycle NT yield was 21 % higher than under CT, while in the second and third crop cycles (amaranth and beans) grain yields were slightly higher under CT. Surprisingly, the main effect of fertilizer application on crop yields were not significant in all three crop cycles in both tillage systems, and both rotation schemes (not shown).

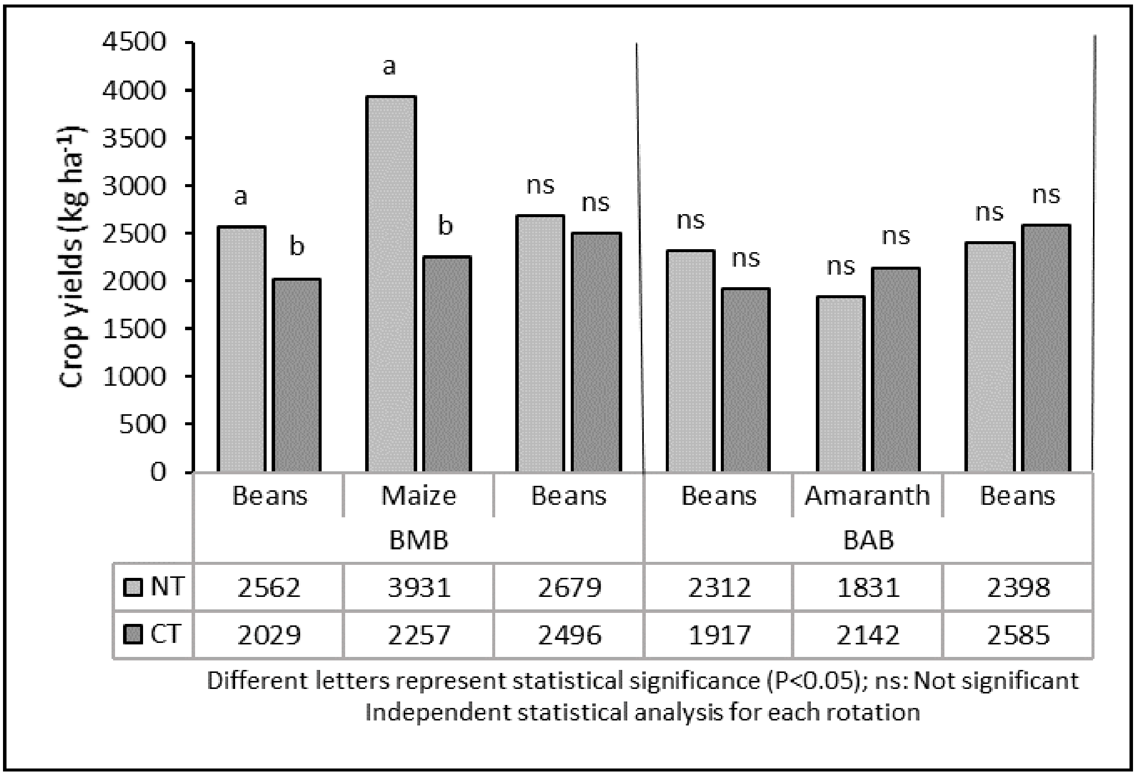


Figure 1. Effect of tillage systems on yield of beans, maize and amaranth at the end of the three crop cycles of two rotation schemes in a Mollisol of volcanic origin in the Highlands of Ecuador.

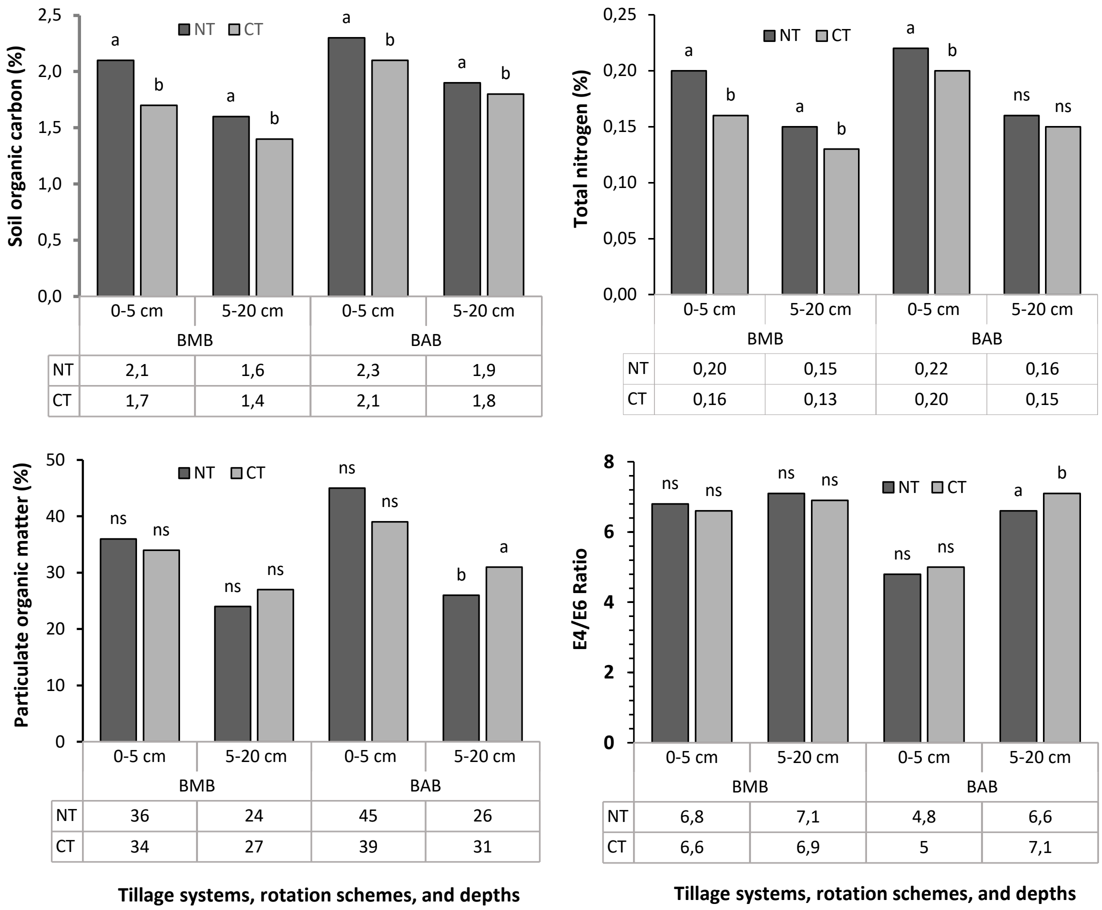
The ANOVA of the effects of tillage, fertilizer application and the interaction tillage – fertilizer on yield of the three crop cycles in both rotation schemes.is presented in **Table 1**. In the first cycle, the differences in bean yield among tillage systems and the interaction tillage-fertilizer application were statistally significant only in the BMB rotation scheme; in the second cycle, the differences in maize yields were statiscally significant only for tillage in the BMB rotation, while the differences in amaranth yields were statiscally different for the main effect of the fertilization and the inteaction tillage-fertilization in the BAB rotation. In the third cycle no statistical differences were found for beans yield (**Table 1**).

Table 1. Summary of ANOVA for crop yield (kg ha^{-1}) effect of tillage, fertilizer rates, and the interaction tillage-fertilizer rates of each of the three crop cycles in two crop rotation schemes evaluated in a Mollisol of volcanic origin in the Highlands of Ecuador.

Cycle	**Rotation scheme**	**Crop**	**ANOVA**		
			Tillage systems[3, 4]	**Nitrogen rates**	**Tillage x nitrogen rates**
First	B-M-B[1]	Beans	0.005*	0.195	0.046*
	B-A-B[2]	Beans	0.225	0.046	0.591
Second	B-M-B	Maize	0.007*	0.321	0.134
	B-A-B	Amarant h	0.106	0.000*	0.000*
Third	B-M-B	Beans	0.320	0.826	0.984
	B-A-B	Beans	0.407	0.797	0.780
BMB[1]: beans-maize-beans rotation scheme; BAB[2]: beans-amaranth-beans rotation scheme					
NT[3] = No-till; CT[4] = Conventional tillage					
* Indicate statistical difference at $p < 0.05$					

4.3.2 Effects of tillage and fertilizer application on soil carbon components

Soil organic carbon (SOC) is the main component of the soil organic matter (SOM); therefore, changes in its content have strong effects on soil physical, chemical and biological properties. Results show a greater accumulation of SOC in the NT treatments in both rotations and sampling depths, being its difference, 24% higher at 0-5 cm depth and 15% at 5-20 cm depth in BMB rotation. Although C accumulation in BAB was higher compared to BMB rotation, the differences between both tillage systems were less significant (**Figure 2**).



Different letters represent statistical significance (P < 0.05); NS: Not significant
Independent statistical analysis for each rotation and sampling depth

Figure 2. Effect of tillage systems on SOC, TN, C-POM (%) and E_4/E_6 ratio at the end of the three crop cycles of two rotation schemes in a Mollisol of volcanic origin in the Highlands of Ecuador.

Tillage systems also modify N cycle in the soil. Superficial accumulation of crop residues of high C/N ratio left in the soil during the first years of NT reduces residue microbial decomposition, therefore reducing N availability due to a transitory N immobilization in the microbial biomass which is further mineralized in the long term. Thereby, the main overall effect of tillage systems on total nitrogen (TN) presented in

Figure 2, indicates that the pattern followed was about the same of TOC showing a not detectable effect of N fertilization on SOC or accumulated N.

Particulate organic matter (POM) is a pool which contributes to SOM turnover because it serves as a readily decomposable substrate for soil microorganisms and as short-term nutrients reservoir for plants. It has been suggested as an early sensitive indicator of SOM changes, due to its responsiveness to management practices. Data from our experiment indicates, as expected, that the highest POM values were obtained in the upper soil layer where more active roots are present, especially in BAB rotation. Here, the POM content in the BMB rotation was 25% and 14% higher under NT and CT respectively, compared what occurred in deeper soil layers. No significant differences were observed at 5-20 cm depth neither with rotation nor tillage systems (**Figure 2**).

It has been suggested that E_4/E_6 ratio is related to the aromatic carbon network condensation degree, carbon content, and molecular weight of humic substances, all of them affected by tillage. The lowest values were observed in BAB rotation at 0-5cm depth, being around 30% lower compared with BMB rotation, suggesting that humic acids from amaranth residues are being humified more quickly that maize ones.

4.3.3 Effects of tillage and fertilizer application over pH, and available phosphorus

The main effect of tillage on soil pH differed significantly in the two sampled horizons only in the BAB rotation suggesting an acidification trend in the CT treatments. The lower pH value at 5-20 cm depth is surely due to the higher root activity at higher soil depth. No pH differences were observed when contrasting NT and CT in the BMB rotation **(Figure 3)**. No statistical differences were evident for the main effect of fertilizer application.

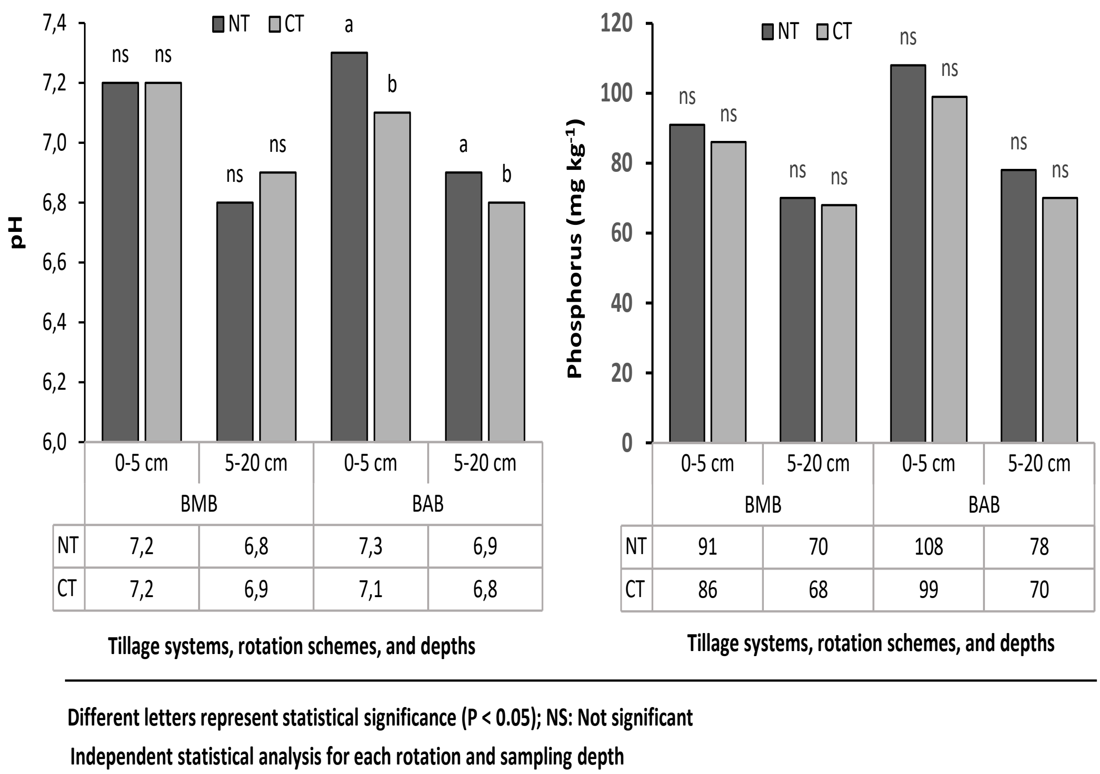


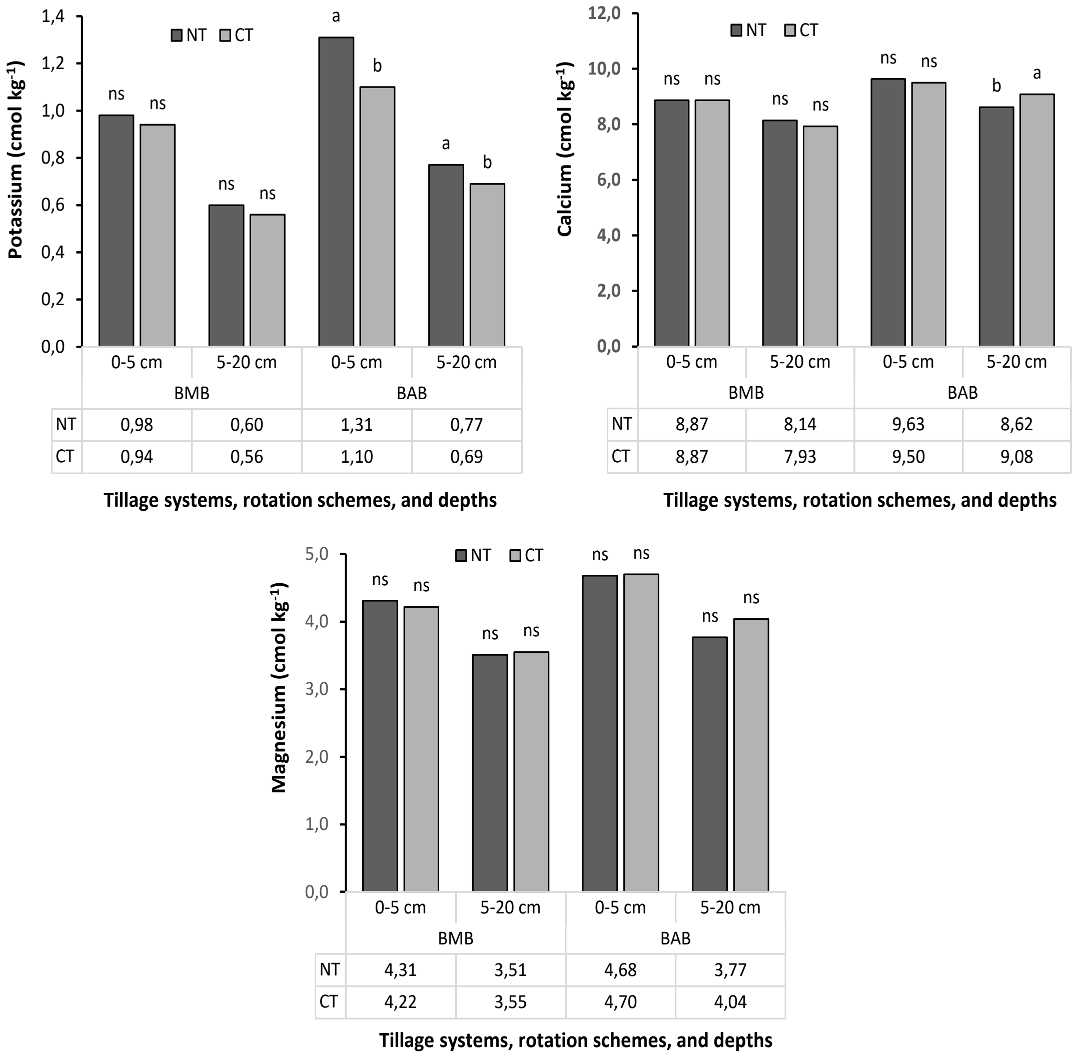
Figure 3. Effect of tillage on pH, and available soil P at the end of three crop cycles of two rotation schemes in a Mollisol of volcanic origin in the Highlands of Ecuador.

Overall data on the main effect of tillage on soil available phosphorus (P) at the end of the third rotation cycle revealed not significant differences for the main tillage effect or the fertilizer main effect in both rotations at both sampling depths, but higher P levels were observed in the upper soil layer. Despite the lack of statistical significance of the differences in available P between NT and CT in both rotation schemes, numerical data shows more available P present in NT treatment in the BAB scheme (**Figure 3**).

4.3.4 Effect of tillage and fertilizer application on soil available of potassium, calcium, and magnesium

The main effects of tillage on the potassium (K), calcium (Ca) and magnesium (Mg) soil content are presented in **Figure 4**. Data indicates that K content presented a statistical difference among NT and CT only the BAB rotation, at both sampling depths, the Ca content was only significant in BAB rotation in the 5-20 soil layer, and the differences in

Mg were not significant in both rotations and sampling depths. The main effects of fertilizer application were not statistically significant.



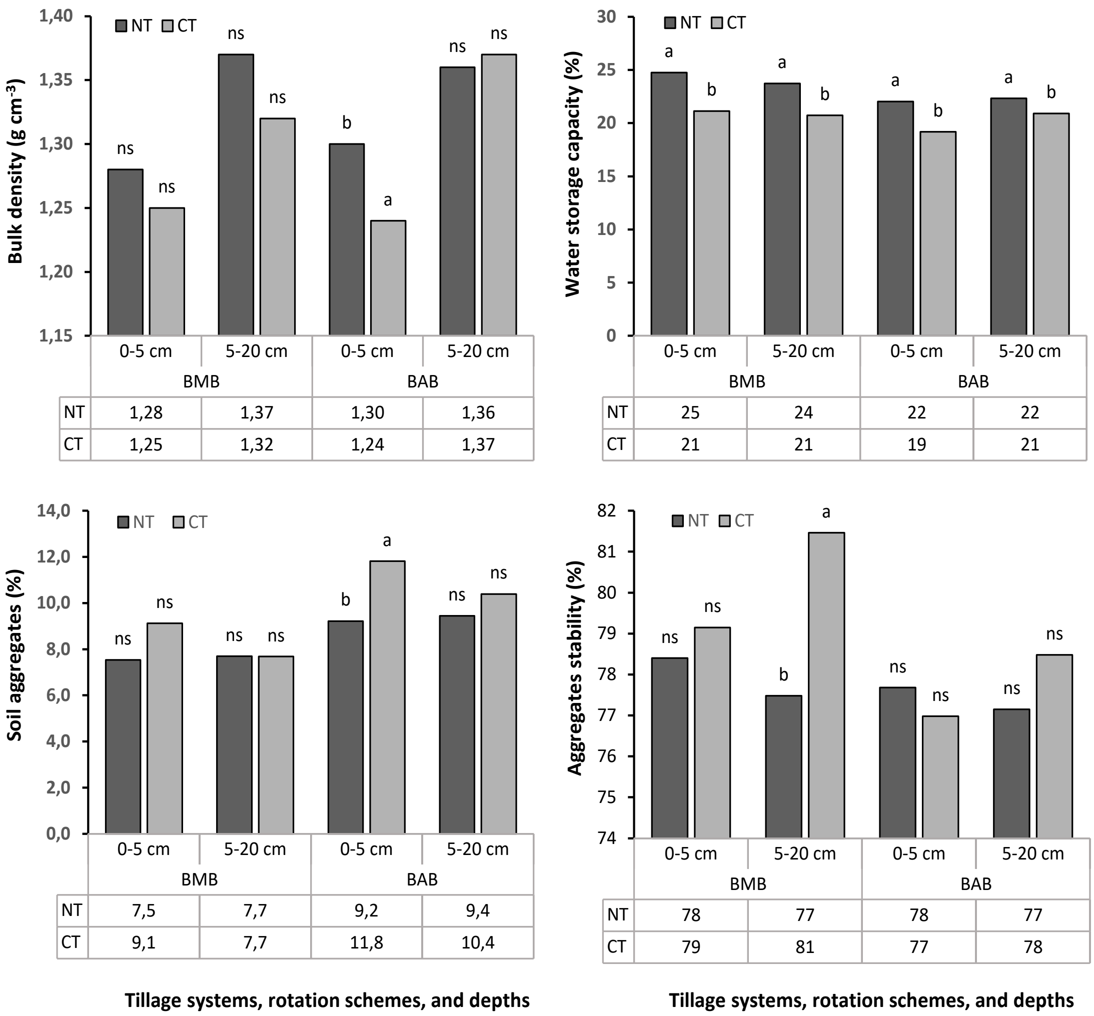
Different letters represent statistical significance (P < 0.05); NS: Not significant
Independent statistical analysis for each rotation and sampling depth

Figure 4. Effect of tillage on the content soil potassium, calcium, and magnesium at two depths at the end of the three crop cycles of two rotation schemes in a Mollisol of volcanic origin in the Highlands of Ecuador.

4.3.5 Effect of tillage and fertilizer application on soil physical characteristics

The main effect of tillage on bulk density (BD), water storage capacity, soil aggregation and water aggregate stability is presented in **Figure 5**. As expected, BD was higher at 5-20 cm compared with 0-5 cm depth. In addition, the main effect of tillage over BD under

NT was higher than CT at both rotations and both sampling depths, however the difference was only significant in the BAB rotation at the 0-5 sampling depth.



Different letters represent statistical significance ($P < 0.05$); NS: Not significant
Independent statistical analysis for each rotation and sampling depth

Figure 5. Effect of tillage on bulk density, water storage, soil aggregates, and aggregates stability at the end of the three crop cycles of two rotation schemes in a Mollisol of volcanic origin in the Highlands of Ecuador.

Frequently, soil aggregation percentage and water stability of soil aggregates are used as indicators in agricultural management, especially tillage and rotation systems. In this study, the differences in the main effect of tillage on water storage capacity were statistically significant in both rotations at both sampling depths, NT being the tillage practice that showed more retention capacity. Soil aggregation and aggregate stability did not show differences except for BAB rotation at 0-5 cm sampling depth. (**Figure 5**).

The ANOVA of the effects of tillage, fertilizer rates and the interaction tillage – fertilizer rates for the changes on soil chemical and physical properties at the end of the three crop cycles in two rotation schemes is summarized in **Table 2**.

4.3.6 Principal component analysis for physical and chemical characteristics of the three crop cycles of two rotation schemes

In this study, the correlation for interdependency of the principal components (PC) grouping the information documented after the three planned crop cycles for both rotations, indicating the overall effect of NT and CT on soil properties are represented in **Figure 6**.

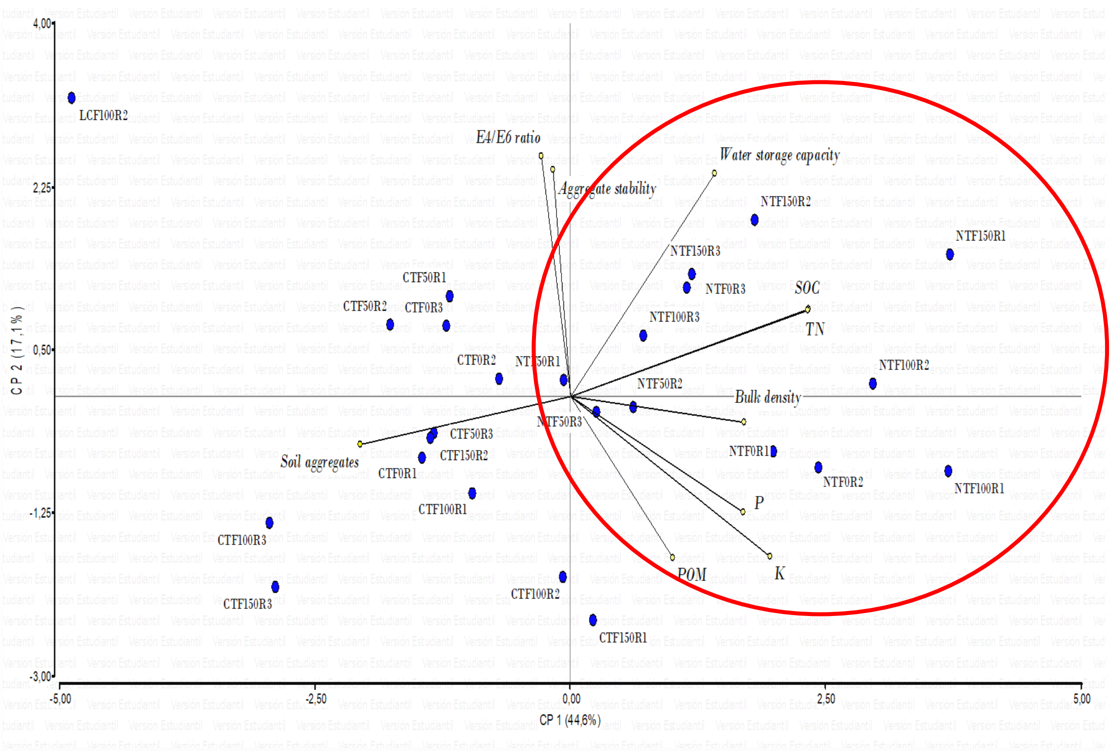


Figure 6. Grouping of the main physical and chemical variables as effected by tillage and fertilizer rates after three crop cycles of two crop rotation schemes evaluated in a Mollisol of volcanic origin in the Highlands of Ecuador. CTF = conventional till with different N rate; NTF no-till with different N rate.

Table 2. Summary of ANOVA for the effects of tillage, fertilizar rates and the interaction tillage-fertilizer rates on soil physical and chemical characteristics at the end of three crop cycles in two crop rotation schemes evaluated in a Mollisol of volcanic origin in the Highlands of Ecuador.

Variable	ANOVA	B-M-B[1]	B-A-B[2]	B-M-B	B-A-B
		Depth 0-5 cm		Depth 5-20 cm	
SOC (%)	Tillage system	0.001*	0.018*	0.005*	0.071
	Fertilizer rates[5]	0.777	0.868	0.890	0.429
	Tillage x	0.291	0.419	0.177	0.696
POM (%)	Tillage system	0.585	0.078	0.194	0.031*
	Fertilizer rates	0.605	0.500	0.139	0.647
	Tillage x	0.942	0.209	0.489	0.786
E_4/E_6 ratio	Tillage system	0.252	0.011*	0.619	0.016*
	Fertilizer rates	0.106	0.997	0.732	0.025*
	Tillage x	0.115	0.999	0.685	0.037*
TN (%)	Tillage system	0.001*	0.020*	0.009*	0.080
	Fertilizer rates	0.706	0.888	0.937	0.019*
	Tillage x	0.338	0.393	0.218	0.595
P (mg kg^{-1})	Tillage system	0.760	0.225	0.913	0.081
	Fertilizer rates	0.499	0.452	0.049*	0.198
	Tillage x	0.987	0.801	0.973	0.942
K (cmol kg^{-1})	Tillage system	0.693	0.019*	0.589	0.028*
	Fertilizer rates	0.792	0.431	0.955	0.276
	Tillage x	0.414	0.965	0.677	0.340
Ca (cmol kg^{-1})	Tillage system	0.991	0.447	0.423	0.010*
	Fertilizer rates	0.484	0.041*	0.945	0.158
	Tillage x	0.994	0.840	0.787	0.859
Mg (cmol kg^{-1})	Tillage system	0.309	0.910	0.641	0.059
	Fertilizer rates	0.236	0.076	0.873	0.318
	Tillage x	0.769	0.994	0.967	0.910
pH	Tillage system	0.756	0.003*	0.055	0.003*
	Fertilizer rates	0.595	0.904	0.639	0.931
	Tillage x	0.477	0.478	0.746	0.353
Bulk density (g cm^{-3})	Tillage system	0.313	0.025*	0.273	0.383
	Fertilizer rates	0.737	0.849	0.682	0.363
	Tillage x	0.148	0.032*	0.260	0.660
Water storage capacity (%)	Tillage system	0.016*	0.017*	0.014*	0.047*
	Fertilizer rates	0.588	0.665	0.762	0.976
	Tillage x	0.759	0.648	0.721	0.971
Soil aggregates (%)	Tillage system	0.081	0.0003*	0.980	0.153
	Fertilizer rates	0.562	0.545	0.759	0.299
	Tillage x	0.812	0.878	0.715	0.961
Aggregate stability (%)	Tillage system	0.537	0.814	0.011*	0.709
	Fertilizer rates	0.587	0.450	0.231	0.225
	Tillage x	0.212	0.055	0.960	0.163

BMB[1]: Rotation scheme beans-maize-beans; BAB[2]: Rotation scheme beans-Amaranth-beans

NT[3] = No-till; CT[4] = Conventional tillage

[5]Nitrogen fertilization rates: Beans 0, 11, 22, 33 kg ha^{-1}; Maize 0, 40, 80, 120 kg ha^{-1}; Amaranth

** Indicate statistical difference at $p < 0.05$*

4.4 Discussion

4.4.1 Effect of tillage and fertilizer rates on yield of the three crop cycles of two rotation schemes

Long time research studies have identified several benefits of conservation tillage, specially no-tillage (NT), over conventional tillage (CT) with respect to soil physical, chemical and biological properties that have a major impact on soil productivity and sustainability (Al-Kaisi and Yin, 2005; Van der Putten, et al., 2010). However, the impact on soil productivity varies depending on soil characteristics and management. (de Felice et al., (2006), in their review of the effect of tillage on crop yield presented a map for the US and Canada which reports a tendency of NT to produce greater yields in the southern and western US regions, similar yields in the central US and lower yields in the northern US and Canada. These patterns are in accordance with soil drainage and rotation schemes, being higher in well-drained than in poorly drained soils and monoculture (Fan, et al., 2012). Consequently, it is necessary to evaluate previously the behavior of NT and crop rotation according to soil characteristics for obtaining adequate yields before recommending its adoption by farmers.

In this study, the trend to higher beans yield under NT was evident already in the first cycle, where the results showed that grain yield was 42 % higher under NT, indicating that the soil improvements promoted by NT had beneficial effects on crop yield (Montesdeoca, et al., 2020; Avila et al 2020). In the same way, NT cob corn yield in the second cycle of the BMB rotation was higher than CT. This trend was not present in the amaranth yield in the second crop cycle of the BAM rotation. Amaranth yield under NT was probably limited by weed management, particularly for the competition with wild amaranth (*Amaranthus spinosus*) during most of the cropping cycle. Wild amaranth is a widely present weed species in CT cultivation in the northern highlands of Ecuador. It important to mention that so far, there were no attempts to cultivate amaranth under NT mentioned in the literature, therefore, no information on weed management was available. It is probable that weed management in the long-term experiment will be capable to suppress wild amaranth presence when grain producing amaranth is used in the rotation scheme. The lack of significant differences in bean yields among tillage systems in the third cycle in both rotations is probably due to the excess of water in the soil profile, promoted by the heavy precipitations in the middle of the rainy season which prompted the incidence of *Rhizoctonia* and *Pythium* affecting root growth and yield (de Toledo-Souza, et al., 2012).

This trend of higher yields under NT was evident in our experiment suggesting that the elimination of soil disturbance improves the general conditions for crop growth. In general, it is expected that under adequate management, grain yields under NT should be at least like those obtained with CT (Derpsch, et al., 2010; Jena, 2019), condition which could lead to the NT adoption by small farmers in the Highlands of Ecuador. Furthermore, we proved that grain producing amaranth can be cultivated under NT without mayor problems in these highland soils.

The lack of statistical significance of the main effect of the fertilizer rates on yield in all three cropping cycles in both tillage systems and rotation schemes could be attributed to the preceding management of the experimental site. Therefore, high rates of plant nutrients have been applied to potato fertilization experiments conducted over the last decades, and despite the actions taken to homogenize the fertility of the experimental site, some historical chemical fertilization memory could have been lingered to our plots.

Results indicate that there is enormous potential for the successful crop production under NT under the utilized rotation schemes, having a legume (beans) as a head crop in the sequence. There is no information related to tillage disturbance on yields of the proposed rotations in the highlands of Ecuador, but land degradation problems on farmers´ fields are evident on most of the landscapes where open pollinated corn for human consumption is cropped. It has been demonstrated that this crop, common in the Highlands of Ecuador, can produce higher yields under NT. Alvarado, et al. (2011) reported grain yields of 5.2 t ha^{-1} for NT contrasting with 4.3 t ha^{-1} in CT cultivated in similar volcanic soils of the Central Highland of Ecuador.

4.4.2 Effect of tillage systems and fertilizer rates on soil carbon components

Organic carbon (OC) is the main component of the SOM; therefore, changes in SOM content have a strong effect on soil physical, chemical and biological properties (Schlesinger and Andrews, 2000; Martínez, et al., 2008) and consequently, this effect is evident when NT is adopted, due to the crop residue accumulation on the surface of soils managed with this conservation practices.

The overall higher SOC accumulation under NT at the end of the three rotation cycles and both rotations, was evident even considering that the initiating crop (bean) in the rotation schemes is a legume with a low C/N ratio, which favors residue mineralization delaying SOC accumulation, particularly in the upper soil layer (Zotarelli, et al., 2012; Raphael, et al., 2016). The higher SOC content at both soil layers in the BAB rotation could probably be due to the different root type of the intermediate crops in the rotation. The amaranth root system is axonomorphic with a thick root from which other thinner roots develop, while corn has a fasciculated and branched root system with principal and secondary roots with the same thickness. For this reason, corn can leave more superficial residues in the soil, in comparison with amaranth which can leave a higher quantity of root residues deeper in the soil profile (Montellano, 2014). In addition, amaranth roots exude high amounts of low molecular weight organic acids, mainly oxalic acid, together with a lot of allelopathic compounds (Bakhshayeshan-Agdam, 2015).

Additionally, data also suggest that rotation schemes including maize, has slower residue decomposition probably due to its residues have high lignin content (Craswell and Lefroy, 2001; Baldock and Broos, 2012).

No-till improves nutrient cycling due to the higher residue accumulation which provides available N for the next crop (Ranaivoson, et al., 2017), while intense soil removal by CT can reduce SOC and TN content due to aggregate destruction and rapid residue mineralization (Issaka, et al., 2019). On the other hand, the general higher TN content observed in the BAB rotation, compared to the BMB rotation, is probably due to the mineralized N losses from the organic pool which was been taken up by the growing maize crop, or leached through the soil profile (Figueroa, et al., 2012).

Additionally, POM is the transitory fraction of the SOM, in an intermediate state of decomposition between fresh residues and stable C compounds (humus). It is defined as the chemical and biologically active fraction of the SOM composed of particles that vary from 0.053 to 2 mm that indicates the presence of recently incorporated SOC (Cambardella and Elliott, 1992; Wander, 2004; Jat, et al., 2019), and is considered as an immediate source for plant nutrients, food, and energy for microorganisms. It is also responsible for the soil buffer capacity increase, and it is a trap for soil contaminants such as pesticides and heavy metals (Nciizah and Wakindiki, 2012; Lehmann and Kleber, 2015). POM is a sensible parameter to indicate the effect of different agronomic management over plant performance (Gregorich and Ellert, 1993; Galantini, et al., 2007).

In this sense, Ávila-Salem, et al. (2021), in a parallel study carried out in these same experimental plots, clearly demonstrated the beneficial effect of NT in comparison with CT, on a series of soil biological traits such as basal respiration, number of arbuscular mycorrhizal fungi spores, enzyme activities of acid phosphatase, β-glucosidase and total glomalin related soil protein, all parameters which have been reported for the first time in the Andean region. These biological traits were strongly associated to the accumulation of SOM originated from crop residues accumulation in the NT post-harvest system which concomitantly improves the soil moisture, basal respiration, microbial enzyme activities, and mycorrhizal fungal activity all of them strongly related to crop establishment and development. This study also concluded that the crop rotation system where amaranth was included in association with beans (legumes), contributed to the enhancement of soil biological activity probably due to the increment in microbiological sources of nutrients and energy.

Furthermore, POM provides early information about the future content of total SOM because POM rapidly reaches a new equilibrium after an episode of soil management such as crop rotation or tillage. Total SOM is not a good quantitative and sensitive indicator of the direct relationship of SOC content with crop productivity and soil quality, relation which is more evident with POM (Martínez et al., 2018). A reduction in POM correlates with a decline in soil fertility and the quality of soil physical properties such as soil aggregation, conditions which are associated to soil degradation and lower resilience. Several studies suggest that macro aggregates are organized around POM (Six, et al., 2002; Ciarlo, et al., 2004; Videla, et al., 2008; Ghisolfi, 2011; Lehmann and Kleber, 2015).

The overall results of POM accumulation throughout the planned rotations in time will determine which crop sequence provides the best soil quality characteristics in terms of SOM, which will reflect in crop performance and yields (McVay, et al., 2006; Basanta, et al., 2012; de Moraes, et al., 2015; Jat, et al., 2019).

Microbial mediated plant residue decomposition leads to the formation of stable carbon compounds broadly called ¨humin¨, but according to the molecular weight and condensation degree, it can be separated into two groups structurally and spectroscopically different in behaviour so-called ¨humic¨ and ¨fulvic¨ acids. During humification process carbohydrates rapidly disappear and phenolic compounds like lignin, tend to accumulate as humic compounds. These compounds are characterized using the E_4/E_6 ratio which is the measurement of adsorption of light at 464 and 665 wave lengths in a spectrophotometer, which in time is related to the degree of condensation or maturity of aromatic humic constituents. The E_4/E_6 ratio is then used as an index of humification relating the aromaticity of the organic carbon chains and their condensation to stable compounds. A reduction in this value indicates progressive condensation of humic substances (Bonometo, 2010; de Moura Luz, 2013; Kachari, et al., 2015). Data obtained (**Figure 2**) suggest a more rapid humification of amaranth residues left in the soil, which is more pronounced under NT than CT, and at 0-5 cm depth than 5-20 cm depth. There is scarce information about humification rates of amaranth residues, in terms of its quality and microflora associated with such process so we think that this is a matter which needs deeper studies to understand its role in the proposed rotation under NT.

4.4.3 Effect of tillage systems and fertilizer rates on some soil chemical components

Soil pH significantly affects soil chemical processes like mineral weathering, SOM decomposition, ion mobility and nutrient availability. Soil management, particularly the use of ammoniacal N fertilization, can produce changes in soil pH which promotes acidification leading to negative soil conditions for crop growth (Bloom and Skyllberg, 2012; Havlin, et al., 2014). The lower pH observed in BAB rotation under CT could be due to the oxalic acid exuded by amaranth roots (Javed, et al., 2017) agreeing with the significant acidification observed in a volcanic soil cultivated with amaranth, or perhaps to a higher ammonia volatilization produced under NT (Liu, et al., 2018). The same trend of a higher pH under NT compared with CT was reported by Borie, et al. (2006) in a field study of tillage rotation including legumes and cereals, grown in a Chilean Ultisol.

Unfortunately, no reports for comparisons have been found regarding the performance of amaranth under NT in field conditions, as well as residue decomposition and root physiological traits.

In relation to available P, data obtained suggest that the lack of soil movement, and the consequent residue accumulation on the surface of soils under NT, promotes stratification of plant nutrients, particularly P. Surface residue buildup and the low P mobility in the soil result in the P accumulation in the 0-5 cm layer, which gradually decreases the content of available P with soil depth (Lupwayi, et al., 2006; Grove, et al., 2007). Greater water, N and C availability in the upper soil layer under NT increase microbial population growth and activity, which is responsible of P cycling, promoting P immobilization and reducing soil labile P content, but such processes are not as marked as the one occurring with N (García and Picone, 2004; Cerón and Aristizábal, 2012).

Available P accumulation was greater in amaranth than in maize for both NT and CT, probably due to a more dynamic mineralization of the organic P from the amaranth residue in comparison with maize. The trend of a higher P content in the 0-5 cm layer suggests that the conditions imposed by NT are promoting the stratification of available P in the soil profile.

The higher concentration of exchangeable cations in the 0-5 cm soil layer also suggests that the process of stratification is consolidating in both rotations. It has been reported that changes in K, Ca, and Mg in the absence of soil removal in NT systems are less intense than those of N and P, and only become evident after prolonged period of NT management (Grove, et al., 2007; Blanco-Canqui and Lal, 2009). In general, the cation saturation of the exchange phase seems to be adequate for suitable crop nutrition.

4.4.4 Effect of tillage systems and fertilizer rates on soil physical characteristics

There is a consensus that agricultural management practices, especially tillage and crop rotations, modify soil chemical, physical and biological properties in the long-term, but less references are found for the short-term changes of the transition from CT to NT in highland soils. No-tillage establishment involves soils with different physical, chemical, and biological properties, which slowly change due to the reduction or elimination of soil disturbance, and the protection of crop residues left in the soil, however, these differences can become larger with enough time under NT management (Blanco-Canqui, 2012; Lal, 2015). This es especially true for the changes on soil physical properties which are expected to be expressed later in time that other soil properties after the NT consolidation (de Moraes, et al., 2015). Until now results reported in the literature on the effect of tillage in soil physical properties have been rather ambiguous an even contradictory depending on the time of application and soil clay content (Ordoñez-Morales et al., 2019) but in general it was expected that NT would decrease bulk density (BD), particularly in the upper soil layer, as an associated effect of SOM accumulation, assuming that plowing breaks soil aggregates, therefore changing soil structure, and stimulating SOM losses by C mineralization (Reichert, et al., 2009; Sapkota, et al., 2012; de Moraes, et al., 2015). However, there are reports of situations where no change or increments in BD under NT, in comparison with CT, have been observed in different rotations and different time periods. Li et al. (2007), working in a Cambisol from China, cultivated for 15 years with a wheat monoculture, documented a higher BD in NT plots during the first six years of the study, probably due to compaction produced by tractor traffic. Roldan, et al. (2007) working with a maize-bean rotation in a high clay Vertisol from Mexico recorded a higher BD in NT compared with CT at the end of a four-year period. It has been argued that BD is difficult to modify under NT and that this change is highly dependent on the type of clay present in the soil (Reichert, et al., 2009; Indoria, et al., 2017).

An important aspect of any tillage system is the influence over its soil moisture content. The volume of stored water and the duration over time depends on soil management, which in turn is related to SOM content (Acevedo, 2003). Our results strongly suggests that there is a higher absolute moisture retention in the NT treatments, a condition which can be explained by the protective effect produced by the plant material residue on the soil surface. Surface residue accumulation prevents soil exposure to sunlight and wind, promoting a greater available moisture content for the growing crop (Vidal, et al., 2002; Crovetto, 2006). No statistical differences were found for the main effect of fertilization, or in the interaction tillage-fertilizer.

An enhanced water use efficiency will be key in the future due to conditions imposed by climate change on rainfall pattern (Kazula, et al., 2017), particularly in areas highly dependent on precipitation, like those of the Highlands of Ecuador. No-till and crop rotations leaving abundant residues on the ground will improve water storage capacity, reducing water stress and contributing to crop yields (de Moraes, et al., 2015; Fonteyne, et al., 2019).

Soil particles are not present as individual entities, except for sandy soils, but they are usually united resulting in discrete clumps, as composite or aggregate structural units. An aggregate is a three-dimensional unit of soil structure that results from the union of individual particles formed by natural processes, and the internal cohesion is a result of the presence of various forces acting between soil particles (Asano and Wagai, 2014). Conservation tillage promotes the formation of soil aggregates (Six, et al., 2000). Recent investigations reported by Veloso, et al. (2019) demonstrated that rotations of legumes with maize and oats under NT had a higher water stable soil aggregates than the same rotations under CT. In this work, the relatively short period of time of the rotations in the field is probably the reason for the higher CT percentage of soil aggregates and, as with other variables reported in this study, we predict that the NT consolidation with time in the field will show their real performance (Six and Paustian, 2014; Cates, et al., 2016). Summarizing, the principal component analysis for chemical and physical characteristics in the bean–amaranth-bean rotation suggests a strong association among NT with SOC, POM, TN, P, K, and water storage capacity, which can explain the improved soil properties and its influence on grain yields.

4.5 Conclusions

Considering all the above, this study strongly suggests that both, tillage management and rotation schemes have beneficial effects on the physical and chemical soil properties of the volcanic soils used, which represents most the soils of the northern highlands of Ecuador. Fertilization rates used in this study did not significantly influence on soil properties, probably due to the nutrients levels of the original soil, however these effects must be deeply studied in a near future. On the other hand, the novelty of this study mainly relies on the rotation scheme used (bean-maize-bean, and bean-amaranth-bean). To the best of our knowledge, this is the first time in which amaranth, an interesting highly profitable crop used in sustainable agriculture, is included in NT rotation studies. In this sense, further investigation must be performed to propose its use to small farmers from the highlands. We expect that the improved soil characteristics trends will consolidate in the next crops in the rotation schemes. The improved soil conditions under NT: SOC, TN content, and water storage capacity will lead to obtain better crop yields together with a soil structure improvement, which could be considered as the most important motivation for NT adoption by small farmers in Ecuadorian highlands preserving the soil as a not renewable resource.

Chapter V

“General discussion, conclusions, and future trends”

5.1. General discussion

In the world there is a higher demand for foods due to the population increase over the last years, this constitutes a greater pressure in the use of sources for food production, mainly soil and water; however historically, the increase of agricultural yield**s** had been associated with the natural resource deterioration (Andrade, 2016). Between the years 1960 to 2000, an increased food production under the "Green revolution" trend, which was characterized by great scientific advances in plant genetics, irrigation technology, agricultural machinery development that permitted the availability of high crop yield and the expansion of the agricultural frontier. This was achieved even in unsuitable soils, complemented with the use of synthetic fertilizers and herbicides relatively cheap, with indiscriminate use; nowadays the pressure of boosting the amount of food production still persists, especially in crops such as corn, wheat, rice (Tester y Langridge, 2010), and soybean.

An increase in yields habitually requires excessive use of chemical fertilizers, especially N and P, causing alteration of these nutrients cycle on the environment (biogeochemical cycles), pollution, and energy inefficiencies (Issaka at al., 2019). Since its continued application causes deficient use, it is known that only 47% of the N applied as fertilizers to the commercial crops is effectively used by the plants (Lassaletta et al., 2014); on the other hand, it is widely recognized that phosphorous (P) absorption by crops is around 10-15%.

The nitrates not used by plants, partially dissipate towards the atmosphere under the form of ammonium (NH_4^+) and nitrous oxide (N_2O), while another part leaches into water tables and flows into the rivers, lakes, and seas; but also, the P applied in excess which is not used by the plants is lost through erosion, surface runoff, and leaching into water bodies causing detrimental effects over all living beings health (Fowler et al., 2013).

The soil erosion that occurs in very steep slopes, is produced by using tillage systems that strip and remove the soil´s top layer when burning the stubble, replacing the native forest by crops on soils with steep slopes, unsuitable to use under conventional agricultural; also, when using agrochemicals resistant to biodegradation, wrong irrigation practices that cause erosion, salinization, and sodification. Annual losses in agriculture due to erosion are estimated for reduction yields by 33.7 million tons, and increasing water abstractions by 48 billion m^3 because is lost annually between two to five million hectares, and those 23% of agricultural soils on the planet are degraded and do not respond to fertilizers application (Panagos et al., 2019). Under these conditions legume plants do not express their N fixation potential (Blesh et al., 2013). In addition, the average temperature increases due to the climate change, exceeding the global average (Pérez and Fellmann, 2015), so that evapotranspiration could increasingly exceed the capacity of the soil to supply water to plants, and therefore, drought stress could cause higher crop losses (Rost et al., 2009).

To counteract the effects described above, the conservation or regenerative agricultural approach is used including suitable soil tillage techniques such as reduced tillage and No-till (NT) and, complemented with crop rotation involving legumes and cereals, distribution of stubble over the soil surface, and the adequate use of fertilizers. With the NT application comes an increase in stabilized soil organic matter (SOM), resulting in a better soil structure, improvement of the cationic exchange capacity and greater availability of nutrients, causing an increase in the soil biological activity and the aerial environment of soil, with an impact on the absence of pests and its control (Pérez, 2021). The NT practices also allows an increase in the infiltration water by protecting the surface structure due to the residues layer that covers the soil surface and leading to a runoff reduction as well as less evaporation of soil moisture, the residues protect it from the sun rays action, avoiding hydric stress to the plants (de Moraes, 2016; Indoria, 2017), hence, No-till (NT) is estimated to reduce evaporation in 25%, while increases crop production of corn by 19% (Rost et al., 2009). On the other hand, from a social point of view, the application of NT by small farmers can positively impact their economy because it reduces the production costs due to a decreased use of agricultural machinery and fuel, and this tillage system, in the long run, also reduces the use of labor (Jena et all, 2019).

Under this context, this Doctoral Thesis had as general objective to compare the effect of NT and CT on soil physical and chemical properties and on the SOM accumulation on an Andean soil of the northern Ecuadorian highlands, cultivated with beans - corn and bean - amaranth rotations under different fertilization rates. It was hypothesized that NT management of crop rotations, including one leguminous (beans), cereal (corn) and amaranth, implemented on soils from the small farmer's areas of the Ecuadorian northern highlands will improve soil physical and chemical characteristics, and the quantity and quality of SOM, in comparison to CT even in the short-term, in three cycles of production. In the process of our study and undergoing the different crop rotations along our medium to long-term study, we have evidenced and recorded the soil characteristics changes under contrasting soil management in this initial and transitional phase.

5.1.1 Effects of tillage systems and rotation schemes on the proposed rotations yields

The trend of higher yields under NT was evident in the Beans-Maize-Beans (BMB) rotation and in the first cycle of the Beans-Amaranth-Beans (BAB) rotation. Amaranth yield under NT was probably limited by weed management, mainly by the competition with wild amaranth (*Amaranthus spinosus*) during most of the cropping cycle. Wild amaranth is a widely present weed species under CT cultivation in the northern highlands of Ecuador. However, it has to be informed that no attempts have been done before related to the amaranth cultivation under NT and no information has been mentioned in the literature, therefore, no data or other information on weed management was available. It is probable that weed management in the long-term will be capable to suppress the wild amaranth presence when grain producing amaranth is used again in the rotation scheme. The lack of significant differences in beans yield among tillage systems in the third cycle, in both rotations, is probably due to the excessive moisture in the soil profile, promoted by the heavy precipitations in the middle of the rainy season which prompted the incidence of *Rhizoctonia* and *Pythium* affecting root growth and yield, as reported by de Toledo-Souza et al., (2012).

A trend of higher yields under NT was evident in our study suggesting that the elimination of soil disturbance improves the general conditions for crop growth (Montesdeoca et al., 2020). In general, it is expected that under adequate management, grain yields under NT should be at least like those of CT (Derpsch et al., 2010; Jena, 2019), which could lead to NT adoption by small farmers in the northern highlands of Ecuador.

The not significant effect of the fertilizers rates on crop yield in all three cropping cycles under both tillage systems and rotation schemes could be attributed to the preceding management of the experimental site which received high rates of plant nutrients, applied to potato fertilization experiments conducted over time. Despite the actions taken to homogenize the fertility of the site before starting this study, some historical memory in the soil may have lingered in our plots (Avila-Salem et al, 2020, Montesdeoca et al., 2020).

Our results shown that there is great potential for a successful production of the crops utilized in the rotation schemes under NT, having a legume as a head crop in the sequence (Montesdeoca et al., 2020). There is no information related to tillage disturbance on yields of the proposed rotations in the highlands of Ecuador, but land degradation problems on farmer´s fields are evident on most of the landscapes (Espinosa and Moreno, 2018). Moreover, recent experiments conducted in Ecuador have reported that NT yields of different crops are as high or higher than yields obtained under CT (Alvarado et al., 2011; Quichimbo et al., 2012; Gallager et al., 2017). The study conducted by Alvarado et al., (2011) with open pollinated corn for human consumption, common in the highlands of Ecuador, informed grain yields of 5.2 t ha^{-1} for NT against with 4.3 for CT.

On the other hand, as mentioned by Avila-Salem et al., (2021) and their continued work on the biological properties of Andean soils (in publication progress), they are sensitive and useful soil quality indicators of the changes and perturbations which occur under soil management. Their study evaluated the effects of tillage, nitrogen fertilization, and crop rotations [bean-maize-bean (BMB) and bean-amaranth-bean (BAB)] on soil physicochemical and biological properties in Ecuadorian highlands. Towards the final crop rotations, NT promoted higher basal respiration (BR), total glomalin-related soil protein (TGRSP), and higher AMF spore density in both crop rotations when compared to CT. The AMF spore density and TGRSP increased more under NT at the end of the BMB, and BAB, respectively. Also, these biological traits were strongly associated to the accumulation of SOM originated from crop residues left in the NT post-harvest system, improving soil moisture, biological activities and AMF presence. All these efforts represent a first attempt to understand how tillage, fertilization, and crop rotation affect physicochemical and biological soil properties in highlands of Ecuador.

Nevertheless, the agricultural sector is not the main contributor of greenhouse gases, on the other hand, it can contribute strongly to the capture of carbon in the soil, while at the same time ensuring that its competitiveness, the increased uptake of technological and management emission mitigation measures would be crucial to offer to farmers cost-effective solutions that increase the income and well-being of farmers and their families, and to reduce GHG emission (Pérez and Fellmann, 2015), using the principles of resilient production systems and food security, conservation, restoration and sustainable, use of biodiversity and ecosystem services, integrated management of water resources with climate change, and a carbon neutral development (Castro, 2021), that Latin American countries need to comply with the commitments recently assumed in Glasgow by COP 26, (2021).

5.1.2 Effects of tillage systems and rotation schemes on soil carbon components

The principal component analysis (PCA) for chemical and physical characteristics in the two rotation schemes suggests a strong association among NT with SOC, POM, TN, P, K, and water storage capacity, can explain the improved soil properties and its influence on grain yields. Organic carbon (OC) is the main component of the soil organic matter (SOM); therefore, changes in SOM content have a strong effect on soil physical, chemical and biological properties (Martínez et al., 2008; Pérez, 2021) and consequently this effect must be evident when NT is adopted. The overall higher SOC accumulation under NT at the end of the three rotation cycles and both rotations, was evident even when taking into account the fact that the crop initiating the rotation scheme is a legume with a low C/N ratio that favors residue mineralization delaying SOC accumulation, particularly in the upper soil layer (Zotarelli et al. 2012; Raphael et al. 2016). The higher SOC content at both soil layers in the BAB rotation is probably due to the different root type of the intermediate crops in the rotation.

The amaranth root system is axonomorphic with a thick root from which other thinner roots develop, while corn has a fasciculated and branched root system with roots of the same thickness. For this reason, the corn root system can leave superficial residues in the soil, in comparison with amaranth roots which can leave a higher quantity of root residues deeper in the soil profile (Montellano, 2014). In addition, amaranth roots exude high amounts of low molecular weight organic acids, mainly oxalic acid together with a lot of other compounds with allelopathic characteristics (Bakhshayeshan-Agdam, 2015). Additionally, data also suggest that rotation including maize has slower residue decomposition probably due to its high lignin content (Craswell and Lefroy, 2001, Baldock and Broos, 2012).

Particulate organic matter (POM) is the transitory fraction of the SOM in an intermediate state of decomposition between fresh residues and stable carbon compounds (humus). It is defined as the chemical and biologically active fraction of the SOM composed of particles that vary from 0.053 to 2 mm that are indicators of the recently incorporated SOC presence (Wander, 2004; Cates et al., 2016; Jat et al., 2019) and is considered as an immediate source of plant nutrients and food and energy for microorganisms and also as a trap for soil contaminants such as pesticides and heavy metals (Nciizah and Wakindiki, 2012; Lehmann and Kleber, 2015).

The POM is a sensible parameter to indicate the effect of different agronomic management on plant nutrients availability (Galantini et al., 2007; Gupta and Germida, 2014). Furthermore, POM provides early information about the future content of total SOM because POM rapidly reaches a new equilibrium after an episode of soil management such as crop rotation or tillage. Total SOM is not a good quantitative and sensitive indicator of the direct relationship of SOC content with crop productivity and soil quality, relation which is more evident with POM. A reduction in POM correlates with a decline in soil fertility and the quality of soil physical properties such as soil aggregation, conditions associated to soil degradation and a lower resilience. Several studies suggest that macro aggregates are organized around POM (Videla et al., 2008; Nciizah and Wakindiki, 2012; Lehmann and Kleber 2015).

The overall results of POM accumulation throughout the planned rotations in time will determine which crop sequence provides the best soil quality characteristics in terms of SOM, POM, which will be reflected in terms of crop performance and yields (Basanta et al., 2012; de Moraes et al., 2015; Jat, et al. 2019).

Microbial mediated plant residue decomposition leads to the formation of stable carbon compounds broadly called humin but according molecular weight and condensation degree can be separated into two groups structurally and spectroscopically different behavior so-called humic and fulvic acids. During humification process carbohydrates rapidly disappear and phenolic compounds like lignin tend to accumulate as humic compounds. These compounds are characterized using the E_4/E_6 ratio which is the measure of light adsorption at 464 y 665 wave lengths in a spectrophotometer. In time it is related to the condensation or maturity degree of aromatic humic constituents. The E_4/E_6 ratio is then used as a humification index relating the aromaticity of the OC chains and their condensation to stable compounds. A reduction in this value indicates progressive condensation of humic substances (Bonometo, 2010; de Moura Luz 2013, Kachari et al., 2015).

Data obtained suggest a more rapid humification of the amaranth residues left in the soil which is more pronounced under NT than CT and at a 0-5 cm depth than 5-20 cm depth. There is scarce information about the amaranth residues humification rates, so in that sense, we think that this matter needs deeper studies before proposing this crop in the rotation schemes under NT.

5.1.3 Effects of tillage systems and rotation schemes on TN, P, and K content

No-till improves nutrient cycling due to the higher residue accumulation which provides available N for the following crop (Ranaivoson, 2014) while intense soil removal by CT can reduce SOC and TN content due to soil aggregates destruction and rapid residue mineralization (Issaka, 2019). On the other hand, the general higher TN content observed in the BAB rotation, compared to the BMB rotation, is probably due to the mineralized N losses from the organic pool taken up by the growing maize crop or leached through the soil profile (Figueroa, et al. 2012). Greater moisture, N and SOC availability in the upper soil layer under NT, increase microbial population which is responsible for P cycling and promoting P immobilization, reducing soil labile P content.

However, the process is not as marked as the one occurring with N (García y Picone 2004; Cerón and Aristizábal 2012). Available P accumulation was greater in amaranth than in maize for both NT and CT, probably due to more dynamic mineralization of the organic P from the amaranth residue, in comparison with maize.

5.1.4 Effects of tillage systems and rotation schemes on soil physical characteristics

Our results strongly suggests that there is higher moisture retention in the soil under NT, condition which can be explained by the protective effect produced by the plant material residue on the soil surface. Surface residue accumulation prevents soil exposure to sunlight and wind, promoting greater available moisture content for the growing crop (Vidal et al., 2002; Crovetto 2006). No statistical differences were found for the main effects of fertilizer and the interaction tillage-fertilizer.

An enhanced water use efficiency will be key in the future due to conditions imposed by climate change on rainfall patterns (Kazula et al, 2017) particularly in areas highly dependent on precipitation, like those of the highlands of Ecuador. No-till and crop rotations which leave abundant residues on the ground will improve water storage capacity and reduce water stress while contributing to crop yields (Fan et al 2020).

5.2 Concluding Remarks

As main conclusions from our study, we can mention the following:

1. This study strongly suggests that both tillage management and rotation schemes have beneficial effects over the main chemical and physical soil properties of the volcanic soil used, which represent almost all the northern highlands soils from Ecuador. The fertilization rates used in this study did not have significantly influence on such properties possibly due to the relative high nutrients levels of the original soil, however this point must be studied in the coming future. Moreover, the novelty of this research relies mainly in the rotation scheme used. To the best of our knowledge, this is the first time that amaranth, an interesting highly profitable crop used in sustainable agriculture, is included in this type of studies; therefore, further investigation must be performed to definitely propose its use by small farmers living in this Andean region.
2. Our data indicates that there has been a consistent buildup of organic carbon (SOC) and N in the upper layer of the soil under NT which includes the amaranth rotation, on the contrary, a lower SOC content was evident in the maize rotation, suggesting a slower corn residue decomposition. The amaranth rotation had a much lower E4/E6 ratio suggesting a faster humification rate compared with corn residues which are degraded at a slower rate.
3. Up to this point, lower bulk density was evidenced under NT in both rotations, as well as higher gravimetric water content also under NT.
4. Stratification of soil chemical and physical characteristics were evident in the rotations, in the NT plots, particularly with soil phosphorous (P). A noticeable

difference was also present in the stratification among the amaranth rotation and the corn rotation. Stratification was more intense in the corn rotation probably due to the type of residue left on the soil surface.

Finally, with this information, the hypothesis for this thesis is accepted in the sense that NT management of crop rotations, including amaranth implemented on soils from the small farmer's areas of the Ecuadorian northern highlands, improved soil physical and chemical characteristics as well as the quantity and SOM stability in comparison to CT, even in the short time.

5.3. Future Directions

Through this research, alternatives were found to break the trend of improving yields regardless of the natural resources the deterioration for the production processes, showing that it is possible to achieve or maintain productivity, recovered and enhanced soil health, and a trend of a more efficient water use. In others words, higher efficiency of productive resources with the use of, crop rotations including those "almost forgotten species" such as amaranth, offers viable productive alternatives to a large group of small farmers that belong to what is called "Peasant Family Economy". This can contribute to the global food security because they are responsible for the food supply of basic food basket of Ecuadorians, and support the economic development of the country (Boada y Espinosa, 2017) which in sum, may contribute to a sustainable development. According to the World on Environment and Development, it is defined as "satisfying the needs of today without compromising meeting yours for the next generations" (Pérez and Fellmann, 2015).

It has to be mentioned however, while the development of this work, that some concerns arose which should constitute the next research topics:

5.3.1 Evaluation of agronomic practices to improve the amaranth cultivation techniques

It is a matter of great interest to diversify the use of crops in agricultural management. In this sense, the importance of amaranth has been highlighted by several authors such as Torres, et al., (2006); Raja, et al., (2012); Rach y Salvarrey (2015); Yangali, (2015), who mention that its nutritional value is relevant in protein (16.8%), especially because of its lysine and methionine content, which is much higher than that of other commonly used plant foods. Another relevant aspect of amaranth is its adaptation to dry environments, growing with rainfall between 176 to 1 378 mm, needing only 3/5 parts of water in relation to what C3 plants need (Montellano, 2014), the total of water required by amaranth throughout its life cycle is only of 60% compared to wheat and barley, producing the same amount of foliage in comparison others cereals (Rach y Salvarrey, 2015). On the other hand, the amaranth grows in a wide range of temperatures (8°C to 40°C), although its optimum is between 12°C to 24°C, its needs high luminosity so it is favored by the equinoctial line such as in the Andean valleys of northern Ecuador. With respect to soils, it also presents wide adaptation as it tolerates soils from acid to strongly alkaline (pH range: 4.5 to 8.5), besides, as such as other few crops, amaranth has Al tolerance (Montellano, 2014).

In this investigation the inclusion of amaranth has been key in the purpose of offering alternatives to improve the crop rotation scheme to small farmers located in the valleys of northern highlands of Ecuador, that year after year they repeat the monoculture of corn, occasionally in rotation with beans. With the inclusion of amaranth, they can improve the quality of their diet and the opportunities for insertion in the markets. Even tough, the best arithmetic means prevailed in favor of CT, comparing with NT there were no statistical differences in the yields (CT: 2 142 kg ha^{-1} vs NT: 1 831 kg ha^{-1}). These relevant result in this present work indicate that it is possible to cultivate amaranth under NT, however, due to the slow growth of this crop during the first stage of development, weed competition is deadly (Montellano, 2014) being a subject interesting to study.

5.3.2 Evaluation of the efficiency of nitrogen and phosphorus use of in corn and amaranth crops

Up to date, it is necessary to evaluate the efficiency use of fertilizers applied to crops that were used in the rotations under this study because a responsible soil nutrients management requires the application of the correct source, adequate dose, right timing, and in the right place (Cerón, 2011; IPNI, 2013). Therefore, the need arises to research site-specific fertilization management (SSFM) which allows greater synchrony achievement between the crop requirements and the resulting offer in each specific site to achieve the maximum efficiency rate of the applied fertilizer. The SSFM seeks to provide nutrients to the plant in the amounts required to achieve a certain yield consistent with its potential, using the native soil nutrients more effectively (Espinosa and García, 2009).

Through SSFM the recommendations for the necessary fertilization to compensate the deficit between nutrients total need for the crop and the nutrients content that naturally exist in the soil are specified, so using this method seeks the plant response in the specific site where it is sown. This means, that the plant indicates the fertilizers rate necessary to achieve the obtainable yield under the climate and soil conditions of a particular site (Espinosa and García, 2009; Blesh and Drinkwater, 2013; Houlton, *et al.*, 2019).

5.3.3 Research replication with the use of other rotation schemes under NT

In the cropping systems in the highlands of Ecuador there are other plant species to be used as *Lupinus mutabilis*, a symbiotic legume for *Bradyrhizobium lupini*, and

Chenopodium quinua; therefore, using the experience gained in the present investigation, a very similar rotation scheme could be replicated: corn-lupinus-quinoa, between 2800 to 3200 m.a.s.l., that will permit the validation of another rotation scheme, quantify the N contribution by lupinus, as a natural N fertilization mechanism and to verify the development of this specie in the P release and mobilization from the non-bioavailable soil through the exudation of organic acids mechanisms (Egle et al., 2003; King and Blesh, 2018) being a more ecofriendly alternative.

5.3.4 Using relevant results to generate a process of technology transfer, impact, and adoption

In this study, the corn yield was unquestionably better under NT with a yield of 74.2% higher than under CT, although amaranth yields were statistically similar, and beans yields did not show consistency up to this time, therefore, it is concluded that this soil tillage system has great potential and could benefit small farmers in the valleys of northern highlands of Ecuador, because the objectives of this research, have been aligned to the farmer needs, since investments to implement a set of soil conservation techniques often have considerable expenses, producing profits only a few years later. Therefore, in order for these technologies to be adopted successfully, they must be combined with processes that improve performance or reduce costs and then produce benefits to farmers at the implementation time (Winters et al.,1998).

In addition, to the environmental benefits exposed through the rational use and conservation of soil and water, the NT technologies complemented by two crop rotation schemes (BMB, and BAB) and stubble distribution on the soil ground developed throughout in these years in the framework of the agreement between the Universidad Central del Ecuador (UCE) and Universidad de la Frontera de Chile (UFRO), meets the immediate benefit requirement for the innovative farmer. As it was shown, in the case of corn, during three cycles and beans during the first cycle, there were higher yields, although the production costs were not evaluated, the bibliographic references assure that it is done at lower costs, generating direct benefits to the farmers immediately upon its application, so it is likely that the technology will be adopted by a significant number of producers. Furthermore, in spite of the indirect benefits on increasing soil quality is difficult to evaluate we must bear in mind that leaving a healthier soil to next generations must be our main guide when proposing new alternatives of agricultural management.

Research, technology transfer, agricultural development organizations such as Agricultural Ministerium (MAG), Faculties of Agronomy from Universities, No Governmental Organizations that are interested in making a crusade for proper soil management, by using the results of this research, could generate training and technologies transfer for farmers who currently manage the beans-corn production system in such a way to improve it and preserve the productive resources such as water and soil. In fact, due to a call from the MAG and the FAO to participate in a project on soil conservation techniques within the sustainable development objectives (SDO), the UCE was motivated to participate and was selected to show the data generated, and to participate in a validation project of sustainable soil management indicators proposed by the Food and Agriculture Organization of the United Nations, a very promising path for all of us.

Chapter VI

“References”

References

Abdalla, M., B. Osborne, G. Lanigan, D. Forristal, M. Williams, P. Smith and M. Jones. (2013). Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use and Management 29(2): 199-209. Doi.org/10.1111/sum.12030.

Acevedo, E. (2003). Sustentabilidad en cultivos anuales. Paper presented at the Cero labranza Manejo de Rastrojos, Santiago, Chile.

Acosta, M. y O. Galárraga. (2011). Efecto de la siembra directa sobre el suelo, desarrollo y rendimiento de dos ciclos sucesivos de maíz, bajo diferentes arreglos de siembra y formas de aplicación de nitrógeno. Tesis de Ingeniero Agropecuario, Escuela Politécnica del Ejército, Departamento de Ciencias de la Vida, Carrera de Ciencias Agropecuarias, Quito, Ecuador. 135 p.

Allison, L. (1996). Organic carbon. In: C. Black, D. Evans, J. White, L. Ensminger and F. Clark (eds). Methods of soil analysis. Part 2. p. 1367-1378. American Society of Agronomy. Wisconsin, USA. Doi.org/10.2134/agronmonogr9.2.c39.

Al-Kaisi, M. M., and Yin, X. (2005). Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. Journal of Environmental Quality, 34(2), 437-445. Doi.org/10.2134/jeq2005.0437.

Alvarado, S., R. Jaramillo, F. Valverde and R. Parra. (2011). Manejo de nutrientes por sitio específico en el cultivo de maíz bajo labranza de conservación para la provincia de Bolívar. Quito, Ecuador, INIAP-IPNI, 27 p.

Alvarez, C., M. Taboada, F. Gutierrez, A. Bono, P. Fernandez and P. Prystupa. 2009. Topsoil properties as affected by tillage systems in the Rolling Pampa region of

Argentina. Soil Science Society of America Journal 73: 1242-1250. Doi.org/10.2136/sssaj2008.0246.

Alvarez-Jubete, L., H. Wijngaard, E. Arendt and E. Gallagher. (2010). Polyphenol composition and in vitro antioxidant activity of amaranth, quinoa buckwheat and wheat as affected by sprouting and baking. Food chemistry 119(2): 770-778. Doi.org/10.1016/j.foodchem. 2009.07.032.

Andrade, F (2016). Los desafíos de la Agricultura, Buenos Aires, Argentina, IPNI and INTA eds. 1° edición. 136 p.

Alwang, J., Norton, G. W., Barrera, V., Botello, R. (2013). Conservation agriculture in the Andean highlands: Promise and precautions. In S. Mann (Ed.), The Future of Mountain Agriculture (pp. 21-38). London, England: Springer. Doi.org/10.1007/978-3-642-33584-6_3.

Arévalo, R. (2011). Evaluación de prácticas de conservación y sistemas labranza en el cultivo de maíz duro (Zea mays L) en la microcuenca del río Alumbre, cantón Chillanes, Provincia Bolívar. (Ingeniero Agrónomo Tesis de Ingeniero Agrónomo). Universidad Estatal de Bolívar, Guaranda, Ecuador.

Asano, M., and Wagai, R. (2014). Evidence of aggregate hierarchy at micro-to submicron scales in an allophanic Andisol. Geoderma, 216, 62-74. Doi.org/10.1016/j. geoderma.2013.10.005.

Ávila-Salem, M., Aponte, H., Montesdeoca, F., Cruz, D., Orellana, M., Pacheco, K., . . . Cornejo, P. (2021). Noticeable shifts in soil biological properties after contrasting tillage management in crop rotations of bean, maize, and amaranth in Ecuadorian highland soils. *In progress*.

Ávila-Salem, M., F. Montesdeoca, M. Orellana, K. Pacheco, S. Alvarado, N. Becerra, et al. (2020). Soil biological properties and arbuscular mycorrhizal fungal communities of representative crops established in the Andean region from Ecuadorian highlands. Journal Soil Science Plant Nutrition. Doi.org/10.1007/s42729-020-00283-1.

Bais, H., T. Weir, L. Perry, S. Gilroy and J. Vivanco. (2006). The role of root exudates in rhizosphere interactions with plants and other organisms. The Annual Review of Plant Biology 57: 233-266. Doi.org/10.1146/annurev.arplant.57.032905.105159.

Baker, J., T. Ochsner, R. Venterea and T. Griffis. (2006). Tillage and soil carbon sequestration - What do we really know? Agriculture, Ecosystems and Environment XXX: 1-5. Doi: 10.1016/j.agee.2006.05.014.

Bakhshayeshan-Agdam, H., Salehi-Lisar, S., Motafakkerazad, R., Talebpour, A., Farsad, N. (2015). Allelopathic effects of redroot pigweed (*Amaranthus retroflexus* L.) on germination, growth of cucumber, alfalfa, common bean and bread wheat. Acta agriculturae Slovenica, 105(2): 193-202. Doi.org/10.14720/aas.2015.105.2.02.

Baldock, J. and K. Broos (2012). Soil organic matter. Handbook of Soil Sciences. P. Huang, Y. Li and M. Sumner. Boca Raton, USA, CRC press**:** 11-37.

Balota, E.L., A. Colozzi Filho, D.S. Andrade and R.P. Dick. 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil and Tillage Research 77: 137-145.

Balemi, T. and K. Negisho. (2012). Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. Journal of Soil Science and Plant Nutrition 12(3): 547-562. Doi.org/10.4067/s0718-95162012005000015.

Basanta, M., C. Cesaretti, E. Lovera and M. Ghiotti (2012). Efecto de labranzas sobre fracciones de carbono en una experiencia de larga duración. XIX Congreso Latinoamericano y XXIII Congreso Argentino de la Ciencia del Suelo "Latinoamérica unida protegiendo sus suelos". C. Videla. Mar de Plata, Argentina, Asociación Argentina de la Ciencia del Suelo**:** 1-5.

Blake, G. (1996). Bulk density. In: C. Black, D. Evans, J. White, L. Ensminger and F. Clark (eds). Methods of Soil Analysis. Part 1. p. 374-391. American Society of Agronomy. Madison, Wisconsin, USA. Doi.org/10.2136/sssabookser5.3.

Blanco-Canqui, H. and R. Lal. (2004). Mechanisms of carbon sequestration in soil aggregates. Critical Reviews in Plant Sciences 23(6): 481-504. Doi: 10.1080/07352680490886842.

Blanco-Canqui, H., and Lal, R. (2009). Crop residue removal impacts on soil productivity and environmental quality. Critical Reviews in Plant Science, 28, 139-163. Doi.org/10.1080/07352680902776507.

Blanco-Canqui, H. (2012). Soil management for sustainable production with emphasis on erosion control and modeling. Paper presented at the XIX Congreso Latinoamericano y XXIII Congreso Argentino de la Ciencia del Suelo "Latinoamérica unida protegiendo sus suelos", Mar de Plata, Argentina.

Blanco-Moure, N., A. Bielsa, R. Gracia and M. López. (2011). Long-term effect of no-tillage on soil organic Matter fractions in rainfed aragon (NE spain). Spanish Journal of Soil Science 1: 116-121. Doi.org/10.3232/sjss.2011.v1.n1.08.

Blesh, J., and Drinkwater, L. (2013). The impact of nitrogen source and crop rotation on nitrogen mass balances in the Mississippi River Basin. Ecological Applications 23(5): 1017-1035. Doi.org/10.1890/12-0132.1.

Bloom, P., and Skyllberg, U. (2012). Soil pH and pH buffering. In P. Huan, Y. Li, & M. Summer (Eds.), Handbook of Soil Sciences (pp. 19-11 - 10-14). Boca Raton, USA: CRC Press.

Boada, R. y Espinosa, J. (2017). Factores que limitan el potencial de rendimiento del maíz de polinización abierta en campos de pequeños productores de la sierra del Ecuador. Siembra (3): 67-82. Doi.org/10.29166/siembra.v3i1.262.

Bongiovanni, M. and A. Degioanni. (2012). Materia orgánica total y particulada en suelos con diferentes usos del sudoeste de Córdoba. In: C. Videla, editor XIX Congreso Latinoamericano y XXIII Congreso Argentino de la Ciencia del Suelo "Latinoamérica unida protegiendo sus suelos" Asociación Argentina de la Ciencia del Suelo, Mar de Plata, Argentina. p. 1-4.

Bonometo, V. (2010). Estudo da humificação da matéria orgânica de um cambissolo em diferentes sistemas de manejo por meio de técnicas espectroscópicas. Maestrado em Ciencias, Universidad Estadual de Ponta Grossa. 94 p.

Borie, F., Rubio, R., Morales, A., Castillo, C. (2000). Relationships between arbuscular mycorrhizal hyphal density and glomalin production with physical and chemical characteristics of soils under no-tillage. Revista Chilena de Historia Natural 73: 749-756.

Borie, F., Rubio, R., Rouanet, J., Morales, A., Borie, G., Rojas, C. (2006). Effects of tillage systems on soil characteristics, glomalin and mycorrhizal propagules in a

Chilean Ultisol. Soil And Tillage Research, 88(1), 253-261. Doi.org/10.1016/j.still.2005.06.004.

Borie, F., R. Rubio and A. Morales. (2008). Arbuscular mycorrhizal fungi and soil aggregation. Journal of Soil Science and Plant Nutrition 8(2): 9-18.

Brassel, F., Ruiz, P., Zapatta, A. (2008). La Estructura Agraria en el Ecuador: una aproximación a su problemática y tendencias. In Brassel, Frank; Herrera, Stalin; Laforge, Michel (eds.) ¿Reforma agraria en el Ecuador? Viejos temas, nuevos argumentos. SIPAE, Quito, Ecuador. p 17-30. ISBN: 978-9942-01-874-8.

Bremner, J. (1996). Total Nitrogen. In D. Sparks, A. Page, P. Helmke, R. Loeppert, P. Soltanpour, M. Tabatabai, C. Johnston, M. Sumner (Eds), Methods of Soil Analysis, Chemical Methods, Part 3 (pp. 1085-1122). Wisconsin, USA: American Society of Agronomy.

Brito, I., M. Goss, M. de Carvalho, O. Chatagnier and D. van Tuinen. (2012). Impact of tillage system on arbuscular mycorrhiza fungal communities in the soil under Mediterranean conditions. Soil and Tillage Research 121: 63-67. Doi.org/10.1016/j.still.2012.01.012.

Bronick, C., and Lal, R. (2005). Soil structure and management: a review. Geoderma, 124(1), 3-22. Doi.org/10.1016/j.geoderma.2004.03.005.

Cambardella, C., and Elliott, E. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society of America Journal, 56(3), 777-783. Doi.org/10.2136/sssaj1992.03615995005600030017x.

Canellas, L. and A. Façanha. (2004). Chemical nature of soil humified fractions and their bioactivity. Pesquisa Agropecuaria Brasileira 39(3): 233-240. Doi.org/10.1590/s0100-204x2004000300005.

Caravaca, F., T. Hernandez, C. Garcıa and A. Roldan. (2002). Improvement of rhizosphere aggregate stability of afforested semiarid plant species subjected to mycorrhizal inoculation and compost addition. Geoderma 108(1): 133-144. Doi.org/10.1016/s0016-7061(02)00130-1.

Carrión, D., and S. Herrera. (2012). Ecuador rural del Siglo XXI: Soberanía alimentaria, inversión pública y política agraria. Instituto de Estudios Ecuatorianos, Quito, Ecuador.

Castilla, F. (2013). La elegida para conservar el suelo: Una decisión agronómica que combina rotación de cultivos, fertilizantes y agricultura de precisión para aumentar la producción y preservar los recursos naturales. Revista de Investigaciones Agropecuarias 39(2): 118-123.

Castro, A., 2021 ¿Cómo llega América Latina a la inminente COP 26? Observatorio de América Latina y el Caribe. 14 p.

Cates, A., Ruark, M., Hedtcke, J., Posner, J. (2016). Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter. *Soil And Tillage Research*, *155*, 371-380. Doi.org/10.1016/j.still.2015.09.008.

Cerón, L. y Aristizábal F. (2012). "Dinámica del ciclo del nitrógeno y fósforo en suelos." Revista Colombiana de Biotecnología 14(1): 285-295.

Ciarlo, E., Cosentino, D., Heredia, O., Conti, M. (2004). Efecto del uso del suelo sobre fracciones de la materia orgánica y cantidad de agregados estables. Revista científica agropecuaria, 8(2), 15-23.

Chen, Y., J. Palta, J. Clements, B. Buirchell, K. Siddique and Z. Rengel. (2014). Root architecture alteration of narrow-leafed lupin and wheat in response to soil compaction. Field Crops Research 165: 61-70. Doi.org/10.1016/j.fcr.2014.04.007.

Coll, M. (2009). Conservation biological control and the management of biological control services: are they the same? Phytoparasitica 37(3): 205-208. Doi.org/10.1007/s12600-009-0028-5.

Cooper, J., M. Baranski, G. Stewart, M. Nobel-de Lange, P. Bàrberi, A. Fließbach, J. Peigné, A. Berner, C. Brock and M. Casagrande. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agronomy for Sustainable Development 36(1): 22. Doi.org/10.1007/s13593-016-0354-1.

Cooper, J., R. Lombardi, D. Boardman and C. Carliell-Marquet. (2011). The future distribution and production of global phosphate rock reserves. Resources, Conservation and Recycling 57: 78-86. Doi: 10.1016/j.resconrec.2011.09.009.

Corsi, S., T. Friedrich, A. Kassam, M. Pisante and J.d.M. Sà. (2012). Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review. Food and Agriculture Organization of the United Nations (FAO). Roma, Italia. ISBN: 9789251071878.

Craswell, E. and R. Lefroy (2001). "The role and function of organic matter in tropical soils." Nutrient Cycling in Agroecosystems 61: 7-18. Doi.org/10.1007/978-94-017-2172-1_2.

Crissman, C. and P. Espinosa. (1996). La degradación de las tierras y adopción de medidas de conservación en la sierra de Ecuador: una revisión de la literatura. Mimeo. CIP-Quito. 40 p.

Crovetto, C. (2006). No-tillage: The relationship between no tillage, crop residues, plants and soil nutrition. Therma Impresores SA, Hualpén, Chile. 216 p.

Curaqueo, G., Acevedo, E., Cornejo, P., Seguel, A., Rubio, R., Borie, F. (2010). Tillage effect on soil organic matter, mycorrhizal hyphae and aggregates in a mediterranean agroecosystem. Ciencias del Suelo y Nutrición Vegetal 10(1):12-21. Doi.org/10.4067/ s0718-2791201 0000100002.

Dai, J., J. Hu, A. Zhu, J. Bai, J. Wang and X. Lin. (2015). No tillage enhances arbuscular mycorrhizal fungal population, glomalin-related soil protein content, and organic carbon accumulation in soil macroaggregates. Journal of Soils and Sediments 15(5): 1055-1062. Doi.org/10.1007/s11368-015-1091-9.

de Felice, M., Carter, P., and Mitchel, S. (2006). Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manage. Doi.org/10.1094/cm-2006-0626-01-rs.

de Moraes, M. T., H. Debiasi, R. Carlesso, J. C. Franchini, V. R. da Silva and F. B. da Luz (2015). "Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil." Soil and Tillage Research 155: 351-362. Doi.org/ 10.1016/j.still.2015.07.015.

de Moura Luz, F. (2013). Técnicas espectroscópicas na análise da humificação da matéria orgânica de solo de Várzea. Maestrado em Ciencias, Universidad Estadual de Ponta Grossa. 72 p.

de Toledo-Souza, E., Marques da Silveira, P., Correa, A., Murillo Lobo, J. (2012). Fusarium wilt incidence and common bean yield according to the preceding crop and the soil tillage system. *Pesquiza Agropecuaria de Brasil, 47*, 1031-1037. Doi.org/10.1590/s0100-204x2012000800002.

Dendooven, L., L. Patino-Zúniga, N. Verhulst, M. Luna-Guido, R. Marsch and B. Govaerts. (2012). Global warming potential of agricultural systems with contrasting tillage and residue management in the central highlands of Mexico. Agriculture, Ecosystems & Environment, 152: 50-58. Doi.org/10.1016/j.agee.2012.02.010.

Dercon, G., G. Govers, P. Poesen, H. Sánchez, R. Rombaut, G. Vandenbroeck, J. Loaiza and J. Deckers. (2007). Animal-powered tillage erosion assessment in the southern Andes region of Ecuador. Geomorphology, 87: 4-15. Doi.org/10.1016/j.geomorph.2006.06.045.

Derpsch, R., Friedrich, T., Kassam, A., Li, H. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering, 3(1), 1-25.

Derpsch, R., Franzluebbers, A., Duiker, S., Reicosky, D., Koeller, K., Friedrich, T., . . . Weiss, K. (2014). Why do we need to standardize no-tillage research? Soil And Tillage Research, 137, 16-22. Doi.org/10.1016/j.still.2013.10.002.

Dexter, A. 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120: 201-214.

Diaz, J.M.R., S. Kirjoranta, S. Tenitz, P.A. Penttilä, R. Serimaa, A.-M. Lampi and K. Jouppila. (2013). Use of amaranth, quinoa and kañiwa in extruded corn-based snacks. Journal of Cereal Science 58(1): 59-67. Doi.org/10.1016/j.jcs.2013.04.003.

Díaz-Zorita, M., M. Barraco and C. Alvarez. (2004). Efectos de doce años de labranzas en un Hapludol del Noroeste de Buenos Aires, Argentina. Ciencia del Suelo 22: 11-18.

Di Rienzo, J., F. Casanoves, M., L. Gonzalez, M. Tablada, and C. Robledo. (2018). InfoStat version 2018. Centro de transferencia InfoStat, FCA, Universidad Nacional de Córdoba, Córdoba, Argentina.

Divito, G.A., H.R.S. Rozas, H.E. Echeverría, G.A. Studdert and N. Wyngaard. (2011). Long term nitrogen fertilization: Soil property changes in an Argentinean Pampas soil under no tillage. Soil and Tillage Research 114(2): 117-126. Doi.org/10.1016/j.still.2011.04. 005.

Drinkwater, L. and S. Snapp. (2007). Nutrients in agroecosystems: rethinking the management paradigm. Advances in Agronomy 92: 163-186. Doi.org/10.1016/s0065-2113(04)92003-2.

Driver, J.D., W.E. Holben and M.C. Rillig. (2005). Characterization of glomalin as a hyphal wall component of arbuscular mycorrhizal fungi. Soil Biology and Biochemistry 37(1): 101-106. Doi.org/10.1016/j.soilbio.2004.06.011.

Egle, K., Römer, W., and Keller H. (2003). Exudation of low molecular weight organic acids by Lupinus albus L., Lupinus angustifolius L. and Lupinus luteus L. as affected by phosphorus supply. Agronomie, EDP Sciences (23): 511-518. Doi.org/10.1051/agro: 2003025.

El-Ramady, H.R., T. Alshaal, M. Amer, É. Domokos-Szabolcsy, N. Elhawat, J. Prokisch and M. Fári. (2014). Soil quality and plant nutrition. Sustainable Agriculture Reviews 14. Springer. p. 345-447. Doi.org/10.1007/978-3-319-06016-3_11.

Espinosa, J. (2008). Distribución, uso y manejo de los suelos de la Región Andina. In: J. Espinosa, editor XI Congreso Ecuatoriano de la Ciencia del Suelo. Sociedad Ecuatoriana de la Ciencia del Suelo, Quito, Ecuador.

Espinosa, J., and García, J. (2009). Herramientas para mejorar la eficiencia de uso de nutrientes en maíz. Memorias del Simposio "Uso eficiente de Nutrientes" presentado por el IPNI en el XVIII Congreso Latinoamericano de la Ciencia del Suelo Costa Rica 2009. International Plant Nutrition Institute (IPNI).

Espinosa, J. (2014). La erosión en Ecuador, un problema sin resolver. Siembra, 2, 56-70.

Espinosa, J., Moreno, J., Bernal, G., Sevillano, G., Valverde, O., Loayza, V., . . . Lasso, L. (2016). Suelos de Ecuador: amplia diversidad en un pequeño país. Paper presented at the XXI Congreso Latinoamericano de la Ciencia del Suelo, Quito, Ecuador.

Espinosa, J., and Moreno J. (2018). Land management. Soils of Ecuador. J. Espinosa, J. Moreno and G. Bernal. Switzerland, Springer**:** 151-163. Doi.org/10.1007/978-3-319-25319-0_6.

Estrada, S., y Calvache, M. (2004). Evaluación de sistemas de labranza de suelos y fertilización en la asociación maíz-fréjol. RUMIPAMBA, 18, 1-14.

Fan, R., Zhang, X., Liang, A., Shi, X., Chen, X., Kunshan, B., . . . Jia, S. (2012). Tillage and rotation effects on crop yield and profitability on a Black soil in northeast China. *Canadian Journal of Soil Science*, *92*, 463-470. Doi.org/10.4141/cjss2010-020.

Figueroa, A., J. Álvarez, A. Forero, C. Salamanca and L. Pinzón (2012). "Determinación del nitrógeno potencialmente mineralizable y la tasa de mineralización de nitrógeno en materiales orgánicos." Temas Agrarios 17(1): 32-43. Doi.org/10.21897/rta.v17i1.694.

Fonte, S., Vanek, S., Oyarzun, P., Parsa, S., Quintero, C., Rao, I. (sf). Explorando Opciones Agroecológicas para el manejo de la Fertilidad del Suelo en Sistemas de Agricultura en Pequeña Escala de Zonas Alto-Andinas. Departamento de Ciencias de Cultivos y Suelos, Universidad Cornel, Ithaca, NY 14853. 72 p.

Fonteyne, S., M. Martinez, A. Saldivia and N. Verhulst (2019). "Conservation Agriculture Improves Long-term Yield and Soil Quality in Irrigated Maize-oats Rotation." Agronomy 9: 1-13. Doi: 10.3390/agronomy9120845. Doi.org/10.3390/agronomy9120845.

Forte, A., N. Fiorentino, M. Fagnano and A. Fierro. (2017). Mitigation impact of minimum tillage on CO 2 and N 2 O emissions from a Mediterranean maize cropped soil under low-water input management. Soil and Tillage Research 166: 167-178. Doi.org/10.1016/ j.still.2016.09.014.

Fowler, D., Coyle, M., Skiba, U., Sutton, M., Cape, N., Reis, S., Sheppard, L., Jenkins, A., Grizzetti, B., Galloway, J., Vitousek, P., Leach, A., Bouwman, A., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M. (2013). The global nitrogen cycle in the twenty-first century. Royal Society (368): 1-13.

Franchini, J., Debiasi, H., Junior, A., Tonon, B., Farias, J., de Oliveira, M., & Torres, E. (2012). Evolution of crop yields in different tillage and cropping systems over two decades in southern Brazil. Field Crops Research, 137, 178-185. Doi.org/10.1016/j.fcr.2012.09. 003.

Fuentes, M., B. Govaerts, F. De León, C. Hidalgo, L. Dendooven, K. Sayre and J. Etchevers. (2009). Fourteen years of applying zero and conventional tillage, crop rotation and residue management systems and its effect on physical and chemical soil quality. European Journal of Agronomy 30(3): 228-237. Doi.org/10.1016/j.eja.2008.10.005.

Galantini, J., M. R. Landriscini and C. Hevia (2007). Contenido y calidad de la materia orgánica particulada del suelo. Revista técnica especial en sd, AAPRESID. Buenos Aires, Argentina p 36-40.

Galbally, I., M. Meyer, S. Bentley, I. Weeks, R. Leuning, K. Kelly, F. Phillips, F. Barker-Reid, W. Gates and R. Baigent. (2005). A study of environmental and management drivers of non-CO2 greenhouse gas emissions in Australian agro-ecosystems. Environmental Sciences 2(2-3): 133-142. Doi.org/10.1080/15693430500395396.

Galizzi, F., M. Sánchez and A. Azar. (2012). Siembra directa y rotaciones: efectos sobre algunas propiedades del suelo. In: C. Videla, editor XIX Congreso Latinoamericano y XXIII Congreso Argentino de la Ciencia del Suelo "Latinoamérica unida protegiendo sus suelos". Asociación Argentina de la Ciencia del Suelo, Mar de Plata, Argentina. 1-6 p.

Gallager, R., R. Stehouwer, V. Barrera, S. Alvarado, L. Escudero, F. Valverde, A. Portilla, K. Webber and J. Domínguez (2017). "Yield and nutrient removal in potato-based conservation agriculture cropping systems in the high altitude Andean region of Ecuador." Agronomy, Soils & Environmental Quality 109(5): 1-13. Doi.org/10.2134/agronj2016. 11.0635.

Galloway, J. and D. Sahagian. (2004). A coordinated approach to investigating human perturbations to the nitrogen cycle. The International Nitrogen Initiative (INI). 1-2 p.

García, F. y Picone, L. (2004). "Fósforo: Dinámica y manejo en sistemas de siembra directa." Informaciones Agronómicas 55: 1-5.

Gardner, W. (1996). Water content. In: A. Black, D. Evans, J. White, L. Ensminger and F. Clark (eds). Method of Soil Analysis. Part 1. American Society of Agronomy. Madison, Wisconsin, USA.

Gattinger, A., J. Jawtusch, A. Müller and P. Mäder. (2011). No-till agriculture - a climate smart solution? MISEREOR, Germany. 24 p.

Ghisolfi, E. (2011). Contenido se materia orgánica en relación con la fertilidad del suelo en siembra directa. Buenos Aires, Argentina: Eduvim.

Glaeser, B. (2010). Agriculture between the Green Revolution and: ecodevelopment: which way to go? In Glaeser, B. The Green Revolution Revisited: Critique and alternatives: 14-20. Doi.org/10.4324/9780203840443.

González-Barrios, J., G. González-Cervantes, I. Sánchez-Cohen, A. López-Santos and L. Valenzuela-Núñez. (2011). Caracterización de la porosidad edáfica como indicador de la calidad física del suelo. Terra Latinoamericana 29(4): 369-377.

Govaerts, B., N. Verhulst, A. Castellanos-Navarrete, K. Sayre, J. Dixon and L. Dendooven. (2009). Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Critical Reviews in Plant Science 28(3): 97-122. Doi.org/10.1080/ 07352680902776358.

Grace, P., J. Antle, S. Ogle, K. Paustian and B. Basso. (2010). Soil carbon sequestration rates and associated economic costs for farming systems of south-eastern Australia. Soil Research 48(8): 720-729. Doi.org/10.1071/sr10063.

Gregorich, E. G., and Ellert, B. H. (1993). Light fraction and macroorganic matter in mineral soils. Soil sampling and methods of analysis, 397-407.

Gregory, P. (2006). Roots, rhizosphere and soil: the route to a better understanding of soil science? European Journal of Soil Science 57(1): 2-12. Doi.org/10.1111/j.1365-2389.2005.00778.x.

Gregory, P. (2010). A history of rhizosphere research–roots to a solution. 19th World Congress of Soil Science, Soil Solutions for a Changing World. IUSS, Brisbane, Australia. 1-6 p.

Green, V., D. Stott, J. Cruz and N. Curi. (2007). Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soil and Tillage Research 92(1): 114-121. Doi.org/10.1016/j.still.2006.01.004.

Grossman, R. and T. Reinsch (2002). The Solid Phase Bulk Density and Linear Extensibility. In G. Campbell, R. Horton, W. Jury, D. Nielsen, H. van Es, P. Wierenga, J. Dane, G. Topp (Eds), Methods of Soil Analysis, Physical Methods, Part 4 (pp. 201-228). Wisconsin, USA: American Society of Agronomy.

Grove, J., R. Ward and R. Weil. (2007). Nutrient stratification in no-till soils. Agronomy Journal 65: 781-783.

Grumberg, B., C. Conforto, A. Rovea, M. Boxler, G. March, C. Luna, J. Meriles and s. Vargas. (2010). La glomalina y su relación con la productividad del cultivo de maíz. Informaciones Agronómicas 47: 23-25.

Gryndler, M. (2000). Interactions of arbuscular mycorrhizal fungi with other soil organisms. Arbuscular mycorrhizas: Physiology and function. Springer. p. 239-262.

Grzesiak, S., M. Grzesiak, T. Hura, I. Marcińska and A. Rzepka. (2013). Changes in root system structure, leaf water potential and gas exchange of maize and triticale seedlings affected by soil compaction. Environmental and Experimental Botany 88: 2-10. Doi.org/10.1016 /j.envexpbot.2012.01.010.

Gupta, V., Germida, J. (2014). Soil aggregation: Influence on microbial biomass and implications for biological processes. Soil Biology & Biochemistry 80 (2015): 3A-9A. Doi.org/10.1016 /j.soilbio.2014.09.002.

Hagedorn, F., D. Spinnler, M. Bundt, P. Blaser and R. Siegwolf. (2003). The input and fate of new C in two forest soils under elevated CO2. Global Change Biology 9(6): 862-872. Doi.org/10.1046/j.1365-2486.2003.00638.x.

Havlin, J., J. Beaton, S. Tisdale and W. Nelson. (2014). In Yarnell D. (Ed.), Soil fertility and fertilizers: An introduction to nutrient management (Eighth ed.). NJ, USA: Pearson Education, Inc.

He, J., H. Li, R. Rasaily, Q. Wang, G. Cai, Y. Su, X. Qiao and L. Liu. (2011). Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. Soil and Tillage Research 113(1): 48-54. Doi.org/10.1016 /j.still.2011.01.005.

Heald, W. (1996). Calcium and magnesium. p. 999-1009. In: C. Black, D. Evans, J. White, L. Ensminger and F. Clark (eds). Methods of soil analysis. Part 2. American Society of Agronomy. Wisconsin, USA.

Heckenmüller, M., D. Narita and G. Klepper. (2014). Global availability of phosphorus and its implications for global food supply: an economic overview. Kiel Working Paper. 27 p.

Hernánez Acosta, E., García Gallegos, E., Ramirez Téllez, J. (2014). Characterization of soils cultivated with amaranth and some agronomic spects of the plant. Revista Mexicana de Ciencias Agrícolas, 5, 421-431.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. Plant and Soil 237(2): 173-195.

Hinsinger, P., Bengough, A., Vetterlein, D., Young, I. (2009). Rhizosphere: biophysics, biogeochemistry and ecological relevance. Plant and Soil 321: 117-152. Doi.org/10.1007/ s11104-008-9885-9.

Horlings, L.G. and T.K. Marsden. (2011). Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. Global environmental change 21(2): 441-452. Doi.org/10.1016/j.gloenvcha. 2011.01.004.

Houlton, B. Z., Almaraz, M., Aneja, V., Austin, A. T., Bai, E., Cassman, K. G. et al. (2019). A world of cobenefits: Solving the global nitrogen challenge. Earth's Future, 7, 865–872. Doi.org/10.1029/2019EF001222.

Hu, J., X. Cui, J. Dai, J. Wang, R. Chen, R. Yin and X. Lin. (2014). Interactive Effects of Arbuscular Mycorrhizae and Maize (Zea mays L.) Straws on Wheat (Triticum aestivum L.) Growth and Organic Carbon Storage in a Sandy Loam Soil. Soil & Water Research 9(3):119-126. Doi.org/10.17221/77/2013-swr.

Hu, S., F.S. Chapin, M. Firestone, C. Field and N. Chiariello. (2001). Nitrogen limitation of microbial decomposition in a grassland under elevated CO2. Nature 409(6817): 188-191. Doi.org/10.1038/35051576.

Huang, G.-b., C. Qiang, F.-X. Feng and A.-Z. Yu. (2012). Effects of different tillage systems on soil properties, root growth, grain yield, and water use efficiency of winter wheat (Triticum aestivum L.) in arid Northwest China. Journal of Integrative Agriculture 11(8): 1286-1296. Doi.org/10.1016/s2095-3119(12)60125-7.

Hurisso, T., J. Davis, J. Brummer, M. Stromberger, M. Mikha, M. Haddix, M. Booher and E. Paul. (2013). Rapid changes in microbial biomass and aggregate size distribution in response to changes in organic matter management in grass pasture. Geoderma 193: 68-75. Doi.org/10.1016/j.geoderma.2012.10.016.

Hütsch, B. (2001). Methane oxidation in non-flooded soils as affected by crop production. European Journal of Agronomy 14(4): 237-260. Doi.org/10.1016/s1161-0301(01)00110 -1.

Indoria, A. K., Rao, S., Reddy, S., Reddy, S. (2017). Conservation agriculture – a panacea to improve soil physical health. Current Science*,* *112,* 52-61. Doi.org/10.18520/cs/v112/i01/52-61 **.**

INIAP. (1990). Informe Anual. Departamento Nacional de Manejo de Suelo y Agua, Estación Experimental Tropical Pichilingue, Instituto Nacional Autónomo de Investigaciones Agropecuarias, Quevedo, Ecuador. p. 53-61.

IPNI. (2013). 4 R de la Nutrición de Plantas: Un Manual para Mejorar el Manejo de la Nutrición de Plantas. International Plant Nutrition Institute. 134 p.

Issaka, F., Shang, Z., Zhao, Z.-Q., Asenso, E., Li, J.-H., Li, Y.-T., Wang, J.-J. (2019). Sustainable Conservation Tillage Improves Soil Nutrients and Reduces Nitrogen and Phosphorous Losses in Maize Farmland in Southern China. *Sustainability*, *11*, 1-13. Doi.org/10.3390/su11082397.

Jat, H., A. Datta, M. Choudhary, A. Yadav, V. Choudhary, P. Sharma, M. Gathala, M. Jat and A. McDonald (2019). "Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate associated carbon and productivity in cereal systems of semi-arid Northwest India." Soil and Tillage Research 190: 128-138. Doi.org/ 10.1016/j.still.2019.03.005.

Javed, M., Akram, M., Habib, N. (2018). Descifrando el crecimiento, exudaciones de ácidos orgánicos y homeostasis iónica de Amaranthus viridis L. y Portulaca oleracea L. bajo estrés por cloruro de plomo. Environ Sci Pollut Res 25, 2958–2971. Doi.org/10.1007/s11356-017-0735-2.

Jena, P. (2019). Can minimum tillage enhance productivity? Evidence from smallholder farmers in Kenya. Journal of Cleaner Production, 218**,** 465-475. Doi.org/10.1016/ j.jclepro.2019.01.278.

Jones, D., A. Hodge and Y. Kuzyakov. (2004). Plant and mycorrhizal regulation of rhizodeposition. New Phytologist 163(3): 459-480. Doi.org/10.1111/j.1469-8137.2004.01130.x.

Kachari, M., P. Belwar, K. Dutta, A. Sarmah, P. Saikia and M. Baruah (2015). "Ultraviolet-visible and infrared spectroscopic studies of soil humic acids." International Journal of Plant & Soil Science 6(4): 194-202. Doi.org/10.9734/ijpss/2015/16032.

Kassam, A., T. Friedrich and R. Derpsch. (2010). Conservation agriculture in the 21st century: a paradigm of sustainable agriculture. In: G. Basch, editor European Congress on Conservation Agriculture. Asociación Española de Agricultura de Conservación, Madrid, España. p. 46.

Kazula, M. J., Lauer, J. G., Arriaga, F. J. (2017). Crop rotation effect on selected physical and chemical properties of Wisconsin soils. Journal of Soil and Water Conservation, *72*. Doi:10.2489/jswc.72.6.553.

Kerr, R.B. (2012). Lessons from the old Green Revolution for the new: Social, environmental and nutritional issues for agricultural change in Africa. Progress in Development Studies 12(2-3): 213-229. Doi.org/10.1177/146499341101200308.

Khan, S., Shah, A., Nawaz, M., Khan, M. (2017). Impact of different tillage practices on soil physical properties, nitrate leaching and yield attributes of maize (Zea mays L.). Journal of Soil Science and Plant Nutrition, *17*(1), 240-252. Doi.org/10.4067/s071895162017005 000019.

King, A. and Blesh, J. (2018). Crop rotations for increased soil carbon: perenniality as a guiding principle. *In progress.* Doi.org/10.1002/eap.1648.

Köhl, L., F. Oehl and M. van der Heijden. (2014). Agricultural practices indirectly influence plant productivity and ecosystem services through effects on soil biota. Ecological Applications 24(7): 1842-1853. Doi.org/10.1890/13-1821.1.

Krauss, M., H. Krause, S. Spangler, E. Kandeler, S. Behrens, A. Kappler, P. Mäder and A. Gattinger. (2017). Tillage system affects fertilizer-induced nitrous oxide emissions. Biology and Fertility of Soils 53(1): 49-59. Doi.org/10.1007/s00374-016-1152-2.

Kuo, S. (1996). Phosphorus. In D. Sparks, A. Page, P. Helmke, R. Loeppert, P. Soltanpour, M. Tabatabai, C. Johnston, M. Sumner (Eds), Methods of Soil Analysis, Chemical Methods, Part 3 (pp. 869-919). Wisconsin, USA: American Society of Agronomy.

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development 17(2): 197-209. Doi.org/10.1002/ldr.696.

Lal, R., D. Reicosky and J. Hanson. (2007). Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research 93(1): 1-12. Doi.org/10.1016/j.still. 2006.11.004.

Lal, R. (2011). Sequestering carbon in soils of agro-ecosystems. Food Policy, 36, S33-S39. Doi.org/10.1016/j.foodpol.2010.12.001.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. Sustainability, 7(5), 5875-5895. Doi.org/10.3390/su7055875.

Lamlom, S. and R. Savidge. (2003). A reassessment of carbon content in wood: variation within and between 41 North American species. Biomass and Bioenergy 25(4): 381-388. Doi.org/10.1016/s0961-9534(03)00033-3.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J. (2014). 50 Year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Research Letters. (9): 1-9. Doi.org/10.1088/1748-9326/9/10/105011.

Lehmann, J. and M. Kleber (2015). "The contentious nature of soil organic matter." Nature 528(7580): 60-68. Doi.org/10.1038/nature16069.

Li, H., H. Gao, H. Wu, W. Li, X. Wang, J. He. (2007). Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. Soil Research. 45(5):344-350. Doi.org/10.1071/sr07003.

Lipiec, J., R. Horn, J. Pietrusiewicz and A. Siczek. (2012). Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil and Tillage Research 121: 74-81. Doi.org/10.1016/j.still.2012.01.013.

Liu, A., Contador, C., Fan, K., Lam, H.-M. (2018). Interaction and Regulation of Carbon, Nitrogen, and Phosphorus Metabolisms in Root Nodules of Legumes. Plant Science, 9. Doi.org/10.3389/fpls.2018.01860.

Liu, A., B. Ma and A. Bomke. (2005). Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Science Society of America Journal 69(6): 2041-2048. Doi: 10.2136/sssaj2005.0032.

Lombi, E., M. McLaughlin, C. Johnston, R. Armstrong and R. Holloway. (2004). Mobility and lability of phosphorus from granular and fluid monoammonium phosphate differs in a calcareous soil. Soil Science Society American Journal 68: 682–689. Doi.org/10.2136/ sssaj2004.6820.

Lopez-Bellido, R., V. Muñoz-Romero, R. Fuentes-Guerra, P. Fernandez-Garcia and L. Lopez-Bellido. (2017). No-till: A key tool for sequestering C and N in microaggregates on a Mediterranean Vertisol. Soil and Tillage Research 166: 131-137. Doi.org/10.1016/ j.still.2016. 09.012.

Luo, Z., E. Wang and O.J. Sun. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment 139(1): 224-231. Doi.org/10.1016/j.agee.2010.08.006.

Lupwayi, N., Clayton, G., O'Donovan, J., Harker, K., Turkington, T., Soon, Y. (2006). Soil nutrient stratification and uptake by wheat after seven years of conventional and zero tillage in the Northern Grain belt of Canada. Journal Soil Science. 86: 767-778. Doi.org/10.4141/s06-010.

Mallarino, A. and R. Borges. (2006). Phosphorus and potassium distribution in soil following long-term deep-band fertilization in different tillage systems. Nutrient Management & Soil & Plant Analysis 70: 702–707. Doi.org/10.2136/sssaj2005.0129.

Margenot, A., Paul, B., Sommer, R., Pulleman, M., Parikh, S., Jackson, L., Fonte, S. (2017). Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol. Soil & Tillage Research 166: 157–166. Doi.org/10.1016/j.still.2016.09.003.

Marquez, C. (2001). Soil aggregate dynamics and aggregate-associated carbon under different vegetations types in riparian soils. Tesis of Phylosophy Doctor, Iowa State University, USA. 226 p. Doi.org/10.31274/rtd-180813-11963.

Martens, D. (2000). Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. Soil Biology and Biochemistry 32(3): 361-369. Doi.org/10.1016/s0038-0717(99)00162-5.

Martínez, E., J. Fuentes and E. Acevedo (2008). Carbono orgánico y propiedades del suelo. Ciencias del Suelo y Nutrición Vegetal 8(1): 68-96. Doi.org/10.4067/s0718-279120080001 00006.

Martínez, J., Galantini, J., Duval, M. (2018). Contribution of nitrogen mineralization indices, labile organic matter and soil propierties in predicting nitrogen mineralization. Journal of Soil Science and Plant Nutrition, 18(1), 73-89. Doi.org/10.4067/s0718-95162018005000401.

Mazzoncini, M., T.B. Sapkota, P. Bàrberi, D. Antichi and R. Risaliti. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil and Tillage Research 114(2): 165-174. Doi.org/10.1016/j.still.2011.05.001.

McVay, K., Budde, J., Fabrizzi, K., Mikha, M., Rice, C., Schlegel, A., . . . Thompson, C. (2006). Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Science Society of America Journal, 70(2), 434-438. Doi.org/10.2136/sssaj2005.0249.

Meijer, A., J. Heitman, J. White and R. Austin. (2013). Measuring erosion in long-term tillage plots using ground-based lidar. Soil and Tillage Research 126: 1-10. Doi.org/10.1016/j.still. 2012.07.002.

Micucci, F. and M. Taboada. (2006). Soil physical properties and soybean (Glycine max, Merrill) root abundance in conventionally-and zero-tilled soils in the humid Pampas of Argentina. Soil and Tillage Research 86(2): 152-162. Doi.org/10.1016/j.still.2005.02. 004.

Miller, S., J. Liu, D. Allan, C. Menzhuber, M. Fedorova and C. Vance. (2001). Molecular control of acid phosphatase secretion into the rhizosphere of proteoid roots from phosphorus-stressed white lupin. Plant Physiology 127(2): 594-606. Doi.org/10.1104/pp. 127.2.594

Mlakar, S., M. Turinek, M. Jakop, M. Bavec and F. Bavec. (2009). Nutrition value and use of grain amaranth: potential future application in bread making. Agricultura 6(4): 43-53.

Molden, D. (2007). Water for food, water for life: a comprehensive assessment of water management in agriculture. Earthscan, 1-48 p. Doi.org/10.5860/choice.45-0867.

Montellano, R. (2014). Estudio de la densidad poblacional del cultivo de amaranto (Amaranthus caudatus) de la línea promisoria uva 039 en la zona Central del Departamento de Santa Cruz - Bolivia, Invierno 2013. (Ingeniero Agrónomo). Universidad Autónoma Gabriel René Moreno, Santa Cruz, Bolivia.

Montesdeoca, F., Ávila, M., Quishpe, J., Borie, F., Cornejo, P., Aguilera, P., . . . Espinosa, J. (2020). Early changes in the transition from conventional to no-tillage in a volcanic soil cultivated with beans (*Phaseolus vulgaris* L.). *Chilean Journal of Agricultural &*

Animal Sciences (ex Agro-Ciencia), 36, 181-189. Doi.org/10.29393/chjaas36-16ctfm80016

Montgomery, D. (2007). Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences 104(33): 13268-13272.

Moreno, J., Alvarado, S., Ávila-Salem, M., Montesdeoca, F. (2017). Clasificación taxonómica de los lotes de SD del CADET. In. Quito, Ecuador: FCA-UCE.

Moreno, J., F. Yerovi, M. Herrera, D. Sánchez and J. Espinosa. (2018). Soils from the ecuadorian highlands. In: J. Espinosa, J. Moreno and G. Bernal (eds). Soils of Ecuador. Springer. Cham, Switzerland. 79-111 p. Doi.org/10.1007/978-3-319-25319-0_3

Morison, J., N. Baker, P. Mullineaux and W. Davies. (2008). Improving water use in crop production. Philosophical Transactions of the Royal Society B: Biological Sciences 363: 639-658.

Mosandl, R., Günter, S., Stimm, B., & Weber, M. (2008). Ecuador suffers the highest deforestation rate in South America. In E. Bleck, I. Kottke, J. Bendix, F. Makeschin, & R. Monsandl (Eds.), Gradients in a tropical mountain ecosystem of Ecuador (pp. 37-40). Berlin, Germany: Springer. Doi.org/10.1007/978-3-540-73526-7_4 .

Munkholm, L., R. Heck and B. Deen. (2013). Long-term rotation and tillage effects on soil structure and crop yield. Soil and Tillage Research 127: 85-91.

Muñoz, C., L. Paulino, C. Monreal and E. Zagal. (2011). Greenhouse gas (CO_2 and N_2O) emissions from soils: A review. Chilean Journal of Agricultural Research 70(3): 485-497.

Muñoz-Romero, V., J. Benítez-Vega, L. López-Bellido and R. López-Bellido. (2010). Monitoring wheat root development in a rainfed vertisol: Tillage effect. European Journal of Agronomy 33(3): 182-187. Doi.org/10.1016/j.eja.2010.05.004.

Muniyandi, B., Pitchaimuthu, M., Balan, K., James, J., and Natchimuthu, K. (2019). Vermiremediation of Urban and Agricultural Biomass Residues for Nutrient Recovery and Vermifertilizer Production. Springer Nature, Waste and Biomass Valorisation: 1-17. Doi.org/10.1007/s12649-019-00899-0.

National Research Council. (1984). Amaranth: modern prospects for an ancient crop. National Academy Press, Washington, USA. Doi.org/10.17226/19381.

Nciizah, A. and I. Wakindiki (2012). "Particulate organic matter, soil texture and mineralogy relations in some Eastern Cape ecotopes in South Africa." South African Journal of Plant and Soil 29(1): 39-46. Doi.org/10.1080/02571862.2012.688882.

Nelson, W. and L. E. Sommers (1996). Total Carbon, Organic Carbon, and Organic Matter. In D. Sparks, A. Page, P. Helmke, R. Loeppert, P. Soltanpour, M. Tabatabai, C. Johnston, M. Sumner (Eds), Methods of Soil Analysis, Chemical Methods, Part 3 (pp. 964-1013). Wisconsin, USA: American Society of Agronomy.

Nieto, C. y Vicuña, A. (2015). Las tierras y territorios rurales como escenarios funcionales para la práctica de la Economía Popular y Solidaria en Ecuador: algunos elementos sobre su uso y aprovechamiento. Siembra 2(1): 1-13. Doi.org/10.29166/siembra.v2i1.62.

Noack, S., M. McLaughlin, R. Smernik, T. McBeath and R. Armstrong. (2012). Crop residue phosphorus: speciation and potential bio-availability. Plant and Soil 359: 375-385. Doi. org/10.1007/s11104-012-1216-5.

Ogle, S.M., A. Swan and K. Paustian. (2012). No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems & Environment 149: 37-49. Doi.org/10.1016/j.agee.2011.12.010.

Oorts, K., H. Bossuyt, J. Labreuche, R. Merckx and B. Nicolardot. (2007). Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. European Journal of Soil Science 58(1): 248-259. Doi.org/10.1111/j.1365-2389.2006.00832.x.

Ordoñez-Morales, K., Cadena-Zapata, M., Zermeño-González, A., and Campos-Magaña, S. (2019). Effect of Tillage Systems on Physical Properties of a Clay Loam Soil under Oats. Agriculture 9(62): 2-14. Doi.org/10.3390/agriculture9030062.

Palm, C., H. Blanco-Canqui, F. DeClerck, L. Gatere and P. Grace. (2014). Conservation agriculture and ecosystem services: An overview. Agriculture, Ecosystems & Environment 187: 87-105. Doi.org/10.1016/j.agee.2013.10.010.

Panagos, P., Borrelli, P., Robinson, D. (2019). FAO calls for actions to reduce global soil erosion. Mitigation and Adaptation Strategies for Global Change (25):789-790. Doi.org/10.1007/s11027-019-09892-3.

Peralta, I., N. Mazón, I. Murillo and D. Rodríguez. (2014). Manual agrícola de granos andinos: Chocho, quinua, amaranto y ataco. Cultivo, variedades, costos de producción. Programa Nacional de Leguminosas y Granos Andinos, INIAP, Quito, Ecuador. 78 p.

Pérez, L., Phillips, L., Seuradge, J., Agomoh, I., Drury, F., Acosta-Martínez, V. (2021). An evaluation of biological soil health indicators in four long-term continuous agroecosystems in Canada. Agrosystems, Geosciences, Environment 4: e20164. Doi.org/10.1002/agg2. 20164.

Pérez, I., Fellmann, T. (2015). The Need for Comprehensive Climate Change Mitigation Policies in European Agriculture. Euro Choices, 14(1): 11-16. Doi.org/10.1111/1746-692x.12076.

Peech, M. (1996). Hydrogen-ion activity. In: A. Black, D. Evans, J. White, L. Ensminger and C. Clark (ed). Methods of Soil Analysis. Part 2. p. 914-925. American Society of Agronomy. Madison, USA.

Piccolo, A. (2001). The supramolecular structure of humic substances. Soil Science 166(11): 810-832. Doi.org/10.1097/00010694-200111000-00007.

Pikul, J., Chilom, G., Rice J., Eynard, A., Schumacher, T., Nichols, K., Johnson, J., Wright, S., Caesar, T., Ellsbury, M. (2009). Organic Matter and Water Stability of Field

Aggregates Affected by Tillage in South Dakota. Soil Science Society of America Journal 73(1): 197-206. Doi.org/10.2136/sssaj2007.0184.

Plaza-Bonilla, D., J.-M. Nolot, S. Passot, D. Raffaillac and E. Justes. (2016). Grain legume-based rotations managed under conventional tillage need cover crops to mitigate soil organic matter losses. Soil and Tillage Research 156: 33-43. Doi.org/10.1016/j.still.2015.09.021.

Porta-Casanellas, J., M. López-Acevedo and R. Poch. (2011). Introducción a la Edafología. Segunda Edición ed. Mundi Prensa, Madrid. 535 p. ISBN: 9788484764052.

Power, A.G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365(1554): 2959-2971. Doi.org/10.1098/rstb.2010.0143.

Powlson, D., P. Gregory, W. Whalley, J. Quinton, D. Hopkins, A. Whitmore, P. Hirsch and K. Goulding. (2011). Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36: S72-S87. Doi.org/10.1016/j.foodpol.2010.11.025.

Pratt, P. (1996). Potassium. In: C. Black, D. Evans, J. White, L. Ensminger and F. Clark (eds). Methods of soil analysis. Part 2. p. 1022-1030. American Society of Agronomy. Wisconsin, Wisconsin, USA.

Qin, R., P. Stamp and W. Richner. (2006). Impact of tillage on maize rooting in a Cambisol and Luvisol in Switzerland. Soil and Tillage Research 85(1): 50-61. Doi.org/10.1016/j. still.2004.12.003

Quichimbo, P., G. Tenorio, P. Borja, I. Cárdenas, P. Crespo and R. Célleri (2012). "Efectos sobre las propiedades físicas y químicas de los suelos por el cambio de la cobertura vegetal y uso del suelo: páramo de Quimsacocha al sur del Ecuador." Suelos Ecuatoriales 42(2): 138-153.

Rach, D. y Salvarrey W. (2015). Evaluación de la fertilización y riego supletorio sobre la producción de semilla y contenido proteico de Amaranthus hypochondriacus. Tesis Ing. Agr. Universidad Nacional de la Pampa. Bahía Blanca, Argentina. 34 p.

Raja, S., Lal, A., Teixeira da Silva, J., and More, T. (2012). Diversity Analysis of Fleshy Leaf Type Amaranthus for Semi-arid Ecosystems. International Journal of plant Breeding (6): 27-33.

Rahman, M., A. Okubo, S. Sugiyama and H. Mayland. (2008). Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. Soil and Tillage Research 101: 10-19. Doi.org/10.1016/j.still.2008.05.006.

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., & Corbeels, M. (2017). Agro-ecological functions of crop residues under conservation agriculture. A review. Agronomy for Sustainable Development, 37, 17. Doi.org/10.1007/s13593-017-0432-z.

Raphael, J., J. Calonego, D. M. Milori and C. Rosolem (2016). "Soil organic matter in crop rotations under no-till." Soil And Tillage Research 155: 45-53. Doi.org/10.1016/j.still.2015.07.020.

Rasse, D., A. Smucker and D. Santos. (2000). Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Science Society of America Journal 64(2): 725-731. Doi.org/10.2136/sssaj2000.642725x.

Redel, Y., Escudey, M., Alvear, M., Conrand, J., Borie, F. (2011). Effects of tillage and crop rotation on chemical phosphorus forms and some related biological activities in a Chilean Ultisol. Soil Use and Management 27: 221-228. Doi.org/10.1111/j.1475-2743.2011. 00334.x.

Reichert, J., Suzuki, L., Reinert, D., Horn, R., Håkansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil And Tillage Research, 102(2), 242-254. Doi.org/10.1016/j.still.2008.07.002.

Riley, H., R. Pommeresche, R. Eltun, S. Hansen and A. Korsaeth. (2008). Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. Agriculture, Ecosystems & Environment 124(3): 275-284. Doi.org/10.1016/j.agee.2007.11.002.

Rillig, M. and D. Mummey. (2006). Mycorrhizas and soil structure. New Phytologist 171(1): 41-53. Doi.org/10.1111/j.1469-8137.2006.01750.x.

Roldan, A., Salinas-Garcia, J., Alguacil, M., Caravaca, F. (2007). Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil And Tillage Research, 93(2), 273-282. Doi.org/10.1016/j.still.2006.05.001.

Rost, S., Gerten, D., Hoff, H., Lucht, W., Falkenmark, M., Rockström, J. (2009). Global potential to increase crop production through water management in rainfed agriculture. Environmenmtal Research Letters 4 (2009) 044002, 9 pp. Doi.org/10.1088/1748-9326/4/4/044002.

Sainju, U., B. Singh and W. Whitehead. (2005). Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agronomy Journal 97: 1279-1290. Doi.org/10.2134/agronj2004.0213.

Salvo, L., J. Hernández, and O. Ernst. (2010). Distribution of soil organic carbon in different size fractions, under pasture and crop rotations with conventional tillage and no-till systems. Soil and Tillage Research 109(2): 116-122. Doi.org/10.1016/j.still.2010.05.008.

Salvo, L., J. Hernández and O. Ernst. (2014). Soil organic carbon dynamics under different tillage systems in rotations with perennial pastures. Soil and Tillage Research 135: 41-48. Doi.org/10.1016/j.still.2013.08.014.

Santander, C., Sanhueza, M., Olave, J., Borie, F. Valentine, A., and P. Cornejo. (2019). Arbuscular mycorrhizal colonization promotes the tolerance to Salt Stress in Lettuce plants through an efficient modification of ionic balance. Journal of Soil Science and Plant Nutrition: 1-19. Doi.org/10.1007/s42729-019-00032-z.

Sapkota, T. B., Mazzoncini, M., Bàrberi, P., Antichi, D., Silvestri, N. (2012). Fifteen years of no till increase soil organic matter, microbial biomass and arthropod diversity in cover crop-based arable cropping systems. Agronomy for sustainable development, 32(4), 853-863. Doi.org/10.1007/s13593-011-0079-0.

Schlesinger, W. H., Andrews, J. A. (2000). Soil respiration and the global carbon cycle. Biogeochemistry, 48(1), 7-20.

Sims, J. (2000). Soil test phosphorus: Olsen P. In G. Pierzynsky (Ed.), Methods of phosphorus analysis for soils, sediments, residuals, and waters (pp. 20). Raleigh, USA: North Caroline State University.

Singh, A., and Singh, G. (2018). Is earthworm a protagonist or an antagonist in greenhouse gas (GHG) emissions from the soil? International Journal of Environmental Science and Technology: 1-14. Doi.org/10.1007/s13762-018-1922-5.

Singh, A., V. Phogat, R. Dahiya and S. Batra. (2014). Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice–wheat cropping system. Soil and Tillage Research 140: 98-105. Doi.org/10.1016/j.still.2014.03.002.

Six, J., Paustian, K., Elliott, E. T., Combrink, C. (2000). Soil Structure and Organic Matter I. Distribution of Aggregate-Size Classes and Aggregate-Associated Carbon. Soil Science Society of America Journal, 64(2). Doi.org/10.2136/sssaj2000.642681x.

Six, J., Feller, C., Denef, K., Ogle, S., Sa, J. C. D. M., Albrecht, A. (2002). Soil organic matter, biota and aggregation in temperate and tropical soils-Effects of no-tillage. Agronomie, 22(7-8), 755-775. Doi.org/10.1051/agro:2002043.

Six, J., R. Conant, E.A. Paul and K. Paustian. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and Soil 241(2): 155-176.

Six, J., and Paustian, K. (2014). Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biology and Biochemistry, 68, A4-A9. Doi.org/10.1016/j.soilbio.2013.06.014.

Smith, V.H. and D.W. Schindler. (2009). Eutrophication science: where do we go from here? Trends in Ecology and Evolution, 24(4)(4): 201-207. Doi.org/10.1016/j.tree.2008.11.009. doi.org/10.1016/j.tree.2008.11.009.

Snyder, C., T. Bruulsema and T. Jensen. December (2007). Greenhouse gas emissions from cropping systems and the influence of fertilizer management. International Plant Nutrition Institute (IPNI) Ref. 07110: 1-25.

Snyder, C., T. Bruulsema, T. Jensen and P. Fixen. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems and Environment 133: 247–266. Doi.org/10.1016/j.agee.2009.04.021.

Soracco, C. G., Lozano, L. A., Sarli, G. O., Gelati, P. R., Filgueira, R. R. (2010). Anisotropy of saturated hydraulic conductivity in a soil under conservation and no-till treatments. *Soil And Tillage Research, 109*(1), 18-22. Doi.org/10.1016/j.still.2010.03.013**.**

Soracco, C. G., Lozano, L. A., Balbuena, R., Ressia, J. M., Filgueira, R. R. (2012). Contribution of macroporosity to water flux of a soil under different tillage systems. *Revista Brasileira de Ciência do Solo*, *36*(4), 1149-1156. Doi.org/10.1590/s0100-06832012000400009 **.**

Soto-Mora, E., Hernández-Vásquez, M., Luna-Zendejas, H., Ortiz-Ortiz, E., García-Gallegos, E. (2016). Evaluación del contenido de materia orgánica en suelos agrícolas y su relación carbono/nitrógeno. Universidad Autónoma de Tlaxcala. Tlaxcala, Tlax.; México. Revista Iberoamericana de Ciencias 3 (5): 97-104. ISSN: 2334-2501.

Stevenson, J., R. Serraj and K. Cassman. (2014). Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. Agriculture, Ecosystems & Environment 187: 1-10. Doi.org/10.1016/j.agee.2014.06.015 .

Stewart, C., Roosendaal, D., Manter, D., Delgado, J., Del Grosso, S. (2018). Interactions of Stover and Nitrogen Management on Soil Microbial Community and Labile Carbon under Irrigated No-Till Corn. Soil Science Society of America Journal 82: 323-331. Doi.org/10.2136/sssaj2017.07.0229.

Strudley, M.W., T.R. Green and J.C. Ascough. (2008). Tillage effects on soil hydraulic properties in space and time: State of the science. Soil and Tillage Research 99(1): 4-48. Doi.org/10.1016/j.still.2008.01.007.

Su, Y., B. Gabrielle, D. Beillouin and D. Makowski (2021). "High probability of yield gain through conservation agriculture in dry regions for major staple crops." Scientific Reports **11**(1): 3344. Doi.org/10.1038/s41598-021-82375-1.

Subbulakshmi, S., N. Saravanan and P. Subbian (2009). "Conventional Tillage vs Conservation Rillage - a review." Agricultural Research Communication Centre, **30,** 56-63.

Swift, R. (1996). Organic Matter Characterization. In D. Sparks, A. Page, P. Helmke, R. Loeppert, P. Soltanpour, M. Tabatabai, C. Johnston, M. Sumner (Eds), Methods of Soil Analysis, Chemical Methods, Part 3 (pp. 1014-1069). Wisconsin, USA: American Society of Agronomy.

Swift, M., A. Izac and M. van Noordwijk. (2004). Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agriculture, Ecosystems & Environment 104(1): 113-134. Doi.org/10.1016/j.agee.2004.01.013.

Takahashi, T. and S. Shoji. (2002). Distribution and classification of volcanic ash soils. Global Environmental Research, English Edition 6(2): 83-98.

Tester M., and Langridge, (2010) Breeding Technologies to Increase Crop Production in a Changing World. Science (327): 818-822.

Thomas, G. (1996). Soil pH and Soil Acidity. In D. Sparks, A. Page, P. Helmke, R. Loeppert, P. Soltanpour, M. Tabatabai, C. Johnston, M. Sumner (Eds), Methods of Soil Analysis, Chemical Methods, Part 3 (pp. 487-502). Wisconsin, USA: American Society of Agronomy.

Thomas, G., R. Dalal and J. Standley. (2007). No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil and Tillage Research 94(2): 295-304. Doi.org/10.1016/j.still.2006.08.005.

Tivet, F., de Moraes, J., Lal, R., Borszowskei, R., Briedis, C., Bürkner, J., Freire, M., Hartman, D., Eurich, G., Farias, A., Bouzinac, S., Séguy, L. (2013). Soil organic carbon fraction losses upon continuous plow-based tillage and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Geoderma 209–210 (2013) 214–225. Doi.org/10.1016/j.geoderma.2013.06.008.

Tormena, C., D. Karlen, S. Logsdon and M. Cherubin. (2017). Corn stover harvest and tillage impacts on near-surface soil physical quality. Soil and Tillage Research 166: 122-130. Doi.org/10.1016/j.still.2016.09.015.

Torres, G., Trinidad, A., Reyna, T., Castillo, H., Escalante, A., y de León. F. (2006). Respuesta de genotipos de amaranto a densidades de población. Fitotecnia Mexicana 29(4): 307-312.

Torres-Guerrero, C.A., J.D. Etchevers, M.H. Fuentes-Ponce, B. Govaerts, F. De León-González and J.M. Herrera. (2013). Influencia de las raíces sobre la agregación del suelo. Terra Latinoamericana 31(1): 71-84.

Treseder, K. and K. Turner. (2007). Glomalin in ecosystems. Soil Science Society of America Journal 71(4): 1257-1266. Doi.org/10.2136/sssaj2006.0377.

Van der Putten, W., Macel, M., Visser, M. (2010). Predicting species distribution and abundance responses to climate change: why it is essential to include biotic interactions across trophic levels. Philosophical Transactions of the Royal Society, 365, 2025-2034. Doi.org/10.1098/rstb.2010.0037.

Van Raij, B., H. Cantarella, J. Quaggio and L. Prochnow. (2010). Resina de intercambio iónico para determinar la disponibilidad de fósforo en el suelo. UTE. p. 1-8.

Vega-Gálvez, A., M. Miranda, J. Vergara, E. Uribe, L. Puente and E. Martínez. (2010). Nutrition facts and functional potential of quinoa (Chenopodium quinoa willd.), an ancient Andean grain: a review. Journal of the Science of Food and Agriculture 90(15): 2541-2547. Doi.org/10.1002/jsfa.4158.

Veloso, M., Cecagno, D., Bayer, C. (2019). Legume cover crops under no-tillage favor organomineral association in microaggregates and soil C accumulation. Soil And Tillage Research, 190, 139-146. Doi.org/10.1016/j.still.2019.03.003.

Verhulst, N., V. Nelissen, N. Jespers, H. Haven, K. Sayre, D. Raes, J. Deckers and B. Govaerts. (2011). Soil water content, maize yield and its stability as affected by tillage and crop residue management in rainfed semi-arid highlands. Plant and Soil 344(1-2): 73-85. Doi.org/10.1007/s11104-011-0728-8.

Vidal, I., J. Etchevers and A. Fischer (2002). "Dinámica del nitrógeno bajo diferentes rotaciones, sistemas de labranza y manejo de residuos en el cultivo de trigo." Agricultura Técnica 62(1): 121-132. Doi.org/10.4067/s0365-28072002000100012.

Videla, L. S., C. M. Rostagno and M. A. Toyos (2008). "La materia orgánica particulada: comparación de métodos para su determinación y su valor como indicador de calidad de suelos del Chubut." Ciencia del suelo 26(2): 219-227.

Vinueza, V., and Calvache, M. (2004). Evaluación de sitemas de labranza de suelo y fertilización fosfórica en maíz (Zea mays L.). Revista Rumipamba, 18, 2-14.

Wander, M. (2004). Soil organic matter fractions and their relevance to soil function. Soil organic matter in sustainable agriculture. F. Magdoff and R. Weil. Boca Raton, USA, CRC Press**:** 67-102. Doi.org/10.1201/9780203496374.ch3.

West, T. and W. Post. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal 66(6): 1930-1946. Doi.org/10.2136 /sssaj2002.1930.

Wingeyer, A., T. Amado, M. Pérez-Bidegain, G. Studdert, C. Perdomo, F. Garcia, et al. (2015). Soil quality impacts of current South American agricultural practices. Sustainability 7: 2213-2242. Doi.org/10.3390/su7022213.

Winters, P., Espinosa, P., and Crissman, Ch. (1998). Manejo de los recursos en los andes ecuatorianos. Manejo del uso sostenible de Tierras Andinas (PROMUSTA) de CARE. Ediciones Abya-Yala. 60 p.

Yangali, N. (2015). Actividad antioxidante de cuatro variedades de Amaranthus caudatus. "Kiwicha". Universidad Nacional de San Cristóbal de Huamanga, Tesis para Químico Farmacéutica. Ayacucho, Perú. 65 p.

Zehetner, F., W. Miller and L. West. (2003). Pedogenesis of volcanic ash soils in Andean Ecuador. Soil Science Society American. J 67: 1797-1809. Doi.org/10.2136 /sssaj2003.

Zotarelli, L., N. Zatorre, R. Boddey, S. Urquiaga, C. Jantalia, J. Franchini and B. Alves (2012). "Influence of no-tillage and frequency of a green manure legume in crop rotations for balancing N outputs and preserving soil organic C stocks." Field Crops Research (132): 185-195. Doi.org/10.1016/j.fcr.2011.12.013.

“Annexes”

Annexed 1. Comparative effect of soil organic matter applied to different tillage systems, reported in recent years

Soil	Time (years)	Crop	Observed effect	Tillage system			Reference
				NT	RT	CT	
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	Soil carbon (kg m-2), depth 0-15 cm		3.26 ns	2.92 ns	Margenot, et al, 2017
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	Soil carbon (kg m-2), depth 0-15 cm		2.97 ns	2.96 ns	Margenot, et al, 2017
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	TOC (Mg C ha-1), depth 0-20 cm	44.2 ab	48.0 a	33.8 c	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	TOC (Mg C ha-1), depth 0-40 cm	25.1 abc	27.7 a	21.8 c	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	HWEOC (Mg C ha-1), depth 0-20 cm	0.57 cdbc	1.16 a	0.37 d	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	HWEOC (Mg C ha-1), depth 0-40 cm	0.23 c	0.66 a	0.15 c	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	CTPS (Mg C ha-1), depth 0-20 cm	7.9 a	8.1 a	5.1 b	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	CTPS (Mg C ha-1), depth 0-40 cm	6.8 a	7.1 a	4.9 b	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	CSCO (Mg C ha-1), depth 0-20 cm	7.1 ab	6.3 bcd	5.4 d	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	CSCO (Mg C ha-1), depth 0-40 cm	6.8 a	6.5 b	5.8 c	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	POC (Mg C ha-1), depth 0-20 cm	9.8 ns	12.7 ns	6.9 ns	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	POC (Mg C ha-1), depth 0-40 cm	2.6 ns	3.7 ns	2.5 ns	Tivet, et al., 2013
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	MAOC (Mg C ha-1), depth 0-20 cm	30.6 abc	34.0 a	26.2 c	Tivet, et al., 2013

...Annexed 1

Soil	Time (years)	Crop	Observed effect	Tillage system			Reference
				NT	RT	CT	
Red Latosol, Typic Haplustox, in Brazil	8	Soybean, maize, brachiaria, millet, pea	MAOC (Mg C ha-1), depth 0-40 cm	20.8 ab	22.6 a	19.1 b	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	TOC (Mg C ha-1), depth 0-20 cm	84.4 a	92.0 a	67.4 b	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	TOC (Mg C ha-1), depth 0-40 cm	53.2 ns	53.7 ns	52.9 ns	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	HWEOC (Mg C ha-1), depth 0-20 cm	2.94 a	3.05 a	1.16 b	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	HWEOC (Mg C ha-1), depth 0-40 cm	0.84 ab	1.10 a	0.41 b	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	CTPS (Mg C ha-1), depth 0-20 cm	20.4 ab	21.4 a	16.6 c	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	CTPS (Mg C ha-1), depth 0-40 cm	15.3 ns	16.1 ns	15,8 ns	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	CSCO (Mg C ha-1), depth 0-20 cm	14.9 ab	19.4 a	14.6 abc	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	CSCO (Mg C ha-1), depth 0-40 cm	13.1 ab	15.0 a	13.7 a	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	POC (Mg C ha-1), depth 0-20 cm	8.8 ab	10.2 a	5.5 cb	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	POC (Mg C ha-1), depth 0-40 cm	0.7 cb	2.3 a	1.7 bc	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	MAOC (Mg C ha-1), depth 0-20 cm	63.6 Aba	71.4 a	55,9 Cb	Tivet, et al., 2013
Oxisol, Rhodic Hapludox, in Brazil	29	Soybean, maize, oat, wheat, vetch	MAOC (Mg C ha-1), depth 0-40 cm	45.0 ns	46.3 ns	45.3 ns	Tivet, et al., 2013

...Annexed 1

Soil	Time (years)	Crop	Observed effect	Tillage system			Reference
				NT	RT	CT	
Subtropical Acrisol in Brazil	18	Oat-maize	Free POM, Depth 0-5 cm	0.80 ns		0.5 ns	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-vicia- maize-cowpea	Free POM, Depth 0-5 cm	1.8		0,9	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-maize	Occluded-MOP	2.2		1	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-vicia- maize-cowpea	Occluded-MOP	3.5		1,6	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-maize	Minerilized MO	7.4		5,4	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-vicia- maize-cowpea	Minerilized MO	8.9		6.0	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-maize	Total MO	10.4		6,9	Conceiao, et al., 2013
Subtropical Acrisol in Brazil	18	Oat-vicia- maize-cowpea	Total MO	14.1		8,5	Conceiao, et al., 2013
Typic Palehumult in Chile	4	Oat-wheat	CO (%), depth 0-5 cm	5.0 ab		4.8 bc	Conceiao, et al., 2013
Typic Palehumult in Chile	4	Lupinus-wheat	CO (%), depth 0-5 cm	5.2 a		4.6 c	Conceiao, et al., 2013
Typic Palehumult in Chile	4	Oat-wheat	CO (%), depth 0-10 cm	5.0 a		4.5 b	Conceiao, et al., 2013
Typic Palehumult in Chile	4	Lupinus-wheat	CO (%), depth 0-10 cm	4.9 a		4.5 b	Conceiao, et al., 2013

Annexed 2. Comparative effect of soil Bulk Density applied to different tillage systems, reported in recent years

Soil	Time (years)	Crop	Observed effect	Tillage system			Reference
				No tillage	Reduced tillage	Conventio-nal tillage	
Typic Endoaquoll, Typic Hapludolls, in USA	7	Corn, no harvest	Soil bulk density (g cm-3)	1.30 b		1.27 a	Tormena, et al. 2017
Typic Endoaquoll, Typic Hapludolls, in USA	7	Corn, moderate harvest	Soil bulk density (g cm-3)	1.42 b		1.19 a	Tormena, et al. 2017
Typic Endoaquoll, Typic Hapludolls, in USA	7	Corn, high harvest	Soil bulk density (g cm-3)	1.40 b		1.31 a	Tormena, et al. 2017
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	Soil bulk density (g cm-3)		1.09	1.05	Margenot, et al, 2017
Vertisol in Spain	27	Wheat-sunflower-wheat-c	Soil bulk density (g cm-3)	0.92 b		0.84 a	López - Bellido, et al, 2017
Tipyc Xerofluvent in Spain	4	Maize, weat, sumflower	Soil bulk density (g cm-3)	1.37		1.41	Sapkota, et al, 2012
Vertisol	10		Soil bulk density (Mgm-3)	1. 4		1.05	Potter y Chichester , 1993
Typic haplustert	4	Maize	Soil bulk density (Mgm-3)	1		0.94	Mora, et al., 2001

Annexed 3. Comparative effect of Phosphorus content applied to different tillage systems, reported in recent years

Soil	Time (years)	Crop	Observed effect	Tillage system			Reference
				No tillage	Reduced tillage	Conventio-nal tillage	
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	P total, dept 0-15 cm		140.3	117.1	Margenot, et al, 2017
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	P organic, dept 0-15 cm		13.6	18.77	Margenot, et al, 2017
Typic Rhodiudox in Kenia	9	Maize-soybean + residuos	P max sorption, dept 0-15 cm		274	258	Margenot, et al, 2017
Typic Palehumult in Chile	4	Oat-wheat	P Total (mg kg-1), depth 0-5 cm	2127 a		1965 b	Redel, et al, 2011
Typic Palehumult in Chile	4	Lupinus-wheat	P Total (mg kg-1), depth 0-5 cm	2144 a		1983 b	Redel, et al, 2011
Typic Palehumult in Chile	4	Oat-wheat	P Total (mg kg-1), depth 0-10 cm	2019 a		2046 a	Redel, et al, 2011
Typic Palehumult in Chile	4	Lupinus-wheat	P Total (mg kg-1), depth 0-10 cm	2093 a		2047 a	Redel, et al, 2011
Typic Palehumult in Chile	4	Oat-wheat	Olsen P (mg kg-1), dept 0-5 cm	24,2 a		19.3 b	Redel, et al, 2011
Typic Palehumult in Chile	4	Lupinus-wheat	Olsen P (mg kg-1), dept 0-5 cm	24.7 a		18.9 b	Redel, et al, 2011
Typic Palehumult in Chile	4	Oat-wheat	Olsen P (mg kg-1), dept 0-10 cm	26.4 a		26.5 a	Redel, et al, 2011
Typic Palehumult in Chile	4	Lupinus-wheat	Olsen P (mg kg-1), dept 0-10 cm	24.6 a		22.0 b	Redel, et al, 2011
Ultisol (Typic Hapludult) in Chile	7	Lupinus-wheat-oat	P Olsen, dept 0-20 cm	23.8 a	19.2 b		Acevedo, et al, 2003
Ultisol (Typic Hapludult) in Chile	7	Lupinus-wheat-oat	P Total, , dept 0-20 cm	2281 a	2384 a		Acevedo, et al, 2003