EFFECTS OF CONSERVATION TILLAGE IN SOIL CARBON SEQUESTRATION AND NET REVENUES OF POTATO-BASED ROTATIONS IN THE COLOMBIAN ANDES

By

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To my husband, family and mentors

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Over 60% of the world's carbon is held in both soils (more than 41%) and the atmosphere (as carbon dioxide; 20%)). However, soil disturbance is redistributing the carbon, augmenting the atmospheric carbon pool. Thus, a part of carbon dioxide increase in the atmosphere is thought to come from agriculture, affecting not just climate change but also productivity and sustainability of agriculture and natural resources. This study was undertaken to investigate the contribution of conservation tillage practices in potato-based rotations of the Fuquene Lake watershed in the Colombian Andes, to reduce Greenhouse Gases (GHG) emissions, sequester soil carbon, to rehabilitate water and carbon-related soil characteristics, and to understand the opportunity costs of changing from conventional to conservation tillage. Field soil sampling was conducted in 7-years old conservation tillage farms and in farms with conventional tillage practices. Soil samples were analyzed in the lab to determine Soil Organic Carbon stocks, SOC in soil aggregates by applying ultrasound, and water-related physical characteristics. In addition GHG net emissions were calculated for conservation and conventional tillage, and contrasted with net revenues. As a result, conservation tillage in potato-based systems improved in a 7 year period the soil organic matter and carbon content in these disturbed soils. The soil carbon

concentration in the whole profile was 29% higher under conservation tillage than under conventional tillage sites and the carbon content was higher by 45%. C content improvement specially occurred in the subsoil (A2 horizon) increasing by 177% although most of the C is stored in the top A1 horizon. This improvement was correlated to the enhancement of soil physical characteristics related with soil water movement and storage such us bulk density, AWC, saturated hydraulic conductivity and mesoporosity. In another hand OM in aggregates represented more than 80% of total OM of these soils and was positively affected by conservation tillage. This improvement showed a preferential C sequestration in smaller macroaggregates (<2 mm). The aggregate dispersion energy curves further suggest this is happening in microaggregates within the smaller macroaggregates fraction. A complementary tradeoff between the economic and environmental benefits was found for our study site. This relies on the fact net farmer revenues were increased —by reduced machinery operations and fertilizers applications—, while GHG emissions were reduced –by increasing soil carbon retention and reducing GHG emissions from machinery operations—. Thus, although conservation tillage practices are not widely adopted in the watershed, payments for net GHG removals could increase more the net revenues and facilitate the investment to cover initial extra costs of conservation agriculture (ie. cultivation of oat as cover crop).

CHAPTER 1
INTRODUCTION

Over 60% of the world's carbon is held in both soils (more than 41%) and the atmosphere (as carbon dioxide; 20%)) (Sundquist, 1993; Stevenson, 1994). However, soil disturbance is redistributing the carbon, augmenting the atmospheric carbon pool. Thus, a part of carbon dioxide increase in the atmosphere is thought to have come from agriculture, affecting not just climate change but also productivity and sustainability of agriculture and natural resources (Robbins, 2004). Therefore, the importance of Soil Organic Carbon (SOC) is being recognized because of its impact on global climate change. However this posses an opportunity for management alternatives in agricultural lands that beyond producing food can provide ecosystems services such as provision of good quality water, water flow regulation and carbon sequestration (Clay, 2004; Boody et al., 2005; Robertson and Swinton 2005; Swinton et al., 2006; De la Torre et al., 2004) . One example of these alternatives is conservation tillage for which there is a growing interest to be adopted by farmers due precisely to environmental benefits (Kern and Johnson, 1993; Burke et al., 1995) and to the fact that carbon sequestered in the soil and other ecosystem services can eventually be traded.

Importance of Soil Aggregation and Soil Management Practices for Carbon Sequestration

Jastrow et al. (1996) found that nearly 90% of Soil Organic Matter (SOM) was found within soil aggregates that can be macroaggregates (>0.25 mm) or microaggregates (0.05–0.25 mm) (Edwards and Bremmer, 1967; Maeda et al., 1977). Kong et al. (2005) showed that the relationship between C input and SOC sequestration was dominated by the increase in SOC within macroaggregates which amount is generally reduced by cultivation (Tisdall and Oades, 1982) by being less stable and therefore, susceptible to tillage disruption (Elliot, 1986; Cambardella and Elliot, 1993). Upon disruption, an increase or flush in C mineralization is observed (Angers and Chenu, 1997), augmenting the atmospheric carbon pool. However with certain soil management practices the SOM protection from decomposition can be enhanced. Management systems involving high C inputs and reduced tillage should favor C storage directly by reducing aggregate breakdown and by enhancing SOM-mediated aggregation (Kern and Johnson, 1993; Burke et al., 1995). Thus, although there are other ways to protect SOM (and SOC) such as by adsorption to clay minerals and by isolation in soil micropores (Bossuyt et al. 2002), physical protection within stable macroaggregates is important since it is sensitive to the type of soil management applied in agricultural areas.

The Need to Measure Soil Organic Carbon (SOC) in Conservation Tillage Sites in the Andes and Its Economic Returns

Agricultural sinks will not be eligible for the Clean Development Mechanism before 2012 (FAO, 2002) and they are also not considered in the Kyoto Protocol. However, the soil is a C sink and it is worth researching how soil carbon is benefited from agricultural practices so that one is prepared for CDM or other opportunities that will inevitably recognize this sink (e.g. BioCarbon Fund, GEF). In this sense research is needed to elucidate two facts from the farmer and market perspective that poses methodological challenges for those interested in developing carbon payments schemes in the agriculture sector. From the market perspective, agricultural lands will be only accepted as sinks if the sequestered carbon is additional to that one already existing in the baseline (Antle et al., 2007) after discounting GHG emissions caused by the carbon sequestering practices. From the farmer's perspective, changing to conservation tillage may imply an opportunity cost equal to the difference between the highest-returning practice and the practice that yields the most soil carbon (Antle et al., 2007). So it is assumed that a farmer will be willing to change if that opportunity costs is compensated or if the new alternative produces equal or higher net returns.

In Colombia, conservation agriculture practices involving reduced tillage and cover crops were adapted by the GTZ and the environmental authority (CAR) to OM-rich soils of *Paramos* —neotropical alpine grasslands that is the transition between the forest and the snowline (from about 3300 m to about 4800 m above sea level) in the Andes (Poulenard et al., 2003)—, that were disturbed many decades ago and cultivated with potato and pastures. This process started in1999 in the steep conditions of the region as a mean to reduce soil losses and improve water quality and quantity. As a result, farmers in some watersheds adopted these practices offering nowadays an extraordinary opportunity to investigate the contribution of these practices to reduce Greenhouse Gases (GHG) emissions, sequester soil carbon, to rehabilitate water and carbon-related soil characteristics, and to understand the opportunity costs of changing from conventional to conservation tillage. This kind of research then provide results very relevant nowadays that carbon markets for agricultural areas are increasingly gaining importance and especially for the Andes were studies about the potential of conservation tillage in this mountainous, highly populated and productive areas for delivering both, environmental and economic benefits are scarce.

Thus, objectives of this research were:

1. To determine if and how soil characteristics under potato-based rotations on soils that were formerly *paramos* are rehabilitated by conservation tillage practices;
2. To determine if SOM can be increased in already OM-rich soils by conservation tillage
3. To estimate the amount of aggregated organic matter (AOM) in stable soil macroaggregates under potato-based rotations using conventional tillage vs. reduced tillage with cover crops.
4. To determine the opportunity costs of implementing conservation tillage in the study area
5. To estimate the net GHG removals caused by conservation and conventional tillage systems.

To address these objectives, chapter 2 focuses on objectives 1 and 2. For the first objective the hypothesis was that conservation tillage, by applying reduced tillage and increasing C inputs to the soil, improves saturated hydraulic conductivity, porosity, available water content and reduces the bulk density; which implies rehabilitation with respect to conventional tillage. The second objective relied on the hypothesis that, in spite the still high OM content of these soils, conservation tillage increases SOC and SOM with respect to conventional tillage.

Chapter 3 addresses objective 3 by studying the AOM in soil macroaggregates using a sonication technique. The hypotheses tested were: 1) Conservation agriculture increases OM in the aggregate organic matter pool, and 2) The OM contained in aggregates is different across size fractions being greater in smaller macroaggregates.

Chapter 4 focuses on objectives 4 and 5. For determining the opportunity costs and to determine the GHG removals economic and carbon estimations for conventional tillage were conducted to characterize the "business as usual" scenario or the baseline and later compared with estimations for conservation tillage. The hypothesis tested was that there is a competitive trade off between economic and carbon sequestration benefits derived from conservation tillage and for this reason carbon payment schemes are needed to bear the opportunity costs of changing from conventional to conservation tillage. Chapter 5 provides an integral summary of results and conclusions of the overall chapters and gives recommendations about future research needs.

CHAPTER 2
EFFECTS OF CONSERVATION TILLAGE ON SOIL ORGANIC CARBON (SOC) AND SOIL PHYSICAL CHARACTERISTICS

Introduction

The agriculture role in society is changing in industrialized and developing countries. Rather than being considered only as a means to produce food, it is becoming a solution to deliver raw material for industries and ecosystem services. It is now seen as an alternative to mitigate climate change and improve water quality. These ecosystem services are related to soil functions and for this reason, the fact of promoting farming systems that produce both food and ecosystem services is becoming more important (Lal, 2007).

Lal et al., (2007) consider an increase in soil organic carbon (SOC) a crucial factor in enhancing soil, air and water quality. Management practices that increase C inputs in farming systems and apply reduced or non-tillage farming practices should increase SOC (e.g., Denef et al., 2004; Bossyut et al., 2002; Kong et al., 2005; Kuo et al., 1997; Rasmussen et al., 1980; Cole et al., 1993). It is well established that increases in SOC are accompanied by increased soil aggregation, plant available water capacity, ion exchange capacity, soil biodiversity (Lal and Bruce, 1999), and crop yields (e.g. Pretty and Ball, 2001).

Reduced tillage, combined with crop residue retention (conservation tillage), is a farming practice that can increase SOC and improve soil structure and soil stability while facilitating better drainage and water holding capacity; limiting the potential for water logging or drought (Holland 2004; Govaerts et al., 2007; Zibilske and Bradford 2007; Lichter et al., 2008). Conservation tillage counters the adverse effect of conventional tillage, namely the destruction of soil aggregates, which reduces the soils ability to hold plant available water (Patiño-Zúñiga et al., 2008). Also when soil aggregates are destroyed by tillage and conventional ploughing, soil organic matter becomes available for decomposition (Bronick and Lal, 2004), decreasing SOC.

Patiño-Zúñiga et al. (2008) found that disturbing a Mollisol in Mexico to make beds for a maize-wheat rotation decreased soil organic C content within 6 years by 10% compared to soil under non-tilled beds. The IPCC (2000) reported increases of 0.32 to 0.36 t SOC ha^{-1} y^{-1}; while in Brazil, soil carbon sequestration was increased by conservation tillage when maize was rotated with mucuna (15.5 Mg CO_2 ha^{-1}) during 8 years, compared to a net emission of 4.32 Mg CO_2 ha^{-1} from the traditional maize/fallow plot (Evers and Agostini, 2000). Thus, soil conservation practices (minimum tillage, rotations, cover crops and others) result in soil carbon increases. However, such increases are not perpetual since there is a carbon sequestration saturation point (20 to 50 years) (Lal and Bruce, 1999). For example, in Canada's cooler climates with high organic matter soils, C inputs and no-till practices did not produce any significant change in soil C (Campbell et al., 1991; Carter and Rennie, 1982; Doyle et al., 2004); suggesting that those soils were C saturated (Six et al., 2002).

There is a growing interest among farmers to adopt management practices such us conservation tillage due to all the described environmental benefits (Kern and Johnson, 1993; Burke et al., 1995) and to the fact that carbon sequestered in the soil through appropriate farming practices can be traded. However measurement, monitoring and verification techniques are still required (Lal, 2007).

In the high Andes of Ecuador, Venezuela and Colombia is found the Paramo ecosystem; a neotropical alpine grassland that is the transition between the forest and the snowline (from about 3300 m to about 4800 m above sea level) (Poulenard et al., 2003). *Paramo* soils are non-allophanic Andisols dominated by organo-metalic complexes (Van Wambeke, 1992) formed by the wet and cold conditions. These soils are recognized by a high water retention capacity, very high infiltration rate, very slow sediment loss (Poulenard et al., 2001) and high organic matter

(Van Wambeke, 1992). However, when these soils are disturbed and used for cultivation, runoff is increased and the saturated hydraulic conductivity is reduced (Poulenard, et al., 2001).

In Colombia, conservation tillage technology was adapted to these soils located generally in steep conditions by the GTZ and the environmental authority (CAR) since 1999 as a measure for soil and water conservation. As a result, some farmers in some watersheds adopted these practices. The Fuquene watershed is an example where these practices were introduced as a measure to control the sediments that are released from potato farms on very steep slopes and OM-riched volcanic soils and that are causing the eutrophication of Lake Fuquene.

Thus, this study was conducted in this watershed and the objectives were 1) to determine if and how soil characteristics under potato-based rotations on soils that were formerly *paramos* are rehabilitated by conservation tillage practices; and 2) if SOM can be increased in these already OM-rich soils. For the first objective the hypothesis was that conservation tillage, by applying reduced tillage and increasing C inputs to the soil, improves saturated hydraulic conductivity, porosity, available water content and reduces the bulk density; which imply a rehabilitation with respect to conventional tillage. The rationale behind this is that conventional tillage in Andosols negatively modifies these characteristics by disrupting soil aggregates and compacting the soil. The relevance of the results is that it would provide insights into the potential for conventional tillage to rehabilitate conventional tillage sites in these high elevation unique ecosystems; something that is presently poorly understood. The second objective relied on the hypothesis that, in spite the still high OM content of these soils, conservation tillage increases SOC and SOM with respect to conventional tillage. The rationale is that once these soils were disrupted by intensive tillage and were not enriched with additional sources of OM, the C stocked in the soil had been released to the atmosphere and would not be recuperated due to the lack of additional C inputs.

The results of this research are important as they provide insights about the role of these practices to rehabilitate conventional tillage sites and to provide bundled ecosystem services by improving 1) water-related soil characteristics that affect water quality and 2) SOC and the soils potential to sequester C. This is relevant for the Andean region because intensive management practices associated with high agricultural productivity risks the soil capacity to deliver food and ecosystem services. Providing insights about the potential of storing soil carbon in these areas by implementing conservation tillage, carbon trade schemes could become incentives to increase the adoption of these practices in the Andes. It is worth noting that currently Colombian national GHG emissions are attributed to agricultural land use change, making conservation tillage a potential significant component of measures to counteract these emissions.

Materials and Methods

Study Sites

The study sites were agricultural parcels located in the upper part of the Lake Fuquene watershed (2985–3070 m.a.s.l.) which is located in the valleys of Ubaté and Chiquinquirá, north of Bogotá, the capital of Colombia (South America) (N 05 20’ W 73 51’). The soils of this location are Andisols classified as Lithic Hapludands (IGAC, 2000). These agricultural areas used to be alpine Andean grasslands (*páramos*), a typical yet unique Andean natural ecosystem. The temperature is stable throughout the year with mean annual values between 12°–13.2°C. The mean monthly humidity varies between 70 and 80%. The annual mean precipitation is 610 mm (JICA, 2000).

Parcels are traditionally used by farmers to grow potatoes with a pasture rotation each 2–3 years. However some farmers are practicing conservation tillage by growing potatoes with reduced tillage and an oat cover crop. Therefore, in this study two types of parcels were selected: 1) parcels with conventional tillage and 2) parcels with conservation tillage. Each used the prescribed treatment during the last 7 years. Three sites per system were selected. The six sites were selected with the same characteristics in terms of: 1) landscape position; 2) land use; 3) slope; and 4) rainfall. Thus all of them were located in backslope positions, with linear and moderate slopes, under potato-based rotations and the same rainfall and regimen.

At each site, two pits were dug in May 2007 and soil horizons were identified and described in each pit. Soil samples per horizon were taken using 3 cylinders per horizon of 2.5 cm height to determine the water retention curves, bulk density and porosity; and 5-cm diameter cylinders per horizon for determining saturated hydraulic conductivity. Additional fresh samples were taken. Five-hundred g of soil was taken per horizon to determine organic matter, carbon concentration, and soil texture.

Laboratory Methods

The sand size distribution and soil texture were determined using the Bouyoucos method (Bouyoucos, 1936). The carbon concentration was determined using the method of Walkley and Black as described in Nelson and Sommers (1996). Soil Organic matter (SOM) was determined by loss of ignition (Schulte and Hopkins, 1996) . The carbon content was estimated using two approaches: the volume-based approach where the bulk density and the average thickness of horizons were used to estimate soil volume and the carbon concentration for that volume; and the equivalent soil mass (mass-depth) to correct for differences in soil bulk density, allowing more precise and accurate quantitative comparisons of soil constituents. This last approach permits one to account for unequal soil masses or densities (Ellert et al., 2002).

The undisturbed samples were used to determine soil bulk density by the cylinder method (Elliot et al., 1999; Klute, 1986); water retention curves at matrix potentials between 0 and 1.5 MPa using a pressure-plate extractor (Soil Survey Staff, 1996; Klute, 1986); and saturated hydraulic conductivity with a permeameter using the constant head method (Klute and Dirksen, 1986). In addition, the total porosity (TP) was determined using the particle (D_p) and bulk density (D_b) values, where TP = (1 – (D_b / D_p) * 100). The pore size distribution was derived from the water retention curves by relating soil water content with different soil matrix potentials. The water content at 1500, 75 and between 75–15000 cm was used for determining micropores, macropores and mesopores, respectively.

Data Analyses

SOM , SOC and physical characteristic data were shown to have near normal distributions. An analysis of variance (ANOVA) was applied to the data using a factorial design after variables were shown to have near normal distributions. The main effects were type of tillage (conservation vs. conventional) and horizons. Preliminary analyses indicated that Horizon 3 was not different between treatments, therefore the ANOVA for SOM and SOC and other physical characteristics involved only the first two horizons. Duncan post hoc mean separations were used to analyze the effect of horizon, treatment and their interaction. To determine possible relation between SOM or SOC and soil physical characteristics, a simple correlation was conducted for all soil horizons.

Results

Soil Descriptions, Physical Characteristics and Horizon Differences

In general, three horizons were found in the 12 profiles with an average thickness of 78 cm (horizon A1, top), 39 cm (horizon A2) and 49 cm (horizon C, bottom). The main differences between horizon descriptions was that the percent of clay increases with depth and the color was very dark in the first two horizons while the third one was mostly yellowish. The horizon A1 consisted of silty-loam or loam soils with dark moist colors: very dark gray, very dark grayish brown and black (10 YR 2.5/1, 10 YR 3/2 or 10 YR 3/1); moderate to strong and subangular blocky or granular structure; and friable to very friable consistency.

The A2 horizon had clay, clay-loam, loam or silty-loam soil textures with dark colors: brownish black, black, brown or very dark grayish brown (7.5YR 3/2, 10 YR 2.5/1, 10YR 4/3, 10YR 3/2 or 7.5YR 4/2). The structure was mostly moderate and its shape was very variable (subangular blocky, angular blocky, platy, moderate or massive). The consistency was mostly friable to very friable.

The C horizon was very different from the other two horizons. The moist colors were lighter than those found in the upper horizons: light olive, yellowish brown, light gray, brown, brownish yellow and in a few cases dark brown (10Y 5/4, 10YR 5/4, 10YR 6/1, 10YR 4/3, 10YR 6/5, 7.5YR 5/2, 5YR 7/1, 10YR 3/3, 10YR 5/6). The soil was structureless, weak or in some cases moderate. The structure shape was mostly massive and sometimes was angular blocky or subangular blocky. The consistency was variable from very friable or friable to firm or very firm. Figure 2-1 represents soil profiles for the six sites with conservation and conventional agriculture are shown. The detailed field soil descriptions for each of the 12 soil profiles are available in Appendix A.

The bulk density, saturated hydraulic conductivity, available water content (AWC), total porosity, macroporosity, mesoporosity, microporosity, SOC and SOM showed no interactions between main effects allowing the ability to contrast treatments and horizons separately (Table 2-1). Horizons were different for saturated hydraulic conductivity, AWC, macropores, mesopores, micropores and SOC at $p<0.05$. The micropores increase with depth while the other characteristics decreased with depth (Table 2-2). Instead porosity, bulk density and SOM did not show differences across horizons.

With regard to soil water, water content at different matrix potentials was different across horizons (Figure 2-2). As the soil dried the A2 horizon held as much as 10% more water than A1 at equal matric potentials. This is consistent with the increase in microporosity evident in the A2 horizon. At saturation, total water content was equivalent in the two horizons as indicated by similar bulk densities.

Effect of Conservation and Conventional Tillage on Soil Characteristics

The tillage system had a significant effect on saturated hydraulic conductivity, AWC and mesopores ($p<0.05$) and on bulk density, volumetric water content, SOM and SOC ($p <0.1$); Table 2-2). The bulk density was lower in conservation tillage while the other characteristics were higher under conservation tillage (Table 2-3).

At $p<0.1$ there was a significant interaction treatment*horizon, being the mean volumetric water content higher in H2 of conservation tillage sites (figure 2-3).

Simple correlation analyses showed that total organic matter (g/Kg) was negatively correlated in both treatments with bulk density and positively correlated with hydraulic conductivity, total porosity, macro-porosity and meso-porosity (Table 2-4). In general, bulk density had a negative correlation with saturated hydraulic conductivity, total porosity and macro porosity.

Soil Carbon Content and Tillage Systems

The horizon depth used in the C content calculation based in the soil volume corresponded to the average of all depths measured per horizon regardless of the treatment due to the fact that horizon depth was not statistically different between treatments (data not shown). The C content was estimated using the mass equivalent method for which the C content was calculated for successive layers of 6635 Mg ha^{-1} and 3943 Mg ha^{-1} representing horizon A1 and A2, respectively. This corresponded to the average soil mass calculated per site according to bulk density and soil depths. With these averaged soil masses the soil depth was adjusted in order to ensure that final C contents were representing the same amount of soil mass.

The results obtained with both methods, soil volume and soil mass equivalent showed that carbon content was different by treatment at $p<0.1$ and by horizon at $p<0.05$. According to the results obtained with the mass equivalent method the A1 horizon had the highest carbon content with 1097 t C ha^{-1}; while the A2 has an average content of 406 t C ha^{-1} (Table 2-6). With respect to treatment, conservation tillage sites had an average carbon content in the soil profile of 891 t C ha^{-1} vs. 612 t C ha^{-1} in conventional tillage; a 45% increase due to conservation tillage.

Discussion

The study sites corresponded to cropping areas that formerly were *paramos*. Moreover, the conservation tillage areas were previously under conventional tillage. Therefore, the results of this study highlight the ability of conservation tillage to recover the soil characteristics of the *paramo* ecosystem once impacted by conventional tillage practices. Basic physical properties of *paramo* soils are high organic C content, open and porous structure,a very high porosity, a rapid hydraulic conductivity and high water retention (Buytaert et al., 2006). Bulk density is known to range from as low as 0.15 g cm^{-3} in wet conditions and weathered soils to about 0.9 g cm^{-3} in younger soils of dryer regions (Buytaert et al., 2005). In this sense reductions on bulk density or increases on hydraulic conductivity, porosity, C content, AWC and water retention in *paramo* disturbed soils under conservation tillage sites will imply an improvement with respect to conventional tillage.

In the Fuquene watershed, conservation tillage has improved the AWC, the saturated hydraulic conductivity and the mesoporosity by 30, 56 and 30% respectively ($p<0.05$). Also, bulk density was reduced by 15% and SOM and SOC concentrations were increased by 23 and 33% respectively ($p<0.1$). The improvement in AWC is a function of the increased mesoporosity under conservation tillage, which is corroborated with the strong correlation found between these two soil characteristics. The AWC characteristic of conservation tillage (9.56%) is in the range reported by Diaz and Paz (2002) for other Colombian *paramos* (6–12%) where they also related its changes to mesoporosity differences attributable to land use change.

With respect to saturated hydraulic conductivity, the improvement is explained by the avoidance of soil crusting or soil air exposure complicated by conventional agriculture and corrected by conservation tillage in the *paramos* (Poulenard et al., 2001). This effect has been identified in other environments throughout the world where long-term conservation tillage systems (no-till or reduced tillage) and a residue cover that protects soil porosity (in our case specifically mesoporosity), soil infiltration and avoids surface crusts caused by intense rain events (Burwell, 1966; Mahboubi et al., 1993; Azooz and Arshad; 1996, 2001) can combat the deleterious influence of conventional tillage. The effect of improving saturated hydraulic conductivity is also related to the enhancement of pore interconnectivity in conservation tillage systems as suggested by Strudley et al. (2008). Given the insignificant change in total porosity, the only explanation for increased saturated conductivity is the improved interconnection of soil pores.

Apart from the improvement in these physical soil characteristics, conservation tillage improved SOC. Soil C concentrations in conservation and conventional tillage sites are in the range reported for undisturbed or recolonized humid *paramos*. In Northern Ecuador and Colombia the A horizon has been reported to have from 101 to 212 g C Kg^{-1} (Podjoweski et al., 2002; Poulenard et al., 2003; E. Amezquita et al., unpublished data. 2005) while this study recorded 152 and 178 g Kg^{-1} in conventional and conservation tillage sites, respectively. Although our conventional tillage values are in that normal range, conservation tillage showed a marked improvement in the C concentration and in the average C content for the whole soil profile (≈100 cm depth) with respect to conventional tillage of 29 and 45%, respectively. The average C content has changed from 612 to 891 t ha^{-1}. Particularly interesting is a 177% increase in the deeper A2 horizon (from 215 to 596 t ha^{-1}) although most of the C is stored in the top A1 horizon (1097 t ha^{-1}). This increase in C content with depth caused by conservation tillage illustrates that redistribution of C is occurring throughout the soil profile; and is consistent with other reports (i.e. Carter and Rennie, 1982; VandenBygaart et al., 2002; Beare et al., 1994). This clearly visible effect is attributed to the effect of oat cover crop roots that tend to be deep roots in these soils. Also, the improvements in C with depth may be related with the fact that under conservation tillage the vegetation cover is kept and then the soil surface is not exposed to air and sun which otherwise favors the mineralization of the organic matter – due to organic-mineral complexes get separated releasing the organic matter susceptible to decomposition by the action of microorganisms (Hofstede, 2001; Stevenson, 1986). The general improvement in SOC also indicates that conservation tillage has shortened the gap between SOC in conventional tillage and in undisturbed paramos – a 45% increase over conventional tillage. Edwards et al. (1992) found that conversion from conventional tillage to conservation tillage in soybeans and corn systems rotated with wheat during winter in a Hapludult of Southern USA also increased soil organic carbon on average by 31% over a 10 yr period. Although the initial organic matter conditions are different between the soils studied by Edwards et al. (1992) and our Andosols (9.8 g Kg^{-1} vs 170 g Kg^{-1} under conventional tillage), conservation tillage improves those initial levels of organic matter, even in OM-rich soils. This confirms this studies second objective showing that conservation tillage is effective in increasing soil OM even in soil that have a high OM content; at least in these unique *paramos* ecosystems.

With respect to organic matter found in other disturbed *paramos*, the average organic matter concentration of conventional tillage sites (170 g Kg^{-1}, Table 2-3) is similar to the concentration found in other potato systems in Southern Colombian *paramos* (100–130 g Kg^{-1}, Diaz & Paz, 2002) and other parcels located in the Fuquene watershed (0.15 g/g, E.Amezquita et al., unpublished data, 2005). The average organic matter content of conservation tillage sites (0.22 g/g, Table 2-3) is instead similar to the content reported also by Diaz & Paz (2002) of 0.17–0.24 g/g in sites that were previously pastures and that were recently cultivated with potato. These authors attributed this to the remaining effect of pasture roots on the organic matter content that may be similar to the effect of the oat roots in our conservation tillage system. The organic matter content is also similar to the averaged organic matter reported by E.Amezquita et al. (unpublished data, 2005) for undisturbed *paramos* of the Fuquene watershed (0.24 g/g)

Thus, conservation tillage presented higher C concentrations (and organic matter) similar to undisturbed *paramos*,; confirming this studies first objective that conservation tillage can be used to rehabilitate soil under potato production in the region. This positive effect of conservation tillage on the organic matter and carbon contents has been reported by many studies. Grant (1997) and Black and Tanaka (1997) recognized that the long term use of conservation tillage increase soil organic carbon, enhance soil quality and improve soil resilience. It has been suggested that the increase in soil organic carbon associated with the adoption of conservation tillage will continue for a period of 25 to 50 yr depending on climatic conditions, soil characteristics, and production management practices (Franzluebbers, 1997; Franzluebbers et al., 1999; Hunt et al., 1996; Wood et al.,1991; Zobeck et al., 1995).

The relevance of these results lies in the fact that while most soil *paramos* studies have reported how land use changes modify the unique properties of *paramos* soils none have explored how better management practices in agriculture can rehabilitate them. The question left unanswered by this study site relates to the time frame for which improvements on SOC and organic matter will be achieved with conservation tillage, and also under which baseline conditions conservation tillage could improve disturbed soil properties in *paramos*. It only suggests that these changes can be brought about in as little as 7 years.

Conclusions

Conservation tillage in potato-based systems improved in a 7 year period the soil organic matter and carbon content in disturbed soils of the *paramos* of Colombia. The soil carbon concentration in the whole profile was 29% higher under conservation tillage than under conventional tillage sites and the carbon content was higher by 45%. C content improvement specially occurred in the subsoil (A2 horizon) increasing by 177% although most of the C is stored in the top A1 horizon. This improvement was attributed to the enhancement of soil physical characteristics related with soil water movement and storage such us bulk density, AWC, saturated hydraulic conductivity and mesoporosity. These improvements reflect that conservation tillage, is allowing the rehabilitation of carbon and water-related soil characteristics compared to conventional tillage systems.

Figure 2-1. Soil profiles in six different sites. A–C) Sites with conservation agriculture; D–E) Sites with conventional agriculture.

Table 2-1. Effects of treatment and horizon on soil characteristics

	p-values								
Main effects/soil characteristic	Bulk density (g cm^{-3})	Sat. Hydraulic Conductivity (cm h^{-1})	Porosity (%)	Macropores (%)	Mesopores (%)	Micropores (%)	SOM (g/Kg)	SOC (g/Kg)	AWC (%)
Treatment	0.078♠	0.024*	0.135	0.503	0.000*	1	0.02	0.057♠	0.000*
Horizon	0.345	0.016*	0.517	0.000*	0.003*	0.001*	0.000*	0.001*	0.003*
Treatment*Horizon	0.124	0.688	0.148	0.282	0.598	0.497	0.413	0.452	0.598

*Significant at 5% ($p < 0.05$). ♠ Significant at 10% ($p < 0.1$).

Table 2-2. Comparison of soil characteristics across soil horizons

	Bulk density (g cm^{-3})	Sat. Hydraulic Conductivity (cm h^{-1})	Porosity (%)	Macropores (%)	Mesopores (%)	Micropores (%)	SOM (g/Kg)	SOC (g/Kg)
Horizon I	0.81 (a)*	18.5 (a)	65.6 (a)	25.1 (a)	9.2 (a)	30.2 (a)	230 (a)	160 (a)
Horizon II	0.96 (a)	7.6 (b)	63.6 (a)	15.1 (b)	6.9 (b)	41.5 (b)	150 (b)	80 (b)

*Within a soil characteristic, the means followed by different letters are statistically different at $p < 0.05$ and show the effect of horizon.

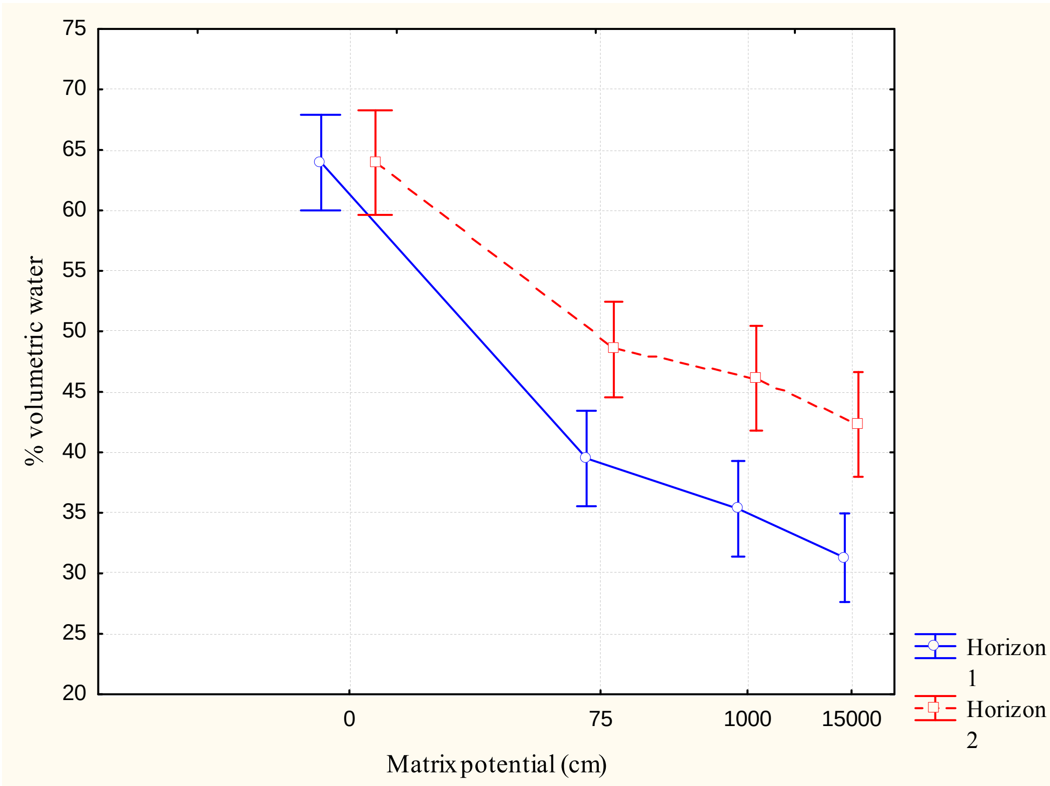

Figure 2-2. Volumetric water content at different matrix potentials in selected soil profile horizons

Note: Vertical bars denote 0.95 confidence intervals. Horizon 1: A1, Horizon 2: A2.

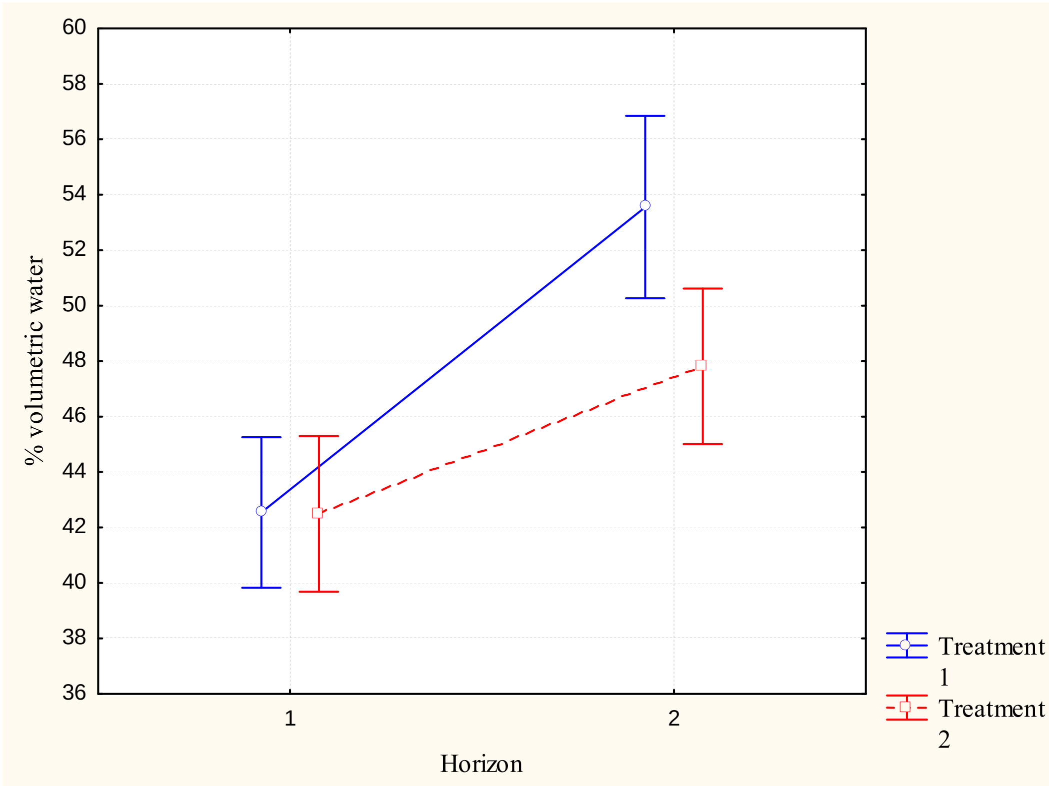

Figure 2-3. Volumetric water content at different tillage systems in selected soil profile horizons

Note: Vertical bars denote 0.95 confidence intervals. Treatment 1: Conservation agriculture; Treatment 2: Conventional agriculture.

Table 2-3. Comparison of soil characteristics across soil treatments

	Bulk density ($g\ cm^{-3}$)♠	Sat. Hydr Conduct. ($cm\ h^{-1}$)♦	Porosity (%)♦	Macropores (%)♦	Mesopores (%)♦	Micropores (%)♦	SOM (g/Kg) ♦	SOC (g/Kg) ♠	AWC (%)♦
Conservation agriculture	0.81 (a)*	18.1 (a)	66.1 (a)	21.5 (a)	9.5 (a)	35.8 (a)	220 (a)	150 (a)	9.56 (a)
Conventional agriculture	0.96 (b)	8.0 (b)	62.6 (a)	19.7 (a)	6.6 (b)	35.8 (a)	170 (b)	100 (b)	6.67(b)

*Within a soil characteristic, the means followed by different letters are statistically different at $p < 0.05$ and show the effect of horizon. ♠ Significantly different at $p<0.1$. ♦ Significantly different at $p<0.05$

Table 2-4. Correlation between physical soil characteristics and soil organic matter (SOM)

r	SOM (g/Kg)	Bulk density (g/cm2)	Sat. Hyd. Cond. cm/h	Porosity	Macro-pores	Meso-pores	Micro-pores	AWC
SOM (g/Kg)	1.00							
Bulk density (g/cm2)	-0.72*	1.00						
Sat. Hyd. Cond. cm/h	0.49*	-0.43*	1.00					
Porosity	0.63*	-0.98*	0.35	1.00				
Macropores	0.53*	-0.57*	0.61*	0.52*	1.00			
Mesopores	0.52*	-0.29	0.63*	0.22	0.46*	1.00		
Micropores	-0.10	-0.23	-0.44*	0.32	-0.62*	-0.52*	1.00	
AWC	0.52*	-0.29	0.63*	0.22	0.46*	1.00*	-0.52*	1.00

* Marked correlations are significant at $p < 0.05$

Table 2-5. Effects of treatment and horizon on soil carbon content

Main effects/soil characteristic	p-values C content Volume-based approach	 C Content Mass equivalent approach
Treatment	0.061♠	0.062♠
Horizon	0.000*	0.000*
Treatment*Horizon	0.479	0.706

* Significant different at $p<0.05$. ♠ Significant different at $p<0.1$

Table 2-6. Effects of horizon and treatment on soil carbon content

Horizon	C (t/ha) Volume-based approach*	C (t/ha) Mass equivalent approach*	Treatment	C (t/ha) Volume-based approach♠	C (t/ha) Mass equivalent approach♠
A1	1066 (a)	1097 (a)	Conservation agriculture	749(a)	891(a)
A2	273 (b)	406 (b)	Conventional agriculture	591(b)	612(b)

* Mean values with different letter inside the same column are significantly different at $p<0.05$.
♠ Mean values with different letter inside the same column are significantly different at $p<0.1$

CHAPTER 3
EFFECTS OF CONSERVATION AND CONVENTIONAL AGRICULTURE ON AGREGATED ORGANIC CARBON (AOM) OF ANDEAN SOILS

Introduction

Over 60% of the world's carbon is held in both soils (more than 41%) and the atmosphere (as carbon dioxide; 20%)) (Sundquist, 1993; Stevenson, 1994). However, soil disturbance is redistributing the carbon, augmenting the atmospheric carbon pool. When soil aggregates are disrupted by tillage practices the decomposition of Soil Organic Matter (SOM) is enhanced (Six et al., 1998). Thus, a part of carbon dioxide increase in the atmosphere is thought to have come from agriculture, affecting not just climate change but also productivity and sustainability of agriculture and natural resources (Robbins, 2004). Therefore, the importance of Soil Organic Carbon (SOC) is being recognized because of its impact on global climate change.
Jastrow et al. (1996) found that nearly 90% of SOM was found within soil aggregates. Aggregates, particulary aggregates in volcanic soils, have been classified into macroaggregates (>0.25 mm) and microaggregates (0.05–0.25 mm) (Edwards and Bremmer, 1967; Maeda et al. 1977). Jastrow (1996) and Six et al. (1999) found that the majority of C in macroaggregates was aggregated organic carbon and that long term C sequestration within micro and macroaggregates is mainly found to be aggregated-C. Kong et al. (2005) showed that the relationship between C input and SOC sequestration was dominated by the increase in SOC within macroaggregates. However, macroaggregates are less stable by being more susceptible to tillage disruption (Elliot, 1986; Cambardella and Elliot, 1993).

Disrupting macroaggregates exposes the microaggregate carbon pool to decomposers which affect the accumulation of SOC (Bajracharya et al., 1997). The most direct evidence of the role of soil structure in protecting SOM from decomposition comes when soil aggregates are disrupted. Upon disruption, an increase or flush in C mineralization is observed (Angers and

Chenu, 1997). Beare et al. (1994) showed that the level of physical protection varies with soil management practices. Generally, there is more aggregate protection in no-till soils than in cultivated ones. Thus, the fate of SOM protected within aggregates will depend upon its decomposability and on the persistence of aggregates, which is related to their stability in water and resistance to other mechanical stresses.

Several researchers found more macroaggregates in non-tillage or reduced tillage systems compared with conventional tillage soils (Carter, 1992; Beare et al., 1994; Six et al., 2000) suggesting that changes in SOM protected in aggregates should be noticed by studying the effect of management practices on macroagregates. Tisdall and Oades (1982) found that cultivation generally results in reduced stability and amount of macroaggregates, but does not affect microaggregate stability. In consequence, the SOM that bind microaggregates into macroaggregates has been suggested to be the primary source of organic matter lost upon cultivation (Elliot, 1986). Thus, although there are other ways to protect SOM (and SOC) such as by adsorption to clay minerals and by isolation in soil micropores (Bossuyt et al., 2002), physical protection within stable macroaggregates is important since it is sensitive to the type of soil management applied in agricultural areas.

Management systems involving high C inputs and reduced tillage should favor C storage directly by reducing aggregate breakdown and by enhancing SOM-mediated aggregation. For example, establishment of perennial grasses or legumes in poorly-structured soils contributed to macroaggregation, which favored the protection of labile C and, as a consequence, the long-term C storage (Angers, 1992). Similar results have been obtained by Carter (1992) and Beare et al. (1994) when no-tillage was practiced. Therefore, soil conservation practices are recommended in order to increase SOC sequestration. Also, conservation farming practices can contribute by avoiding soil moisture and temperature changes that exacerbate SOC depletions. For these reasons, practices such as non-tillage and reduced tillage are increasingly adopted by farmers (Kern and Johnson, 1993; Burke et al., 1995).

Agricultural sinks will not be eligible for the Clean Development Mechanism before 2012 (FAO, 2002) and they are also not considered in the Kyoto Protocol. However, the soil is a C sink and it is worth researching how to measure carbon so that one is prepared for CDM or other opportunities that will inevitably recognize this sink (e.g. BioCarbon Fund, GEF). Measurement of SOC can be direct by monitoring actual soil carbon, and/or indirect by estimating carbon sequestration by monitoring land uses (Post et al., 2001). In fact, direct measurements are needed for indirect ones since trying to compensate farmers per hectare for certain recommended practice (indirect method) requires good numbers be available. Only after that can indirect monitoring be established.

In Colombia, conservation agriculture practices involving reduced tillage and cover crops were adapted by the GTZ and the environmental authority (CAR), starting in1999 to the steep conditions of the region As a result, farmers in some watersheds adopted these practices. The Fuquene watershed is an example where these practices were introduced to control the sediments released from potato farms on very steep slopes and the OM-riched volcanic soils and that are causing the eutrophication of Lake Fuquene. This lake provides potable water to more than half a million people downstream. Although the benefits of conservation agriculture to reduce sediments and to increase net income of farmers are recognized (Rubiano et al., 2006) there are no studies with reference to the impact of these practices on soil carbon sequestration.

The objective of this research was to estimate the amount of AOM in stable soil macroaggregates under two different management systems in the Lake Fuquene watershed: 1) potato-based rotations using conventional tillage and 2) potato-based rotations using reduced tillage with cover crops. To achieve this, the AOM in soil macroaggregates was measured using a sonication technique. The study was focused on macroaggregates since these are the fractions where tillage effects on AOM are evidenced (see explanation above). The hypotheses were: 1) Conservation agriculture increases OM in the aggregate organic matter pool, and 2) The OM contained in aggregates is different across size fractions being greater in smaller macroaggregates. The first hypothesis is based on results from other studies that reported improved soil aggregation and increased SOC levels with no-till compared with conventional tillage (e.g. Carter, 1992; Franzluebbers et al., 1995; Six et al., 1999; Paustian et al., 2000). The second hypothesis is expected since the distribution of SOM among aggregate size fractions can be very heterogeneous (Angers and Chenu, 1997) and Kong et al. (2005) and Denef et al. (2004) found that with non-tillage the AOM is higher in smaller macroaggregates than in larger ones.

Materials and Methods

Study Site

The study sites were agricultural parcels located in the upper part of the Lake Fuquene watershed (2985–3070 m a.s.l.) located in the valleys of Ubaté and Chiquinquirá, north of Bogotá, the capital of Colombia (South America) (N 05 20' W 73 51'). The soils in this region are Andosols and are classified as Lithic Hapludands (IGAC, 2000). These agricultural areas used to be alpine Andean grasslands (*páramos*), a typical Andean natural ecosystem. The temperature is stable throughout the year with mean annual values between 12°–13.2°C. The mean monthly humidity varies between 70 and 80%. The annual mean precipitation is 610 mm (JICA, 2000; IDEAM (climatic station data), 2004).

The parcels are traditionally used by farmers to grow potatoes using conventional tillage with a 2–3 year rotation with pasture. However some farmers are practicing conservation agriculture by growing potatoes with reduced tillage and an oat cover crop. Therefore, in this study two types of parcels were selected: 1) parcels with conventional tillage and 2) parcels with conservation agriculture during the last 7 years. Three sites per system were selected. The six sites were selected with the same characteristics in terms of: 1) landscape position; 2) land cover; 3) slope; and 4) rainfall intensity.

At each site, two pits were dug in May 2007. Soil horizons were identified in each pit, and one soil sample of 500 gr. was taken in the middle of each of the identified horizon for aggregation and carbon analyses. In general, three horizons were found in the profiles with average thicknesses of 78 cm (horizon A1, top), 39 cm (A2) and 49 cm (C).

Laboratory Methods

The 35 fresh samples were segregated and classified by size using "dry" sieving with a nest of sieves representing 5, 2 (larger macroaggregates), 1, 0.5 and <0.5 mm (smaller macroaggregates) screen sizes[1]. Field moist samples were used to avoid changes associated with drying (Maeda et al., 1977). The samples were sieved in a mechanical shaker for 5 minutes. To examine the AOM content, SOM content of each aggregate size class was extracted using a sonication procedure (North, 1976; Six et al., 2001; Swanston et al., 2005; Sarkhot et al., 2006). Through this procedure, different ultrasound energy inputs are applied to aggregates allowing to release some of the SOM in the aggregates and other part remains in the aggregates even after sonication. Thus, this procedure permits to measure the aggregate stability as well as the amount of carbon held inside the aggregates (Sarkhot et al., 2006). In this study, the organic matter extracted from the aggregate by sonication was called AOM (aggregate OM) as it contained fine organic matter from inside aggregates. Organic matter remaining in the same particle size class

[1] Macroaggregates from each size fraction were labeled as : SF1 (> 5mm size fraction), SF2 (2 - 5 mm size fraction), SF3 (1 – 2 mm size fraction), SF4 (0.5 – 1 mm size fraction) and SF5 (<0.5 mm size fraction).

after sonication was termed particulate organic matter (POM). Up to ten different levels of energy were applied (from 5.1 to 11 kJ) to see how different is the AOM (g/g) in aggregates of varying dispersion energy. A Sonic Dismembrator (Fisher Scientific, model 550) was used to apply these energy levels. The energy levels were obtained by combining different amplitudes (20 to 60%) and time periods (1 to 5 minutes). The pulse method (60 sec ON and 30 sec OFF) was used to avoid an excessive rise in temperature.

Up to 10 sub-samples of approximately 5 g were separated per each of the 5 size fractions derived from the 35 fresh samples. To each sub-sample one of the ten energy levels were applied. The energy levels were applied starting from the lowest and incrementing it until reaching the maximum level (11 kJ) or before in cases where a sub-sample was completely breakdown. The actual energy inputs (J/mL) were calculated based on the particle size density (g/cc) and the initial soil weight (g) available for each sample, the water volume used for sonication (mL), the energy output (Joules) given by the sonicator for each run, and a correction factor (0.7) that corresponds to the ratio of energy output given by the sonicator energy output calculated by rise in temperature of a given mass of water (Sarkhot et al., 2007).

Before sonicating the sub-samples, a suspension was prepared in a 250 ml beaker with 100 ml of water. The probe of the sonicator was immersed into the beaker at a depth of 8 cm. After sonicating, the suspension was passed through the sieve corresponding to the original size fraction class of the sub-sample. In all cases, one of the ten sub-samples was suspended in water and not subjected to sonication to estimate the OM that is water-dispersible.

The OM passing through the sieve (AOM) and remaining on it (POM+remaining AOM) were measured through the loss on ignition procedure, and %AOM was calculated as percentage of total SOM (AOM+POM). All SOM measurements were converted to estimates of SOC concentration by multiplying by the Van Bemmelen factor of 0.58 (Lal et al., 1998). With the overall results it was possible to relate percentage of AOM (an in consequence of carbon in aggregates) and the actual AOM concentration with different energy inputs for both conventional and conservation agriculture soil samples.

Data Analyses

Because the measured energy inputs showed a minimum variance across soil samples (data not shown), the effect of energy (J) on %AOM was analyzed using energy class categories, ranging from 1 (3.5 J/mL) to 10 (75.5 J/mL). The effect of different energy levels, treatment and size fraction were analyzed for the % of AOM released after sonication by applying an ANOVA analysis using STATISTICA (Version 7; 2004). This analysis was done separately for the surface 2 horizons. Horizon 3 was excluded from analysis since it was present at a depth greater than 1 m; tillage effects on SOM (g/g) were not significant (data not shown); and the sample size was small in some size fractions of the smaller macroaggregates. Also, SF 5 was excluded from all analyses because the low number of observations in this size fraction.

Differences were considered significant at $p<0.05$. Further statistical analysis was done separately for %AOM of each size fraction to analyze the effects of energy level and treatment. A post hoc comparison procedure with the Duncan adjustment was used to compare %AOM in size fractions where treatment had a significant effect. Since energy levels showed a significant effect on %AOM in all size fractions, a post hoc Duncan analysis was conducted to compare %AOM differences across the different energy levels for each size fraction.

The %AOM was transformed to the actual value of AOM (g/g) released after applying different energy levels in each sample. An analysis of variance (ANOVA) was done to see the effect of treatment, energy, horizon and size fraction on the AOM (g/g). Since there were significant interactions Treatment*Size fraction; Treatment*Energy level and Size fraction*Energy level for the two horizons, a further analysis of variance was done separately per size fraction. A post hoc Duncan analysis was conducted for the main effects and significant interactions when existing into each size fraction. The AOM (g/g) and the energy (J/mL) were plotted per size fraction and treatment.

In addition, the total %AOM (the maximum obtained with the energy levels spectrum used) were analyzed. Non-parametric analysis was done to determine the variability of total %AOM in conservation and conventional agriculture systems. Also an analysis of variance (ANOVA) was conducted to determine the significance of treatment, size fraction class and horizon as main effects. To do this, the total %AOM data was transformed as the inverse of log AOM (%) to normalize the data on the inverse of log %AOM. Since the effect of size fraction was significant ($p<0.05$) then a post hoc Duncan Analysis was conducted to identify differences between size fractions.

Results

Size Fraction x Energy Level and Size Fraction x Treatment interactions for Horizon A1 make direct interpretation of the main effects for Treatment, Size Fraction and Energy Level impractical (Table 3-1). Horizon A2 was characterized by a three way interaction among all main effects (Table 3-1). Subsequent analysis of variance for each size fraction showed that, for both horizons, as the ultrasonic energy applied to the soil increased, more aggregates were destroyed, increasing the amount of AOM removed (Figure 3-1, 3-2).

SF2, in both horizons, was directly influenced by tillage treatment. The %AOM, across all energy levels, was uniformly higher with the more conservative system (Table 3-4). In contrast, SF3 for Horizon A1 and SF3/SF4 for Horizon A2 showed significant interaction with the Energy level (Table 3-2; 3-3). The post-hoc Duncan Mean Separation of the Treatment*Energy level interaction showed that the differences between management systems were due to the %AOM released after applying energy levels. At lower energy levels, treatment differences were small. However, for SF3 of the two horizons, conservation agriculture had higher %AOM when applying energy levels 7 and 8 (17 and 32 J/mL, respectively). In SF4 of horizon 2, the %AOM was also higher in conservation agriculture at energies of 17, 22 and 28 J/mL. (Figures 3-1 and 3-2, Table B-1, B-2 and B-3). SF1 in both horizons and SF4 from horizon 1 were unaffected by the tillage system (Table 3-2 and 3-3, Figure A-1)

The %AOM*Energy (J/mL) curves indicated that, for all size fractions, the curve eventually flattened; indicating that all AOM was released with the exception of size fraction class 1 (>5mm) which did not reach a plateau within the Energy range used in this study (figure B-1, 3-1 and 3-2). After converting the %AOM to AOM (g/g), the analysis of variance showed that the size fractions 2,3, and 4 had a significantly higher concentration of AOM in conservation agriculture samples from both horizons (figure 3-3 and figure 3-4, table B-5). For size fraction 1 there is no treatment effect. Also, size fractions 3 and 4 of horizon A2 had exhibited a significant Treatment*Energy (J/mL) interaction (Table B-4), showing that main differences were that AOM (g/g) was released differentially with Energy Level. In SF 3, the differences are given in levels 7, 8 and 9. In SF 4 the differences are in energy levels 5, 6, 7 and 8. (Figure 3-5, Table B-6 and Table B-7).

Total AOM

The total aggregated organic matter corresponds to the maximum %AOM released after applying the highest Energy Levels. The ANOVA analysis results showed a significant effect of size fractions on the log inverse of total %AOM and no significant effect of the different treatments (Table B-8). The subsequent post-hoc Duncan Mean Separations of the size fractions indicated that the smaller macroaggregates (1–2mm and 0.5–1 mm) held more total AOM as a % of the total AOM than did the larger macroaggregates (>5 and 2–5 mm) (Table 3-5). However, since the SF1 (> 5mm size fraction) curve did not reach a plateau, the %AOM released at the highest level should not be considered as the Total %AOM. In general, the total %AOM released after applying the highest energy (8.4–11 kJ) was high on most soil samples (>80% of total organic matter), and only 17% of soil samples released <80% of the total organic matter. This means that about 80% of the total organic carbon is in the aggregate pool.

The non-parametric analysis, which compared the median values of total %AOM, showed differences between treatments in SF2 and SF3 of horizon A1 (Table B-9), with the higher values seen for the conservation tillage system. Also there was a higher variability of total AOM (%) in samples from conventional agriculture (figure 3-6 and 3-7).

Aggregation Hierarchy

All the aggregate energy dispersion curves exhibited a step-wise pattern. All curves present steps at similar Energy Levels. In general, a first step is recognized at about 17 J/mL, a second step is reached at about 32 J/mL and, in some cases, a third one at 57 J/mL. This third step was seen for SF2. Conservation agriculture, as mentioned above, produced different curves for SF3 of both horizons and SF4 of horizon A2. In SF3, the effect of conservation agriculture was to accentuate the third step of the curve. It is worth saying that this third step was not pronounced in the conventional agriculture sites (figure 3-2 and 3-3). For SF4 in the horizon A2, the effect of conservation agriculture was mainly on the second step making it more pronounced (Figure 3-3).

Discussion

Higher AOM and Soil Organic Matter (SOM) in Conservation Tillage

The greater amount of %AOM and SOM (g/g) in aggregates from soils under conservation agriculture was aligned with results from other studies that also found greater SOC in no-till compared to conventional tillage for a variety of soils types (e.g. Alfisol, Oxisol, Mollisol, Ultisol; Denef et al., 2004; Bossyut et al., 2002). However, most of the SOM and SOC studies were concentrated in superficial soil horizons (20 cm depth; Bossuyt et al., 2002). This study explored differences to an average depth of 117 cm. Higher values of SOM (g/g) with conservation agriculture suggested that SOM improvements were promoted throughout the soil profile. Also the low variability of SOM (g/g) in the first 76 cm of depth (horizon A1) demonstrated the uniformity of the effects of conservation agriculture on total %AOM. This uniformity in change caused by reduced tillage or no- till systems has been reported in other studies for other soil characteristics; but never to this soil depth. Boone et al. (1986), Carter 1992, found that soil macroporosity was improved uniformly throughout the soil profile particularly in the horizon just below the depth that corresponds to the “plow level”. Increases in macroporosity were related to improvements in organic matter, which is recognized as an agent responsible for soil aggregation. This was corroborated with findings from this study area were increments on organic carbon were positively correlated with macroposotiy (Quintero, chapter 2). Also, the higher amount of OM found under conservation reflects the effect of the roots from the cover crops (oats). The penetration of these roots deep into the soil (personal observations) is expected to cause a flush of microbial activity at a lower depth, causing the formation of aggregate binding agents, thus enhancing the formation of aggregates (Bossuyt et al., 2002); and therefore the physical protection of OM by these aggregates.

Higher AOM and SOM in Smaller Macroaggregates

Bossuyt et al. (2002) found in Ultisols, that microaggregate-protected and micro within macroaggregate-protected C was higher in no-till (NT) systems than in conventional tillage systems. This was a result of disruption avoidance of macroaggregates characteristic of no-till systems. The reason is that when disruption of macro aggregates is avoided, residue that forms the center of a macro aggregate decomposes into finer organic matter that gradually becomes encrusted with clay particles and microbial products, forming micro aggregates within macro aggregates (Oades, 1984). Contrary when macroaggregates are disrupted by conventional tillage, OM is released and never has the time to form microaggregates, resulting in a much smaller amount of microaggregates within macroaggregates (Six et al., 1998, 1999, 2000). Thus although these results suggest that micro aggregates are important for ensuring SOM protection, macro aggregates stabilization is important for this protection to occur (Bossuyt et al., 2002)

Six et al. (1999) suggested that a reduced rate of macroaggregate turnover under no-till increases the formation of microaggregates in which C is stabilized and sequestered in the long term. The same author found later that the amount of microaggregates protected in macroaggregates was two times greater with no-till compared to conservation tillage (Six et al., 2000). Similarly, Denef et al. (2004) reported for a Mollisol and increase of microaggreates within smaller macroaggregates (0.25 – 2 mm size) between 20–39% with no-till compared to conventional treatment. We postulate that higher amounts of SOM in SF2, SF3 and SF4 found in this study, and specially a relative greater increase of AOM in SF3 and SF4 (0.5 – 2 mm size) with respect to conventional agriculture, should also related to an increase of microaggregates within these smaller macroaggregates. While this was not tested, it should be looked into in future studies. The rationale behind this is that most of the AOM in SF3 and SF4 was released at certain energy levels. The pattern of aggregation explained by Oades and Waters (1991) for Mollisols and Alfisols consisted in a hierarchical structure where larger, weaker aggregates break down to release smaller, stronger aggregates, before breaking down into primary particles. These distinct units that are bonded and organized forming aggregates can be separated as defined by our aggregate dispersion energy curves. When increasing levels of energy are applied, aggregates of most soils fall apart into smaller aggregates in a stepwise manner (Duiker, 2002). Based on this we inferred that at those specific energy levels where we found more AOM —and that are noted clearly by a step-wise curve denoting a hierarchical order of aggregation—, corresponds to the energy level where the macroaggregates broke down into microaggregates.

Denef et al. (2004) found in different soil types that 91% of the difference in total SOC between no-till and conventional tillage was explained by the C associated with microaggregates that were isolated from smaller macroaggregates (0.25 – 2 mm) Considering that this study found more than 80% of the total carbon in aggregates, we suggest that the 29% difference in Total SOM (g/g) between conservation tillage and conventional tillage (Chapter 2), is explained by increments of AOM in SF2, SF3 and SF4. Kong et al. (2005) also found that the majority of the accumulation of SOC due to additional C inputs in agricultural lands was preferentially sequestered in the microaggregates within-small-macroaggregates (mM). For this reason they proposed the use of the mM fraction as an indicator for C sequestration potential in agroecosystems. This corresponds to the same macroaggregate fraction for which we found improvements of AOM. In horizon A1 (0–78 cm) the differences between conservation agriculture and conventional agriculture were 37, 33 and 30% for SF2, SF3 and SF4 respectively, and 58, 99 y 98% in SF2, SF3 and SF4 of horizon 2 (78–117 cm).
Thus, this study confirms the findings of Denef et al. (2004) and Kong et al. (2005) in that most changes in total SOC were explained by differences in AOM caused by no-till (in our case reduced tillage) in smaller macroaggregates (0.25 – 2 mm). Therefore our results tentatively support Kong et al. (2005) in the use of the microaggregate-within small macroaggregate fraction as an potential indicator of long term C sequestration in agricultural lands. Further studies on the protection mechanisms invoked by this relationship should be the topic of future studies.

Other Considerations

Studies have shown a positive linear relationship between SOC and the proportion of crop residues returned to soil (Kuo et al., 1997; Rasmussen et al., 1980; Cole et al., 1993). Our study supports these previous results, showing that the incorporation of cover crops in the potato rotation and reduced tillage increased SOM even though these volcanic soils in the Andes are already naturally high in organic matter (15% with conventional agriculture). This counters the results of others who reported that for high OM soils varying C inputs did not have any effect on SOC levels; indicating a state of soil C saturation (Campbell et al., 1991; Six et al., 2002). Also, our results showed that major changes were evident in the lower horizon. In this case this treatment effect in the lower horizon suggests a significant amount of roots penetrating to this depth from the oats cultivated as cover crop twice per year prior to the potato cultivation. The role of plant roots and vesicular-arbuscular mycorrhizal hyphae associated with roots is already recognized as being important biding agents at the scale of macroaggregates (Tisdall and Oades, 1982, Cambardella, 2002). Considering the thickness of this horizon, this increment on AOM (g/g) can have important repercussions on the soil carbon content (Chapter 2).

With regard to size fractions and C sequestration our results showed a preferential C sequestration in smaller macroaggregates (<2 mm) also found by Kong et al. (2005), Six et al. (2000), Bossuyt et al., (2002) and Denef et al. (2004) (see above). Also the higher values of %AOM derived from smaller macroaggregates (SF3 and SF4) suggests that in these fractions the C has a slower turnover that the C in bigger macroaggregates (>2 mm). Based on Kong et al. (2005) findings, where increases on C stabilization in the smaller macroaggregates were associated to greater aggregate stability and long-term sequestration , we suggest in the same direction, that the higher AOM and SOM in smaller macroaggregates in our soils is linked to greater C and aggregates stability and in consequence is contributing to long term C sequestration in the Andes. In addition, increases of AOM may be related to improvement of soil structure. The conservation agriculture curves for SF3 and SF4 had better defined hierarchal steps than did the conventional agriculture curves. Since well defined steps indicate well developed structure, we suggest that conservation agriculture in these Andean soils also improves structure.

To summarize, reduced tillage is ensuring the protection of the AOM added in smaller macroaggregates. There are evidences of the role of aggregate structure in physically protecting organic matter from microbial decomposition. In studies where aggregates were crushed or grounded, C and N mineralization rates increased greatly when the aggregate structure was disrupted. This is attributable to the exposure of organic matter, which was previously inaccessible to microbial attack (Cambardella, 2002).

Conclusions

In the Andosols analyzed in this study, the soils had more than 80% of total OM as AOM, and conservation agriculture involving reduced tillage and cover crops in these Andean soils increased AOM. This study was able to evaluate the effects of conservation and conventional agriculture by studying differences on AOM. The major differences on AOM were seen to occur in smaller macroaggregates (0.5 – 1 mm size fractions). The aggregate dispersion energy curves further suggest this is happening in microaggregates within the smaller macroaggregates fraction. Similar results have been obtained for other soils suggesting that smaller macroaggregates can be used to evaluate potential of long term C sequestration in Alfisols, Mollisols, Ultisols and now Andosols.

Table 3-1. Effects of management systems, aggregate size and energy level on %AOM (Aggregated Organic Matter) for horizon A1 and A2

	Horizon A1 (p value)	Horizon A2 (p value)
Treatment♠	0.057	.000*
Size Fraction Class	0.000*	.000*
E level	0.000*	0.000*
Treatment*Size Fraction Class	.003*	.000*
Treatment*E level	0.254	0.192
Size Fraction Class*E level	.000*	0.155
Treatment*Size Fraction Class*E level	0.182	.025*

♠ Treatments: Conservation and conventional tillage;* Significant at 5% (p = 0.05).

Table 3-2. Analysis of variance of %AOM and energy levels per size fraction classes in Horizon 1

	p-values			
	SF 1 (>5mm)	SF 2 (2–5mm)	SF 3 (1–2mm)	SF 4 (0.5–1mm)
Treatment♠	0.06	.019*	.013*	0.14
E level	0.000*	0.000*	0.000*	0.000*
Treatment*E level	0.70	0.41	.024*	0.28

♠ Treatments: Conservation and conventional tillage ;* Significant at 5% (p = 0.05).

Table 3-3. Analysis of variance of %AOM and energy levels per size fraction classes in Horizon A2

	p-values			
	SF 1 (>5mm)	SF 2 (2–5mm)	SF 3 (1–2mm)	SF 4 (0.5–1mm)
Treatment ♠	0.52	.026*	.000*	.000*
E level	.000*	0.000*	0.000*	.000*
Treatment*E level	0.62	0.63	.036*	.017*

♠ Treatments: Conservation and conventional tillage;* Significant at 5% (p < 0.05).

Table 3-4. Comparison between %AOM in different management systems and horizons for size fraction 2 (2–5 mm)

Treatment	Horizon 1 %AOM Mean	Duncan group*	Horizon 2 %AOM Mean	Duncan group
Conservation tillage	33.0	a	41.6	a
Conventional tillage	27.8	b	33.9	b

* Mean values with different letter inside the same column are significantly different at p<0.05

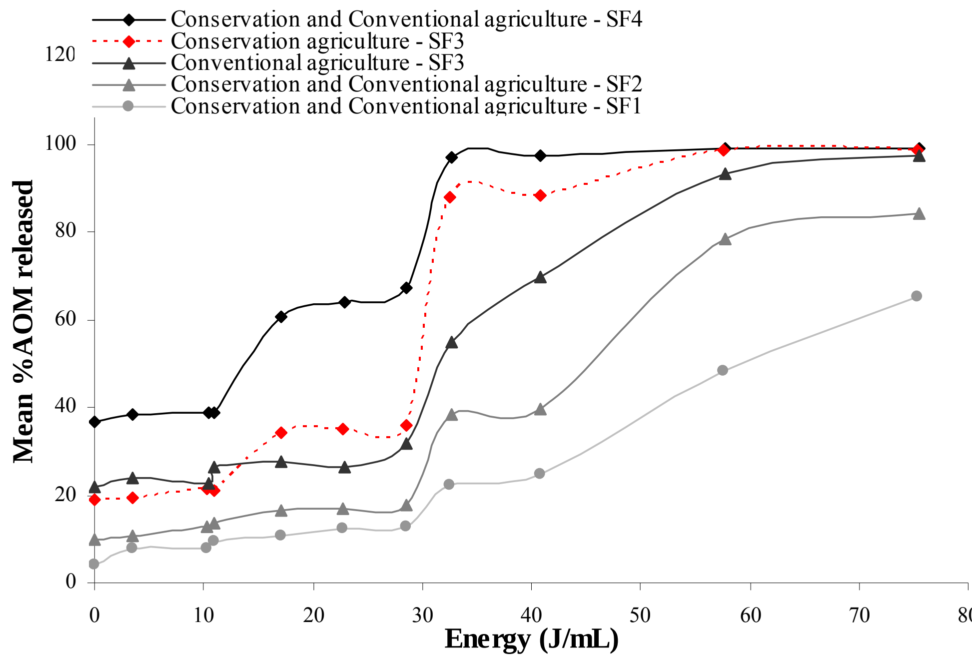

Figure 3-1. Aggregated organic matter (percent of total organic matter) of all aggregates size fractions from horizon A1 (top horizon), released with different energy inputs in two potato management systems

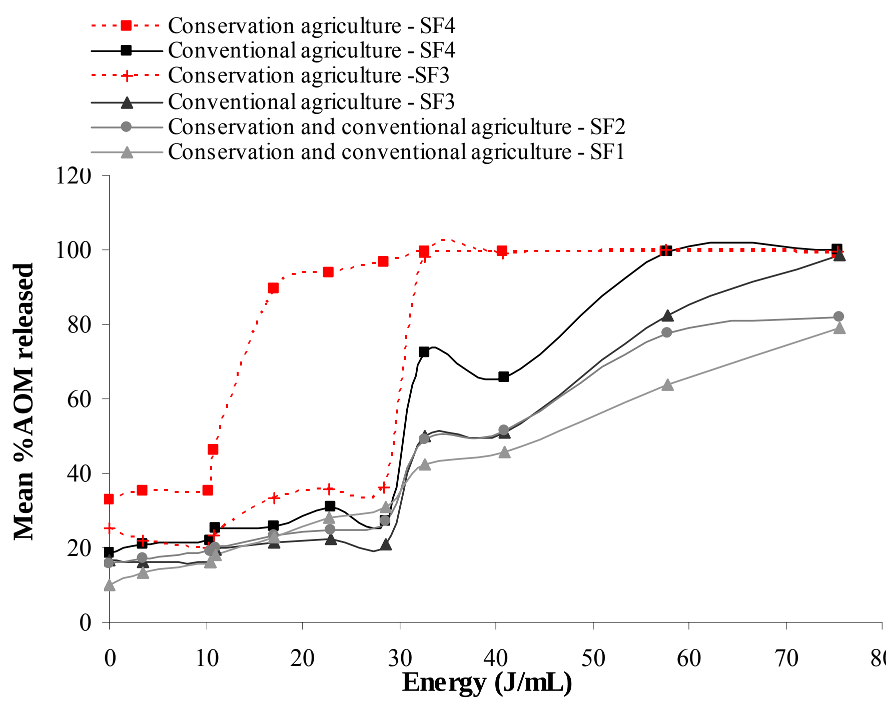

Figure 3-2. Aggregated organic matter (percent of total organic matter) of all size fractions aggregates of horizon A2, released with different energy inputs in two potato management systems

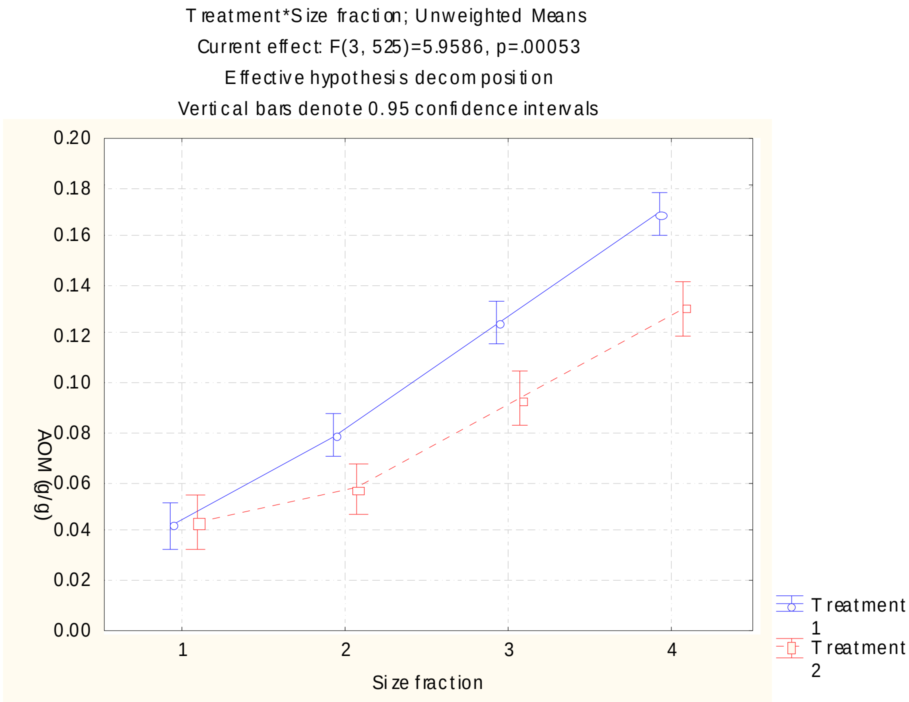

Figure 3-3. Effect of different management systems on aggregated organic matter (g/g) of different size fractions horizon A1.(Treatment 1: conservation tillage; treatment 2: conventional tillage)

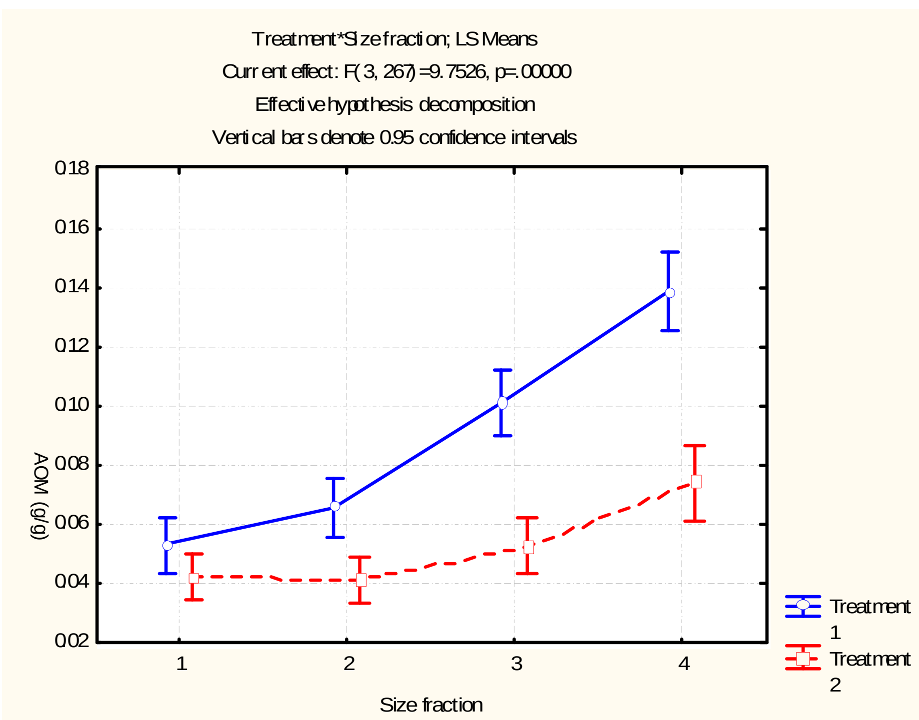

Figure 3-4. Effect of different management systems on aggregated organic matter (g/g) of different size fractions horizon A2. (Treatment 1: conservation tillage; treatment 2: conventional tillage)

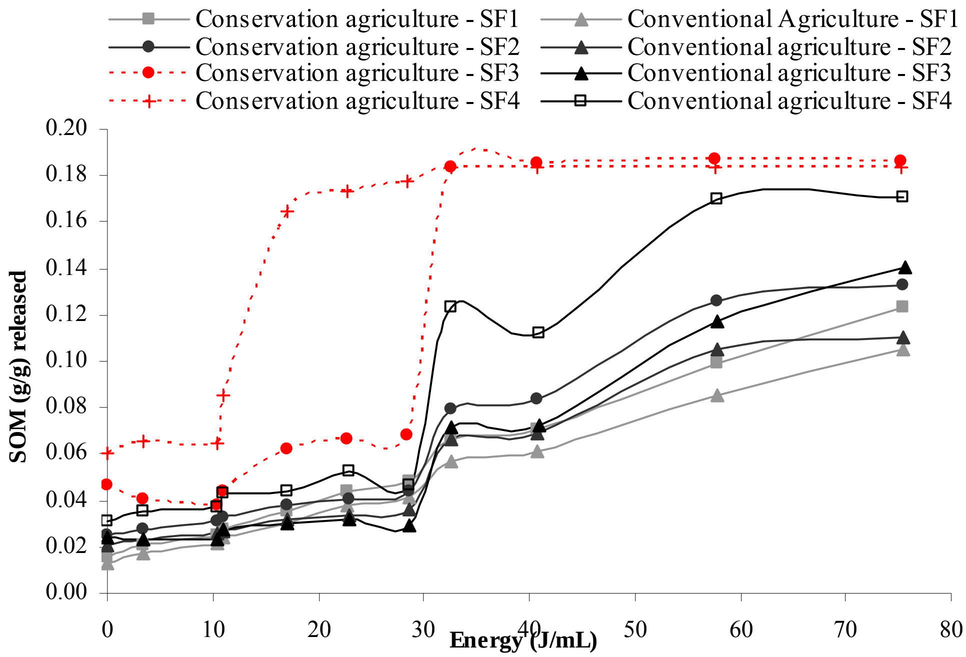

Figure 3-5. Effect of different management systems on aggregated organic matter (g/g) of different size fractions of horizon A2.

Table 3-5. Duncan test - post hoc for AOM and size fractions from Horizons A1 and A2

Size Fraction Class♠	Log Inverse AOM% Mean	%AOM	Duncan group*
1	1.02	74.8	b
2	0.84	85.4	b
3	0.37	96.8	a
4	0.20	99.3	a

♠ Size fraction classes: 1 (> 5mm size fraction), 2 (2–5 mm size fraction), 3 (1–2 mm size fraction), 4 (0.5–1 mm size fraction) and 5 (<0.5 mm size fraction). * Mean values with different letter inside the same column are significantly different at $p<0.05$.

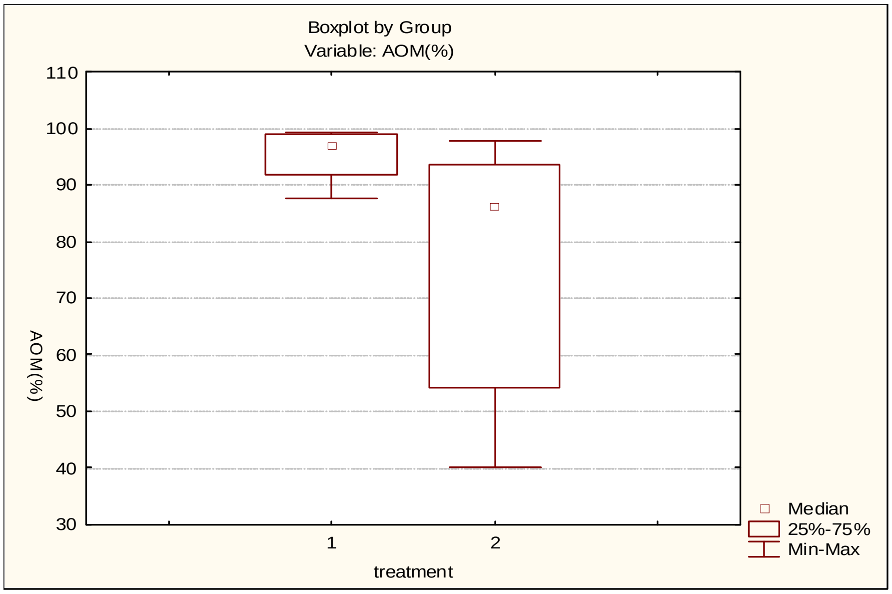

Figure 3-6. Non-parametric analysis of %AOM in Conservation agriculture vs. Conventional agriculture for size fraction 2 (>2mm) and Horizon A1. (Treatment 1: conservation tillage; treatment 2: conventional tillage)

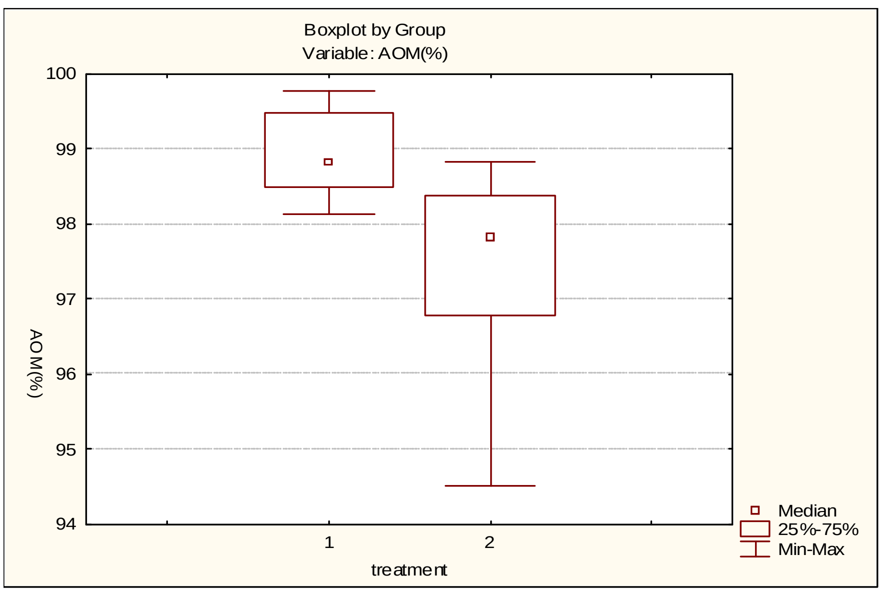

Figure 3-7. Non-parametric analysis of %AOM in Conservation agriculture vs. Conventional agriculture for size fraction 3 (>1mm) and Horizon A1. (Treatment 1: conservation tillage; treatment 2: conventional tillage)

CHAPTER 4
EFFECTS OF CONSERVATION TILLAGE ON ECONOMIC RETURNS AND GREENHOUSE GAS (GHG) REDUCTIONS IN THE ANDES

Introduction

Management alternatives in agricultural lands can provide ecosystem services beyond the production of food (Clay, 2004; Boody et al., 2005; Robertson and Swinton, 2005; Swinton et al., 2006; De la Torre et al., 2004) such as carbon sequestration. In fact, research has shown that agricultural soil carbon sequestration could be cost effective, and would have other economic and environmental co-benefits (Antle et al., 2007). One example of these alternatives is conservation tillage for which there is a growing interest to be adopted by farmers due precisely to environmental benefits (Kern and Johnson, 1993; Burke et al., 1995) and to the fact that carbon sequestered in the soil can eventually be traded.

In consequence, there is increasing interest in schemes of Payment for Environmental Services (PES) to encourage the provision of ecosystem services from agricultural lands. However few examples of such schemes exist (Bohlen et al., 2009). With regard to water-related services provided by agricultural practices there are some PES schemes in the Andes. Nevertherless, most of them have been created without sound analysis documenting impacts of land uses and practices in the services resulting in schemes that instead of paying for the service are paying for a land use change that is believe to affect positively the ES (Porras et al., 2008).

For carbon sequestration there are studies that reported benefits of practices such us conservation tillage (Denef et al., 2004; Bossyut et al., 2002; Kong et al., 2005; Kuo et al., 1997; Rasmussen et al., 1980; Cole et al., 1993). However, the fact that this will not be eligible as a sink for the Clean Development Mechanism before 2012 (FAO, 2002) and they are also not considered in the Kyoto Protocol might have delayed the implementation of carbon payments in agricultural areas compared to the state of advance of the carbon market for the forestry and industrial sectors. However, the soil is a C sink —over 41% of worlds carbon is held in soils— (Sundquist, 1993; Stevenson, 1994) and it is worth researching how soil carbon is benefited from agricultural practices so that one is prepared for CDM or other opportunities that will inevitably recognize this sink (e.g. BioCarbon Fund, GEF). In this sense research should contribute to elucidate two facts from the farmer and market perspective that poses methodological challenges for those interested in developing carbon payments schemes. From the market perspective, agricultural lands will be only accepted as sinks if the sequestered carbon is additional to that one already existing in the baseline (Antle et al., 2007) after discounting GHG emissions caused by the carbon sequestering practices. From the farmer's perspective, changing to conservation tillage may imply an opportunity cost equal to the difference between the highest-returning practice and the practice that yields the most soil carbon (Antle et al., 2007). So it is assumed that a farmer will be willing to change if that opportunity costs is compensated or if the new alternative produces equal or higher net returns.

In Colombia, conservation tillage technology was adapted to soils of *Paramos* — neotropical alpine grasslands that is the transition between the forest and the snowline (from about 3300 m to about 4800 m above sea level) in the Andes (Poulenard et al., 2003)—, that were disturbed many decades ago and cultivated with potato and pastures. Conservation tillage practices —that manage crop residues with minimum tillage— were adapted and promoted by the GTZ and the environmental authority (CAR) since 1999 as a measure for soil and water conservation. As a result, some farmers in some watersheds adopted these practices. After some years of being adopted in some farms, this cases offer an extraordinary opportunity to investigate the contribution of these practices to reduce Greenhouse Gases (GHG) emissions and sequester soil carbon, and to understand the opportunity costs of changing from conventional to conservation tillage.

Being said this, the objectives of this chapter is to determine the opportunity costs of implementing conservation tillage in the study area and to determine the net GHG removals caused by these practices. For determining the opportunity costs and to determine the GHG removals economic and carbon estimations for conventional tillage were conducted to characterize the “business as usual” scenario or the baseline. The conventional tillage data came from the same study area where conservation tillage was adopted as the point of comparison must be the typical common practice for the time and location of the assessment (Uri et al., 1999).

The relevance of comparing net returns of conventional vs. conservation tillage —as a means to determine the opportunity cost—, and the estimated net GHG removals is that this permits to identify possible trade offs between economic and carbon sequestration benefits derived from these practices giving an idea of how feasible this practices are for farmers and for the society interested on reducing GHG. Moreover, the results are very relevant nowadays that carbon markets for agricultural areas are increasingly gaining importance and especially for the Andes were studies about the potential of conservation tillage in this mountainous, highly populated and productive areas for delivering both, carbon sequestration services and economic benefits are scarce.

Methods

Economic Analysis

To determine the opportunity costs it was necessary to estimate the net returns of a “business as usual” scenario (conventional tillage) and the proposed scenario to sequester soil carbon (conservation tillage). Annual net revenues for each treatment were determined by subtracting production and input expenses from gross revenue as described by Zentner et al. (2002). Two treatments were assessed, a “business as usual” rotation where there is not incorporation of a cover crop and uses conventional tillage; and the carbon sequestering rotation which incorporated oat as cover crop and reduced tillage. The incorporation of oat as cover crop occurs typically in the conservation tillage rotation 4 months ahead potato is sowed. The rotations were tested for a 7 year period, for which variations on SOC were analyzed in Chapter 2 and 3. The rotations are: i) ryegrass-potato-potato-ryegrass-ryegrass-potato- potato and ii) ryegrass-oat-potato-potato-ryegrass-ryegrass-oat-potato-potato as they were practiced in the study area.

Economic data of growing potato with conventional and conservation tillage was based on economic data for this specific production systems in the study area, particularly from GTZ-CAR (unpublished data, 2000, 2006) and Lopez (2009, pers. comm.). Later all economic data was expressed on a total rotation basis covering the 2000–2006 period thus they include the costs and returns for all crops comprising the rotation systems. Therefore, rotation-based budgets were developed. Inputs used in each cropping system were included in the analysis, considering only variable costs such us field operations (plowing, disking, planting, cultivating, harvesting, etc.) and materials (seed, herbicide, fungicide, fertilizer, etc.). Since the purpose of this economic analysis was to compare returns between conservation and conventional tillage, fixed costs such as cost of land, land taxes, etc were excluded from calculations because they were assumed to be the same for the two treatments. All inputs costs and prices valued at 2000 and 2006 in Colombian pesos were converted in dollars, and from there average values were derived and held constant for the economic analysis of the rotations. Later, net revenue and annual cash flows were expressed in net present value terms applying a discount rate of 5%. Net revenue was then the result of discounting variable costs and labor costs from gross returns. In table 1, there is a summary of inputs cost, products prices, productivity and livestock parameters used in the economic analysis.

To facilitate this analysis the ECOSAUT model was used. It uses linear programming to optimize net income from different land-use and management systems (Quintero et al., 2006). It was employed here to evaluate the economic impacts of the two rotations and to determine the optimal one in terms of net return. In addition the obtained net return from conventional tillage system was compared with the actual rental price of land to validate our estimations (the current rental price per hectare is \$1200 $ha^{-1}yr^{-1}$, according to Otero, 2009, comm.pers.). However it mignt be noticed that most of producers owned the land and there are few tenants in the area.

Net GHG Removals

The net GHG removals by conservation tillage were estimated as the difference between changes in soil organic carbon stock and the emission sources. The emissions considered in this estimation were N_2O emissions from fertilizers, CH_4 and N_2O from fossil fuel burning caused by soil preparation and transportation of farm products and; CH_4 and N_2O by grazing animals (cattle). The estimations were done in a hectare basis per each of the two rotations (treatments) economically assessed as well.

Changes in soil organic carbon were derived from chapter 2 of this manuscript. Thus, the marginal soil organic carbon content found in conservation tillage systems —when compared with conventional tillage— was interpreted as the change in SOC. However, only 80% of this was considered in the estimation since this is the average amount of SOC found in soil aggregates and therefore, the more protected in these soils (Chapter 3). This value was converted to CO_2 using the conversion factor 3.667 ($tCO_2\ t^{-1}C$).

Nitrous oxide (N_2O) emissions from fertilizers

Emissions of nitrous oxide from nitrogen fertilization were based on the methodological tool approved by the Clean Development Mechanism (CDM) Executive Board: *Estimation of direct nitrous oxide emission from nitrogen fertilization*[1]. The estimation was given by:

$$N_2O_{fertilizer} = F_t \cdot EF_1 \cdot \frac{44}{28} \cdot GWP_{N_2 0} \quad (4.1)$$

$$F_t = N_t \cdot (1 - Frac_{GASF}) \quad (4.2)$$

where:

$N_2O_{fertilizer}$ = the direct N_2O emission as a result of nitrogen application in time *t**; t CO_2-e.

F_t = amount of fertilizer nitrogen applied at time *t* adjusted for volatilization as NH_3 and NO_x; t N

$N_{,t}$ = amount of fertilizer nitrogen applied at time *t*; t N

EF_1 = emission factor for emissions from N inputs; t N_2O-N (t N input)$^{-1}$

$Frac_{GASF}$ = fraction that volatilises as NH_3 and NO_x for fertilizers; dimensionless

GWP_{N2O} = Global Warming Potential for N_2O; t CO_2-e./t N_2O

These N_2O emissions were estimated considering the Intergovernmental Panel on Climate Change (IPCC) default value of the emission factor for emissions from N inputs (0.0125), the Global Warming Potential for N2O (= 310 for the first commitment period) and the IPCC default value for the fraction that volatilizes as NH_3 and NO_x for synthetic fertilizers (0.1).

GHG emissions from burning of fossil fuel

These emissions result from the use of machinery and vehicles during site preparation and transportation of harvest and inputs. These emissions estimation was based on the methodological tool approved by the CDM Executive Board: *Estimation of GHG emissions related to fossil fuel combustion in A/R CDM project activities*[15.] The estimation was given by:

[1] <http://cdm.unfccc.int/methodologies/ARmethodologies/approved_ar.html>.

$$E_{FuelBurn} = E_{Vehicle,CO_2} \tag{4.3}$$

and:

$$E_{Vehicle,CO_2} = \sum_{t=1}^{t^*} \sum_{x} \sum_{y} (EF_{xy} \cdot FuelConsumption_{xyt}) \tag{4.4}$$

where:

$E_{FuelBurn}$ = total GHG emissions due to fossil fuel combustion from vehicles; t CO_2-e. yr^{-1}

$E_{Vehicle,CO2}$ = total CO_2 emissions due to fossil fuel combustion from vehicles; t CO_2-e. yr^{-1}

x = vehicle type

y = fuel type

EF_{xy} = CO_2 emission factor for vehicle type x with fuel type y; dimensionless

$FuelConsumption_{xyt}$ = consumption of fuel type y of vehicle type x at time t; liters

$$FuelConsumption_{xyt} = n_{xyt} \cdot k_{xyt} \cdot e_{xyt} \tag{4.5}$$

n_{xyt} = number of vehicles

k_{xyt} = kilometers traveled by each of vehicle type x with fuel type y at time t; km

e_{xyt} = fuel efficiency of vehicle type x with fuel type y at time t; liters km^{-1}

For the soil preparation component estimations were made using a consumption of 15 l $hr^{-1.}$ For transportation, soil preparation machinery fuel efficiency is 0.38 l Km^{-1} and of vehicles for transporting fertilizers is 0.075 l $Km^{-1.}$ Seeds and labor forces usually are not transported in the study area as seeds are produced in the farm and most of labor is familiar or contracted in the same neighborhood. The emission factor (EF) used for the calculation of emissions from fossil fuel burning were 2.83 Kg CO2e l^{-1} for diesel and 2.33 Kg CO_2e l^{-1} for gasoline (default IPCC values).

Emissions from livestock

Emissions from nitrous oxide and methane are caused by enteric digestion and manure management. These emissions estimation was based on the methodology approved by the CDM

Executive Board: "*Afforestation or reforestation on degraded land allowing for silvopastoral activities*"[2]. The estimation was given by:

$$E_{livestock} = (Pop) * ((\mathrm{EF}_{\mathrm{Enteric\,CH4}} + EF_{ManureCH4}) * GWP_{CH4} + EF_{ManureN2O} GWP_{N2O}) \tag{4.6}$$

Where,

$E_{livestock}$ = total GHG emissions due to livestock population in the study area; t CO_2-e yr^{-1}

Pop = population of livestock in the study area; head

$EF_{Enteric\mathrm{CH4}}$ = Emission factor for enteric methane production for livestock; kg CH_4 $head^{-1}$ yr^{-1}

$EF_{ManureCH4}$ = Emission factor for methane production from manure for livestock; kg CH_4 $head^{-1}$ yr^{-1}

$EF_{ManureN2O}$ = Emission factor for nitrous oxide production from manure for livestock; kg N_2O $head^{-1}$ yr^{-1}

GWP_{CH4} = Global warming potential for CH_4 (IPCC default = 21); kg CO_2-e kg^{-1} CH_4

GWP_{N2O} = Global warming potential for N_2O (IPCC default = 310); kg CO_2-e kg^{-1} N_2O

And,

$$E_{ManureN2O} = N_{rate} * \frac{TAM}{1000} * 365 * EF_{depositedmanure} \tag{4.7}$$

Where,

N_{rate} = Excretion rate for livestock; kg N (1000 kg animal mass)$^{-1}$ day^{-1}

TAM = Typical animal mass; kg $head^{-1}$

$EF_{depostiedmanure}$ = Emission factor for N2O emissions from dung and urine deposited on pasture; kg N2O-N (kg N input) $^{-1}$

1000 = Conversion factor; kg to tonnes

365 = Conversion factor; days to years

For the calculation cattle population was held constant in time (2 animals ha^{-1}) and with a typical mass of 450 kg $head^{-1}$. $EF_{Enteric\mathrm{CH4}}$ was 56; $EF_{ManureCH4,}$ was 1 since manure is left on pasture instead of being collected and stored; N_{rate} was 0.36 and $EF_{depostiedmanure}$ was 0.02. All these values were taken from IPCC default values (IPCC, 2006).

[2] < http://cdm.unfccc.int/methodologies/ARmethodologies/approved_ar.html>

To conduct all emission estimations, the TARAM v1.3 tool (Tool for Afforestation and Reforestation Approved Methodologies) (Pedroni and Rodriguez-Noriega, 2006) was used for calculations only considering its components for GHG emissions estimations.

Results

Economic Analysis

When the ECOSAUT model was run to look for an optimal solution –the one that maximizes net revenues in a hectare giving the two treatments as the only land use alternatives, the conservation tillage rotation was the optimal solution. The 7-year cumulative net revenues for the assessed rotations indicated that conservation tillage rotation increased the net revenues by 17% compared to the conventional tillage rotation. This increment is due to particularly the improvement on potato income in 23% when conservation tillage is practiced (Table 4-2).

This improvement was high enough to compensate the additional investment required in the conservation tillage rotation that is the production costs of incorporating oat as a cover crop in the rotation (\$337 ha^{-1} yr^{-1}). A greater net return from potato cropping using conservation tillage practices was related to a reduction of production costs by 11% and to an increment of potato productivity by 10%. Lower production costs were due mainly to a reduction on fertilizers and machinery costs rather than in a substantial reduction on the use of workdays which instead was similar in both, conservation and conventional tillage (table 4-3).

Net GHG Removals

The soil carbon stock change used for estimating the net GHG removals was 818 tCO2 ha^{-1} which is equal to the 80% of the marginal soil carbon stock (chapter 2) expressed in tCO_2. With respect to GHG emissions findings showed that these are reduced with conservation tillage by 21% compared to conventional tillage. This reduction is caused primarily by the reduction of CO2 emissions from fossil fuel burning –mainly from machinery during site preparation and of

N2O emissions from nitrogen fertilization. This reduction compensates the emissions caused by the incorporation of oat to the conservation tillage rotation which involves additional fertilization (Table 4-4, 4-5). With respect to the net GHG removals, when emissions of conservation tillage were discounted to the SOC stock changes achieved with conservation tillage, the net GHG removal is equal to 788 tCO_2e for a 7-yr period.

Discussion

The purpose of the economic analysis was to determine the opportunity cost of implementing conservation tillage by farmers of the Upper Fuquene watershed. The rational behind this was that for a farmer to change from conventional to conservation tillage, he must bear an opportunity cost (Antle et al., 2007) which is the difference in this case between conventional tillage and the conservation tillage returns. Therefore, only conservation tillage systems capable of producing equivalent or greater yields and returns than conventional tillage are likely to be readily accepted by the producer (Muller et al., 1981).

The results of this study showed that conservation tillage increases net return implying a negative opportunity cost and therefore a net economic benefit for the farmer. Our results compared well to the current rental price of a hectare of land in the study area (US$1870 vs. $1200, for the simulated conventional tillage system vs, the actual rental price of land, respectively) if we take into account that net revenue should not only be a retribution to land price but also to the administrative costs, being this last the difference between the two values. This explains the fact that currently land is cultivated by its owners instead of being rented as they can get greater returns cultivating by themselves and using their own labor in most of the activities. Also, we suggest that as net revenues increases with the conservation tillage system as less the willingness of owner to rent their land will be.

On the other hand, better mean net returns from conservation tillage are also reported by Sandretto (2001) and Jeong and Forster (2003) who attributed this to decreases in input costs particularly due to reduced labor hours due to a decrease in the number of trips to crop fields, reduced machinery wear, and a saving in fuel consumption. In our case reduction of input costs are only related to reduced machinery operations and fertilizers applications.

In another hand, conservation tillage reduces GHG emissions and increases the soil carbon stock resulting in a positive net GHG removal. This is in line with other studies that consider two main effects of conservation tillage in carbon emissions: i) an increase on soil carbon retention because less organic matter is loss to oxidation as mixing the soil and soil temperature are reduced; and ii) carbon emissions are reduced because it requires fewer machinery operations (Uri et al., 1999)

Thus the results of this study indicate that conservation tillage is a “win-win” alternative for Fuquene farmers by benefiting economically the farmer and by providing clearly an ecosystem service or in other words there is a complementary tradeoff between the economic and environmental benefits. However, Uri et al. (1999) recognized that conservation tillage on highly erodible land will unquestionably result in an increase in social benefits, but the expected gains will be modest. In the same sense a 17% of increase in net revenues in our study area could be not enough to overcome the possible aversion to risk of farmers (or other adoption barriers) and to encourage them to make an additional investment to cover initial extra costs of conservation agriculture (ie. cultivation of oat as cover crop). This fact may explain why this practice is not widely adopted in the Fuquene watershed (Currently there are about 1800 ha implementing these practices of 16933 ha under potato production in the watershed, (Otero, pers. comm.2009; Quintero and Otero, 2006)). This same situation has been described by Sandretto (2001) who showed that although mean net returns on reduced tillage practices are equal to or greater than the returns from conventional tillage, mainly because of decreases in input costs, yet conservation tillage practices have been adopted on only 35% of US agricultural lands. The factors that has been reported as barriers to adoption of conservation agriculture practices are various and different. One the additional risks perceived by farmers when adopting reduced tillage including the human and/or physical capital investments that producers may have to incur (De la Torre et al., 2004). Also, the availability of credit to assist with conservation tillage increased need for purchased inputs (such green manure cover crop seeds, herbicides, etc) is another factor. In fact, successful experiences of conservation agriculture practices adoption in Latin America have demonstrated the importance of credit as an important enabling factor (FAO, 2001). In another hand, according to Tweeten (1995), for farmers with short-term planning horizons the benefits of conservation agriculture are not immediate becoming this as an additional barrier for adoption. Also, there may be other barriers particular to culture and recent history (Nyagumbo, 1997), and to information aspects such as contact with extension agents, availability to technical assistance, attendance to field demonstrations and plots, etc. (FAO, 2001).

Therefore, our results show that although conservation tillage practices are feasible in mountainous areas and low income countries as is our study area, some barriers may be existing constraining a wide adoption of these practices. One of these may be the required investment and therefore credits or other financial or economic incentive may be important for enhancing the adoption (Carcamo et al., 1994). In fact, this has been demonstrated in the study area were a small revolving fund was created to provide credits to farmers willing to implement conservation tillage in their potato-based production systems. The credits were created only to cover the required investment to implement the cover crop as the potato production costs are assumed to be covered by the farmers as they are used to do. This system, although small, has proven to be effective since 2005 incorporating about 180 small farmers every year and using the capital of the fund at its maximum capacity (Quintero and Otero, 2006; Rubiano et al., 2006).

However, a mechanism to reach a widely adoption of these practices is required weather by incrementing the capacity of the fund or by providing an extra incentive. This last may be come via payments for the net GHG removals. Taking into account 788 tCO_2 ha^{-1} in 7 years could mean an extra income of US$450 yr^{-1} (assuming a carbon price of $4 tCO_2 which is a conservative price. It is assumed a constant carbon price as currently carbon contracts are negotiated in a constant price basis). This carbon payment could alone cover oat production costs that are around $377 ha^{-1} and increased the net revenues the rest of years of the rotation when oat is not cultivated (in a 7yr period oat is cultivated twice), This may mean to the farmer a 29% increase in net return instead of 17% caused by the economic benefits of conservation tillage alone.

Although this estimation is based on a conservative carbon price of US$4 tCO2, this price already covers the cost of sequestering 1 tCO2 in the 7yr-period. If we consider that this cost may be equal to the additional investment the farmer had to incur, which is the oat production cost (US$377 x 2), then each ton of CO2 required an additional investment of US$1. Of course, this calculation does not include the costs of technical assistance that is currently provided by the regional environmental authority (CAR).

It is worth noting that these results and the values should not be generalized and extrapolated to any situation where conservation tillage is practice, since the potential for soil carbon sequestration depends on the type of crop grown, the cropping pattern, the type of soil and the climatic conditions (Donigian et al., 1994; Uri et al., 1999). Moreover for our study site the identified carbon sequestration potential can not be extrapolated in time assuming a linear behavior of it as carbon increases are not perpetual. It is believed that there is a carbon sequestration saturation point (20 to 50 years) (Lal and Bruce, 1999) depending on climatic conditions, soil characteristics, and production management practices (Franzluebbers, 1997; Franzluebbers et al., 1999; Hunt et al., 1996; Wood et al.,1991; Zobeck et al., 1995).

To finalize, it is recognized that off-site benefits of conservation tillage are not only related to carbon sequestration and therefore financial incentives should be designed on this basis. Carbon sequestration by conservation tillage can imply various other co-benefits for society such as soil retention and therefore the reduction of downstream sedimentation, regulation of rivers flows (FAO, 2001) —as soil water characteristics influencing water movement and storage are improved (Quintero, chapter 2)—, among others. Thus, showing all conservation tillage benefits for society together may be a strong strategy to design robust and stable financial incentives for enhancing adoption of conservation agriculture in the Andes.

Conclusions

The results of this study indicated that conservation tillage in the upper Fuquene watershed (Colombia) is a “win-win” alternative as it increases net revenues benefiting economically the farmer and reduced GHG emissions. In other words there is a complementary tradeoff between the economic and environmental benefits.Better net returns are explained basically by reduced machinery operations and fertilizers applications. In another hand, net GHG removals are positive due to increments on soil organic carbon and reductions on GHG emissions caused by machinery operations and fertilizers.

However, these practices are not widely adopted in the watershed but payment for net GHG removals (and possibly to other ecosystem services such us regulation of river flows and reduction of sedimentation) could increase furthermore net returns and facilitate the investment to cover initial extra costs of conservation agriculture (ie. cultivation of oat as cover crop).

Table 4-1. Summary of annual inputs cost, products prices, productivity and livestock parameters used in economic analysis (based on GTZ and CAR, unpublished data, 2000, 2006) (all values are in hectare basis and are constant values).

	2000 [a]						2006 [b]					
	Traditional			Conservation			Traditional			Conservation		
	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)
POTATO												
LAND PREPARATION												
Machinery (hours)	11	8.99	97	3	8.99	27	14	13.13	184	7	13.13	92
Animal work (hours)							8	2.41	19	8	2.41	19
Inputs (herbicide) (lt)	4	7.74	27	2	7.74	15						
Labor (Day's work)	2	6.14	9	1	6.14	8						
Sub-Total			133			50			203			111
SOWING												
Inputs												
Seeds (Kg)	1575	0.15	235	1500	0.15	224	1104	0.19	210	1104	0.19	210
Fertilizers (NPK 13-16-6) (Kg)	1200	0.30	363	1300	0.30	394	1200	0.44	525	1500	0.44	657
Organic manure (i.e. chicken manure) (Kg)	1750	0.05	93									
Ca and P (i.e. Calfos) (Kg)				525	0.05	29	1000	0.08	83	1000	0.08	83
Insecticides (lt)				0.7	11.57	9						
Labor (Day's work)	11	6.14	64	15	6.14	93	13	8.76	114	13	8.76	114
Sub-Total			757			749			933			1064
CROP HEALTH												
Inputs [c]			563			396			360			460
Labor (Day's work)	34	6.14	208	24	6.14	148	31	8.76	271	34	8.76	298
Sub-Total			772			544			631			757
WEED CONTROL, EARTHING UP, etc												
Labor (Day's work)	17	6.14	104	16	6.14	98	27	8.76	236	14	10.95	153
Inputs (fertilizers NPK 15-15-15) (kg)	650	0.29	191	559	0.29	164	600	0.41	244			
Sub-Total			295			262			481			153
HARVEST												
Packing and Transportation (US$/50Kg)	386	1.08	418	424	1.09	463	562	1.41	793	651	1.12	727
Labor (Day's work)	43	6.14	264	41	6.14	250	74.3	8.76	651	81.8	8.76	716
Sub-Total			682			712			1444			1443
PRODUCTION												
Productivity (kg - $)	24125	0.13	3185	26500	0.13	3500	29750	0.27	8010	32750	0.28	9084

Table 4-1. Continued.

	2000 [a]						2006 [b]					
	Traditional			Conservation			Traditional			Conservation		
	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)	Quantity	Price or Cost (Unit)	Price or Cost (Total)
OAT												
Land preparation										4	13.37	53
Fertilizers (NPK 15-15-15)										200	0.89	178
Ca (Kg)										1000	0.07	71
Seeds (Kg)										80		33
Labor (#workdays)										1	8.92	9
Raygrass - Cattle												
Labor (#workdays)										20	8.92	178
Meat sale price (US$/t)												1000
Milk sale price (US$/t)												180
Annual health costs (US$/animal)												60
Annual cattle nutritional requirements (per animal)												
Energy (megacalories x 1000/yr)										4.8		
Protein (t/yr)										0.21		
Nutritional composition of pasture												
Energy (megacalories/kg)										2.7		
Protein (kg of protein/kg dry matter)										0.17		
Dry matter (%)										20		

[a] Express in dollars at 2000: Exchange rate = US$1873/1 Colombian peso. [b] Express in dollars at 2006: Exchange rate = US$2284/1 Colombian peso. [c] Includes different type of crop health products

Table 4-2. Economic benefits from conventional and conservation tillage in potato-based systems in Fuquene watershed (Colombia)*.

Characteristic	Rotations Conventional tillage	Conservation tillage
Net income (US$)	13,092	15,280
Marginal income	n.a.	2,188
Average annual income (US$)	1.870	2,183
Marginal annual income	n.a.	313
Income due to potato (US$)	11,689	14,341
Marginal potato income	n.a.	2,652
Income due to milk	4,119	4,119
Marginal milk income	n.a.	n.a
Income due to meat	105	105
Marginal meat income	n.a.	n.a
Use of workdays	564	554
Marginal change (%)	n.a.	-2

* Estimations made in a hectare basis and for a 7-yr period and discounted by a 5% rate

Table 4-3. Annual average values for potato production under two tillage systems

Characteristic	Conventional tillage	Conservation tillage	Change (%)
Production costs (US$ ha^{-1})*	2077	1857	-11
Labor costs ($US ha^{-1})	909	906	0
Potato productivity (kg ha^{-1})	26937	29625	10
Potato sale price (US$ kg^{-1})	0.217	0.217	0
Use of workdays (ha^{-1})	126	122	-3

* Without including labor costs

Table 4-4. Carbon stock changes and Greenhouse gas (GHG) emissions of conventional tillage practices in potato-based production systems in Fuquene watershed, Colombia

		Carbon stock changes (tCO2e yr-1)	GHG emissions (tCO2e yr-1)		
Year	Crop/cover	SOC	CO2 due to use of fossil fuels	N2O due to nitrogen fertilization	CH4 and N2O due to livestock increase
1	ryegrass	n.a.	0	0	6.3
2	potato	n.a.	0.56	4.37	0
3	potato	n.a.	0.56	4.37	0
4	ryegrass	n.a.	0	0	6.3
5	ryegrass	n.a.	0	0	6.3
6	potato	n.a.	0.56	4.37	0
7	potato	n.a.	0.56	4.37	0
Sub-total		n.a.	2.24	17.48	18.9
Total					38.62

Table 4-5. Carbon stock changes and GHG emissions of conservation tillage practices in potato-based production systems in Fuquene watershed, Colombia

		Carbon stock changes	GHG emissions (tCO2e yr-1)		
Year	Crop/cover	SOC (tCO2e yr-1)	CO2 due to use of fossil fuels	N2O due to nitrogen fertilization	CH4 and N2O due to livestock increase
1	ryegrass-oat	116.9	0.18	0.33	6.3
2	potato	116.9	0.24	2.43	0
3	potato	116.9	0.24	2.43	0
4	ryegrass	116.9	0	0	6.3
5	ryegrass-oat	116.9	0.18	0.33	6.3
6	potato	116.9	0.24	2.43	0
7	potato	116.9	0.24	2.43	0
Total		818.3	1.32	10.38	18.9
Total GHG emissions					30.6
Net GHG removal					787.7

CHAPTER 5
SUMMARY AND CONCLUSIONS

The Rehabilitation Ability of Conservation Tillage in Disturbed *Paramo* Soils

The results of this study highlight the ability of conservation tillage to recover the soil characteristics of the paramo ecosystem once impacted by conventional tillage practices. In the Fuquene watershed, conservation tillage has improved the AWC, the saturated hydraulic conductivity and the mesoporosity by 30, 56 and 30% respectively. Also, bulk density was reduced by 15%. These improvements result from the correcting effect of conservation tillage on soils where soil porosity and soil infiltration were compromised by conventional agriculture which indeed causes soil crusting or soil air exposure (Poulenard et al., 2001).

Apart from the improvement in these physical soil characteristics, conservation tillage improved SOC. Conservation tillage showed a marked improvement in the C concentration and in the average C content for the whole soil profile (≈100 cm depth) with respect to conventional tillage. This indicates that conservation tillage has shortened the gap between SOC in conventional tillage and in undisturbed paramos – a 45% increase in C content over conventional tillage (from 612 to 891 t ha^{-1}). Particularly interesting is a 177% increase in the deeper A2 horizon (from 215 to 596 t ha^{-1}) although most of the C is stored in the top A1 horizon (1097 t ha^{-1}). This clearly visible effect is attributed to the effect of oat cover crop roots that tend to be deep roots in these soils. Also, the improvements in C with depth may be related with the fact that under conservation tillage the vegetation cover is kept and then the soil surface is not exposed to air and sun which otherwise favors the mineralization of the organic matter – due to organic-mineral complexes get separated releasing the organic matter susceptible to decomposition by the action of microorganisms (Hofstede, 2001; Stevenson, 1986). Although this effect has been showed for a variety of soil types and environments (e.g. Alfisol, Oxisol, Mollisol, Ultisol; Denef et al., 2004; Bossyut et al., 2002; Edwards et al.,1992; Grant, 1997; and Black and Tanaka, 1997) what is interesting from this study is that conservation tillage improves those initial levels of organic matter, even in our OM-rich soils proper of paramos ecosystems. In addition, most of the SOM and SOC studies were concentrated in superficial soil horizons (20 cm depth; Bossuyt et al., 2002) contrasting with this study that explored differences to an average depth of 117 cm. In general, the relevance of these results lies in the fact that while most soil paramos studies have reported how land use changes modify the unique properties of paramos soils none have explored how better management practices in agriculture can rehabilitate them.

In Which Soil Fraction Soil Organic Carbon (SOC) and Soil Organic Matter (SOM) Improvements Are Occurring?

Considering that more than 80% of the total carbon was in aggregates and that AOM increased in SF2, SF3 and SF4 could indicate that the 29% difference in Total SOM (g/g) between conservation tillage and conventional tillage (Chapter 2) can be explained by increments of AOM in these size fractions that correspond to small macroaggregates. In horizon A1 (0–78 cm) the differences between conservation agriculture and conventional agriculture were 37, 33 and 30% for SF2, SF3 and SF4 respectively, and 58, 99 y 98% in SF2, SF3 and SF4 of horizon 2 (78–117 cm).Thus, this study confirms the findings of Denef et al. (2004) and Kong et al. (2005) in that most changes in total SOC were explained by differences in AOM caused by no-till (in our case reduced tillage) in smaller macroaggregates (0.25 – 2 mm). Therefore our results tentatively support Kong et al. (2005) in the use of the microaggregate-within small macroaggregate fraction as a potential indicator of long term C sequestration in agricultural lands. Bossuyt et al. (2002) and Six et al. (1999) showed that same results are explained by the enhancement of microaggregate-protected and micro within macroaggregate-protected C in conservation tillage systems than in conventional tillage systems. This was a result of disruption avoidance of macroaggregates characteristic of no-till systems permitting the formation of microaggregates in which C is stabilized and sequestered in the long term. The role of plant roots from cover crop should be playing an important role as biding agent by ensuring the formation of macroaggreates (Tisdall and Oades, 1982, Cambardella, 2002). Thus, we postulate that higher amounts of SOM in SF2, SF3 and SF4 found in this study, and specially a relative greater increase of AOM in SF3 and SF4 (0.5 – 2 mm size) with respect to conventional agriculture, should also be related to an increase of microaggregates within these smaller macroaggregates. The rationale behind this is that most of the AOM in SF3 and SF4 was released at certain energy levels that may correspond to the energy level where the macroaggregates broke down into microaggregates. It is worth mentioning that the application of different ultrasound energy levels permitted the separation of larger, weaker aggregates into smaller, stronger aggregates, before breaking down into primary particles. This hierarchical order of aggregation was noted clearly by a step-wise curve.

Based on Kong et al. (2005) findings, where increases on C stabilization in the smaller macroaggregates were associated to greater aggregate stability and long-term sequestration, we suggest in the same direction, that the higher AOM and SOM in smaller macroaggregates in our soils is linked to greater C and aggregates stability and in consequence is contributing to long term C sequestration in the Andes. Greater stability in conservation tillage was suggested in the aggregates dispersion curves where clearer step-wise curves were obtained.

Changing To Conservation Tillage: A Trade Off Between Net Economic Revenues And Net Greenhouse Gas (GHG) Removals?

Chapter 4 results showed that conservation tillage increases net return implying an absence of opportunity costs and therefore a net economic benefit for the farmer. Better net returns from conservation tillage were attributed to decreases in input costs particularly due to reduced machinery operations and fertilizers applications. In another hand, conservation tillage reduced GHG emissions and increased the soil carbon stock resulting in a positive net GHG removal (788 vs 39 tCO2 ha^{-1} in conventional tillage) and in line with other studies that consider two main effects of conservation tillage in carbon emissions: i) an increase on soil carbon retention because less organic matter is loss to oxidation as mixing the soil and soil temperature are reduced; and ii) carbon emissions are reduced because it requires fewer machinery operations (Uri et al., 1999). Thus the results of this study indicate that conservation tillage is a “win-win” alternative for Fuquene farmers by benefiting economically the farmer and by providing clearly an ecosystem service or in other words there is a complementary –rather than a competitive tradeoff between the economic and environmental benefits.

Although this, a 15% of increase in net revenues in our study area could be not enough to overcome the possible aversion to risk of farmers and to encourage them to make an additional investment to cover initial extra costs of conservation agriculture (ie. cultivation of oat as cover crop). This fact may explain why this practice is not widely adopted in the Fuquene watershed.

Therefore, our results showed that although conservation tillage practices are feasible in mountainous areas and low income countries as is our study area, the required investment could be constraining the adoption and therefore credits may be important for enhancing the adoption (Carcamo et al., 1994) or by providing an extra incentive. This last may be come via payments for the net GHG removals. This could add up to US$450 yr^{-1} (based on 788 tCO2 ha^{-1} in 7 years (see chapter 4), and assuming a flat carbon price of $4 tCO_2 which is a conservative price). This carbon payment could alone cover oat production costs and increased the net revenues of the farmer by 29% instead of 15% caused by the economic benefits of conservation tillage alone.

It is worth noting that these results and the values should not be generalized and extrapolated to any situation where conservation tillage is practice, since the potential for soil carbon sequestration depends on the type of crop grown, the cropping pattern, the type of soil and the climatic conditions (Donigian et al., 1994; Uri et al., 1999). Moreover for our study site the identified carbon sequestration potential can not be extrapolated in time assuming a linear behavior of it as carbon increases are not perpetual. It is believed that there is a carbon sequestration saturation point (20 to 50 years) (Lal and Bruce, 1999) depending on climatic conditions, soil characteristics, and production management practices (Franzluebbers, 1997; Franzluebbers et al., 1999; Hunt et al., 1996; Wood et al.,1991; Zobeck et al., 1995).

Further Research Needs

Although, it has been suggested that the increase in soil organic carbon associated with the adoption of conservation tillage will continue for a period of 25 to 50 yr depending on climatic conditions, soil characteristics, and production management practices (Franzluebbers, 1997; Franzluebbers et al., 1999; Hunt et al., 1996; Wood et al.,1991; Zobeck et al., 1995), still the question left unanswered by this study site relates to the time frame for which improvements on SOC and organic matter will be achieved with conservation tillage, and also under which baseline conditions conservation tillage could improve disturbed soil properties in paramos. It only suggests that these changes can be brought about in as little as 7 years. On the other hand, further studies on the protection mechanisms favoring C sequestration in smaller macroaggregates should be the topic of future studies as also should be confirmed if this is related to an increase of microaggregates within these smaller macroaggregates as suggested by our results.

To finalize, it is suggested to evaluate the impacts on soil carbon and water-related soil properties of using in this conservation tillage system, other type of green manure cover crops (i.e. turnip and common vetch). Based on the evidenced important role of roots to increase soil carbon in the subsoil, it is suggested to evaluate the trade off between the economic and environmental benefits (carbon sequestration and soil water retention and infiltration) of using the above-ground biomass of the cover crop for feeding animals –keeping the root biomass in the soil vs. leaving the above-ground biomass as residues.

General Conclusions

Conservation tillage in potato-based systems improved in a 7 year period the soil organic matter and carbon content in disturbed soils of the *paramos* of Colombia. The soil carbon concentration in the whole profile was 29% higher under conservation tillage than under conventional tillage sites and the carbon content was higher by 45%. C content improvement specially occurred in the subsoil (A2 horizon) increasing by 177% although most of the C is stored in the top A1 horizon. This improvement was correlated to the enhancement of soil physical characteristics related with soil water movement and storage such us bulk density, AWC, saturated hydraulic conductivity and mesoporosity. These improvements confirm this studies first objective that conservation tillage can be used to rehabilitate soil under potato production in the region.

On the other hand OM in aggregates is important in these soils by representing more than 80% of total OM of these soils and by been positively affected by conservation tillage. This improvement showed a preferential C sequestration in smaller macroaggregates (<2 mm). Also the higher values of %AOM derived from smaller macroaggregates (SF3 and SF4) suggests that in these fractions the C has a slower turnover that the C in bigger macroaggregates (>2 mm). The aggregate dispersion energy curves further suggest this is happening in microaggregates within the smaller macroaggregates fraction. Similar results have been obtained for other soils suggesting that smaller macroaggregates can be used to evaluate potential of long term C sequestration in Alfisols, Mollisols, Ultisols and now Andosols.

To finalize when these environmental benefits were weight up with the economic impacts of conservation tillage, a complementary tradeoff between the economic and environmental benefits was found for our study site. This relies on the fact net farmer revenues were increased — by reduced machinery operations and fertilizers applications—, while GHG emissions were reduced —by increasing soil carbon retention and reducing GHG emissions from machinery operations—. Thus, although conservation tillage practices are not widely adopted in the watershed payments for net GHG removals could increase more the net revenues and facilitate the investment to cover initial extra costs of conservation agriculture (ie. cultivation of oat as cover crop).

APPENDIX A
DESCRIPTION OF SOIL PROFILES

Table A-1. Description of soil profiles in conservation and conventional tillage sites of the Upper Fuquene Lake watershed

Horizon				Texture		Color			Structure		Consistency	Redoximorphic Features*		
Pedon depth(cm).	No.	Lower depth (cm)	Bound dist.†	USDA Class‡	Clay %	Hue	Value	Chroma	Grade§	Shape**	Moist††	Redox concen.	Redox deplet.	Red.matrix
Conservation tillage – site 1														
140	1	55		sil	19	10 YR	2.5	1	mo	sbk	fr	N	N	N
	2	105	g	sl	9	7.5 YR	3	2	mo	abk	fi	Y	N	N
	3		c	c	51	10 Y	5	4	mo	sbk	fi	Y	N	N
Conservation tillage – site 2														
140	1	34		l	26	10 YR	3	2	st	gr	vfr	N	N	N
	2	89	c	sil	22	10 YR	2.5	1	mo	gr	vfr	Y	N	N
	3	120	g	c	46	10 YR	3	2	mo	abk	vfi	Y	N	N
	4		a	cl	39	10 YR	5	4	st	ma	vfi			
Conservation tillage – site 3														
140	1	140		sil	12	10 YR	2.5	1	st	gr	fr	N	N	N
Conservation tillage – site 4														
130	1	130		sil	13	10 YR	2.5	1	st	gr	fr	N	N	N
Conservation tillage – site 5														
150	1	72	g	sil	23	10YR	2.5	1	st	gr	fr			
	2	123	c	sic	42	10 YR	4	3	sl	ma	vfr	Y		N
	3			sic	46	10 YR	6	1	sl	ma	vfr	Y		Y

* Y (yes), N (No)

† Boundary distinctness: g (gradual), c (clear), d (diffuse).

‡ USDA class: sil (silty loam), cl (clay loam), c (clay), l (loam), sl (sandy loam), sic (silty clay)

§ Grade: mo (moderate), st (strong), wk (weak), sl (structureless)

** Shape: gr (granular), abk (angular blocky), sbk (subangular blocky), ma (massive), pl (platy)

†† Consistence: fr (friable), vfi (very firm), vfr (very friable)

Table A-1. Continued

Horizon				Texture		Color			Structure		Consistency	Redoximorphic Features[‡‡]		
Pedon depth(cm).	No.	Lower depth (cm)	Bound dist.[§§]	USDA Class[***]	Clay %	Hue	Value	Chroma	Grade[†††]	Shape[‡‡‡]	Moist[§§§]	Redox concen.	Redox deplet.	Red. matrix
Conservation tillage – site 6														
150	1	110	d	sil	22	10YR	2.5	1	st	gr	fr	N	N	N
	2	135	c	l	17	10 YR	2.5	1	mo	pl	fr	Y	N	Y
	3			c	48	10 YR	4	3	mo	pl	fr	Y	N	N
Conventional tillage – site 7														
144	1	70	c	sil	25	10YR	2.5	1	st	gr	vfr	N	N	N
	2	90	g	c	54	10 YR	3	2	mo	pl	fr	Y	N	N
	3			sic	44	10 YR	6	5	sl	ma	vfr	Y		Y
Conventional tillage – site 8														
150	1	93	c	sil	22	10YR	2.5	1	st	gr	vfr	N	N	N
	2	123	g	cl	30	7.5 YR	4	2	mo	abk	vfr	Y	N	N
	3			sic	42	7.5 YR	5	2	sl	ma	vfr	Y	N	Y
Conventional tillage – site 9														
150	1	55	c	l	18	10YR	2.5	1	st	gr	vfr	N	N	N
	2	75	g	cl	39	10 YR	3	2	mo	abk	vfr	N	N	N
	3			l	21	5 YR	7	1	sl	ma	vfr	Y	N	Y
Conventional tillage – site 10														
150	1	60	d	sil	17	10YR	3	1	mo	sbk	fr	N	N	N
	2	123	c	l	24	10 YR	2.5	1	st	abk	fr	N	N	N
	3			cl	35	10 YR	3	3	mo	abk	fr	Y	N	N
Conventional tillage – site 11														
150	1	25	c	l	25	10YR	3	2	mo	gr	fi	N	N	N
	2	35	g	cl	36	10 YR	2.5	1	st	sbk	fr	N	N	N
	3	150		c	65	10 YR	5	6	wk	abk	vfi	Y	N	N
Conventional tillage – site 12														
130	1	25	c	l	26	10YR	3	2	mo	gr	fi	N	N	N
	2	35	g	c	45	10 YR	2.5	1	st	sbk	fr	N	N	N
	3	130		c	65	10 YR	5	6	wk	abk	vfi	Y	N	N

[‡‡] Y (yes), N (No);

[§§] Boundary distinctness: g (gradual), c (clear), d (diffuse).

[***] USDA class: sil (silty loam), cl (clay loam), c (clay), l (loam), sl (sandy loam), sic (silty clay)

[†††] Grade: mo (moderate), st (strong), wk (weak), sl (structureless)

[‡‡‡] Shape: gr (granular), abk (angular blocky), sbk (subangular blocky), ma (massive), pl (platy)

[§§§] Consistence: fr (friable), vfi (very firm), vfr (very friable)

APPENDIX B
EFFECTS OF DIFFERENT MANAGEMENT SYSTEMS AND ENERGY INPUTS ON AGGREGATED ORGANIC MATTER (AOM)

Table B-1. Effect of treatment and energy levels in %AOM in aggregates of size fraction 3 (1–2 mm) in the horizon 1.

Treatment*	E level**	%AOM Mean	Duncan group***
1	0	19.2	a
1	1	19.3	a
1	3	21.2	a
1	2	21.4	a
2	0	21.9	a
2	2	22.5	a
2	1	23.8	a
2	3	26.4	a
2	5	26.4	a
2	4	27.7	a
2	6	31.6	a
1	4	34.3	a
1	5	35.2	a
1	6	35.9	a
2	7	54.7	b
2	8	69.6	b
1	7	87.9	c
1	8	88.1	c
2	9	93.3	c
2	10	97.2	c
1	9	98.6	c
1	10	98.7	c

* Treatment 1: Conservation tillage; Treatment 2: Conventional tillage
** Energy levels: 1(3.4 J/ml), 2 (10.3 J/ml), 3 (10.9 J/ml), 4 (17.0 J/ml), 5 (22.8 J/ml), 6 (28.5 J/ml), 7(32.6 J/ml), 8 (40.7 J/ml), 9 (57.6 J/ml) and 10 (75.4 J/ml).
* **Mean values with different letter inside the same column are significantly different

Table B-2. Effect of treatment and energy levels in %AOM in aggregates of size fraction 3 (1–2 mm) in the horizon 2.

Treatment*	E level**	%AOM Mean	Duncan group***
2	2	16.2	a
2	1	16.4	a
2	0	16.9	a
2	3	19.7	a
1	2	20.1	a
2	6	20.8	a
2	4	21.5	a
1	1	21.8	a
2	5	22.2	a
1	3	23.5	a
1	0	25.0	ab
1	4	33.3	ab
1	5	35.7	ab
1	6	36.2	ab
2	7	50.0	b
2	8	50.8	b
2	9	82.3	c
1	7	98.2	c
2	10	98.5	c
1	8	99.2	c
1	10	99.5	c
1	9	99.8	c

* Treatment 1: Conservation tillage; Treatment 2: Conventional tillage
** Energy levels: 1(3.4 J/ml), 2 (10.3 J/ml), 3 (10.9 J/ml), 4 (17.0 J/ml), 5 (22.8 J/ml), 6 (28.5 J/ml), 7(32.6 J/ml), 8 (40.7 J/ml), 9 (57.6 J/ml) and 10 (75.4 J/ml).
*** Mean values with different letter inside the same column are significantly different at $p<0.05$

Table B-3. Effect of treatment and energy levels in %AOM in aggregates of size fraction 4 (0.5–1 mm) in the horizon 2.

Treatment*	E level**	%AOM Mean	Duncan group***
2	0	18.4	a
2	1	21.0	a
2	2	21.9	a
2	3	25.1	a
2	4	25.9	a
2	6	27.1	a
2	5	31.0	ab
1	0	32.9	ab
1	2	35.0	ab
1	1	35.4	ab
1	3	46.1	abc
2	8	66.0	bcd
2	7	72.2	cd
1	4	89.4	d
1	5	93.9	d
1	6	96.4	d
1	10	99.3	d
1	8	99.5	d
1	7	99.6	d
2	9	99.6	d
1	9	99.6	d
2	10	100.0	d

* Treatment 1: Conservation tillage; Treatment 2: Conventional tillage
** Energy levels: 1(3.4 J/ml), 2 (10.3 J/ml), 3 (10.9 J/ml), 4 (17.0 J/ml), 5 (22.8 J/ml), 6 (28.5 J/ml), 7(32.6 J/ml), 8 (40.7 J/ml), 9 (57.6 J/ml) and 10 (75.4 J/ml).
*** Mean values with different letter inside the same column are significantly different at $p<0.05$

Table B-4. Analysis of variance of AOM (g/g), energy levels and treatments per size fraction classes in two horizons

	Horizon 1 / p-values				Horizon 1 / p-values			
	Size Class 1 (5mm)	Size Class 2 (2mm)	Size Class 3 (1mm)	Size Class 4 (0.5mm)	Size Class 1 (5mm)	Size Class 2 (2mm)	Size Class 3 (1mm)	Size Class 4 (0.5mm)
Treatment	0.774	.001*	.000*	.000*	0.102	.000*	.000*	.000*
E level	0.000*	0.000*	0.000*	0.000*	.000*	.000*	0.000*	.000*
Treatment*E level	0.984	0.06	0.098	0.614	0.953	0.164	.010*	.035*

* Significant at 5% ($p < 0.05$).

Table B-5. Comparison between AOM and SOC (g/g) (Soil Organic Carbon) in different management systems, horizons and size fractions.

	AOM (g/g) Mean				SOC (g/g) Mean			
	Horizon 1			Horizon 2	Horizon 1			Horizon 2
Treatment	Size Class 2 (2mm)	Size Class 3 (1mm)	Size Class 4 (0.5mm)	Size Class 2 (2mm)	Size Class 2 (2mm)	Size Class 3 (1mm)	Size Class 4 (0.5mm)	Size Class 2 (2mm)
Conventional tillage	0.06 (a)*	0.09(a)	0.13(a)	0.04(a)	0.03(a)	0.05(a)	0.08(a)	0.02(a)
Conservation tillage	0.08 (b)	0.12(b)	0.17(b)	0.07(b)	0.05(b)	0.07(b)	0.10(b)	0.04(b)

*The means followed by different letters within a same column are statistically different at $p < 0.05$

Table B-6. Effect of treatment and energy levels on AOM(g/g) in aggregates of size fraction 3 (1–2 mm) in the horizon 2.

Treatment*	Energy level**	AOM (g/g) Mean	Duncan group***
2	1	0.02	a
2	0	0.02	a
2	2	0.02	a
2	3	0.02	a
2	6	0.02	a
2	5	0.03	a
2	4	0.03	a
1	2	0.04	a
1	1	0.04	a
1	3	0.04	a
1	0	0.05	a
1	4	0.06	a
2	8	0.06	a
2	7	0.07	a
1	5	0.07	a
1	6	0.07	a
2	9	0.13	b
2	10	0.15	bc
1	7	0.18	c
1	8	0.19	c
1	10	0.19	c
1	9	0.19	c

* Treatment 1: Conservation tillage; Treatment 2: Conventional tillage

** Energy levels: 1(3.4 J/ml), 2 (10.3 J/ml), 3 (10.9 J/ml), 4 (17.0 J/ml), 5 (22.8 J/ml), 6 (28.5 J/ml), 7(32.6 J/ml), 8 (40.7 J/ml), 9 (57.6 J/ml) and 10 (75.4 J/ml).

*** Mean values with different letter inside the same column are significantly different at $p<0.05$

Table B-7. Effect of treatment and energy levels on AOM(g/g) in aggregates of size fraction 4 (0.5–1 mm) in the horizon 2.

Treatment*	Energy level**	AOM (g/g) Mean	Duncan group***
2	0	0.03	a
2	1	0.03	a
2	3	0.04	a
2	2	0.04	a
2	4	0.04	a
2	6	0.04	a
2	5	0.05	ab
1	0	0.06	ab
1	2	0.06	ab
1	1	0.06	ab
1	3	0.09	ab
2	8	0.10	abc
2	7	0.12	bcd
1	4	0.16	cd
2	9	0.17	d
2	10	0.17	d
1	5	0.17	d
1	6	0.18	d
1	10	0.18	d
1	8	0.18	d
1	7	0.18	d
1	9	0.18	d

* Treatment 1: Conservation tillage; Treatment 2: Conventional tillage
** Energy levels: 1(3.4 J/ml), 2 (10.3 J/ml), 3 (10.9 J/ml), 4 (17.0 J/ml), 5 (22.8 J/ml), 6 (28.5 J/ml), 7(32.6 J/ml), 8 (40.7 J/ml), 9 (57.6 J/ml) and 10 (75.4 J/ml).
*** Mean values with different letter inside the same column are significantly different at $p<0.05$

Table B-8. Analysis of variance of Total %AOM using the log of 101-AOM%

Aggregated Organic Matter in Horizon 1 and 2	SS	df	MS	F	p
Horizon	0.387	1	0.387	1.58	0.212
Size Fraction Class	9.679	4	2.42	9.88	.000*
treatment	0.304	1	0.304	1.24	0.269
Horizon*Size Fraction Class	0.178	4	0.045	0.182	0.947
Horizon*treatment	0.003	1	0.003	0.014	0.907
Size Fraction Class*treatment	1.247	4	0.312	1.273	0.288
Horizon*Size Fraction Class*treatment	0.292	4	0.073	0.298	0.878

* Significant at 5% ($p < 0.05$).

Table B-9. Non parametric analysis of % AOM in Horizon 1

	Aggregated Organic Matter		
	Treatment 1	Treatment 2	
Size fraction	Median	Median	p value
5 mm	59	81	0.2801
2 – 5 mm	97	86	0.0308*
1 – 2 mm	98.7	97.8	0.0308*
0.5 – 1 mm	99.6	99.2	1

Significant at 5% ($p < 0.05$).

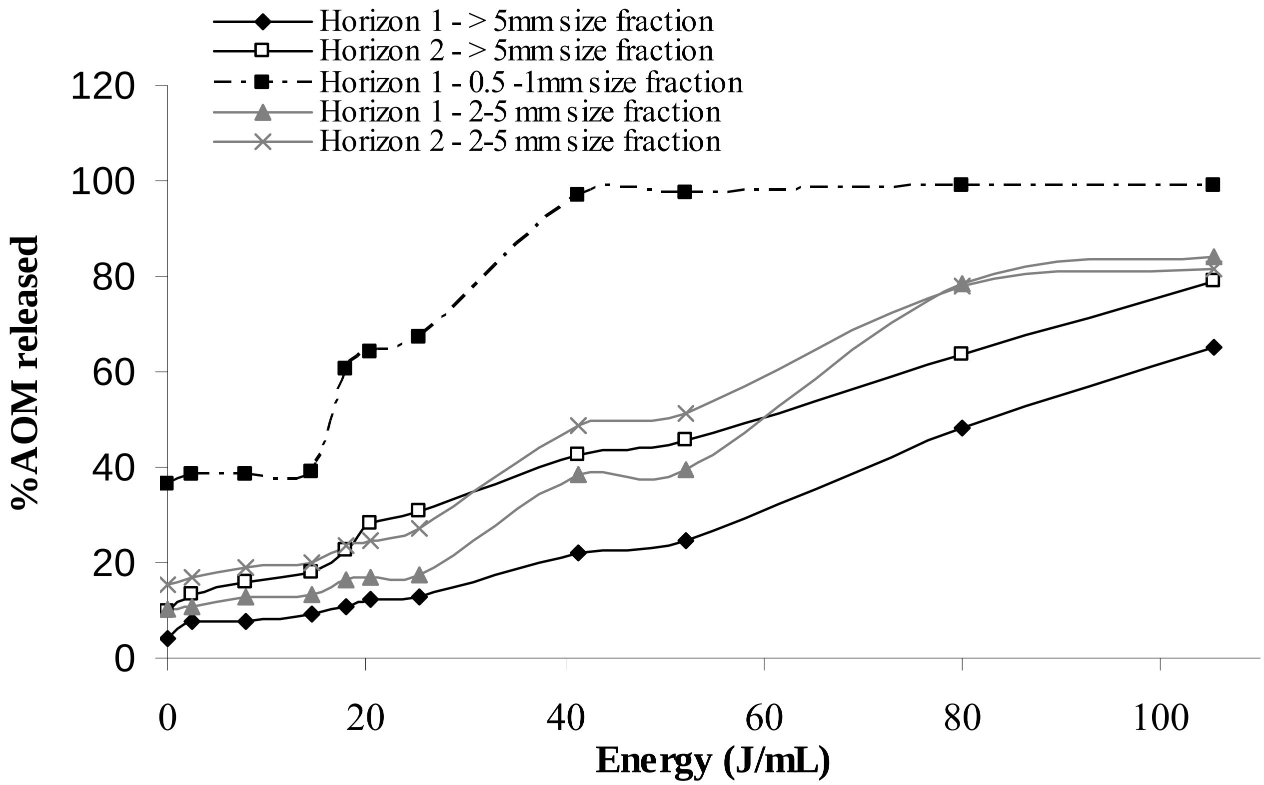

Figure B-1. Aggregated organic matter (percent of total organic matter) of > 5 mm and 0.5–1 mm aggregates size fractions, released with different energy inputs, in two management systems.

APPENDIX C
DESCRIPTION OF A MODEL FOR THE ECONOMIC, SOCIAL, AND ENVIRONMENTAL EVALUATION OF LAND USE (ECOSAUT)

The ECOSAUT model uses linear programming to optimize net income from different land-use systems, taking into account social, economic, and environmental criteria (Quintero et al., 2006). It has been employed to evaluate the socioeconomic impacts of land use alternatives in past studies (i.e. Quintero et al., 2009; Rubiano et al., 2006) and therefore, to support stakeholders in making decisions about multiple land-use options.

To use this model it is required to know the system to be modeled and how each variable affects the activities in the system and how the system affects the variables. It has been found that ECOSAUT is useful for analyzing what could be the possible impacts of land use/management alternatives at a plot or watershed scale which is useful to demonstrate the environmental and socioeconomic impacts to decision-makers; and for analyzing trade offs between land use scenarios and different types of benefits (environmental, social and economical).

According to Quintero et al. (2006) the model was built on the basis of the relationship between decision variables and decision alternatives. Decision variables correspond to the constraints established by the system's biological and economic capacities, farmer considerations, or regional policies. Decision alternatives refer to activities that are carried out in the system to maintain its functioning. Table C-1 presents the principal decision variables and alternatives considered in this model. Once these variables and alternatives were interrelated, the model was built, using an Excel spreadsheet. On this spreadsheet, a matrix for making optimizations was prepared, using linear programming. The type of information that the user should enter depending on the analysis objectives is described below.

Information on Production Systems

Agriculture

- Crops and forages that are part of the production system
- Design of rotations over 5 years (or 10 semesters)
- Costs of establishing each crop or forage ($/ha)
- Labor used for each crop per semester
- The value of a work day for purchase and sale (the option of generating income by working outside the farm is also considered)
- Yield per selected crop per semester or harvest (t/ha)
- Prices of agricultural and livestock products ($/t)
- Management practices (e.g., infiltration ditches and live barriers)[*]
- Area used for each management practice (ha)
- Costs of implementing each management practice ($/ha)
- Time of rotation in which management practices are implemented

[*] Optional: depending on the case, entering data on this variable may not be necessary.

Table C-1. Principal variables and decision alternatives in the optimization model

VARIABLES[†]	DECISION ALTERNATIVES SCENARIOS									
	Rotations of crops (ha/ yr) with/without minimum tillage	Permanent forests (ha)	Permanent pastures with/without green manures	Supplements for feeding cattle	No. cows	Farm incomes (sales of meat, milk, wood, harvest) (t/yr-	Environmental incomes for environmental services	N and P pollution residual waters (t/yr or sem.)	Buys & sells labor according to job profiles	Bank loans
Net incomes (n yr) (objective function)	X	X	X	X	X	X	X		X	X
Capital	X	X	X	X	X					X
Cash flows (by sem. or yr)	X	X	X	X	X	X	X		X	
Land availability (upper, medium and downstream watershed) (ha)	X	X	X							
Erosion thresholds by land use (t/sem.)	X	X	X							
Hydrological balance, contribution to the superficial aquifer (m^3/ha/sem.)	X	X	X		X		X			
N contributed to water flows by land uses (t/ha/sem.)	X	X	X	X	X			X		
CO_2 fixation by vegetative cover (t/ha/sem.)	X	X	X							
Labor profiles by land uses (no. workdays/sem.)	X	X	X						X	
Wood production by planted forests (t/ha)		X								
Wood production by native forests (t/ha)		X								
Energy production for livestock (megacal./K/ha)	X		X	X	X					
Protein production for livestock (kg dry matter/ha)	X		X	X	X					
Dairy production (t/sem./individual)					X					
Meat production (t/sem./individual)					X	X				

[*] X indicates the presence of a relationship between an alternative and a variable. The X could be a value that indicates the magnitude of the relationship (e.g. ton of sediments, $, hectares, etc.)

Livestock[1]

- Weight per animal unit (kg)
- Livestock's water consumption (L/day per animal)
- Milk production (L/day per animal)
- Meat production (kg/animal per semester)
- Concentrate value ($/t)
- Composition of concentrates for livestock feed:
- Metabolizable energy (t megacalories/t concentrates)
- Digestible protein (t/t concentrates)

- Nitrogen and phosphorus inputs released to water resources from the intake of concentrates (t/t)
- Protein and energy generated by forages (grasses, green forages, and crop residues):
- Percentage of residues from each crop destined for livestock feed (%)
- Percentage of dry matter per forage type (%)
- Energy content of each forage type (megacalories/kg)
- Protein contents of each forage type (kg protein/kg dry matter)
- Protein digestibility (%)

Information Related To Externalities‡

Sedimentation Processes§

- Sediment yield per land cover per semester (t/ha)
- Sediment yield per land cover per semester on implementing management practices (t/ha)

Availability of Water in Water Resources

- Water yield per land cover per semester (t/ha)
- Water yield per land cover per semester on implementing management practices (t/ha)
- Sale price of water per semester ($\$/m^3$)

Carbon Sequestration

- Capture of carbon dioxide per semester per land cover/use (t/ha)
- Value of carbon dioxide emission removals ($/t)

Water Pollution

- Nitrogen and phosphorus inputs (leachates) from fertilizers per land cover/use (t/ha per semester or year)
- Nitrogen and phosphorus inputs from erosion per land cover/use (t/ha per semester or year)
- Nitrogen and phosphorus inputs from livestock intake of forages (t/ha per semester or year)
- Nitrogen and phosphorus inputs from livestock intake of concentrates (tons of N + P per ton of concentrates)

‡ Depending on the particular environmental problems, not all the externalities (considered) listed here would necessarily be (motive for study) used as inputs to the simulation.

§ The model has been applied using hydrological information generated by hydrological modelling

Information Related to Climatic Risks

- Impact of frosts on production of each crop or forage (% of reduction in production) per semester or year.
- Impact of drought on production of each crop or forage (% of reduction in production).

For further information about the model see: http://www.condesan.org/index.shtml?apc=Ea--mic-x-x4-&x=7603

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BIOGRAPHICAL SKETCH

Ecologist from the Javeriana University in Bogotá, Colombia and Master Candidate of the University of Florida at the Water and Soil Department. She is a student, a CIAT (International Center for Tropical Agriculture) employee and a consultant. She works most of her time for CIAT, and during her last 5 years she worked as a project member of the Challenge Program on Water and Food (CPWF) project named "Environmental Services Promoting Rural Development" in the Andean region (South America). Her core work experience has been on analyzing ecosystem services as well as its valuation and quantification in Peru, Colombia, Ecuador and Nicaragua. Marcela has been involved in many other projects at CIAT. In addition to her participation at the CPWF project, she is currently responsible at CIAT of a carbon sequestration project in Colombia negotiated with the BioCarbon Fund of the World Bank; and is part of the research team working on a project in Nicaragua to assess the socioeconomic and environmental trade offs of legume-based systems. Also, she collaborated with the Theme 2 of the CPWF supporting two African projects in the application of the ECOSAUT (Economic, Social, and Environmental Evaluation of Land Use) model, developed in the Andes and now being applied in other regions. She was awarded as Outstanding Young Scientist at CIAT for year 2006. As a consultant, she collaborates with other institutions such as the GTZ (Technical German Cooperation), CONDESAN (Consortium for Sustainable Development of the Andean Ecorregion) and The Katoomba Group.