TILLAGE AND RESIDUE MANAGEMENT EFFECTS ON SOIL ORGANIC MATTER DYNAMICS IN A SANDY-LOAM

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ABSTRACT

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The accumulation and mineralization of soil organic matter is of great interest to both farmers and policy makers, because of its important functions in soil structure and in the global carbon cycle. The purpose of this study was to determine the long term effects of tillage practices and residue management on (1) the yield of *Zea mays* L. grown for corn grain or corn silage, (2) the size of the total soil organic carbon pool, (3) the relative sizes of the labile soil organic carbon and nitrogen pools, and (4) the size and structure of the microbial biomass. The experimental plots in Ste. Anne de Bellevue, Quebec, Canada were established on a sandy-loam soil in 1991 with a factorial design that includes three levels of tillage (no-till, reduced tillage, and conventional tillage), and two levels of residue input (corn roots and stover, corn roots only). At harvest in 2007, the corn grain yield was between 11.2 and 11.7 Mg dry matter ha^{-1}, but not affected by tillage or residue treatments. Soils were collected from the plots following harvest at two depths: 0-5 cm and 5-20 cm. The total soil organic carbon pool contained between 37 and 58 Mg C ha^{-1} in the top 20 cm. There was no difference between tillage treatments, but the high residue plots had more soil organic carbon than the low residue input plots (P<0.05, Tukey test). Carbon and nitrogen mineralization during a 20 week laboratory incubation was used as an indicator of the relative size of the labile carbon and nitrogen pools under the different tillage and residue treatments. Both labile carbon and nitrogen pools were affected significantly by tillage and residue inputs. In the 0-5 cm depth, the labile carbon and nitrogen pools were greater in no-till followed by reduced tillage and conventional tillage (P<0.05, t-test), but in the 5-20 cm depth, there was more labile carbon and nitrogen in the reduced tillage than the other tillage treatments (P<0.05, t-test). Labile carbon and nitrogen pools were greater in plots with high residue than low residue inputs, regardless

of the soil depth (P<0.05, t-test). Although the microbial biomass carbon and nitrogen concentrations were affected significantly (P<0.05, ANOVA test) by tillage and residue inputs, the carbon:nitrogen ratio of microbial biomass was not, indicating that microbial communities were similar in all experimental treatments. I conclude that long-term tillage and residue treatments on sandy-loam soil in a cold, moist climate had no effect on the corn grain yield or microbial community structure. Tillage and residue treatments both had an effect on the labile carbon and nitrogen pools and on the size of the microbial biomass, but only the residue treatment had an effect on the size of the total soil carbon pool.

RESUMÉ

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L'accumulation et la décomposition de la matière organique du sol est de grand intérêt aux fermiers et aux décideurs politiques, en raison de ses fonctions importantes en structure de sol et dans le cycle de carbone global. Le but de cette étude était de déterminer les effets à long terme des pratiques de labourage et de la gestion de résidu sur (1) le rendement du *Zea mays* L. pour le maïs-grain ou le maïs d'ensilage, (2) la taille du réservoir de carbone organique du sol, (3) la quantité des formes labiles de carbone organique et d'azote organique du sol, et (4) la biomasse et la structure de la communauté microbienne. Les parcelles expérimentales à Ste-Anne-de-Bellevue, Québec, Canada ont été établies dans un sol sableux-loameux en 1991 avec un design factoriel qui inclut trois niveaux de labourage (semi-direct, labourage réduit et labourage conventionnel), et deux niveaux d'entrant de résidu (les racines plus la tige, les racines seulement). En 2007, le rendement de maïs-grain était entre 11.2 et 11.7 Mg matière sèche ha^{-1}, mais non affecté par des traitements de labourage ou de résidu. Après la récolte, échantillons du sol ont été ramassés des parcelles à deux profondeurs : 0-5 cm et 5-20 cm. Le réservoir de carbone organique de sol a été entre 37 et 58 mg C ha^{-1} à une profondeur de 20 cm. Il n'y avait aucune différence entre les traitements de labourage, mais les parcelles avec haut résidu (racines plus tiges) ont eu plus de carbone organique de sol que lesquelles avec bas résidu (P<0.05, test de Tukey). La minéralisation de carbone et d'azote pendant une incubation de laboratoire durant 20 semaines a été employée comme indicateur de la taille relative des formes labiles de carbone organique et d'azote organique sous les différents traitements expérimentaux. Les quantités de carbone et d'azote labiles ont été affectées sensiblement par labourage et d'entrant de résidu. Dans la profondeur de 0-5 cm, les quantités de carbone et d'azote labiles étaient plus grandes avec semi-direct, suivi par labourage réduit et du labourage conventionnel (P<0.05, t-test), or dans la profondeur de

5-20 cm, il y avait plus de carbone labile et d'azote labile dans le labourage réduit que les autres traitements de labourage ($P< 0.05$, t-test). Les quantités de carbone et d'azote labiles étaient plus grandes dans les parcelles recevant haut résidu que bas résidu, indépendamment de la profondeur de sol ($P<0.05$, t-test). Bien que les concentrations de biomasse microbiennes en carbone et en azote aient été affectées sensiblement ($P<0.05$, ANOVA) par labourage et d'entrant de résidu, le rapport carbone : azote de la biomasse microbienne n'était pas, indiquant que les communautés microbiennes étaient semblables dans tous les traitements expérimentaux. Je conclus que les traitements à long terme de labourage et de gestion de résidu sur un sol sableux-loameux dans un climat froid n'ont exercé aucun effet sur le rendement de maïs-grain ou la communauté microbienne. Le labourage et les entrants de résidu ont exercé un effet sur les quantités de carbone et d'azote labiles et sur la concentration de la biomasse microbienne, mais le réservoir de carbone organique du sol a été affecte seulement par l'entrant de résidu.

CONTRIBUTION OF AUTHORS

This thesis consists of a literature review and two manuscripts. The two manuscripts were prepared for submission to scientific journals, with the candidate as first author, Dr. Joann Whalen, Dr. Chandra Madramootoo and Dr. Don Smith as co-authors. The candidate was responsible for collecting soil samples and conducting the carbon and nitrogen mineralization experiments. He was also responsible for organizing the data, statistical analysis, data interpretation, and writing the text of the thesis. Measurements of the total C, total N, MBC, and MBN in selected soil samples were obtained from Dr. Whalen. The long-term experimental plots were established by Dr. C. Madramootoo and have been managed by Mr. Peter Kirby. Funding for the candidate and the research came from a Fonds quebecoises de recherche sur la nature et les technologies (FQNRT) team grant awarded to Dr. Chandra Madramootoo, Dr. Joann Whalen, Dr. Lyle Whyte and Dr. Charles Greer.

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TABLE OF CONTENTS

Contents

LIST OF TABLES

LIST OF FIGURES

GENERAL INTRODUCTION

Current research on how agricultural practices affect soil organic carbon (SOC) is justified for two reasons. The first reason involves the global carbon (C) cycle. There has been a 31% increase of atmospheric carbon dioxide (CO_2) since the 1850s, stemming from anthropogenic activities such as the burning of fossil fuels and changes in land use. The increase of atmospheric CO_2 is thought to be changing the global climate, potentially damaging ecosystems and human well-being (Lal 2008). Since the mass of C stored in the soil is three times the mass of C stored in the atmosphere, and C is transferred regularly from the atmosphere to the soil through natural photosynthetic activity, soils are thought to be a possible sink for atmospheric C. Agricultural practices are therefore being examined to discover which ones increase the amount of C in soils, a process known as C sequestration.

The second reason to study the effects of agricultural practices on SOC is linked to agricultural productivity. Many of the world's agricultural soils have lost significant amounts of SOC, rendering them less productive. To feed the growing global population without encroaching further on natural ecosystems, we will have to increase the productivity of agricultural soils. Lal (2005) estimated that judicious use of agricultural practices that increase SOC could raise global food production by 32 million Mg y^{-1}. This would also translate into greater yields for individual farmers; it would raise their profits, and ensure that their land would be productive for years to come.

The objectives of this thesis are 1) to determine the effects of different tillage practices and residue inputs on the total SOC and crop yield on a sandy-loam soil after 16 years of treatment, and 2) to determine the effects of the different tillage practices and residue management on the labile C and nitrogen (N) pools in the soil.

The thesis is divided into three chapters. The first chapter is a literature review that summarizes our current knowledge about SOC dynamics and agricultural

management. The second chapter discusses the effects of the treatments on crop yield and total SOC. The third chapter describes two incubation studies which were conducted in the laboratory, and what the results show about the effects of tillage and residue management on the labile N and C pools. Key results and recommendations for future research are provided in the General Conclusions to the thesis.

CHAPTER 1: LITERATURE REVIEW

1.0. The Importance of SOC

1.1. The global carbon cycle

Since 1850, the concentration of atmospheric CO_2 has risen approximately from 280 ppm to 380 ppm due to land use changes and the combustion of fossil fuels. This is believed to be causing global climate change that we are experiencing currently, which has detrimental effects on ecosystem health and human welfare. There is therefore great scientific interest in finding ways to ameliorate this problem by reducing the concentration of atmospheric CO_2 (Lal 2008).

In order to understand the rising atmospheric CO_2 concentration, it is important to understand the dynamics of the global C cycle. There are five major pools of C on Earth:

1) the oceanic pool (38 400 Pg C),

2) the pedologic pool (1550 Pg C),

3) the atmospheric pool (76 Pg C)

4)the biotic pool (560 Pg C)

5)the fossil pool (4130 Pg C)

The fluxes between the pools are presented in Fig 1.

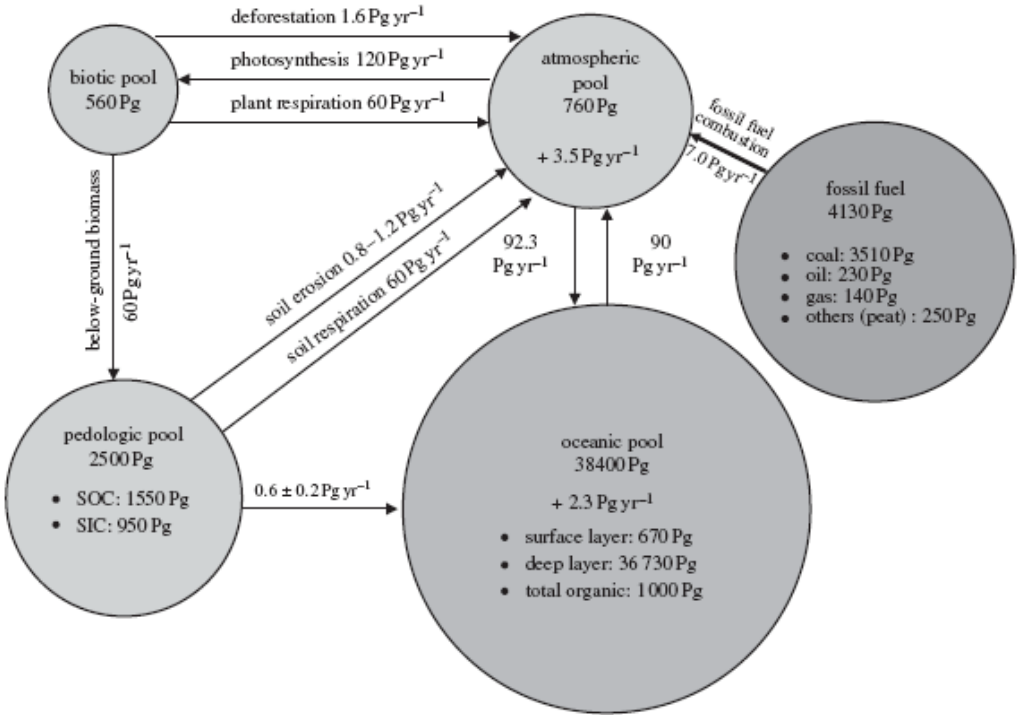

Fig. 1. The five major C pools on Earth and the fluxes between these pools (from Lal 2008).

The pedologic pool contains 1550 Pg of SOC, which is intimately connected to the atmospheric pool through the processes of photosynthesis (through the biotic pool) and microbial respiration.

SOC has declined by approximately 320 Pg since the dawn of agriculture 10 000 years ago and therefore restoring SOC to previous levels is thought to be a possible sink for atmospheric C (Lal 2008). Agricultural practices that increase the flux of C into the soil or reduce the C flux from the soil build the SOC pool over time. Bruce et al. (1999) estimated that the implementation of such practices in Canada and the United States would result in a net transfer 85 Tg C from the atmosphere to the soil each year. The agricultural practices that increase SOC will be discussed in Part 3 of this review.

1.2. Soil organic carbon and the productivity of the soil

Individual farmers may be more interested in the productivity of their soils than in the global C cycle. Increased amounts of SOC have been shown to increase the productivity of the soil (Lal 2005; Magdoff and Van Es 2000). This relationship was quantified in a four-year study on spring wheat in North Dakota by Bauer and Black (1994). They found that for every Mg ha^{-1} of SOC lost, the dry weight of the grain fell by 26.5 kg ha^{-1}. Similarly, an experiment using simulated erosion by Larney et al. (2000) showed a loss of crop productivity when SOC was lost from soils in Alberta. They found spring wheat (*Triticum aestivum* L.) grain yield decreased by 39 kg ha^{-1} in irrigated plots in Lethbridge and 19 kg ha^{-1} in Taber per Mg SOC ha^{-1} lost through erosion. Zhukov et al. (1993) showed an increase of 13 Mg ha^{-1} in wheat yield with an increase of 1 Mg SOC ha^{-1}. Experiments conducted over the last 20 years in Latin America, South Asia, Africa, Canada, the United States, Britain and Russia all show similar relationships between SOC and soil productivity (Lal 2005).

The increase in SOC is thought to improve soil productivity and crop growth through two mechanisms:

(1) Improving the physical structure of the soil

(2) Changing soil chemical characteristics that enhance the nutrient supply to plants

1.2.1. Soil physical structure and SOC

Perhaps the most important way that SOC improves the soil physical structure is by enhancing the water stability of macroaggregates (Tisdall and Oades 1982). The irregularly shaped macroaggregates fit together rather loosely, creating macropores between the aggregates (Magdoff and Van Es 2000). This soil structure has several beneficial effects on crops. It increases the water infiltration rate, enhances the drainage,

and allows for rapid gas exchange and easy root growth (Wolf and Snyder 2003). An increase of SOC also increases the available water capacity of soils (Emerson 1995).

Macropores lead to increased water infiltration, drainage and gas exchange. These are of tantamount importance to plant growth, since plant roots require both oxygen and water in order to function. If the infiltration rate is too slow, most of the rain and irrigation water will run off the surface of the soil, and never reach the root zone. Furthermore, the water running off the soil surface will most likely cause erosion, carrying away valuable nutrients into lakes and rivers, where they cause environmental damage. If the terrain is relatively flat, the rainwater may pool on the field, leading to poor aeration of the soil (Wolf and Snyder 2003). Gas exchange is also important. On average, the various inhabitants of the soil, including microorganisms and plant roots, respire approximately 10 L CO_2 m^{-3} d^{-1}. If that volume of CO_2 does not diffuse into the atmosphere, to be replaced by O_2 on a daily basis, the plant roots will be inhibited by lack of oxygen (Wolf and Snyder 2003). Similar problems can occur if water does not drain from the soil quickly enough after a rainfall, since the diffusion rate of O_2 and CO_2 through water is slow compared to its diffusion rate through air. Since any space occupied by water is low in oxygen, it is important for the soil to have macropores, since they drain quickly allowing gas exchange. Macropores are also important for root penetration. If there are no pores large enough for the root to penetrate, the plant will have trouble extending its roots throughout the soil (Wolf and Snyder 2003), reducing its anchorage, transpiration capability, and mineral nutrition.

The available water capacity (i.e., the difference between the field capacity and the wilting point) is the size of the water reservoir that is available to the plant, and therefore has an important effect on crop yield wherever plants are not being watered on a continual basis. The available water capacity was found to be linearly correlated to the SOC content of the soil in a series of seven experiments reviewed by Emerson (1995). These experiments each showed an increase in available water capacity, ranging from 1g to 10g of water for every gram of SOC added to the soil, depending on the soil texture.

Emerson hypothesized that the increase of available water capacity was as a result of polysaccharide gels that formed in the soil pores, which hold the water in place, raising the amount of water stored at field capacity. Hudson (1994) came to a similar conclusion, stressing that as the amount of SOC increases, the field capacity of the soil rises faster than the wilting point, causing the soil to have a larger available water capacity.

1.2.2. Soil chemical characteristics and SOC

Soil organic carbon can also influence the soil chemical reactions, which affect the availability of nutrients to the crops and the pH of the soil. There are two ways in which SOC can increase the availability of nutrients to the plant. The first way is that SOC is always associated with other elements such as N, sulphur, and phosphorus. When SOC is mineralized, it releases these nutrients in forms available for absorption by plants. Buaer and Black (1994) found that the extra N that is mineralized in soils with larger pools of organic matter can account for the improved crop productivity in these soils. They also noted that increased N fertilization can mask the difference in productivity between soils of differing SOC content. Once the SOC is mineralized and the nutrients are released, it can no longer perform all the other beneficial functions attributed to SOC. As a result, farmers are always faced with the short-term benefits of mineralization, weighed against the long term benefits of keeping the SOC in the soil (Weil and Magdoff, 2004).

The second way which SOC can increase the availability of nutrients is by increasing the cation exchange capacity (CEC) of the soil. This reduces leaching of essential cations, and helps maintain a consistent supply to the roots. This potentially increases crop yields by ensuring that essential nutrients are always available (Wolf and Snyder 2003).

The SOC also buffers the pH in the soil, which ameliorates a significant impediment in the 17% of agricultural soils that are limited by acidity. In these soils, the

buffered pH tends to decrease the availability of toxic aluminum ions, which become available in more acidic conditions (Weil and Magdoff, 2004). A high concentration of SOC also helps soils to resist fluctuations in pH due to acid rain or fertilizer additions (Wolf and Snyder 2003).

2.0. The Size and Dynamics of the SOC pool

Carbon is always cycling between the soil and the atmosphere. Green plants fix atmospheric CO_2 via photosynthesis and transform it into simple sugars and more complex C-rich compounds like cellulose, hemicelluloses and lignin. Plant C is cycled through the biosphere until it reaches the soil in the form of dead plants, dead animals, root exudates, or feces (Fig. 2). The C in the soil is decomposed by soil microbes, whose biomass is itself considered part of the SOC, and by the soil fauna, and is respired back into the atmosphere as CO_2. Part of the SOC becomes stabilized as humus or organo-mineral compounds, and stays in the soil for an extended period of time. The size of the C pool in the soil is determined by the rate of C inputs and the rate of decomposition (Haynes 2005). In a study of the temperate soils of eastern Canada, Angers et al. (1997) found an average of 40-50 Mg C ha^{-1} in the top 20 cm of the soil profile.

The SOC pool is not homogeneous. It is composed of many different organic compounds originating from plants, animals and microorganisms, as well as byproducts of decomposition and new compounds synthesized by decomposer organisms. Since these compounds are too large and diverse to be easily defined, it is convenient to divide the SOC into different fractions, depending on their properties. One possible fractionation is to divide the SOC based on the speed that complex molecules are broken down into simpler sugars and eventually converted back to CO_2. According to this system, the SOC is divided among three pools: the labile pool, the intermediate pool, and the recalcitrant pool. The SOC in the labile pool has a half life in the soil ranging from days to a couple of years. The intermediate pool has a half life in the soil ranging from years to decades. The recalcitrant pool can remain in the soil for centuries (Wander 2004).

Fractions that are part of the labile pool include the fresh litter, the unprotected particulate organic matter (POM), the microbial biomass C (MBC). These fractions contain polysaccharides, carbohydrates, and other easily mineralizable chemicals. The intermediate pool is made up of aggregate protected POM, and often contains more recalcitrant chemicals such as amino compounds and glycoproteins and some humic materials. The recalcitrant pool is made up of organo-mineral compounds, charcoal, and high molecular weight humic materials (Wander 2004).

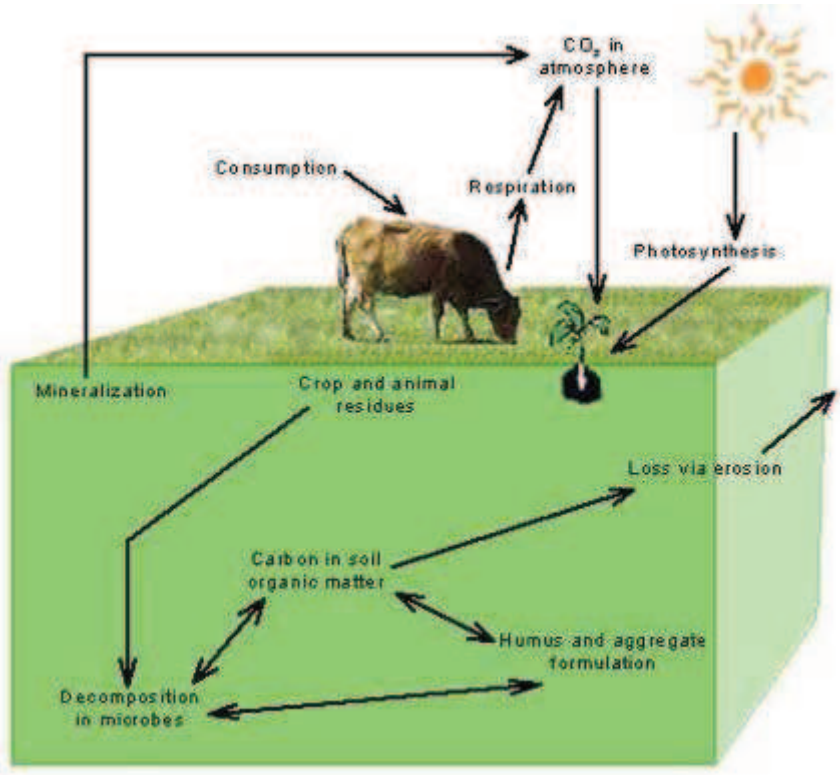

Fig. 2. The carbon cycle in an agroecosystem (from Bellows 2001).

2.1. Factors affecting C inputs

The rate at which C enters the soil is mainly determined by the net production of organic matter by the plants inhabiting the soil, known as the net primary production (NPP). Warm climates with sufficient moisture tend to have high NPPs, whereas places where plant growth is limited due to temperature or aridity tend to have lower NPPs (Lieth 1973).

The rate at which C enters the soil can also be affected by human activity. In agricultural fields, much of the crop biomass is removed from the field to meet human and animal requirements for food and fiber, reducing the amount of C that enters the soil (Haynes 2005). On the other hand, manure or other organic matter might be brought and added to the soil, increasing the amount of C that enters the soil (Wolf and Snyder 2003). Fertilizers, irrigation, high yielding crops, and cover crops tend to increase the NPP and therefore the amount of C added to the soils (Wolf and Snyder 2003).

2.2. Factors affecting the rate of decomposition and stabilization of SOC

The rate of decomposition is determined by the degree to which the soil is hospitable to microbial activity. The physical factors that determine the rate of decomposition are the concentration of oxygen and moisture, as well as the temperature and pH of the soil. The rate of decomposition increases when these conditions are optimum, and decreases or stops completely when they are less hospitable. The rate of decomposition is also determined by the degree to which the SOC is stabilized, or protected against microbial decomposition.

2.2.1. Oxygen

Although anaerobic organisms exist in the soil, aerobic organisms generally perform the bulk of the decomposition in the soil. Soils that have limited gas exchange due to insufficient drainage generally accumulate SOC because the decomposition

proceeds very slowly. This also accounts for part of the difference in the size of SOC pools in the various soil textures. Sandy soils tend to be well aerated and therefore do not accumulate much organic matter, whereas clayey soils tend to have more limited gas exchange, allowing SOC to accumulate. Human activities which aerate the soil, such as tillage, tend to increase the decomposition rate and reduce the amount of SOC (Wolf and Snyder 2003). The effects of tillage on decomposition will be discussed in more detail in section 3.1.1.

2.2.2. Moisture

Soil microbes are living creatures that require moisture for metabolic functions, including SOC decomposition. The optimal moisture for microbial activity is generally quite close to the optimal moisture for plant growth, which means that the increased decomposition is offset by the increased primary production. In dry soils, the decomposition may be inhibited, but the NPP is very low and therefore there is no accumulation of SOC. In waterlogged soils, oxygen becomes a limiting factor for decomposition, and SOC increases (Wolf and Snyder 2003).

Microbial activity tends to grow in response to increased moisture, until the soil becomes wet enough that oxygen becomes a limiting factor. One way to describe the balance between oxygen and water in a given soil is to calculate the water-filled pore space (WFPS). This expresses what percent of the total pore volume is filled with water. It is calculated using eq. 1 (Franzluebbers 1999)

$$WFPS = M_s \times (\rho_b \times \rho_m / \rho_m - \rho_b) \times 100\% \quad (1)$$

where WFPS is the percentage (%) of the pores space filled with water.

M_s is the soil moisture content (g/g)

ρ_b is the bulk density of the soil (g cm^{-3})

ρ_m is the mineral density of the soil (2.65 g cm^{-3})

Maximum microbial activity takes place between 40% and 60% WFPS (Franzluebber 1999; Linn and Doran 1984).

2.2.3. Temperature

The effects of temperature on microbial activity have been studied for over a century. Deherain and Demoussey (1896) published a paper which showed that the flux of CO_2 from the soil increased with increasing temperatures between 20^{o}C and 65^{o}C (Bunt and Rovira, 1955). This is partly accounted for by increasing biological activity and partly by chemical processes (Bunt and Rovira, 1955). Wagner and Wolf (1998) stated that the optimal temperature for microbial decomposition is between 30 and 45^{o}C. From 13-35^{o}C, microbial activity doubles approximately every 10^{o}C (Wolf and Snyder 2003). Microbial activity is considered to be negligible when soil temperatures are less than 4^{o}C. When other factors are constant, SOC tends to accumulate more in cooler climates than in warm climates, because of temperature constraints on microbial-mediated decomposition processes. This phenomenon is cause for concern, since CO_2 induced global warming could cause CO_2 to be released from the soil, thus creating a positive feedback loop (Kirschbaum 1994).

2.2.4. Soil pH

There is some evidence that microbial activity is highest around near neutral pH (Wolf and Snyder 2003; Motavalli et al. 1995), although there is no clear correlation between pH and microbial activity. Groups of bacteria and fungi that grow in acidic or alkaline soils tend to be adapted to those conditions, and therefore are not significantly inhibited in non-neutral pH soils (Baath 1996). Since the correlation between microbial activity and pH is quite unclear, pH is not used as a factor in the CENTURY Model or Rothamsted Model which are used to predict SOC dynamics (Motavalli et al. 1995).

2.3. Mechanisms leading to SOC stabilization

It is convenient to divide SOC into two groups, labile and stabilized. This is a simplification of reality in which SOC falls on a continuum from very labile to very stabilized (Haynes 2005). Fresh plant matter is generally quite labile and it becomes stabilized over time. There are three ways in which organic matter becomes stabilized: bio-chemical, chemical, and physical stabilization (Jastrow et al. 2007).

2.3.1. Bio-chemical stabilization

Bio-chemically stabilized SOC is organic C that can only be decomposed by microbes using specific extracellular enzymes. These enzymes have limited adsorption sites on the substrate, and therefore once the substrate is saturated, the enzymes diffuse further from the cell, leading to diminishing returns for the microbe and slowing decomposition (Schimel and Weintraub 2003).

There are two ways that organic matter becomes bio-chemically stabilized, and together these processes are referred to as humification. The first way is through selective consumption. Plant matter is composed of many different types of organic compounds, some of which are more available for microbial consumption than others. For example, hemicellulose has an average residence time in the soil of approximately 14 days, whereas lignin has an average residence time of 500 days. The labile group, including cellulose and hemicellulose are quickly consumed, leaving organic matter that is composed primarily of more recalcitrant compounds such as lignin. There is therefore a positive correlation between the amount of time that organic matter has resided in the soil, and the concentration of lignin in the organic matter (Yadav and Malanson 2007). The higher the concentration of lignin, the more stable the organic matter becomes.

The second way that organic matter is bio-chemically stabilized is through polymerization reactions. As the more complex molecules are broken down by microbial activity, some of the resulting monomers polymerize into large, undefined conglomerates which are held together by hydrogen bonds and hydrophobic interactions. The

recalcitrant qualities of these conglomerates results partly from reactions between sugars, amino acids and the quinones, molecules are released as lignin is decomposed. This creates melanin-type compounds that are resistant to microbial attack (Jastrow et al. 2007).

2.3.2. Chemical stabilization

Organic matter that is stabilized through bio-chemical processes is still relatively labile, and is usually mineralized within a few months or years. However, if the stabilized organic matter is absorbed onto silt or clay minerals, the residence time can be centuries. These compounds are called organo-minerals (Blanco-Canqui and Lal 2004). Since organo-minerals are very recalcitrant, there tends to be a positive correlation between the concentration of clay and silt in the soil and the concentration of C in the soil (Six et al. 2002). Organo-minerals are also important for stabilizing aggregates, which will be discussed in section 2.3.3 (Blanco-Canqui and Lal 2004).

Organic matter is generally absorbed to clay mineral surfaces through polyvalent cation bridges. Therefore, clays saturated with polyvalent cations such as Ca^{++} or Mg^{++} tend to absorb organic matter better than clays saturated with Na^{+} (Jastrow et al. 2007). The surface area of the clay is a limiting factor for the formation of organo-minerals, and therefore soils that contain clays with high specific surface areas tend to sequester more C (Jastrow et al. 2007). Since the amount of organic matter that can be protected by absorption is limited by the number of sorption sites, it is possible for soil to become saturated with C, such that any additional C will be unprotected and quickly mineralized (Six 2002). The interaction between tillage practices, residue management, and soil texture and mineralogy will be discussed in Section 3.3.

2.3.3. Physical stabilization

Besides bio-chemical and chemical stabilization, organic matter can be physically protected from decomposition when it becomes concealed or covered by soil particles during the process of aggregate formation. The smallest micro-aggregates (<250 μm) are formed when clay and silt sized particles are bound together by humic material or polysaccharides produced by microbial decomposition of plant matter. Micro-aggregates are bound together by fine roots and fungal hyphae, or are cemented together by labile organic material to form macro-aggregates (> 250 μm) (Jastrow et al. 2007). These aggregates protect the organic matter in two ways: 1) the organic matter is not accessible to the microbial population due to pore size exclusion, where the microbes are too large to fit into the pores leading to the organic matter, 2) the gas exchange is compromised due to the small size of the pores leading to the organic matter. This leads to an anaerobic environment within the aggregate, causing the microbial activity to slow down significantly (Six 2002). Aside from protecting organic matter, aggregates have a very important role in soil structure, which was discussed in Section 1.2.1.

3.0. Agricultural practices affecting the size and dynamics of the SOC pool

Agricultural management practices can have a large impact on SOC dynamics. The rate of decomposition is often affected by the tillage practices. Furthermore, the amount of organic matter entering the soil is largely determined by the amount of residue that the farmer leaves in the field. This section will examine the different tillage practices and residue management that can affect the size and dynamics of the SOC pool.

3.1. Tillage

Since ancient times, tillage has been an important agricultural activity. Ploughs have been used in some form or another since the advent of agriculture approximately

10000 years ago. The muoldboard plough, which is widely used today, has been used in Europe since the 11th century. This device inverts the soil after breaking it up, completely mixing the soil in the plough layer (Huggins and Reganold 2008). Tillage loosens the soil, prepares the seed bed, kills weeds, warms the soil, and promotes mineralization of organic matter, releasing nutrients important for crop growth.

During the 1930s, the dustbowl in the western Prairies starkly demonstrated the major disadvantage of continuous tillage, namely, that the practice destroys the soil structure and increases erosion. In 1943, Edward Faulkner wrote a controversial book called "The Plowman's Folly", introducing the possibility that ploughing is not an agricultural necessity. Since then, herbicides have been invented, and planting machines have been modified, making large scale agriculture possible without tillage (Huggins and Reganold 2008). This method has been named "no-till", and is becoming more popular in recent years. Between 1990 and 2004, the area of land under no-till cultivation in the United States has approximately tripled, reaching 22% of all cultivated land (Huggins and Reganold 2008). In Canada, no-till is practiced on 28% of the cultivated land, although it is mostly practiced in the western provinces. In Quebec, no-till accounts for a mere 3% of cultivated land (Hoffman 2008). A more moderate approach is to reduce the area and intensity of tillage, without completely discontinuing the practice. There are a number of ways of reducing tillage, and together with no-till, they are generally grouped under the term "conservation tillage". This term is defined as any combination of tillage practices that leaves at least 30% of the crop residue on the surface of the soil (Central West Farming Systems, 2008) after planting the crop. In this thesis, both reduced tillage (which consists of shallow harrowing with offset disc harrow in the fall and tandem harrow in the spring) and no-till are referred to as "conservation tillage".

3.1.1. Effects of tillage on SOC decomposition

Conventional tillage with a mouldboard plough increases the decomposition rate of SOC. Conant et al. (2007) stated that after a tillage event, large amounts of CO_2 are

released from the soil, compared to the normal levels of respiration. Watts et al. (2000) performed a laboratory experiment where soils were subjected to mechanical disruption to simulate tillage. Respiration rates increased immediately after the mechanical disruption, and the increase was positively correlated to the energy of the disruption.

The increased rate of respiration is caused by the enhancing of the conditions for microbial activity that were discussed in Section 2.2. Tillage breaks up the soil, allowing enhanced gas exchange. This increases the concentration of oxygen in the soil pores, and also allows oxygen to permeate into aggregates that were occluded before the tillage event (Wolf and Snyder 2003). Also, SOC that was not available for microbial consumption because it was physically stabilized is released and decomposed (Jastrow et al. 2007). Furthermore, tillage incorporates the residues into the soil. This protects them from the fluctuations of moisture and temperature and puts them in intimate contact with the soil microbial biomass, making them available for decomposition (Franzluebbers 2004). Incorporating the residues also warms up the surface of the soil, since it is no longer shaded from solar radiation (Angers et al. 1997), which increases microbial activity. Therefore, agronomic practices that reduce or eliminate tillage generally experience slower decomposition rates than conventionally tilled soils, causing those soils to develop a higher concentration of SOC.

There are many studies that show that reduced tillage and no-till increase the size of the SOC pool. In a 12-year study on Grantsburg soil in Southern Illinois, Olson et al. (2005) showed an increase of 0.71 Mg C ha^{-1} $year^{-1}$ in the no-till plots compared to the conventionally tilled plots. Potter et al. (1998) showed an increase of 0.570 Mg C ha^{-1} $year^{-1}$ on a Pullman clay loam in Northern Texas in no-till plots compared to conventionally tilled plots. Potter et al.(1998) also showed an increase of 0.157 Mg C ha^{-1} $year^{-1}$ on an Orelia sandy clay loam in Southern Texas. Allmaras et al. (2000) reviewed the effects of no-till and reduced tillage in comparison to conventional tillage, and found that in most cases, there was significantly more SOC in the no-till and reduced tillage plots.

There are, however, some studies that show no difference between tillage treatments. Angers et al. (1997) compared no-till and conventionally tilled plots in eight experimental sites in eastern Canada. They found significant differences in the distribution of the SOC, but no difference in the total amount of SOC in the soils (to a depth of 60 cm). Similarly, in an experiment with 36 fields in four different regions of Illinois, Needelman et al. (1999) concluded that there was generally no difference in the total SOC between conventionally tilled and no-till plots. The factors that affect whether or not conservation tillage causes an accumulation of SOC will be explained in Section 3.3.

3.2. Residue management

Residues are the parts of the crop that are of little market value. Residues can be removed from the field in order to be used for fodder, building materials or fuel. Alternatively, they can be left to decompose in the field (Franzluebbers 2004).

3.2.1. Effect of residue management on SOC

Since the crop residues are a significant source of organic C, practices that remove the residues from the field often cause SOC to decline. Conversely, when the residues are left to decompose in the field, SOM tends to increase (Franzluebber 2004). In a study in Lafayette, Indiana, Barber (1979) showed that removing corn residues caused a decline of 3 g SOC kg^{-1} soil in 11 years, whereas doubling the corn residues added to the soil caused the SOC to increase by 3.1 g SOC kg^{-1} soil. He calculated that approximately 11% of the residues were eventually incorporated into the SOC, whereas 89% was mineralized. Residue management had no significant effect on the yield. Wilhelm et al. (2004) reviewed the effects of residue removal on corn yield and the SOC. They concluded that removing the residue often led to significant declines in crop yield, although the effect was variable and depended on tillage practices and environmental conditions. They also concluded that the removal of residues caused a decline in SOC.

This conclusion is supported by observations made in the field and by predictions made by the CENTURY model (Wilhelm et al. 2004).

There is also an interaction effect between tillage and residue management. Since tillage affects the decomposition rate, it is not surprising that the fate of the added residues should be affected by tillage. In a 13-year study of the effects of tillage on a continuous corn culture, only 11% of the added residue C was transformed into SOC in the top 30 cm under mouldboard tillage, whereas 24% of crop residues became SOC under a no-till regime (Wilhelm et al. 2004).

3.3. Effects of climate and soil texture on SOC dynamics

The flux of C into and out of the soil is not only determined by agricultural management practices, but is also affected by climate and soil texture. The climate affects the rate of C input into the soil, since the temperature and moisture have a great impact on the NPP. Decomposition is also affected, since temperature and moisture determine the rate of microbial activity. The soil texture also has an impact on the rate of decomposition, since the concentration of clay in the soil determines the amount of SOC that is protected within organo-minerals, discussed in section 2.3.2.

Climate and soil texture also affect the response of the SOC pool to tillage and residue management. In cool climates, where temperature limits the activity of the microbial population, exposing the SOC by tilling the soil will not cause it to be decomposed. High residue inputs, on the other hand, should be more effective in cool climates since the added residues will decompose slowly (Franzluebbers 2004).

Soil texture will also affect the response of the SOC to tillage treatments and residue management. In sandy soils, reduced tillage and added residues may not have much of an impact, since the soils are well aerated and very little of the SOC is protected in organo-mineral complexes. These soils tend to become saturated with C, meaning that they are unable to protect any more C, regardless of the tillage treatments or residue

management. These interactions explain the lack of response of the SOC to tillage treatments reported by Angers et al. (1997) and Needelman et al. (1999) (see section 3.1.1). Angers et al. (1997) conducted their study in the cool climate of eastern Canada, and so tillage did not have a significant effect on the SOC pool. Needelman et al.(1999) conducted their study on sandy soil, which became C-saturated and so tillage did not affect the SOC pool.

Sandy soils and cool climates have opposite effects on the SOC pool. The cool climate slows the decomposition process, regardless of the tillage treatment, whereas the sandy soil accelerates the decomposition process, regardless of the tillage treatment. It is unclear how tillage and residue management would affect the SOC pool in a sandy soil in a cool climate. This question will be addressed in section 4 of this review.

Section 4. Future research on SOC: objectives and hypotheses

Agricultural practices that increase the size of the SOC pool are important for mitigating atmospheric CO_2 levels and for increasing crop yields. It is clear, however, that not all soils react in the same way to these agricultural practices, due to differences in climate and soil texture. The purpose of this study is to investigate the effects of conservation tillage and high residue inputs on the SOC pool on a sandy-loam soil in the cool moist climate of southwest Quebec, Canada. Since the cool climate tends to slow down decomposition, and the soil texture at this site accelerates decomposition processes, it is unclear which factor predominates. It is possible that the tillage practices will determine whether the decomposition will be fast or slow, which will in turn affect the size of the SOC pool. Furthermore, it is unclear what the effect of high residue input into the soil will be under these conditions. Will the cool climate preserve these residues until they can be transformed into the stable SOC pool, or will the residues decompose quickly due to the coarse soil texture? Also, what will be the effect of tillage practices and residue management on the labile pool of the SOC? Will they be the same as the effects on the total SOC pool? Perhaps the labile pool will be much more clearly affected, since

the labile pool cycles quickly and is therefore more sensitive to changes in the residue input and decomposition rate. I hypothesize that: 1) conservation tillage and high residue inputs will cause the total SOC pool to increase in size on our sandy-loam soil in a cool, moist climate, and 2) that the labile pool will be highly affected by these management changes, disproportionally to the change in the total SOC pool. The first hypothesis will be tested in Chapter 2 of this thesis, and the second will be tested in Chapter 3 of this thesis.

CHAPTER 2: THE EFFECT OF TILLAGE AND RESIDUE MANAGEMENT ON THE TOTAL SOIL ORGANIC CARBON

ABSTRACT

One of the proposed ways to mitigate the rise of atmospheric CO_2 is to adopt agricultural practices that increase the amount of C in the soil, thereby diverting it from the atmosphere. The purpose of this study is to examine the effect of tillage and residue management on the total SOC. The experimental plots in Ste. Anne de Bellevue, Quebec, Canada have been under a continuous experimental regime since 1991. Corn (*Zea mays* L.) is grown in plots under a factorial design with three tillage treatments (no till, reduced tillage, and conventional tillage), and two levels of residue input (roots plus corn stover, roots only). There was no tillage or residue effect on the corn grain yield in the fall of 2007. Soils were sampled in the fall of 2007, and the SOC in the samples from two depths (0-5 cm, 5-20 cm) were measured. There was no difference in SOC due to 16 years of tillage treatments, although there was a residue effect, after accounting for the within-plot variation that existed before 1991. The extra SOC in the high residue input plots was approximately 7.7-8.3% of the extra residues that were applied to those plots. This indicates that very little of the C input to this sandy-loam soil was stabilized and retained in the long-term, suggesting that the soil is C-saturated.

1.0 Introduction

As the CO_2 concentration in the atmosphere continues to rise at a rate of 1.7 ppmv y^{-1}, there is strong scientific interest in finding ways to slow or reverse this trend. One of the proposed ways to mitigate the rise of atmospheric CO_2 is to adopt agricultural practices that increase the amount of C in the soil, thereby diverting it from the atmosphere (Lal 2008). Conservation tillage and leaving crop residues in the field are practices thought to increase the soil organic C (SOC) pool (Wolf and Snyder 2003; Madgoff and Weil 2004). Conservation tillage refers to tillage practices that disturb the soil less than the conventional mouldboard plough. No-till is the most extreme form, in which the soil is not ploughed at all. Reduced tillage, which involves shallow tillage or leaves part of the field unturned, is another form of conservation tillage. Leaving large amounts of crop residues unharvested in the agroecosystem tends to complement the effects of conservation tillage. Bruce et al. (1999) estimated that the introduction of SOC conservation practices, including conservation tillage, would sequester 85 Tg C y^{-1} in Canada and the United States. This estimate assumes an increase of 0.2-1 Mg C ha^{-1} y^{-1} on approximately 443 million ha of agricultural land. This would offset approximately 1.2% of the 7076 Tg C that was emitted in the United States in 2006 (Energy Information Administration 2007).

However, the effect of tillage and residue management on SOC pools varies by soil type and region, and not all soils sequester C when converted from conventional to no-tillage. Sandy soils are known to sequester less C than clayey soils, since they have a lower proportion of reactive clay surfaces where organo-mineral bonds form. Once all the available bonding sites are C-saturated, the remaining SOC is chemically unprotected, and is therefore quickly mineralized (Six et al. 2002).

More SOC sequestration is generally reported in drier, warmer climates than cool, wet climates (Franzluebber 2004). Marked increases in SOC following adoption of conservation tillage practices such as no-till are often reported in western Canada, but

modest increases or no change in SOC is more typical in eastern Canada. In Ontario, Quebec and Prince Edward Island, Angers et al. (1997) reported no significant difference in the size of the total SOC pools of no-till and conventionally tilled soils after 11 years of treatment. Angers et al. (1997) hypothesized that the low temperatures and high moisture content slowed the decomposition of SOC in the conventionally tilled plots to the same rate as the no-till plots. This suggests that adding residues to the soil should be particularly effective in building SOC pools in eastern Canadian soils, since the climate slows the decomposition of the residues, allowing the residue C to accumulate in soils. However, in the sandier soils of eastern Canada, the accumulation of SOC may be limited by the soil's capacity to bind and protect organic molecules from soil decomposers.

A similar observation was made by Deen and Kataki (2003). They measured the size of the total SOC pool at the Elora Research Station of the University of Guelph in no-till and conventional tilled soils after 25 years of treatments. They noted that the concentration of the SOC and bulk density did change significantly, as well as the distribution of SOC, but the differences disappeared when the size of the SOC pool was calculated on an equivalent mass basis (Ellert and Bettany 1995) along the entire soil profile.

The purpose of this study is to evaluate the total SOC pools (0-20 cm) calculated on an equivalent mass basis in corn agroecosystems as affected by 16 years of tillage practices and residue inputs.

2.0 Materials and Methods

2.1. Site Description

The experiment was conducted on a 2.4 ha field on the Macdonald Research Farm of McGill University in Ste-Anne de Bellevue, Quebec (45^{o}30'N, 73^{o}35'W, elevation 35.7 m). The mean annual temperature was 6.2^{o}C with 979 mm of precipitation, based on meteorological data collected from 1971 to 2000 at the Pierre Elliott Trudeau

International Airport in Dorval, Quebec (Environment Canada, 2002), which is approximately 16 km from the site. The soil was a Typic Endoaquent (Dystric Gleysol) belonging to the St-Amable and Courval series. This sandy soil contained an average of 815 g kg^{-1} sand, 89 g kg^{-1} silt, and 96 g kg^{-1} clay in the top 20 cm with 19.9 g SOC kg^{-1} when the study was initiated. Further details of the site characteristics and preparation were described by Burgess et al. (1996), Callum (2001) and Dam et al. (2005).

2.2. Experimental Design

In the spring of 1991, the alfalfa growing at the site was ploughed under and the site was amended with 6-8 Mg lime ha^{-1}. A factorial experiment with three types of tillage (conventional tillage, reduced tillage and no-till) and two types of residue management (low residue input, high residue input) was established, for a total of six factorial treatments. The plots were 80 m by 18.5 m, arranged in a randomized complete block design with three blocks, giving 18 experimental plots (Fig. 1). A 2 m wide buffer separated the plots, while blocks were separated by a 3-4 m wide buffer. The buffers were cultivated regularly during the growing season to remove weeds.

After initial site preparation, no additional tillage operations were undertaken in the no-till (NT) plots. The conventional tillage (CT) plots were tilled with a Kongskilde 20 series mouldboard plough to a depth of 20 cm each fall after harvest and with a Burch tandem disk harrow each spring before seeding. The reduced tillage (RT) plots were tilled to a depth of approximately 15 cm with an offset disk harrow in the fall after harvest and a tandem disk harrow to a depth of approximately 10 cm in the spring each year before planting. All plots were seeded with a John Deere 7100 Max Emerge seeder and planted with corn (*Zea mays* L.). All plots were seeded with the same hybrid each year at a rate of 76 000 seeds ha^{-1}. The planting dates and hybrids used from 1991 to 2002 were reported by Dam et al. (2005). In 2003, Mycogen 2610 was planted and Mycogen 2K350 was planted during the period 2004 to 2007.

Since 1991, the nutrients required for corn production were supplied with inorganic fertilizers. Generally, a blend of calcium ammonium nitrate and monoammonium phosphate (23.4-11.7-0) was banded at planting to supply 40 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1}, with a side-dress application of 140 kg N ha^{-1} and 76 kg K_2O ha^{-1} from a blend of calcium ammonium nitrate and muriate potash (21.7-0-11.8) when corn reached the height of approximately 20cm. Weeds were controlled with a post-emergence applications of Aatrex (213g ha^{-1}a.i atrazine), Impact (11 mL ha^{-1} a.i. topramezone), Frontier (0.87 L ha^{-1} a.i. dimethenamide) The herbicide was applied with a dose of Crop Booster- a foliar fertilizer (2.676 L ha^{-1}), and Agral- a surfactant(0.40 L ha^{-1}a.i. nonylphenoxy polyethyoxyethanol) in order to enhance herbicide activity. Herbicide, surfactant, and foliar fertilizer treatments were generally identical for each plot, although additional applications were sometimes made to solve a specific pest problem. For example, plots 1, 11, and 14 were treated with Pardner (a.i. bromoxynil octanoate and bromoxynil heptanoate) in 2004 to control an outbreak of broadleaf weeds.

2.3. Corn Yield and Residue Management

Corn was harvested each year after the crop had reached physiological maturity and contained less than 20% moisture content. Yields were estimated by harvesting the corn plants along a 5 m transect at six locations within each plot. Corn was cut with a machete, just above the soil surface to assess the aboveground biomass, then separated into grain and stover (stems and leaves). Subsamples of grain and stover were dried (60^{o}C for at least 48 h) and yields were expressed on a Mg dry matter ha^{-1} basis. Following the yield assessment, the low residue input (O) plots were harvested with a silage harvester, which removed the stalks and leaves, leaving only 15 cm of stalk and the roots as residues in the field. The high residue input plots (R) were harvested with a combine harvester, and only the grain was removed, leaving the cobs, leaves, stems, and roots in the field. The mass of stover (Mg ha^{-1} of dry matter) left in the R plots was estimated from the hand-harvested subsamples (Table 1).

2.4. Soil Sampling and Analysis

Soil samples were taken after corn harvest, before fall tillage operations in October 2007. Soils were collected with a hand trowel and separated into two depths, 0-5 cm and 5-20 cm. A composite sample for each depth was made by mixing subsamples from five randomly selected locations within the plot. Soils were sieved through a 6 mm mesh screen in the field to remove rocks and residues, placed in sealed polyethylene bags and stored at 4^{o}C. The gravimetric soil moisture content was determined after drying (60^{o}C for 48 h). Then, the soil was finely ground to pass through a 1 mm mesh sieve and analyzed for total C and N with a Carlo-Erba Flash EA CN analyzer (Milan, Italy).

Soil bulk density was determined in April 2008 by taking 4 cores per plot (8.4 cm diameter, 7.7 cm height). Two cores were taken at the surface of the soil, and two cores were taken from the soil directly underneath the first cores. The cores were dried to a constant mass at 60^{o}C and the soil was weighed to determine the bulk density. Although the cores were slightly longer than 5 cm, the top cores were used to estimate the bulk density of the top 5 cm layer, and the bottom cores were used to estimate the bulk density of the 5-20 cm layer.

2.5. Calculation of the Total SOC Pool

The Carlo-Erba provided total C values (g C kg^{-1}), which were assumed to equal SOC because there were no carbonates in this soil. The SOC in the soil layers (0-5 cm, 5-20 cm) of each plot was converted to a Mg C ha^{-1} basis and added to give the total SOC pool (0-20 cm) per plot. To nullify the bias introduced by denser soils, however, the SOC pool was calculated for a constant mass of soil (2063 Mg ha^{-1}) based on the equivalent soil mass concept, modified from Ellert and Bettany[1] (1995). This mass was chosen since

[1] The Ellert and Bettany (1995) method requires the equivalent mass to be the total mass of the *densest* soil in a particular layer. The other soils are made equivalent by adding a layer of subsoil to the other layers. This method was not possible to follow exactly in this case, since I had no information on the layer below the 5-20cm soil layer. Instead, the mass of the least dense soil in the top 20cm was chosen to be the equivalent mass, and a thinner layer of the denser soils was considered so that the masses being considered of each soil was equivalent for each plot.

it is the mass of the top 20 cm of the least dense soil. The mass of denser soils was made equivalent by considering a slightly thinner layer. This was accomplished by following the steps below:

(a) The mass of soil in the 0-5 cm layer was calculated with eq. (1)

$$W_{0\text{-}5} = A \times D \times \rho_{b0\text{-}5cm} \qquad (1)$$

where $W_{0\text{-}5}$ is the mass of the 0-5 cm soil layer in Mg ha^{-1},

A is the area of one ha in m^2 (10000 m^2),

D is the depth of the layer in m (0.05 m), and

$\rho_{b0\text{-}5}$ is the bulk density of the 0-5 layer of soil (Mg m^{-3}).

(b) The mass of the lower layer of soil is calculated with eq. (2)

$$W_{5\text{-}20} = W_e - W_{0\text{-}5} \qquad (2)$$

where $W_{5\text{-}20}$ is the mass of the 5-20 cm layer in Mg ha^{-1}, and

W_e is the equivalent mass of the 0-20 cm layer. (2063 Mg ha^{-1}).

(c) The depth of the 5-20 layer is adjusted using eq. (3)

$$D_{adj} = W_{5\text{-}20} / (\rho_{b5\text{-}20} \times A) \qquad (3)$$

where D_{adj} is the adjusted depth of the 5-20 cm layer in Mg ha^{-1}, and

$\rho_{b5\text{-}20}$ is the bulk density of the 5-20 layer of soil (Mg m^{-3}).

(d) After normalizing the soil mass, the mass of SOC (Mg C ha^{-1}) for each layer was calculated using eq. (4).

$$SOC = (C_{0\text{-}5} \times A \times D_{0\text{-}5} \times \rho_{b0\text{-}5}) + (C_{5\text{-}20} \times A \times D_{adj} \times \rho_{b5\text{-}20}) \qquad (4)$$

where SOC is the mass of soil organic C (Mg ha^{-1}) in approximately 0-20 cm layer (adjusted so the masses are equivalent).

$C_{0\text{-}5}$ is the concentration of C measured in the 0-5 cm layer (kg C Mg^{-1}soil)

$D_{0\text{-}5}$ is the depth of the top layer (0.05 m)

$C_{5\text{-}20}$ is the concentration of C measured in the 5-20 cm layer (kg C Mg^{-1}soil)

(e) The mass of SOC in each plot in 1991 was calculated using the concentration of SOC in the top 25 cm that was measured in 1991 (Callum 2001), normalized to the same equivalent mass that was used for the 2007 data in eq. (5).

$$SOC_{1991} = C_{0\text{-}25} \times W_e \qquad (5)$$

where SOC_{1991} is the mass of soil organic C (Mg ha^{-1}) in 1991 in the 0-20 cm (approx.) layer (adjusted so the masses are equivalent).

$C_{0\text{-}25}$ is the concentration of C in the 0-25 cm layer in 1991 (kg C Mg^{-1} soil)

W_e is the adjusted mass used in 2007 (2063 Mg ha^{-1})

(f) The change in SOC from 1991-2007 is calculated using eq. (6)

$$\Delta SOC = SOC - SOC_{1991} \quad (6)$$

where ΔSOC is the change in SOC (Mg ha^{-1}) between 1991 and 2007, and SOC is the soil organic carbon (Mg ha^{-1}) in 2007.

2.6. Statistical Analysis

Data were tested for normality with a Kolmogorov-Smirnov test to ensure equal variance among populations prior to analysis of variance. The corn yield and total SOC were found to be normal once an outlier, plot 14, was removed from the dataset, but the change in SOC from 1991 needed to be transformed to 1/y to achieve normality. Differences in corn yields and SOC pools due to tillage, residue management and the tillage x residue management interaction were evaluated with analysis of variance (ANOVA) using SAS statistical software (SAS for Windows, version 9.1, SAS Institute Inc., Cary, NC). When treatment effects were significant ($P<0.05$), mean values were compared with a least significant difference (LSD) test at the 95% confidence level. Data presented in the tables and figures are the untransformed means (± standard errors).

3.0. Results and Discussion

3.1. Grain and Stover Yield

In 2007, the grain yield was not affected by the tillage or residue treatments (Fig. 2, Table 2). The grain yield in 2007 was between 11.3 and 11.7 Mg ha^{-1}, which is above the average yield of 7.3 Mg ha^{-1} reported by Dam et al.(2005), but within the range of natural variation, and comparable to the average grain harvest of 11.85 Mg ha^{-1} they

reported in 1999. In addition, there has seldom been a difference in grain yield on these plots due to tillage or residue treatments (Dam et al. 2005).

The stover yield and the total dry weight at harvest was significantly (P<0.05) affected by residue management, with the high residue plots yielding more than the low residue plots (Fig. 2, Table 2). However, Dam et al. (2005) did not observe any positive effect of high residue treatments on stover yield from 1991-2002. This is an interesting result, but it should be confirmed by the harvests in the coming years before any conclusions can be drawn from it.

3.2. Total SOC Pool

The total SOC under each experimental treatment in 2007 in the plough layer is presented in Figure 3, with ANOVA results presented in Table 3. The SOC pool ranged in size between 37 and 58 Mg ha^{-1}, which is comparable to the average values presented by Angers et al. (1997) for the SOC pools in various agroecosystems of eastern Canada. There were no significant tillage effects, which is also consistent with the results presented by Angers et al.(1997). They hypothesized that the limiting factors of soil moisture and temperature control SOC pools in soils of eastern Canada, so tillage is expected to have a relatively minor effect on the accumulation or depletion of the SOC pool in this region.

Residue treatments had a marginal effect (P=0.071) on the SOC pool size in 2007. The fact that this effect is only marginal is probably caused by the natural variation of the soil masking the true effect of the residue management. This can be shown by the following analysis: The high residue input plots received an estimated 115.2 to 123.2 Mg dry matter ha^{-1} of corn stover residues during the past 16 years (Table 1). Assuming that corn stover contains 40% C (Wilhelm et al. 2007), this suggests a cumulative C input of 51.8 to 55.5 Mg ha^{-1}. We would expect a minimum of 10% of the residue C to be transformed into the SOC pool (Gregorich et al. 1996). Therefore, there should be an

extra 5.2-5.5 Mg SOC ha^{-1} in the R plots compared to the O plots. This expectation was actually exceeded, since on average the R plots contained 6.5 Mg SOC ha^{-1} more than the O plots. This difference, however, was not enough to show an effect with a Pr>0.05, since the natural variability in the plots masked the difference.

It is therefore useful to try to nullify some of the natural variation. This was accomplished by calculating the change in SOC in each plot since 1991. Comparing the change in SOC from 1991-2007 instead of the total SOC in 2007 accounts for natural soil variation that existed at this site before 1991. The data are presented in Figure 4, with results from the ANOVA in Table 3. There was a significant effect of residue management on the ΔSOC between 1991 and 2007 (Pr=0.001), with a difference of 4.3 Mg C ha^{-1} between the high residue and low residue plots. This is approximately 7.7% to 8.3% of the cumulative plant C input from the high residue treatment (Table 1).

Gregorich et al. (1996) concluded that 10-20% of the crop residues added to the soil were converted to SOC. Although close to the minimum SOC conversion rate presented by Gregorich et al. (1996), the conversion of residues into SOC in this experiment was relatively low compared to other experiments. Blanco-Canqui and Lal (2007) showed that approximately 33% of all C from plant residues added to the soil in a 10-year experiment was sequestered in the soil as SOC. This study was done on a silty loam soil, which, having more silt and clay, can ostensibly protect added C better than the soil in our experiment.

Whalen et al. (2008) measured the change in the SOC over 5 years caused by composted cattle manure applications on a sandy loam soil adjacent to our site. Their data show that 17-21% of the C applied as compost remained in the soil as SOC. The lower residue to SOC conversion rate in our study can be explained by the saturation of protected sites in the soil. Since our study lasted much longer than the study by Whalen et al. (2008), it is possible the soil became C-saturated, which would explain why the residues added in later years were unprotected and completely mineralized. Furthermore,

the compost added by Whalen et al. (2008) was already partially stabilized when it was applied, unlike crop residues which are quite labile.

4.0. Conclusion

This study shows that there was no effect of tillage practices on the total SOC pool on a monoculture corn field with a sandy-loam soil in Ste-Anne de Bellevue, Quebec. This result is possibly a result of the cool climate, which controls the rate of decomposition to a much greater degree than tillage practices. The rate of residue input, however, had a highly significant effect. After 16 years of residue management, the mean difference between the high residue and the low residue treatments was 4.3 Mg C ha^{-1} stored as SOC. This is approximately 7.7 to 8.3 % of the amount of C added to the high residue treatment over 16 years. This represents a gain in SOC of less than 1% per year, which is lower than C sequestration rates reported in the scientific literature. It seems likely that the organo-mineral sites in this sandy-loam soil were C-saturated and so additional plant C was not transformed into the stable SOC pool.

Tables for Chapter 2

Table 1: Residue input (Mg dry matter ha^{-1}) from corn stover to high-residue plots under no-till, reduced tillage and conventional tillage from 1991-2002 (from Dam et al. 2005), 2006 and 2007. The cumulative C input (Mg C ha^{-1}) from plant residues during the period 1991 to 2007 was estimated by calculating the mean stover harvest in 1991-2002, 2006, and 2007 and multiplying it by 16 years.

	Residue input to soil (Mg ha^{-1})		
Year	No till	Reduced tillage	Conventional tillage
1991	7.8	6.6	6.8
1992	6.9	6.7	7.7
1993	6.5	5.9	7.4
1994	5.5	7.4	7.9
1995	7.1	5.6	7.1
1996	6.6	5.9	6.3
1997	7.6	8.1	8.3
1998	7.7	7.1	8.3
1999	10	8.2	9
2000	6.3	7.4	7.8
2001	7	10	8.6
2002	4.6	4.5	4.6
2006	6.9	7.3	8.2
2007	10	9.6	10.3
Mean	7.2	7.2	7.7
Standard deviation	1.5	1.5	1.3
Estimated C input due to high residue additions	115.3	115.3	123.2

Table 2: Effect of tillage and residue management of the weight of the stover, grain, and the total dry weight of the corn crop in 2007. Values are the F statistic and the probability values (Pr) from analysis of variance (n=17).

	Degrees of Freedom	Stover		Grain		Total	
		F	Pr	F	Pr	F	Pr
Tillage	2	1.85	0.163	0.29	0.749	0.8	0.453
Residue	1	7.4	0.008	1.36	0.246	6.26	0.014
Tillage*Residue	2	0.53	0.589	0.06	0.943	0.28	0.755
Block	2	14.74	<0.001	0.72	0.488	9.32	<0.001

Table 3. Effect of tillage and residue management on the total SOC in 2007 (Mg ha^{-1}) and the change in SOC between 1991 and 2007 (Mg ha^{-1}).Values are the F statistic and the probability values (Pr) from analysis of variance (n=18).

	Degrees of Freedom	Total SOC 2007		ΔSOC 1991-2007	
		F	Pr	F	Pr
Tillage	2	1.32	0.311	2.33	0.148
Residue	1	4.07	0.071	20.96	0.001
Tillage*Residue	2	0.65	0.543	0.38	0.696
Block	2	2.08	0.176	0.06	0.939

Figures for Chapter 2

CT+R	NT+O	NT+R	CT+O	RT+R	RT+O
NT+O	RT+R	CT+O	RT+O	NT+R	CT+R
CT+O	RT+O	CT+R	NT+R	NT+O	RT+R

Fig. 1. Factorial experiment in corn agroecosystems at the Macdonald Campus Farm (Ste-Anne-de-Bellevue, Quebec). The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

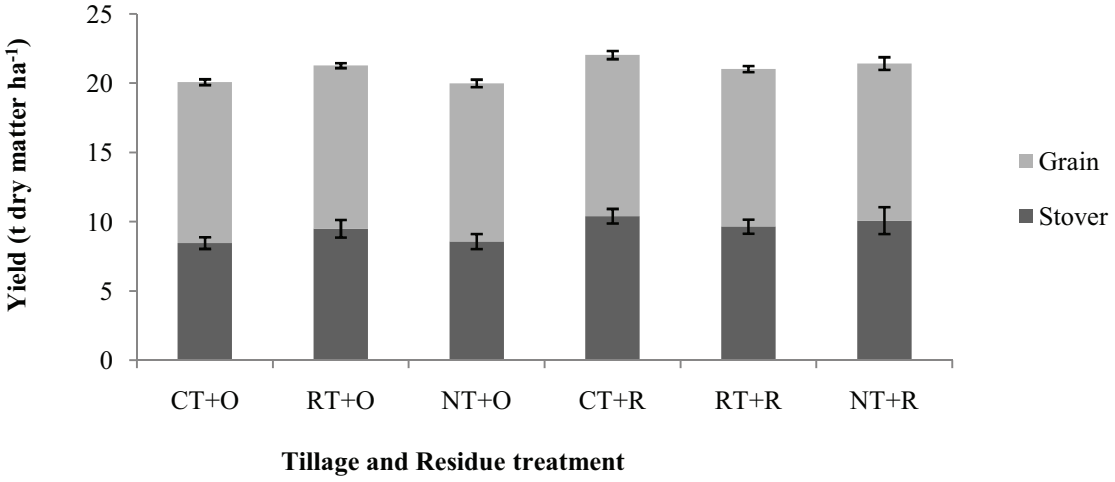

Fig. 2: Corn yield (Mg dry matter ha^{-1}) of grain and stover from plots at the Macdonald Campus Farm (Ste-Anne-de-Bellevue, Quebec) in 2007, after 16 years of experimental treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

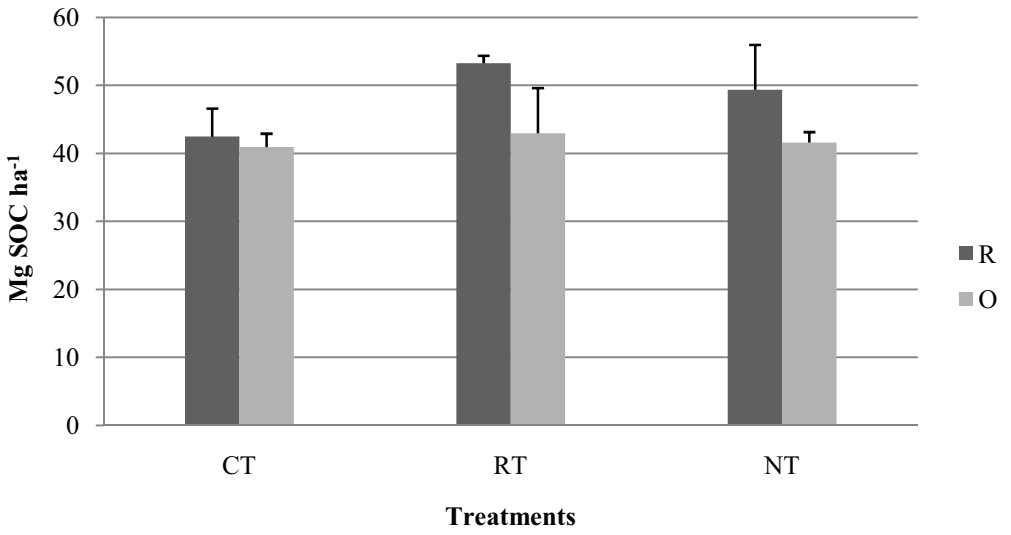

Fig 3. The SOC pool (Mg C ha^{-1})in the 0-20 cm depth from experimental plots at the Macdonald Campus Farm (Ste-Anne-de-Bellevue, Quebec) in 2007, after 16 years of experimental treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

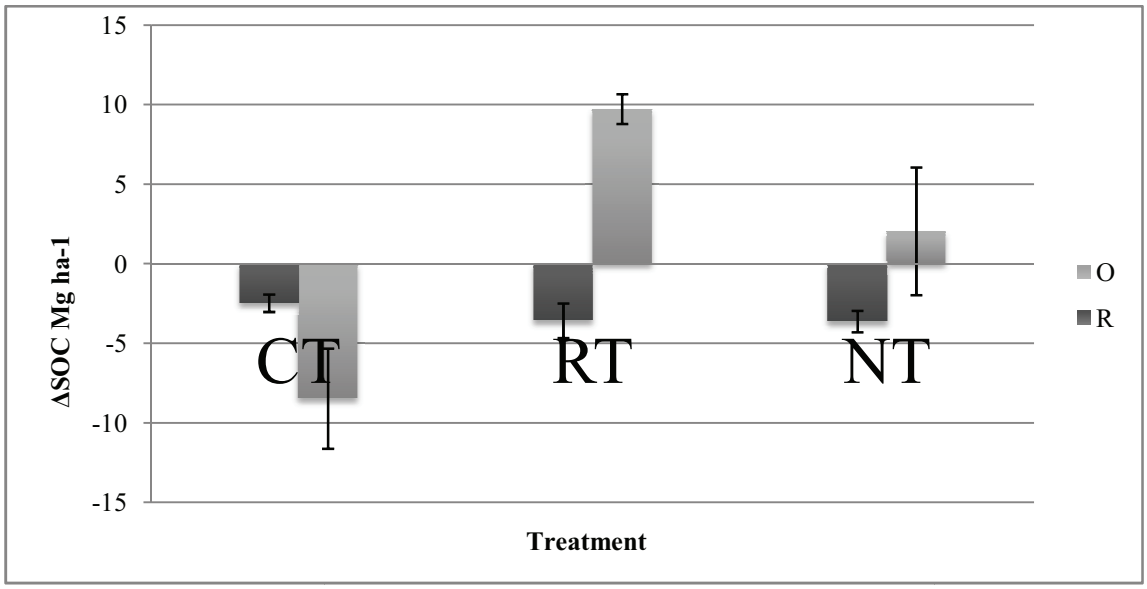

Fig 4. The change in the size of the SOC pool from 1991-2007. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

Connecting paragraph

In Chapter 2, I discussed the effect of agricultural management practices on the SOC pool in a sandy-loam soil. I observed that tillage practices did not affect the size of the SOC pool (0-20 cm depth), but plots receiving high residue inputs had a larger SOC pool than plots with low residue inputs. In the next chapter, I will discuss how these agricultural management practices affect the potential C and N mineralization from the soil organic matter (SOM), which is an indicator of the size of the labile C and N pools in soil (described in Chapter 1, Section 2).

CHAPTER 3: THE EFFECTS OF TILLAGE AND RESIDUE MANAGEMENT ON THE LABILE CARBON AND NITROGEN POOLS

Abstract

The labile pool of soil organic matter (SOM) is the immediate source of C and N for soil microorganisms and N for plants, and it also positively affects the physical structure of the soil, despite its small size relative to the total SOM. The objective of this study was to determine how the labile SOM pool is affected by agricultural practices, namely tillage and crop residue management. The C and N mineralization potential was measured on soil from a long-term (16 y) field experiment where corn (*Zea mays* L.) was produced in factorial plots with three tillage treatments (NT, RT and CT) and a high and low level of residue input (roots plus corn stover, roots only). The microbial biomass C and N (MBC and MBN) were also measured to determine what effects agricultural treatments had on the microbial population. The mineralization experiments showed that the labile C and N pools in the 0-5 cm layer were larger when the soil was less disturbed (NT≥RT>CT). In the 5-20 cm layer, the RT treatment had a larger labile C and N pools than the NT and CT treatments. There was more labile C and N with high residue inputs than low residue inputs, regardless of the soil layer examined. The MBC and MBN concentrations in the top 20 cm were greater in less disturbed soils (NT>RT>CT) and greater with high residue inputs. The MBC:MBN ratio was highly variable, and there were no significant differences between the tillage treatments. Both the tillage and residue treatments were found to have significant effects on the labile SOM pool, which indicates that they have an impact on soil microbial communities and soil fertility.

1.0 Introduction

Soil organic matter (SOM) is an important reservoir of C and N, and is protected by physical, chemical and biochemical mechanisms (Jastrow et al. 2007; Six et al. 2002). SOM can be divided into three theoretical fractions – labile, intermediate and recalcitrant - based on the degree to which the organic compounds are protected from microbial degradation (Wander 2004). Although the labile pool is relatively small compared to the total SOM, it is the main immediate source of C and N for microbes and N for plants. Furthermore, the labile pool has a disproportionate positive effect on the physical qualities of the soil (Haynes 2005).

There is no agreement in the literature on the method to quantify the labile SOM pool, but C and N mineralization rates can provide an indication of the size of the labile pool. The results of mineralization studies cannot be interpreted as a measure of the true size of the labile C and N pools, but they can be used to compare the relative sizes of labile C and N pools within the same study, as they are affected by agricultural practices (Haynes 2005).

Tillage methods often have an effect on the size of the labile C and N pool (Sharifi et al. 2008; Haynes 2005). Soils are known to have increased respiration rates immediately after tillage events, and the respiration rate then falls below the original rate of the undisturbed soil (Calderon et al. 2001). This implies that tillage destroys the physical protection that has been partially preserving the labile pool. The labile pool is therefore quickly mineralized, and becomes greatly reduced, which means that later on it can support less microbial activity. A similar flush of mineralized nitrogen is observed after a tillage event (Calderon et al. 2001).

The amount of residues that is allowed to stay in the field often has a significant impact on the size of the total SOM pool (Barber 1979; Wilhelm 2004). The labile SOM

pool is generally more sensitive than the total SOM pool to management induced changes (Haynes 2005), and therefore it is reasonable to expect residues to have an impact on the labile SOM pool as well. Furthermore, over 50% of the fresh residues and comprised of labile materials such as cellulose and hemicellulose (Wilhelm et al. 2004), and therefore residues are a direct addition to the labile pool.

Tillage and residue management also affects the size and type of microbial population that exists in the soil (Calderon et al. 2001). Disturbed soils tend to support a primarily bacterial population, whereas undisturbed soils tend to support greater fungal populations (Thiet et al. 2006). These populations have different C:N ratios (White 2006), so the C:N ratio of the microbial biomass will change as the population shifts. Residue inputs tend to increase the amount of organic matter available for microbial decomposition, and thus soils with greater residue inputs are expected to have larger microbial populations than soils that receive less residue (Collins 1992).

The labile SOM and the microbial population are known be affected by tillage, even when the total SOC pool is not affected. Angers et al. (1993) measured the effect of tillage on total SOM, labile SOM, and microbial biomass carbon (MBC) in experimental plots in St. Lambert, Quebec. After 11 years of treatment, they found that although there was no increase in total SOC, the labile SOC pool and the MBC were significantly larger in soils that received minimum tillage.

The objective of this study was to examine the effects of agricultural practices on labile C and N pools, including microbial populations. Specifically, I examined the effects of tillage and residue management on the potentially mineralizable C and N during soil incubation. The microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) concentrations were also evaluated to determine how microbial populations were affected by these agricultural treatments.

2.0. Materials and Methods

2.1. Site description

The experiment was conducted on a 2.4 ha field on the Macdonald Research Farm of McGill University in Ste-Anne de Bellevue, Quebec (45°30'N, 73°35'W, elevation 35.7 m). The mean annual temperature was 6.2°C with 979 mm of precipitation, based on meteorological data collected from 1971 to 2000 at the Pierre Elliott Trudeau International Airport in Dorval, Quebec (Environment Canada, 2002), which is approximately 16 km away from our site. The soil was a fine, mixed, frigid Typic Endoaquent (Humic Gleysol) belonging to the St-Amable and Courval series.This sandy soil contained an average of 815 g kg^{-1} sand, 89 g kg^{-1} silt, and 96 g kg^{-1} clay in the top 20 cm with 19.9 g SOC kg^{-1} when the study was initiated. Further details of the site characteristics and preparation were described by Burgess et al. (1996), Callum (2001) and Dam et al. (2005).

2.2. Experimental design

In the spring of 1991, the alfalfa growing at the site was ploughed under and the site was amended with 6-8 Mg lime ha^{-1}. A factorial experiment with three types of tillage (conventional tillage, reduced tillage and no-till) and two types of residue management (low residue input, high residue input) was established, for a total of 6 factorial treatments. The factorial plots were 80 m by 18.5 m, arranged in a randomized complete block design with three blocks, giving 18 experimental plots (Fig. 1 in Chapter 2). A 2 m wide buffer separated the plots, while blocks were separated by a 3-4 m wide buffer. The buffers were cultivated regularly during the growing season to remove weeds. More details on the experimental treatments and site management were described in Chapter 2 of this thesis.

2.3. Soil sampling and analysis

Soil samples were taken after corn harvest, before fall tillage operations in October 2007. Soils were collected with a hand trowel and separated into two depths, 0-5 cm and 5-20 cm. A composite sample for each depth was made by mixing subsamples from five randomly selected locations within the plot. Soils were sieved through a 6 mm mesh screen in the field to remove rocks and residues, placed in sealed polyethylene bags and stored at 4^{o}C. The gravimetric soil moisture content was determined after drying to a constant mass (60^{o}C for 48 h).

2.4. Soil incubation

About 40 g (dry weight basis) of soil was placed into an open plastic vial (4 cm diameter). The soil was moistened to 40% water filled pore space (WFPS), which was calculated using eq. 1 (Franzluebbers 1999).

$$WFPS = M_s*(\rho_b*\rho_m/\rho_b-\rho_m) \quad (1)$$

where WFPS is equal to the fraction of the pores space filled with water (v/v).

M_s is the soil moisture content (v/v)

ρ_b is the bulk density of the soil (g cm^{-3})

ρ_m is the mineral density of the soil (2.65 g cm^{-3})

The plastic vial was placed in a 500 mL Mason jar and about 3 mL of water was added to the bottom of the Mason jar to maintain soil humidity (Fig. 1). The jar was capped with an air-tight lid, equipped with a septum for CO_2 measurements on jars used to evaluate C

mineralization (no septum on jars used for N mineralization). The Mason jars were placed in an incubator at 25°C, and were aerated by removing the lid for 2-3 min (N mineralization jars) and 10-15 minutes (C mineralization jars) each week to prevent anaerobic conditions from developing and to dissipate the accumulated CO_2 from the previous week.

2.4.1. Carbon mineralization

The C mineralization experiment consisted of 38 experimental jars to accommodate soil samples from each experimental plot and soil depth (18 plots x 2 soil depths) plus two empty jars that contained no soil (blanks). Gas was sampled on a weekly basis for 20 weeks (see calendar in Appendix 1 for further details). About 20 mL of gas from the headspace of the Mason jar was taken with a gas-tight syringe and stored in a pre-evacuated 12 mL exetainers (Labco, High Wycombe, UK) until analysis. A gas chromatograph with a thermal conductivity detector was used for CO_2 analysis (Hewlett-Packard 5890 Series II, Hewlett-Packard Company, Avondale, PA, USA).

The gas chromatograph measured the concentration of CO_2 in ppm. The change in CO_2 concentration caused by the soils was calculated with eq. 2

$$C_{soil}=C_{total}-(C_{b1}+C_{b2})/2 \qquad (2)$$

where C_{soil} is that concentration of CO_2 (ppm) caused by respiration from the soil,

C_{total} is the concentration of CO_2 (ppm) in the Mason jar, and

C_{b1} and C_{b2} are the concentrations of CO_2 (ppm) in the blank samples.

The mass of the C respired from the soil was found using eq. 3.

$$M = C_{soil} * (PV/RT) * M_c/1000 \quad (3)$$

where M is the mass of C respired from the soil (mg),

P= is the gas pressure in the Mason jars (1 atm),

V is the volume of the Mason jar (0.5 L),

R is the universal gas constant (0.082 L atm $mole^{-1}K^{-1}$),

T is the temperature of the Mason jar (298^{o}K), and

M_c is the molar mass of C (12 mg $mmole^{-1}$).

The total amount of C respired from the sample was equal to the sum of the C respired each week during the 20-week incubation. Cumulative C mineralization (mg C kg^{-1} soil) is equal to the total C respired (mg C) divided by the soil dry weight (kg).

After the first week of incubation, it became clear that some of the soils had become compacted and waterlogged. These samples needed to be repeated for both the C and N mineralization experiments and so the experimental units were removed, fresh soil was moistened and placed in the jars, and the units were returned to the experiment. Appendix 1 provides details of the dates on which these samples entered the experiment and were analyzed. A list of repeated samples is given in Appendix 2.

2.4.2. Nitrogen mineralization experiment

The N mineralization experiment consisted of 252 experimental units, 7 units for each of the 36 soil samples. One experimental unit for each soil sample was selected at random and destructively sampled at week 1, 2, 4, 8, 12, 16 and 20 after the incubation study began (see calendar in Appendix 1 for details). Non-incubated soil was also analyzed to determine the initial N concentration (week 0). Like the C mineralization experiment, some of the samples needed to be repeated. The details are explained in Appendices 1 and 2.

2.4.3. Soil analysis

The gravimetric moisture content of the soil was determined by drying about 5 g of soil (non-incubated and incubated samples) for 48 hours in a 65^{o}C oven. Moist samples were extracted following the procedure outlined by Maynard et al. (2008) with 2M KCl (1:5 soil:extractant). The concentration of N-NH_4 and N-NO_3 (mg L^{-1}) were determined colorimetrically using a Lachat Quick Chem flow injector autoanalyzer (Lachat Instruments, Milwaukee, WI 53218 USA). The concentration of mineral N (NH_4-N and NO_3-N) in mg N kg^{-1} soil was calculated using eq. 4

$$N_{min} = ((N_m - N_b) * (V + M_s * Ds/100))/D_s \quad (4)$$

where N_{min} is the amount of N mineralized from the sample (mg N kg^{-1} soil),

N_m is the concentration of N measured in the extract (mg L^{-1}),

N_b is the average concentration of N measured in the blank extracts (mg L^{-1}),

V is the volume of 2 M KCl added to the soil during the extraction process (0.05 L),

D_s is the dry weight of the extracted soil (kg), and

M_s is the moisture content of the soil (%).

2.4.4. Microbial biomass analysis

Two subsamples of 10 g each were taken from each bag containing non-incubated soil (soil came from 18 plots x 2 soil depths = 36 samples). One subsample was immediately extracted with 40 ml 0.5 M K_2SO_4, and the other was fumigated with chloroform for 5 days and then extracted with 40 ml 0.5 M K_2SO_4. The C concentration was then determined in both the fumigated and unfumigated samples using a Shimadzu TOC-V carbon analyzer. The MBC (mg C kg^{-1}soil) was calculated using equations 5 and 6.

$$DOC = (TOC - TOC_b) x [V_e + V_s] \times d_f / D_s \quad (5)$$

where DOC is the dissolved organic C (mg kg^{-1} soil)

TOC is the concentration of C in the extract (mg L^{-1})

TOC_b is the concentration of measured in the blank samples (mg L^{-1})

V_e is the volume of 0.5 M K_2SO_4 used to extract the C (L)

V_s is the volume of water in the wet soil sample (L)

d_f is the dilution factor (5 ml: 20ml)

D_s is the dry weight of the soil in kg.

The MBC is found using eq 6.

$$MBC = (DOC_f - DOC_u) / K \quad (6)$$

Where DOC_f is the DOC in the fumigated sample (mg kg^{-1})

DOC_u is the DOC in the unfumigated sample (mg kg^{-1})

K is a constant (0.45) (Joergensen et al. 1996a).

The extracts were then digested using an alkaline persulfate solution. The N concentration were then determined using a Lachat Quick Chem flow injector autoanalyzer. The MBN (mg N kg^{-1} soil) was calculated using equation 7:

$$MBN = ((N_f - B_f) - (N_u - B_u)) * (V_s + V_e) * (d_f) / (S_w * K_{en}) \quad (7)$$

Where N_f is the concentration of $N\text{-}NO_3$ in the fumigated and digested extract (mg L^{-1})

N_u is the concentration of $N\text{-}NO_3$ in the unfumigated and digested extract (mg L^{-1})

B_f and B_u are the concentration of NO_3 in the blank fumigated and unfumigated samples.

V_e is the volume of 0.5 M K_2SO_4 used to extract the C (L)

V_s is the volume of water in the wet soil sample (L)

d_f is the dilution factor

D_s is the dry weight of the soil in kg.

K_{en} is a constant (0.54) (Joergensen and Mueller 1996b)

2.5. Statistical Analysis

The N_{max} and C_{max} were determined from the N and C mineralization data using the non-linear least-square regression function in SPSS statistical software (SPSS statistical software, version 16.0, SPSS Inc., Chicago, IL). The data points were fitted by eq. 8 (Curtin and Campbell 2008):

$$X_t=X_{max}(1-e^{-kt}) \qquad (8)$$

Where X_t is the amount of C or N mineralized in a given time period (mg kg^{-1}).

X_{max} is an estimate of the total size of the mineralizable pool of C or N (mg kg^{-1})

k is the rate constant (estimated at 0.054 $week^{-1}$)(Curtin and Campbell 2008)

t is time since the beginning of the incubation (weeks)

The N_{max} and C_{max} values were compared among tillage treatments and residue treatments, with a simple Student's t-test at the 95% confidence level.

The MBC, MBN, and MBC:MBN data were tested for normality to be sure that the assumptions for analysis of variance (equal variance among populations) were not violated using a Kolmogorov-Smirnov test. If the test showed the normality assumption to be violated, the data were transformed to 1/y and tested again. Differences MBC, MBN, and the MBC:MBN ratio due to tillage, residue management and the tillage x residue management interaction were evaluated with analysis of variance using Minitab statistical software (Minitab, version 14, Minitab Inc. State College, PA). When treatment effects were significant (P<0.05), mean values were compared with a Tukey test at the 95% confidence level. Data presented in the tables and figures are the means (± standard errors).

3.0. Results and Discussion

3.1. C mineralization

The cumulative C mineralization that occurred in the incubated samples over time from the 0-5 cm soil layer is presented in Fig. 2 and 3. These data points fit well into the first-order rate equation (eq. 8), and the R^2 of the fitted equations ranged from 0.993 to 0.997 (Table 1). The C_{max} values, which are an indication of the size of the labile C pool, were significantly affected by tillage (NT>RT>CT, t-test P<0.05) and by residue management (R>O, t-test P<0.05) in the 0-5 cm layer.

Cumulative C mineralization in the 5-20 cm soil layer was also affected by tillage (Fig. 4) and residue management (Fig. 5). The C_{max} values (Table 2) were significantly affected by tillage (RT>NT>RT, t-test P<0.05) and by residue management (R>O, t-test P<0.05). The data fit well into the first order rate equation, with R^2 values ranging from 0.985 to 0.991 (Table 2). It may not be appropriate to compare cumulative C

mineralization from this study with other reports in the scientific literature due to differences in experimental conditions (e.g., soil handling and incubation conditions). However, the C_{max} value can be used to compare the relative sizes of the labile C pool due to agronomic treatments.

The C_{max} mineralization in soils under various tillage and residue management treatments (see Table 1-2 and Fig. 2-5)) ranged from 851-2075 mg C kg^{-1} soil during a 20-week incubation. This is about 3-8% of the total C in the soil, which is within the 0.5-12% range suggested by Haynes (2005).

Although the tillage effect was not discernable in the total SOC pool (see Chapter 2), it is not surprising that tillage had a significant effect on the labile C pool. The labile pool is smaller and more transient than the total SOC pool, and is therefore more measurably affected by tillage treatments. Haynes (2005) reported that the change in the mineralizable C pool is often proportionally much greater than the effect on the total SOC pool. Tracy et al. (1990) found that soils incubated after 16 years of reduced tillage on a Durac loam soil had nearly double the amount of mineralizable C than their conventionally tilled counterparts. On the other hand, Sainju et al. (2008) found no tillage effect on the mineralizable C after 9 years of no till and conventional tillage treatments.

The effect of different levels of residue input on the labile C pool was consistent with my hypothesis. Residues are labile organic matter containing approximately 40% C (Wilhelm et al. 2007), most of which is labile (Wilhelm 2004) and adding them to the soil increases the size of the labile C pool.

3.2. N mineralization

The cumulative N mineralization that occurred in the incubated samples over time from the 0-5 cm soil layer is presented in Fig. 6 and 7. These data points fit well into the first-order rate equation (eq. 8), and the R^2 of the fitted equations ranged from 0.975 to 0.996 (Table 3). The N_{max} values, which are an indication of the size of the labile N pool,

were significantly affected by tillage (NT=RT>CT, t-test $P<0.05$) and by residue management (R>O, t-test $P<0.05$) in the 0-5 cm layer.

Cumulative N mineralization in the 5-20 cm soil layer was also affected by tillage (Fig. 8) and residue management (Fig. 9). The N_{max} values (Table 4) were significantly affected by tillage (RT>NT=CT, t-test $P<0.05$) and by residue management (R>O, t-test $P<0.05$). The data fit well into the first order rate equation, with R^2 values ranging from 0.92 to 0.98 (Table 3). It may not be appropriate to compare cumulative N mineralization from this study with other reports in the scientific literature due to differences in experimental conditions (e.g., soil handling and incubation conditions). However, the N_{max} value can be used to compare the relative sizes of the labile N pool due to agronomic treatments.

Several studies found similar results. Tracy et al. (1990) incubated soil samples after 16 years of no-till on a Durac loam soil and found that more N was mineralized in the no-till soils than in the conventionally tilled soils. Liebig et al. (2004) found similar results after 16 years of no-till on a silty loess soil. When comparing no till to conventional tillage at four Canadian sites, Sharifi et al. (2008) found a significantly more mineralizable N in no-till soils at three out of the four sites.

The significant effect of tillage and residue on the N_{max} is similar to the results for the C mineralization experiment. This is to be expected, because the labile organic matter contains both C and N, and when it is decomposed, both the C and the N are mineralized.

Although some researchers use cumulative N mineralization and N_{max} values to elucidate the N dynamics under field conditions and to make N fertilizer recommendations, it does not seem appropriate in this study. Soil handling (sieving and moistening) and the conditions of the experiment (ideal temperature, humidity for microbial activity) can greatly affect the amount of N mineralization that occurs. The results are best interpreted as the size of a potentially mineralizable N pool, as opposed to

how much N is actually mineralized in the field. In fact, the larger pool of mineralizable N in the NT and RT soils (0-5 cm) implies that there is *less* mineralization in the field, leading to a buildup of labile N which is mineralized during the experiment (Haynes 2005). This implies that the first few years of a NT regime might require extra fertilizer. The significantly larger mineralizable N pool in the high residue plots shows that not all the residues that are added to the soils are immediately mineralized or transformed into biochemically- or chemically-stable organic N forms. At least some of the added residue becomes part of a labile N pool that is readily mineralized during laboratory incubation. It seems likely that this labile N was part of residues that were physically protected in the field, but the physical protection was lost upon sieving and handling. Further research into the physical protection of SOM under field conditions is warranted.

3.3. Microbial biomass

The MBC concentration ranged from 190 to 417 mg C kg^{-1} soil, while the MBN concentration was between 19 and 190 mg N kg^{-1} soil (Figs. 10 and 11). These results indicate more variability due to tillage and residue treatments than the results presented by Spedding et al. (2004) from the same experimental plots, which gave microbial biomass measurements ranging from 135-200 mg C kg^{-1}, and 17-27 mg N kg^{-1}. In this study, the MBC concentration in the 0-5 cm layer differed (P<0.05, Tukey test) among the following treatments: NT>CT and R>O (Table 5). Similarly, there were significant differences (P<0.05, Tukey test) in the MBN concentration with NT>CT in the 0-5 cm layer, and RT>NT,CT and R>O in the 5-20 cm layer (Table 6). The MBC:MBN ratio in the tillage treatments and residue input levels was highly variable, and the only significant difference was a greater MBC:MBN ratio with low residue input than high residue input in the 5-20 cm layer (Fig. 12 , Table 7).

In the 0-5 cm layer, the MBC was found to be 1.2 times greater and the MBN 2.1 times greater in the high-residue plots than in the low residue plots. This is to be expected, because the added residues are a source of nutrients and energy for the

microbial community. Higher residue input allowed the microbial community to thrive, resulting in higher microbial biomass. This result was also observed by Spedding et al. (2004). The lack of significant effect of the residue input on the 5-20 cm layer MBC was also reported by Spedding et al. (2004). However, there is a significant increase of MBN, indicating that the nutrients available to the microbial population in the 5-20 cm layer were somewhat affected by the residue management. The interaction of tillage and residue effects on the MBN in the 5-20 cm layer probably indicates that the availability of N from the residues was only increased in conservation tillage plots, since in the conventionally tilled plots, the N in the residues was quickly mineralized and either absorbed by plants, immobilized in microbial biomass and converted to stable organic N, or lost from the agroecosystem via leaching or gaseous losses.

The tillage effect was significant in the 0-5 cm layer, and the Tukey test ranked the MBC by tillage in this order: NT >CT. This is similar to the results presented by Spedding et al. (2004). In a way, this result is surprising, because tillage is known to improve conditions for microbial life by improving the aeration, moisture, and availability of organic matter (Wolf and Snyder 2003).

These results can be explained in two possible ways. The first possibility is that although tillage can improve the conditions for microbial life, the disturbance caused by the tillage hurts the microbial community and decimates its numbers. This is particularly plausible if there was a large fungal population, whose hyphal network is known to be destroyed by tillage. This possibility was considered by Calderon et al. (2000). If this explanation were true, it would be expected that the microbial community structure in the soil would be changed significantly by tillage; specifically the fungi:bacteria ratio would shrink. This change in the fungi:bacteria ratio would be manifest in a fall in the MBC:MBN ratio, since fungi have significantly higher MBC:MBN ratios than bacteria (White 2006). The results of this experiment show no changes in the MBC:MBN ratio due to tillage, and Spedding et al. (2004) reported that the effect of tillage on the

microbial community composition in these plots was small compared to the normal seasonal variation.

The second possible explanation for the tillage effect on the MBC is that the tillage changed the rate at which sources of energy and nutrients were available to the microbial population. Following the tillage event, once physically protected SOM was suddenly exposed leading to a growth in microbial activity. After a time, the increased microbial activity exhausted the extra food source, and they died and were decomposed by subsequent microbial populations. By the time the soils were sampled in the fall, the microbial population was greatly reduced compared to the plots that were not tilled, in which the SOM became available at a slow and steady rate. Evidence for this hypothesis was presented by Calederon et al. (2001), who showed that the microbial respiration rate in the soil rose significantly after a tillage event followed by a steady fall of the respiration rate. To test this hypothesis, it would be necessary to measure the MBC immediately after a tillage event, and follow the change in MBC through time.

4.0 Conclusions

The mineralization experiments showed that conservation tillage, especially no-till, increased the size of the labile C and N pools in the top 0-5 cm. Furthermore, the labile C and N pools increased with higher crop residue inputs. In the 5-20 cm layer, the RT had a larger labile C and N pool than the NT, ostensibly because the crop residues were mostly retained at the surface of the NT plots. These results show that tillage and residue management both have a significant effect on the labile C and N pools, even when there is no clear effect on the total amount of SOC in the soil (see Chapter 2). The size of the microbial population was reduced in soils with long-term tillage treatments. This is probably related to the amount of labile C and N available for microbial growth in these soils, which is reduced by a wave of microbial activity immediately after tillage. This hypothesis could be tested by measuring the microbial biomass and respiration immediately after tillage, to see whether there are elevated levels in the CT soils. The

MBC:MBN ratio was not significantly affected by the tillage treatments, which implies that the type of microorganisms living in the soils were not significantly altered. Complementary microbial community analysis using phospholipid fatty acid analysis and molecular profiling techniques are currently underway by other research collaborators.

Tables for Chapter 3

Table 1. The labile C pool available for mineralization (C_{max} mg kg^{-1} soil) in the 0-5 cm layer of soils from a long-term tillage and residue management experiment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT). The residue treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

Tillage Treatment	C_{max}	Standard Error	Lower limit	Upper limit	R^2
CT	851.040	4.596	841.385	860.696	0.997
RT	1303.817	11.439	1279.784	1327.850	0.993
NT	2074.627	12.553	2048.254	2101.001	0.997
Residue Treatment					
O	1129.308	9.721	1108.884	1149.731	0.993
R	1690.349	9.505	1670.381	1710.317	0.997

Table 2. The labile C pool available for mineralization ($C_{max,}$ mg kg^{-1} soil) in the 5-20 cm layer of soils from a long-term tillage and residue management experiment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT). The residue treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

Tillage Treatment	C_{max}	Standard Error	Lower limit	Upper limit	R^2
CT	950.200	12.440	924.068	976.335	0.985
RT	1392.232	9.821	1371.598	1412.866	0.995
NT	1286.415	15.596	1253.649	1319.182	0.987
Residue Treatment					
O	1012.740	9.919	991.902	1033.578	0.991
R	1406.491	14.557	1375.886	1437.116	0.991

Table 3. The labile N pool available for mineralization ($N_{max,}$ mg kg^{-1} soil) in the 0-5 cm layer of soils from a long-term tillage and residue management experiment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT). The residue treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

Tillage treatment	N_{max}	Standard error	Lower limit	Upper limit	R^2
CT	73.397	1.328	70.148	76.646	0.993
RT	110.972	1.688	106.842	115.102	0.996
NT	124.268	4.213	113.958	134.557	0.981
Residue treatment					
O	90.037	2.072	84.967	95.106	0.991
R	115.106	4.225	104.767	125.445	0.975

Table 4. The labile N pool available for mineralization ($N_{max,}$ mg kg^{-1} soil) in the 5-20 cm layer of soils from a long-term tillage and residue management experiment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT). The residue treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

Tillage Treatment	N_{max}	Standard Error	Lower limit	Upper limit	R^2
CT	69.948	4.666	58.529	81.366	0.93
RT	108.961	3.591	100.173	117.749	0.982
NT	82.412	4.96	70.276	94.549	0.946
Residue Treatment					
O	72.82	4.959	60.686	84.954	0.929
R	98.426	4.218	88.104	108.747	0.97

Table 5: Effects of tillage and residue management on the MBC concentration. Values are the F statistic and the probability values (Pr) from analysis of variance (n=18).

	Degrees of Freedom	0-5 cm		5-20cm	
		F	Pr	F	Pr
Tillage	2	8.14	0.008	0.16	0.857
Residue	1	10.2	0.01	0.43	0.527
Tillage*residue	2	1.59	0.251	0.66	0.536

Table 6: Effects of tillage and residue management on the MBN concentration. Values are the F statistic and the probability values (Pr) from analysis of variance (n=18).

	Degrees of Freedom	0-5 cm		5-20cm	
		F	Pr	F	Pr
Tillage	2	4.7	0.036	5.98	0.022
Residue	1	4.5	0.06	15.64	0.003
Tillage*residue	2	2.61	0.122	5.21	0.031

Table 7: Effects of tillage and residue management on the MBC:MBN ratio. Values are the F statistic and the probability values (Pr) from analysis of variance (n=18).

	Degrees of Freedom	0-5 cm		5-20 cm	
		F	Pr	F	Pr
Tillage	2	1.48	0.273	2.33	0.153
Residue	1	2.67	0.133	13.45	0.005
Tillage*residue	2	1.44	0.282	2.29	0.157

Figures for Chapter 3

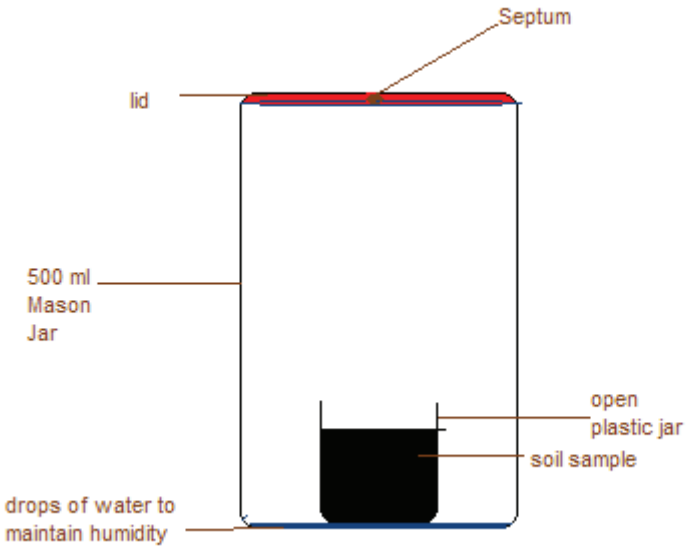

Fig. 1: The experimental unit in the mineralization experiments.

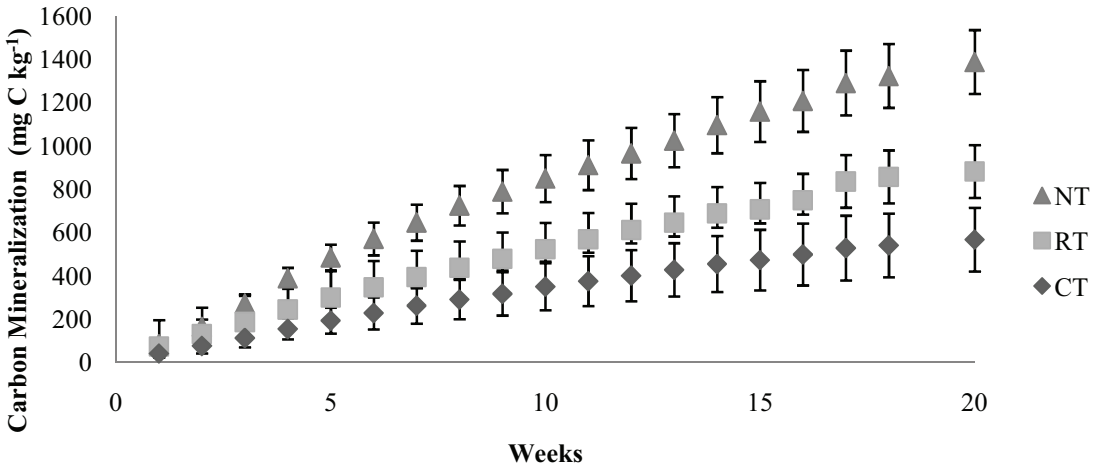

Fig. 2: Cumulative C mineralization (mg C kg^{-1} soil) in the 0-5 cm layer during a 20 week incubation, as affected by tillage treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT).

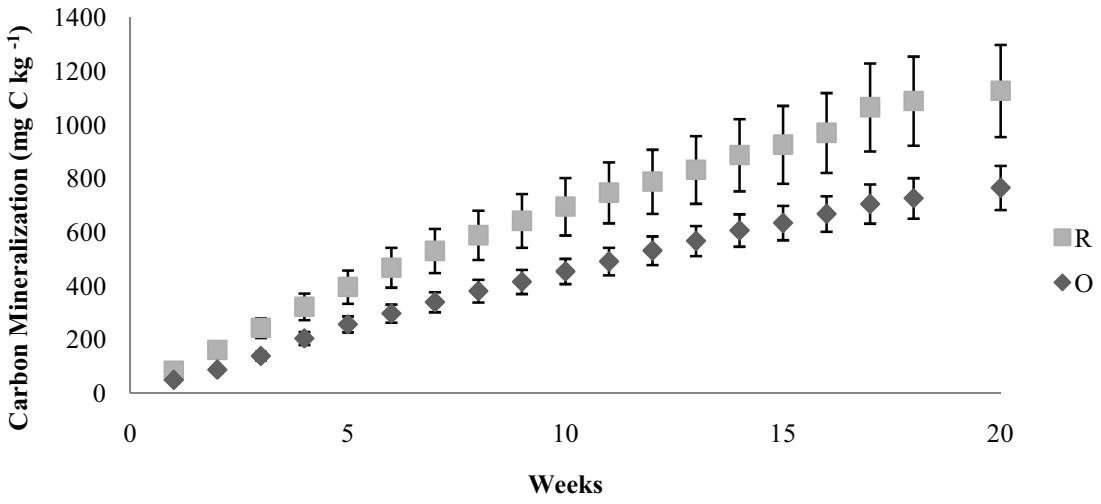

Fig. 3: Cumulative C mineralization (mg C kg^{-1} soil) in the 0-5 cm layer during a 20 week incubation, as affected by residue treatments. The treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

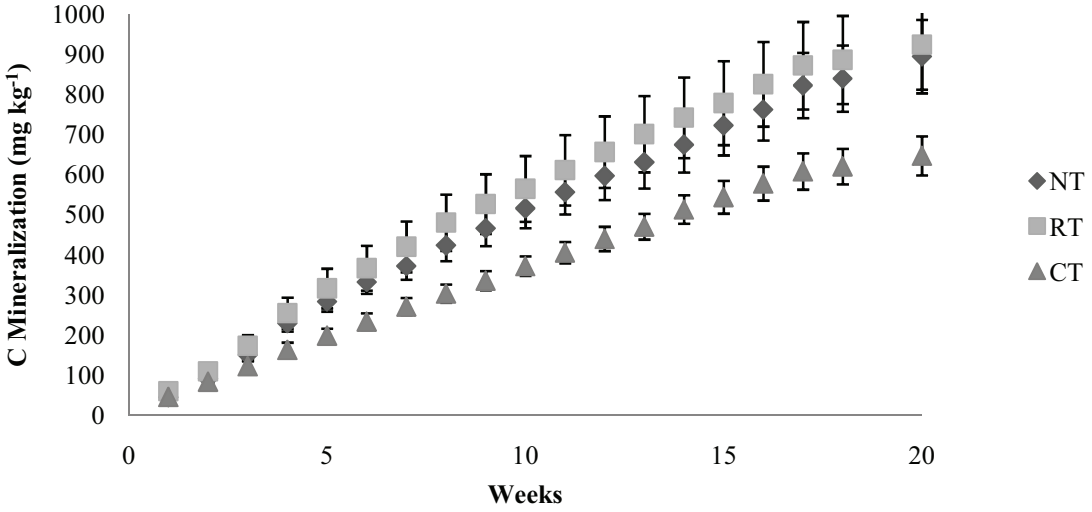

Fig. 4: Cumulative C mineralization (mg C kg^{-1} soil) in the 5-20 cm layer during a 20 week incubation, as affected by tillage treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT).

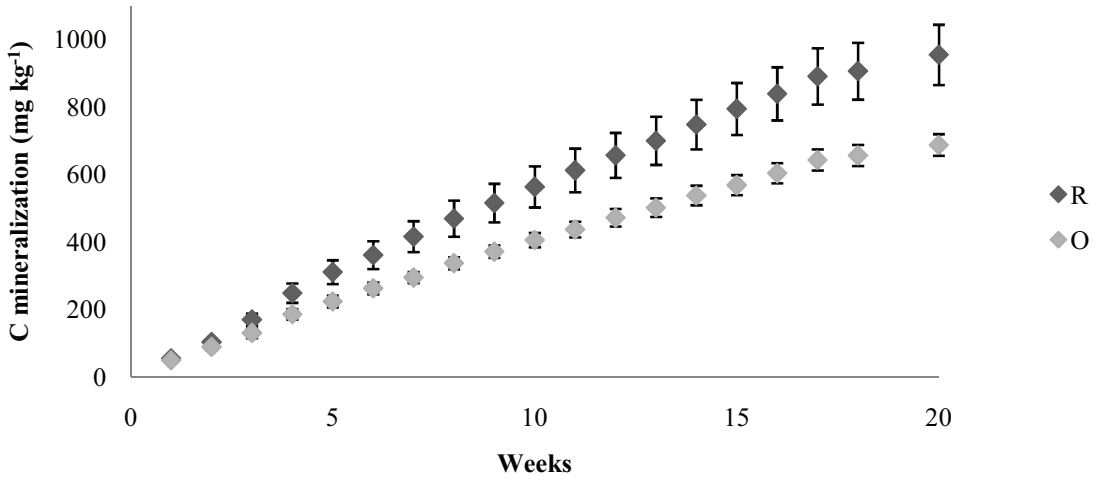

Fig. 5: Cumulative C mineralization (mg C kg^{-1} soil) in the 5-20cm layer during a 20 week incubation, as affected by residue treatments. The treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

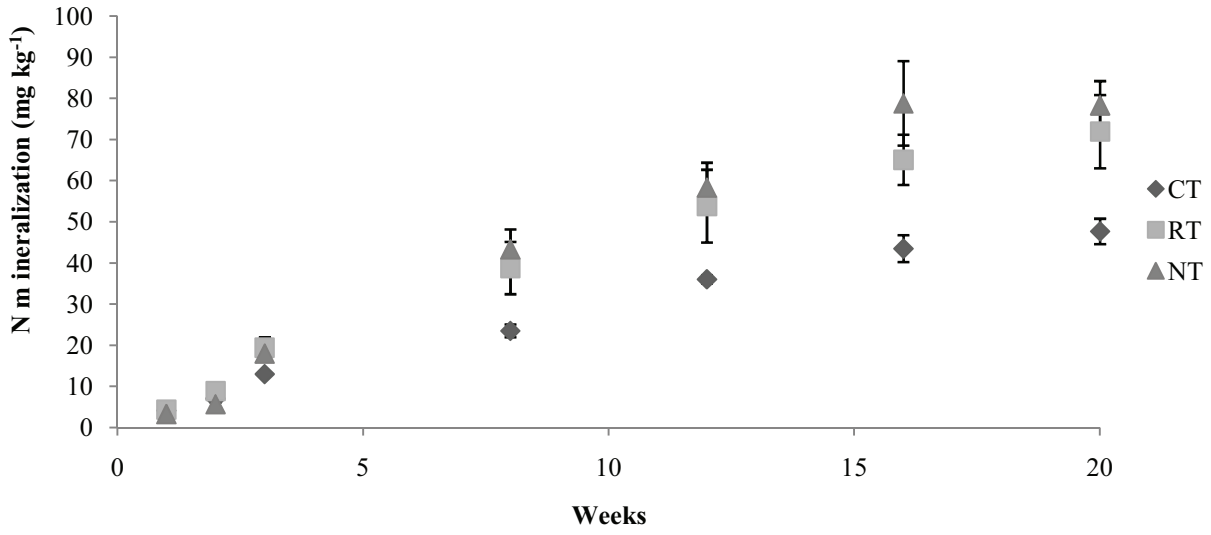

Fig. 6: Cumulative N mineralization (mg N kg^{-1} soil) in the 0-5 cm layer during a 20 week incubation, as affected by tillage treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT).

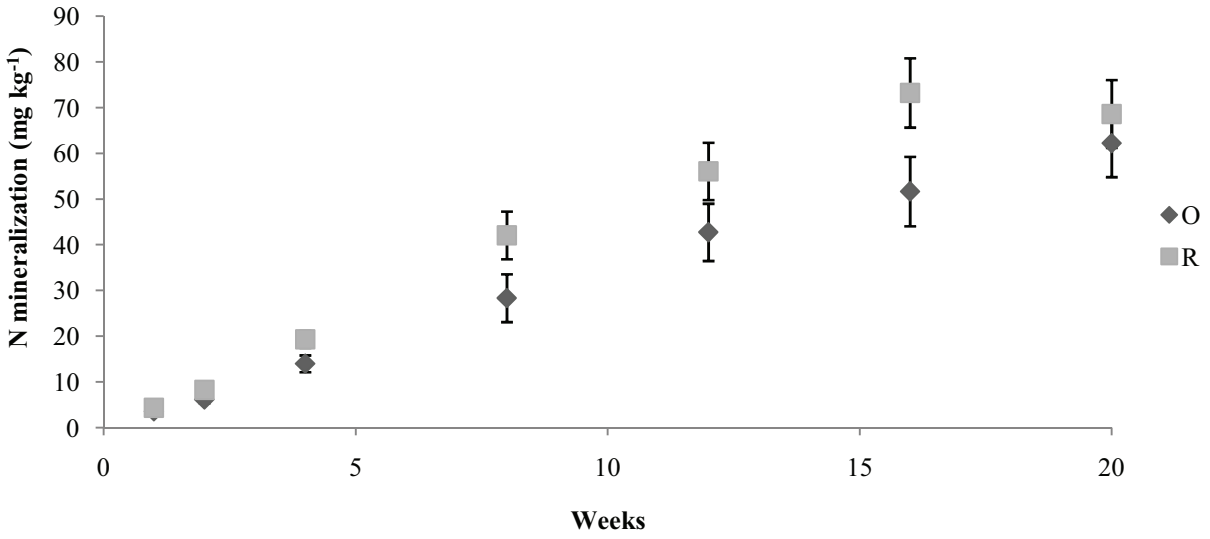

Fig. 7: Cumulative N mineralization (mg N kg^{-1} soil) in the 0-5 cm layer during a 20 week incubation, as affected by residue treatments. The treatments were low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

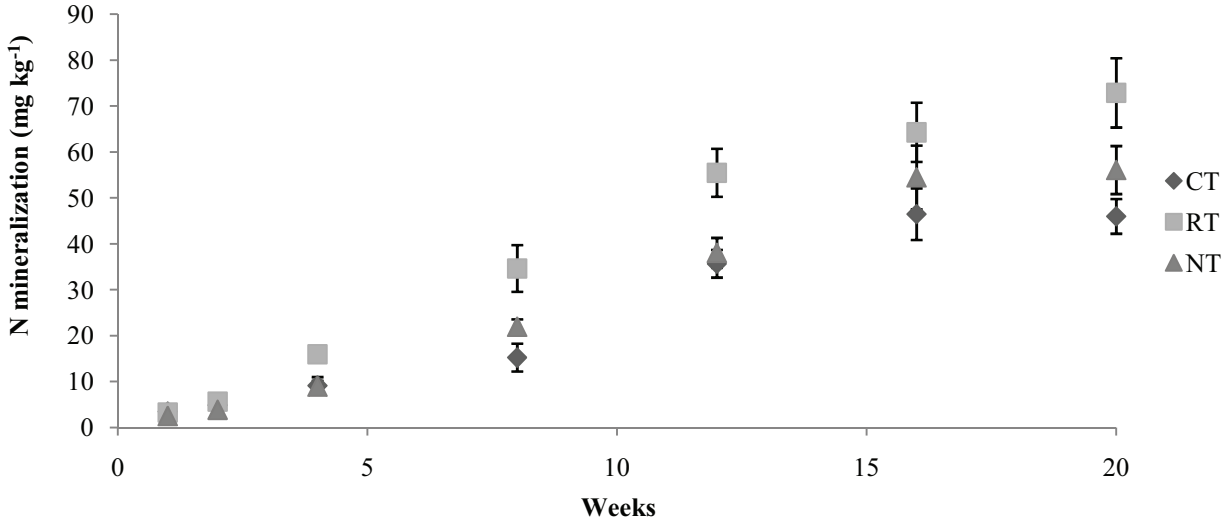

Fig. 8: Cumulative N mineralization (mg N kg^{-1} soil) in the 5-20 cm layer during a 20 week incubation, as affected by tillage treatments. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT).

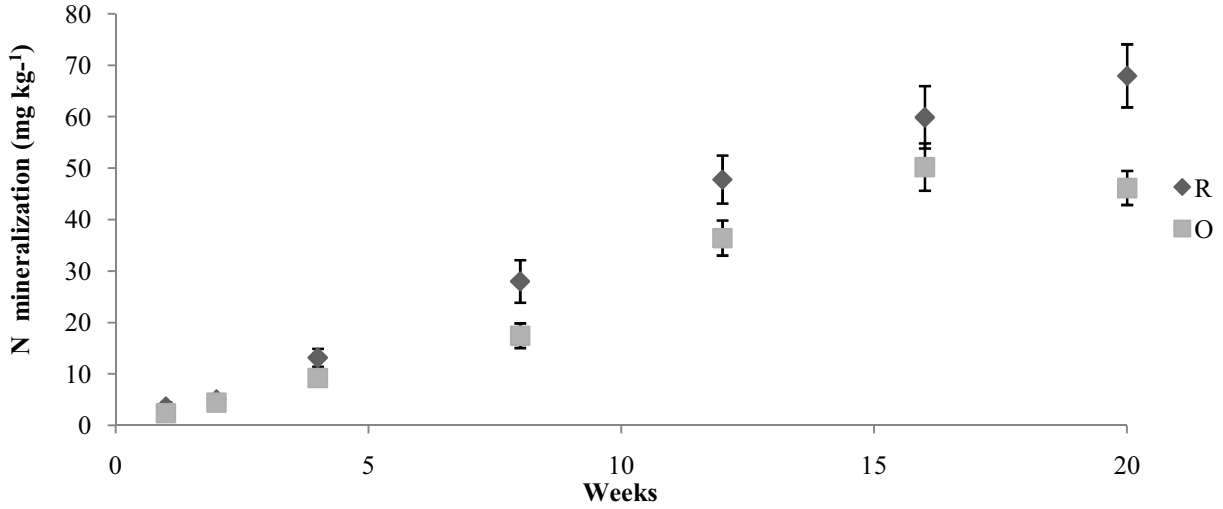

Fig. 9: Cumulative N mineralization (mg N kg^{-1} soil) in the 5-20 cm layer during a 20 week incubation, as affected by residue treatments. The treatments were low residue input (O) and low residue input (R) (roots only vs. roots and corn stover).

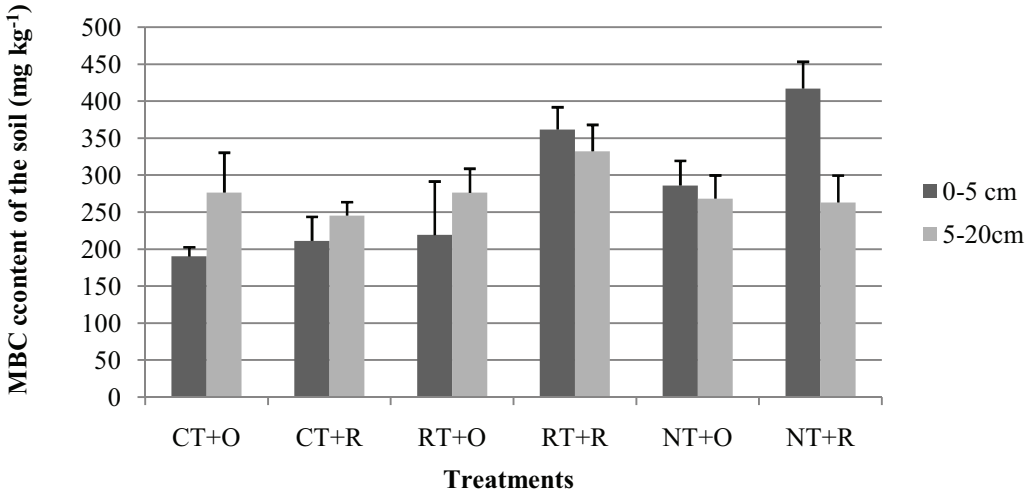

Fig. 10 The MBC concentration (mg C kg^{-1} soil), presented by depth and by treatment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

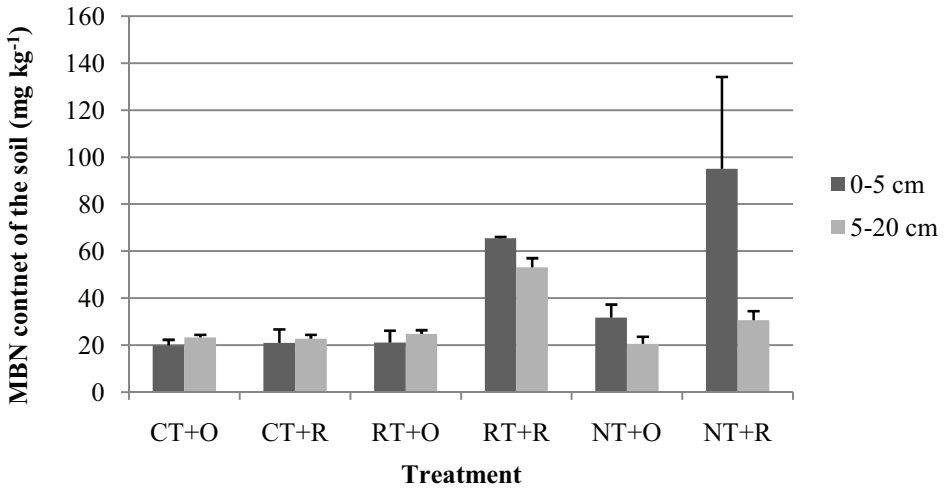

Fig. 11: The MBN concentration (mg N kg^{-1} soil), presented by depth and by treatment. The tillage treatments were conventional tillage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

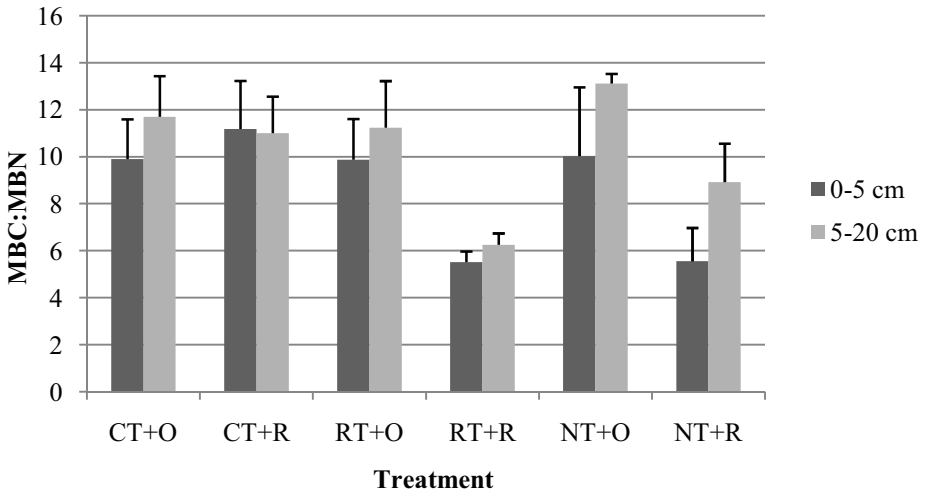

Fig. 12: The MBC:MBN ratio of soils from a long-term field experiment, presented y depth and agricultural treatments. The tillage treatments were conventional tillbage (CT), reduced tillage (RT) and no-till (NT), with low residue input (O) and high residue input (R) (roots only vs. roots and corn stover).

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GENERAL CONCLUSIONS

The two main benefits of agricultural practices that raise the amount of organic matter in the soil are: 1) They offset the rise of atmospheric and C 2) they raise the fertility of the soil. In this thesis, tillage practices and residue management were examined to see whether they would confer these two benefits.

In Chapter 2, the total change in SOC caused by tillage practices was found to be insignificant, whereas a high residue input was found to raise the SOC by about 0.5% per year. This indicates that there was no advantage to adopting no-tillage practice on a sandy-loam soil in this part of Quebec to sequester more C. The SOC that is added by the high residue input was significant, and perhaps this knowledge can be used to offset atmospheric C. However, it is important to recognize that only 7.3-8.4% of the extra residue C was sequestered. This needs to be compared to other possible uses of the stover (e.g., as a biofuel), which may have more value in terms of offsetting greenhouse gas emissions.

The effect of agricultural practices on the corn yield was also examined in Chapter 2, and the tillage practices were found to have no significant effect on the grain yield. This implies that the fertility of the soil was not significantly changed by the tillage and residue management. This means that whichever management practices are deemed to be cheaper or more environmentally friendly can be used, without any detrimental effect on yield.

In Chapter 3, the effects of tillage and residue management on the labile C and N pools, as well as the MBC and MBN were examined. Both the treatments were found to have significant effects. This showed that there were significant differences in the size of the nutrient storage of the soil, and in the amount of microbial life that was supported by the organic matter in the soil. Although tillage and residue management showed no

significant effects on the yield this year, the results in Chapter 3 imply that there is a difference in the nutrient cycles, and therefore a difference in yield might be observed later.

In order to promote more efficient crop production in no-till production systems, future research may be conducted to understanding the benefits/liabilities of a large labile SOM pool, and how the dynamics of the labile SOM pool should affect fertilizer recommendations. Further research to elucidate the effects of a large microbial biomass on crop production is also warranted.

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APPENDIX 1

Calendar of C and N mineralization experiments

N mineralization study:

Starting incubations

12/6/2007-The week 1-16 samples were entered into the incubator

12/12/2007-The week 20 samples were entered into the incubator

27/12/2007 The week 1 was weighed out and incubated again, because they weren't measured properly the first time.

2/1/2008 The week 20 repeated samples were entered into the incubator

10/1/2008 The week 2-16 repeated samples (RS) were entered into the incubator

Aerations

Note: Since the week 20 samples were used for both the C and N mineralization experiments, we have included the aeration of these jars under the C mineralization experiment. All other samples that had not been analyzed yet were aerated at the same times

12/18/2007

12/26/2007

1/2/2008

1/10/2008

1/17/2008

1/24/2008

1/31/2008

2/7/2008

2/14/2008

2/21/2008

2/27/2008

3/5/2008

3/13/2008

3/20/2008

3/28/2008

4/3/2008

4/13/2008

4/24/2008

4/30/2008

5/7/2008

5/14/2008

Extractions

Often the samples were taken out of the incubator and put into a refrigerator ($4^{o}C$) for several days before the soils were extracted. It is assumed that during that time there was no further mineralization. In this part of the calendar, there will be two dates given. 1) When the soils were taken out of the incubator and refrigerated (Incubation terminated or IT) 2) When the soils were extracted (E).

12/20/2008 (IT and E) Week 2 samples

1/3/2008 (IT and E) Week 1 samples (repeated)

1/3/2008 (IT), 1/7/2008 (E) Week 4 samples

1/24/2008 (IT and E) Week 2 RS

1/31/2008 (IT and E) Week 8 samples

2/7/2008 (IT and E) Week 4 RS

2/28/2008 (IT and E) Week 12 samples

3/6/2008 (IT) and 3/12/2008 (E) Week 8 RS

3/27/2008 (IT) and 4/1/2008 (E) Week 16

4/3/2008 (IT) and 4/16/2008 (E) Week 12 RS

4/30/2008 (IT) and 5/7/2008 (E)Week 20

5/1/2008 (IT) and 5/8/2008 (E) Week 16 RS

5/21/2008 (IT) and 5/26/2008 (E) week 20 RS

C mineralization study

Starting incubations

12/12/2007-The week C mineralization samples were entered into the incubator.

2/1/2008 The C mineralization repeated samples (RS) were entered into the incubator

Sampling dates

Unless otherwise indicated, the samples were always aerated immediately after they were sampled.

12/19/2007 Week 1

12/26/2007 Week 2

1/2/2008 Week 3

1/9/2008 Week 4+1RS

1/16/2008 Week 5+2RS

1/23/2008 Week 6+3RS. Aerated on 1/24/2008.

1/20/2008 Week 7+4RS

2/6/2008 Week 8+5 RS

2/13/2008 Week 9+6RS

2/21/2008 Week 10+7RS

2/27/2008 Week 11+8RS

3/5/2008 Week 12+9RS

3/13/2008 Week 13+10RS

3/20/2008 Week 14+11RS

3/28/2008 Week 15+12RS

4/3/2008 Week 16+13RS

4/13/2008 Week 17+14 RS

4/18/2008 Week 18+15 RS

4/30/2008 week 20 and 17 RS.

Note: Week 19+16RS was skipped. The gas analyzed on 4/30/2008 contained 2 weeks worth of CO_2

5/7/2008 Week 18RS

5/14/2008 Week 19RS

5/21/2008 Week 20RS

APPENDIX 2
A list of the samples that were repeated

Plot	Depth (cm)
1	0-5
4	0-5
4	5-20
6	0-5
7	5-20
9	0-5
9	5-20
11	0-5
13	0-5
13	5-20
14	0-5
15	0-5
15	5-20