Soil organic carbon in tree-based intercropping systems of

Quebec and Ontario, Canada

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Soil organic carbon in temperate tree-based intercropping systems

ABSTRACT

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Tree-based intercropping (TBI) is an agroforestry system where a crop, generally an annual, is planted between established tree rows. TBI systems have a greater potential for carbon storage than conventional cropping systems because carbon is stored in the biomass of growing trees and trees provide additional carbon inputs (leaves, roots) that contribute to the soil organic carbon (SOC) pool. Differences in the litter quality and amount of litter deposited in the tree row versus the intercropped space are expected to generate spatial heterogeneity in the SOC pool. The objectives of this work were to evaluate the spatial variability of the SOC pool in TBI systems, to compare SOC stocks in the TBI system with a nearby conventional agroecosystem, and to describe the SOC dynamics in a TBI system using the *ecosys* model. Research sites included in this study were 4-year old TBI sites at St. Paulin and St. Edouard (Quebec, Canada), an 8-year old TBI site in St. Remi, Quebec, and a 21 year old TBI site in Guelph, Ontario, Canada. Spatial heterogeneity in SOC pools due to the presence of trees was observed in two of the four sites, but obscured by field variability at one site and even distribution of leaf litter associated with large trees at the oldest TBI site. The SOC pool increased in older TBI sites, relative to the nearby conventional agroecosystem, but the magnitude of SOC change was affected by the land use history. A simulation of changes in SOC using the *ecosys* environmental model predicted a 5.0% decrease in SOC pools twenty-one years after the site was converted to TBI, while field experiments showed a 12% increase in the SOC pool compared to the conventional agroecosystem. A spatial algorithm that describes the distribution of trees and crops in TBI systems would improve *ecosys* model

predictions. Overall, field results suggest that the trees growing in TBI systems will increase SOC levels after a number of years of TBI establishment.

RESUMÉ

M.Sc. Amanda D. Bambrick Sciences de Resources Naturelles

Un système de culture intercalaire (SCI) est un système d'agrosylviculture où une récolte, généralement annuelle, est établie entre les rangées d'arbres plantées. Le SCI a un potentiel important pour être adoptés dans les régions tempérées dû aux avantages environnementaux liés à ces systèmes. Un tel avantage environnemental fourni par SCI est le stockage accru de carbone dans les sols et la biomasse des plantes. Le SCI a un potentiel important pour le stockage de carbone (C) car il contienne de carbone dans la biomasse des arbres croissants, et l'ajout au sol des résides d'arbres (feuilles, racines) contribuent au C organique du sol (SOC). On s'attend à ce que des différences dans la qualité et la quantité des résides organiques déposées dans la rangée d'arbre contre l'espace intercalaire produisent de l'hétérogénéité spatiale de SOC. Les objectifs de cette thèse étaient i) d'évaluer la variabilité spatiale de SOC dans le SCI, ii) comparer des stocks de SOC dans le SCI à un agro-écosystème conventionnel, et iii) décrire la dynamique de SOC dans le SCI utilisant le model *ecosys*. Les sites expérimentaux incluant dans cette étude étaient des emplacements de quatre ans à St. Paulin et St. Édouard (Québec, Canada), de huit ans à St. Rémi, Québec et de 21 ans à Guelph (Ontario, Canada). L'hétérogénéité spatiale au SOC due à la présence des arbres a été observée dans deux des quatre sites, mais obscurcie par la variabilité de terrain a un site et par la distribution égale de feuillage liée à de grands arbres à l'emplacement de SCI le plus ancien. Le stock de SOC accrue dans des sites de SCI le plus anciens, relativement à l'agro-écosystème conventionnel, mais l'importance de changement de SOC a été affectée par l'histoire d'utilisation de la terre. Une simulation des changements du SOC utilisant le modèle *ecosys* a prévu une diminution 5.0% en stock de SOC vingt et un ans après la conversion à SCI, alors que les expériences au terrain montraient une augmentation de 12% en stock de SOC comparée à l'agro-écosystème conventionnel. Un algorithme spatial qui décrit la distribution des arbres et des cultures annuelles dans le SCI améliorerait les prévisions de modèle *ecosys*. De façon générale, les résultats de champ suggèrent que les arbres s'élevant dans le SCI augmentent des niveaux de SOC après un certain nombre d'années.

CONTRIBUTION OF AUTHORS

This thesis consists of a literature review and two manuscripts. Chapter 2, the first manuscript, is co-authored by the candidate, her supervisor Dr. Joann Whalen, Dr. Robert Bradley, Dr. Alain Cogliastro, Dr. Alain Olivier, Dr. Naresh Thevathasan and Dr. Andrew Gordon. Chapter 3, the second manuscript was co-authored by the candidate, Dr. Joann Whalen and Dr. Robert Grant. The field experiments described in Chapter 2 were designed and partially maintained by grants held by Drs. Bradley, Cogliastro and Oliver (St-Paulin, St-Edouard, St-Remi) and by Drs. Thevathasan and Gordon (Guelph). Field sampling advice was provided by Drs. Bradley and Thevathasan, who also kindly supplied historical datasets of soil test analyses. Training and guidance on the use and interpretation of the *ecosys* model was provided by Dr. Robert Grant, who hosted the candidate at the University of Alberta from May-August, 2008. Overall direction for the thesis research, guidance in soil sampling and analysis, data interpretation and editorial assistance came from Dr. Joann Whalen. The candidate was responsible for data collection, laboratory analysis, statistics, data interpretation, initialization and calibration of the *ecosys* model, and the preparation of manuscripts.

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This work is dedicated to my mother, who was
not able to remain with me for this achievement,
yet used her endless strength and love to ensure
that I would make it here.

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GENERAL INTRODUCTION

Awareness of the ecological and environmental health of our surrounding ecosystems has been increasing in recent years. As a consequence of this, there has been a growing interest in sustainable agricultural alternative practices such as agroforestry. In Canada the agricultural community has been criticized for problems with soil erosion, degraded soil structure, greenhouse gas release into the atmosphere, decreased water quality and a loss of wildlife habitat. Many farmers may find it difficult, however, to manage the costs of more sustainable and environmentally friendly farming practices (Gordon and Williams 1991). Agroforestry has been associated with an increasing amount of environmental and ecological benefits such as enhancement of microclimatic conditions, improved use and cycling of soil nutrients, improved soil and water quality, creation of suitable habitats for insect and animal species, protection from erosion, and protection from wind and snow (Jose et al. 2004). The alternative practice has the potential to alleviate both economic and ecological stress on farms (Matthews et al. 1993). It has been said that the ecological benefits provided by agroforestry systems along with the yields of trees and crops combined puts the alternative practice above conventional agriculture in terms of long-term productivity (Thevathasan and Gordon 2004).

Agroforestry can be defined as “a collective name for land use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the two different components” (Gordon et al. 1997).

CHAPTER 1: LITERATURE REVIEW

Agroforestry can be defined as "a collective name for land use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions between the two different components" (Gordon et al. 1997).

1. Types of Agroforestry

There are many different types of agroforestry systems in practice. Some of the most common are:

1. Windbreaks or shelterbelts: These are linear plantings of trees or shrubs used to protect either crops or farm structures from wind and/or snow buildup, decreasing heating costs, odour problems, and also the energy consumption of livestock in the winter months. A windbreak can prevent the damage of fragile crops and can also increase air temperature near the windbreak, often increasing plant growth rates (Brandle et al. 2004; Gordon et al. 1997).

2. Silvopastoral Systems: An agricultural system where there is an interaction between trees and livestock qualifies as a silvopastoral system. This interaction can be formed when trees are used to provide shelter for livestock or when woodlands are grazed. Research has shown that a reduction in exposure to environmental stress, such as wind or sun exposure can greatly enhance livestock growth and survival rates (Garrett et al. 2004).

3. Tree-Based Intercropping or Alleycropping: This is when cropping systems are established between rows of planted trees. The width of the “alley” between tree rows is often defined by the size of machinery that must be driven between rows for the maintenance of the crop. Much consideration is put into decisions regarding management practices and the species of trees and companion crops in agroforestry systems because without proper care, trees and crops can compete for light, nutrients and soil moisture. There are also considerations to be made regarding altered microclimate, incidence of pests and disease and allelopathy in intercropped systems. One major benefit of intercropped systems to farmers in temperate zones is the increased energy utilization efficiency of agricultural systems converted to intercropping. Energy use efficiency is increased in intercropped systems because the increased variety of species in the system means that more energy can be trapped through the various plant growth cycles and trophic levels in the system (Gordon et al. 1997; Thevathasan and Gordon 2004). Intercropping has traditionally been used as a method to maintain income while establishing orchards in southern Ontario (Williams and Gordon 1995).

4. Riparian Systems: This is when trees are used as a “buffer” to create space between cropland and waterways. Riparian systems can protect waterways from sediment deposition due to erosion, nutrient loading from surrounding fields through the uptake of excess nutrients such as nitrogen, block cattle access to streams, and can even decrease water temperatures through shading, which improves stream habitat. Riparian zones have also been reported to increase the health of stream ecosystems through the provision of leaf litter as a food source in underwater communities. Riparian systems are one of the most commonly used and widely recognized agroforestry systems in North America (Matthews et al. 1993; O'Neill and Gordon 1994; Oelbermann et al. 2004).

5. Forest Farming: The regular harvest of timber and other economically valued products from woodlots is a type of forest farming. Examples of economically valued products harvested from woodlots in temperate regions are maple syrup, mushrooms and ginseng (Gordon et al. 1997).

2. History of Agroforestry

Agroforestry was initially developed in tropical countries where population explosions brought forth both land shortages and an increasing need for both food and fuel-wood supplies. The advantage of agroforestry is that both wood and agricultural resources could be provided from the same land base. When it was found that this type of system also diversified income and conserved soil properties in low-input management systems it grew more popular (Matthews et al. 1993). Research in the 1970s demonstrated that land-clearing for food and fuel production was a major cause of deforestation in tropical forests. Agroforestry was recognized by governmental organizations as a system that would provide food and fuel, while possibly preventing additional deforestation. In 1977, agroforestry was recognized through the establishment of the International Center for Research in Agroforestry (ICRAF) in Nairobi, Kenya. This institute served as a catalyst for agroforestry, resulting in the inclusion of agroforestry initiatives in the national agricultural and forestry research agendas of many developing countries in following years (Nair 2007).

In temperate agroforestry regions, research initiatives gained momentum in the 1990s. Degradation of agricultural lands, harm to the environment and loss of forested lands due to economically driven, intensive, conventional agricultural systems raised alarm for environmental and ecological issues in the temperate zone. Public demand for more sustainable and ecologically friendly agricultural practices brought forth the concept of agroforestry into industrialized nations (Nair 2007). Recent interest in agroforestry in North America is mainly due to the wide range of ecosystem services it provides, such as water quality and biodiversity conservation, carbon sequestration, good land stewardship and aesthetics (Gordon et al. 1997; Nair 2007).

In Canada, the University of Guelph Agroforestry Research Station was established at Guelph, Ontario, in 1987. The research site is operated by the University of Guelph and the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). At this research site, 30 hectares of agricultural land were converted to an intercropping system with ten different tree species permanently planted into rows. The research site was designed to accumulate knowledge on tree growth in combination with various crops on the same site, overall system productivity and how well different cropping practices work with various tree species. The field plots were also designed to allow investigation of the effect of tree-row spacing on tree and crop growth (Thevathasan and Gordon 2004; Williams and Gordon 1995). To provide a forum for those working in agroforestry in temperate zones to connect, the “First Conference on Agroforestry in North America” was organized and finally held in Guelph, Ontario in August of 1989. Approximately 100 delegates attended the meeting and decided to continue the agroforestry conference theme in the following years. The next agroforestry conference for North America was held at the University of Missouri in 1991. The conference series is now held as a regular biannual event (Association for Temperate Agroforestry (AFTA) 2007; Gordon and Williams 1991).

3. Agroforestry and the Environment

Agroforestry aims to optimize the use of agro-ecosystem resources by optimizing positive and reducing negative interactions among the components of the ecosystem (Jose et al. 2004). For example, in tree-based intercropping systems, producers aim to maximize the benefit of nutrient cycling from tree leaf litter into the agricultural crops by planting enough trees in their field to benefit from this positive effect. On the other hand, TBI producers must also reduce the negative impact of competition between trees and crops for resources. They have options such as increasing the spacing between trees, choosing trees that grow tall instead of with wide crowns, or regularly thinning out the crowns of trees to manage these issues.

Research has shown that there are significant improvements in carbon sequestration, water quality and biodiversity in agroforestry systems (Alavalapati et al. 2004). Because of economic returns due to high input requirements of "marginal" or degraded lands and the beneficial ecosystem services provided by agroforestry systems, marginal land is a perfect candidate for improvement through the use of agroforestry systems. It is estimated that there are 140 million hectares of marginal or degraded lands in North America where agroforestry could be established. Approximately 50 million hectares of these marginal lands are located in Canada (Thevathasan and Gordon 2004).

The value of the two-way benefit (environment and income) of agroforestry systems is vast for temperate farmers, given that they must continually face the conflict between preserving the integrity of their land while trying to maintain income in an increasingly competitive agricultural marketplace (Matthews et al. 1993).

Agroforestry is seen as a way to improve socioeconomic situations and environmental sustainability in both tropical and temperate regions. I will focus mainly on agroforestry as a system that can increase carbon sequestration in the temperate zone.

4. The Carbon Cycle

The four main carbon pools in the environment are the atmosphere, terrestrial biota, soils and the ocean; and these pools contain approximately 800 Pg, 500 Pg, 1500-2000 Pg and 39,000 Pg of carbon, respectively (1 Pg = 1 billion tonnes). Above estimates for carbon in soils are in the top meter of soil, and most of the carbon in the oceans exists in deeper layers. All soil carbon pools are dynamic, so carbon is constantly exchanged between them. It is estimated that 120 Pg of C is removed from the atmosphere each year through photosynthesis, and half of this is immediately returned through plant respiration. The remaining plant carbon generally becomes assimilated into the soil as plant litter, and a large portion of this is returned to the atmosphere through microbial respiration as well (Janzen 2005). A diagram of the global carbon cycle can be found in Fig. 1.

Approximately half of all terrestrial carbon exists in forest ecosystems, and these forest ecosystems account for about 80% of the annual carbon exchange between terrestrial ecosystems and the atmosphere. It is estimated that forests absorb up to 3 Pg of C each year, though much of this is returned to the atmosphere through deforestation and forest fires (Montagnini and Nair 2004), making it clear that the protection of forested lands and reforestation of cleared lands is crucial to increase the storage of atmospheric CO_2. Grasslands and savannas also account for approximately another 30% of global soil carbon stocks (Janzen 2005).

Agricultural systems are also crucial in the global carbon cycle as well. Agricultural stock may only contain approximately 3 Pg of C, which comes to less than 1% of the earth's total vegetative C (Janzen 2005), but agricultural soils contain approximately 12% of the world's soil carbon (Dixon et al. 1994). Since the carbon cycling of agricultural systems are entirely subject to human control they will prove to be increasingly important in our efforts to mitigate atmospheric carbon. Due to the fact that livestock often graze grasslands and savannas, humans directly control many of these lands as well (Janzen 2005).

5. Carbon Dioxide and other Greenhouse Gases in the Atmosphere

Current interest in global carbon cycling is due to the fact that atmospheric CO_2 concentrations have increased from 280 ppm to 380 ppm in the past 150 years (IPCC, 2007). This accounts for a 31% increase in CO_2 (Christopher and Lal 2007; Smith et al. 1993). Another estimate states that over the past 150 years, anthropogenic activities have increased carbon concentrations in the atmosphere by approximately 28%. This translates into an accumulation of approximately 3.5 Pg of C into the atmosphere per year (Oelbermann et al. 2004). There are two main anthropogenic causes for the increase in CO_2 concentrations in the atmosphere. The first reason is land use change. The conversion of forests or grasslands to agriculture causes large shifts of carbon from these pools to the atmosphere. Approximately 30% of the carbon stored in Canada's cultivated grassland soils was lost in the first thirty years of their conversion to croplands. The second factor increasing atmospheric CO_2 levels is the combustion of fossil fuels. While land use change redistributes carbon to the atmospheric pool, fossil fuel burning takes carbon that was once inert underground stores and adds it to the pools of exchangeable carbon already present in soils, air, plants and the ocean (Janzen 2005).

It is becoming increasingly accepted that the accumulation of greenhouse gases (GHGs) in the atmosphere due to fossil fuel burning, deforestation and other anthropogenic activities is changing the earth's climate. There is much debate about how the planet's response to elevated GHG levels will manifest themselves. Greenhouse gases affect the Earth's climate through "radiative forcing", a process where increased concentrations of GHGs in the atmosphere increase the amount of radiative energy absorbed by the earth's surface (Lal 2004). It is projected that the increase of GHGs in the atmosphere will cause a temperature increase of 1.5 to 4.5 °C by the mid 21^{st} century (Oelbermann et al. 2004). This could then cause a shift in weather patterns, changes in plant growth dynamics, and a redistribution of the earth's vegetation (Dixon et al. 1993). There is research evidence stating that elevated atmospheric CO_2 levels can accelerate plant growth in crops and forests (Oelbermann et al. 2004), but this fact must be taken lightly considering that there are other limiting factors in plant growth to be considered. Research has also shown that following one year of elevated CO_2 exposure; some species of plants acclimate to raised CO_2 levels and return to normal photosynthetic rates (Smith et al. 1993). Although CO_2 will be the main topic of this discussion, it is important to mention other greenhouse gases that also absorb infra-red (IR) radiation in the atmosphere. These other greenhouse gases include CH_4, N_2O, O_3 (in lower atmospheric levels) and CFCs. Though released into the atmosphere in lesser amounts, these GHGs all have greater radiation absorption potentials than CO_2, meaning that much smaller amounts of these gases can have a greater effect on IR absorption in the atmosphere. For example, CO_2 has a radiative absorption potential of 1 while N_2O has a radiative potential of 150, meaning that N_2O is a much more powerful GHG (Flach et al. 1997).

5.1 Integration of Carbon into the Soil

Carbon enters the soil pool through the incorporation of soil organic matter (SOM) into the soil. Stable SOM, or humus, is formed when plant or animal matter is broken down and stabilized by soil microorganisms (Christopher and Lal 2007). The rate of humus formation depends on many factors in the system, such as plant matter input, nitrogen input, soil moisture content, soil pH, and oxygen availability (Flach et al. 1997).

Nitrogen input has an effect on humus formation because microorganisms require a specific C:N ratio to be able to metabolize organic matter. The specific C:N ratio depends on the ratio maintained within their bodies. The typical ratio required by microorganisms is 8:1. This means that if crop residues with a very high C:N ratio is added to soils, the microorganisms will only be able to metabolize the residue if nitrogen is available to them from some other source. The microorganisms will often take the necessary nitrogen from the soil around them, resulting in decreased crop growth (Halvin et al. 1999). If nitrogen is not available at all, decomposition and therefore SOM formation rates slow down. Decomposition rates also slow throughout decomposition because microorganisms first decompose the labile substrates and leave recalcitrant substrates for later on. Since soil microorganisms must metabolize SOM to break it down into a stable form, a majority of the carbon put into the soil is lost back to the atmosphere through microbial respiration (Christopher and Lal 2007). It is estimated that approximately 70% of carbon added to agricultural soils from crop residue incorporation is released back into the atmosphere as CO_2 each year (Thevathasan and Gordon 2004).

This phenomenon results in a paradox in agricultural systems, where the goals of increased carbon storage in soils and increased crop productivity conflict with each other. To increase carbon storage in agricultural soils, one must keep microbial respiration of crop residues to a minimum to reduce the loss of CO_2 through respiration; but to increase crop productivity, crop residues must be metabolized to facilitate the release of nutrients into the soil (Janzen 2006). Producers must attempt to achieve a delicate balance a between healthy SOM content in their soils while maintaining crop productivity.

6. Carbon Dioxide: International Laws and Strategies Relevant to Agroforestry Systems

Concern about rising CO_2 and other GHG levels in the atmosphere was first recognized at the international level through the creation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. The main goal of the framework was for participating countries to quantify their GHG emissions and sinks and to reduce future emissions into the atmosphere. At the third meeting of the UNFCCC in Kyoto, Japan in 1997, participating countries made an agreement to reduce their GHG emissions to 5% below their 1990 levels by 2012. At the time of the agreement, Canada was responsible for 2% of global CO_2 emissions and would have to reduce its total emissions by 65×10^6 Mg of C to meet its goal (Montagnini and Nair 2004; Oelbermann et al. 2004). Canada has since then increased its rate of carbon emissions, so now more effort is required to reach this target. The Kyoto Protocol allowed for GHG reductions to take place either by direct reduction of GHG emissions or through the accumulation of organic carbon in soils and/or plants.

6.1 Carbon Trading

The Kyoto Protocol allows for emitting nations to purchase "carbon credits" from other countries if they cannot accomplish projected GHG mitigation goals. This carbon credit system is a mechanism for payment for environmental services. Markets such as this must be developed under a "cap-and-trade" system. Cap-and-trade systems are when there is an upper limit to the amount of CO_2 that can be emitted by an industry or country. The country will then allocate upper limits of emissions to carbon-emitting industries. The industries must then reduce their carbon emissions to the required amount, or purchase carbon credits from an outside agency as another way to meet CO_2 mitigation targets (Montagnini and Nair 2004). As a general trend, carbon trading has allowed developed countries to offset their CO_2 emissions by investing in carbon sequestration practices in developing countries. Developing countries have been able to use this payment for environmental services system to implement more ecologically friendly practices that could not be funded originally. Costa Rica was the first developing country to take advantage of this system by selling carbon credit bonds to European countries to fund rainforest conservation and reforestation projects in 1997 (Oelbermann et al. 2004). In Canada carbon-trading markets are provided by the Western Climate Initiative, a cooperative between seven American states (Arizona, California, Montana, New Mexico, Oregon, Utah and Washington) and four Canadian provinces (British Columbia, Manitoba, Ontario and Quebec) to explore and implement cooperative ways to reduce atmospheric greenhouse gas levels through the market-based cap-and-trade system (Western Climate Initiative (WCI) 2009). The Montreal Climate Exchange was established in 2006 in partnership with the Chicago Climate Exchange and has recently introduce "carbon futures trading" in Canada (MCeX, 2009). Carbon trading systems can be utilized in the temperate zone to aid producers in the funding of more environmentally sustainable land management practices, such as agroforestry.

6.2 Mitigation Strategies

There are a few ways we can try to reduce the amount of CO_2 present in the atmosphere. First of all, the reduction of CO_2 emissions from fossil fuels is important. This can be achieved through increased energy efficiency, decreased energy use, and the consumption of renewable biofuels (Flach et al. 1997). Another method is to increase the amount of carbon stored in our terrestrial plants and soil pools by either avoiding carbon releasing practices, such as deforestation, or by adopting practices that increase the amount of carbon stored in plant and soil stocks (Janzen 2005). Regardless of the benefits of CO_2 sequestration for the atmosphere, building up SOM in agricultural soils should always be a goal of agricultural producers, considering that increased SOM content of soils has many other benefits. Soil organic matter can increase crop yields in degraded soils by increasing soil water holding capacity, improving nutrient supply to plants (by providing nutrients and increasing soil cation exchange capacity) and by enhancing overall soil structure along with other physical properties (Lal 2006; Oelbermann et al. 2004).

7. Soil Carbon Sequestration

Carbon sequestration is known as the removal of CO_2 from the atmosphere into long-lived terrestrial and geologic pools (Lal 2004). The amount of carbon sequestered by a management practice is best calculated by comparing the carbon balance for the same number of rotations between the new and previous management practice on a parcel of land (Dixon et al. 1994).

The amount of carbon sequestered by agroforestry systems must first be reliably quantified in order to allocate carbon credit values to lands managed under agroforestry in Canada. As carbon sequestration is a very complicated process, there are many factors that must be taken into consideration when making such calculations. According to Montagnini and Nair (2004) there are three factors that are needed to be able to determine carbon sequestration amounts. These factors are: (1) the increased amount of carbon in standing biomass, (2) the increased amount of recalcitrant (stable) carbon remaining in the soil and (3) the amount of carbon sequestered in products created from harvested wood (for example, is the wood burned to release CO_2 into the atmosphere, or does it remain intact in wood products such as furniture?). Most carbon sequestration calculations do not take long-term carbon storage of wood products into account, so care must be taken that it will be accounted for in agroforestry management calculations (Dixon et al. 1994). Since the value of carbon sequestration is calculated from a baseline point, it has been noted that landowners managing marginal lands with low baseline carbon stocks can economically benefit more from carbon trading than other producers (Wise et al. 2007). More stringent and accurate sampling procedures are needed for SOC testing for carbon sequestration calculations than traditional SOC testing for fertility reasons. This is because very small increases in SOC must be measured against very high backgrounds. In situations where small changes must be measured against high backgrounds, it can be very difficult to establish significant changes in carbon storage. More powerful and stringent methods of SOC sampling must be examined to make this possible (Ellert et al. 2008).

8. The Potential of Agroforestry for Carbon Sequestration

It is understood that although we cannot come close to replacing the amount of carbon that was once held in primary forests, grasslands and soils, it is possible to regain some level of carbon storage through improved management techniques. Agroforestry is very special in this respect because the management system allows for increased carbon sequestration into the soil as well as providing food, a renewable fuel source, and environmental and ecosystem services to the environment (Montagnini and Nair 2004).

Agroforestry has the potential to contribute to global carbon sequestration efforts in many forms. Due to the massive atmospheric carbon increases caused by deforestation, it is evident that reforestation practices would remove incredible amounts of carbon from the atmosphere. However, increasing land area and food needs of an increasing population make such efforts increasingly difficult. Agroforestry management is valuable in this respect because it allows for the planting of trees on lands that can provide for other human needs, such as food production, at the same time. Agroforestry systems also have an indirect impact on carbon sequestration because they reduce pressure on existing forests by providing alternative sources for wood (Montagnini and Nair 2004). Agroforestry management can be more beneficial than conventional agriculture systems in terms soil carbon storage as well. The diversity of species (crops and tree species) in agroforestry can increase net primary productivity (NPP) through the capture of more photosynthetic energy at different trophic levels and growth periods among the intercropped species (Montagnini and Nair 2004; Thevathasan and Gordon 2004). Increases in NPP lead to increases in organic matter being returned to the soil. According to Sanchez (2000), the optimized tradeoffs between environmental conservation, poverty alleviation and increased food production can make agroforestry a superior land use system for carbon sequestration.

Agroforestry management is often initially associated with increased costs, due to the cost of purchasing and planting trees, increased labour intensity, and often a reduction in crop yields due to competition with trees for resources (Gordon et al. 1997). The ability to tap into payments for carbon sequestration would help producers to deal with potential increased management costs, allowing a move towards more ecologically sustainable land management practices in Canada.

8.1 Research on Carbon Sequestration in Agroforestry Systems

There has been a range of carbon storage estimates for agroforestry intercropping practices in temperate systems. Temperate systems tend to hold more carbon in their soils than tropical systems due to decreased decomposition rates at lower temperatures, which allows more SOM to remain in the soil (Christopher and Lal 2007). Various studies have estimated potential carbon storage of tropical and temperate agroforestry systems to be 21 to 240 t C ha^{-1} and 10 to 208 t C ha^{-1}, respectively. The tropical system values are calculated to be for a cutting cycle of one to two decades, while the temperate estimates are based on a longer cutting cycle of two to five decades (Peichl et al. 2006). In a review of tropical agroforestry research, Sanchez (2000) stated that in the conversion of forests to cropland or pasture, 80% of the original carbon content of the ecosystem is lost in the first two years. However, if agroforests are established immediately after the conversion from forestland, 35% of the original carbon stock of the forest can be recovered. Over 20 to 25 years carbon stocks in vegetation can increase by 50 Mg ha^{-1}, and soil carbon can increase by 7 Mg ha^{-1}. This increased sequestration of approximately 57 Mg C ha^{-1} accounts for roughly three times the amount of carbon storage that a conventional cropping system is able to store.

8.2 Carbon Sequestration in Temperate Intercropping Systems

Within the temperate latitudes there is limited research on the potential of intercropping systems to sequester carbon. In one particular study Thevathasan and Gordon (2004) studied the carbon sequestration of a 13-year-old poplar intercropping system. During the 13 years of their field study, sampled poplar trees were estimated to sequester 14 Mg of C per ha. Leaf litter and fine root input was estimated to add 25 Mg of C per ha into the soil. This means that approximately 39 Mg of C per ha was stored during the 13-year period. This calculates into 154 Mg per hectare of CO_2 sequestration in 13 years. A later study on the same site compared the carbon storage of a barley sole cropping site to two different agroforestry systems containing poplar or spruce trees. Poplar, spruce and barley systems had soil carbon pools of 78.5, 66 and 64 tonnes of carbon per hectare, respectively. A significant difference in carbon storage values only exists when poplar intercropping carbon storage is compared to that of sole barley cropping. Estimated carbon fluxes for the systems were +13.2, +1.1 and -2.9 tonnes of carbon per hectare for poplar, spruce and sole barley cropping, respectively. The same study also further investigated potential differences in carbon storage for spruce and poplar trees. It was found that after 13 years of growth, the total carbon content of the poplar trees was higher than that of spruce, suggesting that perhaps poplar intercropping systems are more effective for carbon sequestration than spruce systems. Another aspect of the study showed that distance from the tree row did not affect soil carbon content (Peichl et al. 2006), a property that is expected in older agroforestry systems where taller trees can more evenly place litter among cropping rows (Thevathasan et al. 2004). It is important to note that carbon sequestration amounts estimated by research studies can often underestimate carbon storage potential of agroforestry systems because they do not account for prolonged carbon storage in wood products as well as offsets of fossil fuel consumption through the use of wood. A decrease in pressure to existing woodlands must also be considered (Dixon et al. 1994).

9. Conclusion and Future Directions

When carbon sequestration in agroforestry intercropping systems is fully understood, sequestration estimates may be used to quantify intercropping contributions to Canada's carbon budget. Associated payments for carbon sequestration would act as an incentive for farmers to convert degraded lands to agroforest management, also benefiting our environment through a conversion to a more ecologically-friendly land use management system. Further research required to drive such an endeavor includes: (1) investigation of varying carbon storage of intercropping systems with different types of trees and intercrops, (2) investigation of variability in carbon storage at different distances from tree rows throughout the life cycle of the system, (3) examination of different sampling techniques to find the most sensitive way to significantly trace small changes in soil organic carbon, and (4) studies on appropriate soil sampling depths to test for changes in soil organic carbon due to management. Given these challenges, in my research I will focus primarily on variability in carbon storage at different distances from tree rows and will use TBI sites of varying ages to investigate changes in this variability in different lifecycle stages of TBI systems. I will also compare SOC pools in TBI systems with nearby conventionally managed agroecosystems, to estimate the increase in SOC storage in TBI systems. My specific research objectives are (1) to quantify the horizontal variability of the SOC pool in TBI systems and (2) to compare SOC pool in TBI systems with the SOC pool in nearby conventional agroecosystems, which addresses the hypotheses described above. The hypotheses that will be tested are:

(1) Horizontal SOC variability:

H_o: SOC content will not change with distance from tree row

H_a: SOC content will decrease with distance from tree row

It is hypothesized that SOC content will decrease with distance from the tree row because leaf litter inputs will be greater near the base of the tree (Peichl et al. 2006). It is also expected that this horizontal variability in SOC due to leaf litter inputs will decrease in older TBI plots because larger trees will spread their litter more evenly (Thevathasan et al. 2004).

(2) TBI vs. conventional agroecosystems SOC:

H_o: SOC content will not be different between TBI and conventionally managed systems

H_a: SOC content will be elevated in TBI systems due to the tree carbon inputs

It is expected that TBI systems will have larger SOC pools than conventionally managed agricultural systems due to the increased carbon input from trees (Smith 2008).

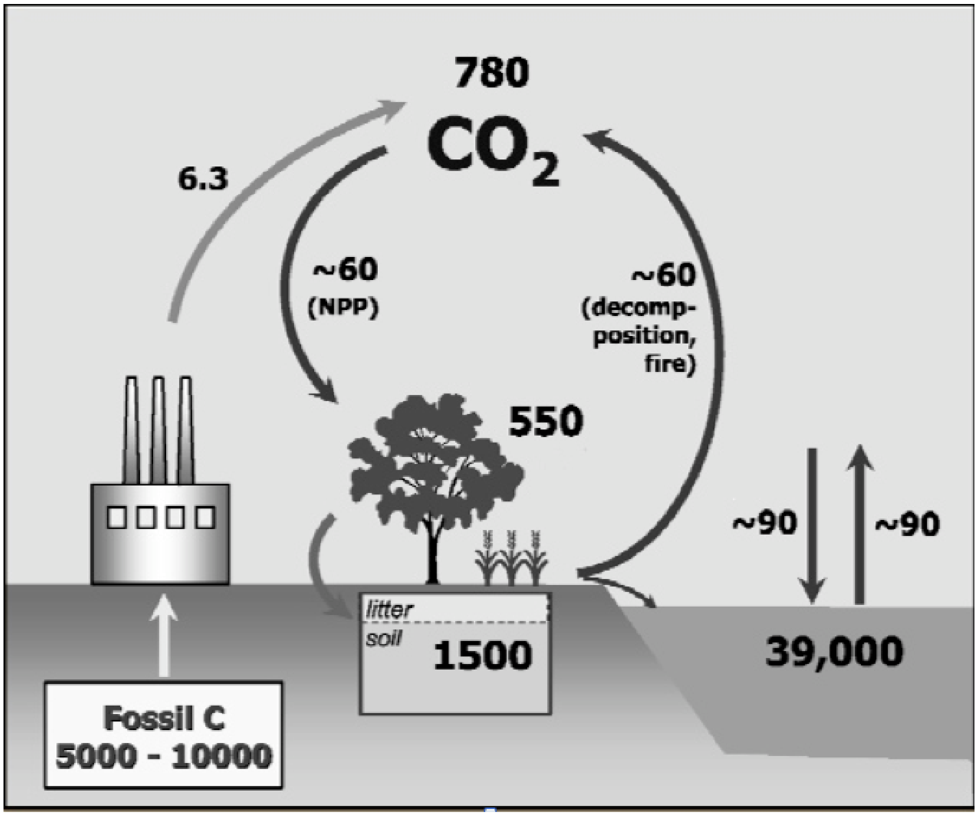


Fig. 1. Diagram of global carbon cycle from Janzen (2005). The C in active global circulation occurs mainly in four pools: the atmosphere, terrestrial biota, soil and the ocean. Carbon stocks are in units of Pg C and flows between pools are in Pg C yr^{-1}. Net annual changes in pool size (Pg C yr^{-1}) are indicated in italics. Estimate of atmospheric CO_2 is for the year 2000.

CHAPTER 2: SPATIAL HETEROGENEITY IN SOIL ORGANIC CARBON POOLS IN TREE-BASED INTERCROPPING SYSTEMS AND CONVENTIONAL AGROECOSYSTEMS IN QUEBEC AND ONTARIO

Abstract

Tree-based intercropping (TBI) is an agroforestry system where a crop, generally an annual, is planted between established tree rows. TBI systems have a greater potential for carbon storage than conventional cropping systems because carbon is stored in the biomass of growing trees and trees provide additional carbon inputs (leaves, roots) that contribute to soil organic carbon (SOC) storage. Growing trees and herbaceous vegetation in the same field could lead to considerable spatial heterogeneity in the SOC content due to differences in plant litter input and litter quality. The objectives of this work were (1) to quantify the horizontal variability of the SOC pool in TBI systems and (2) to compare SOC pool in TBI systems with the SOC pool in nearby conventional agroecosystems. A third objective of the work was to determine whether soil chemical properties, such as the total nitrogen (N) concentration, plant-available nutrient concentrations (mineral N, P, K), soil pH and electrical conductivity (EC), were related to the SOC concentration in TBI systems. The research sites include 4-year old TBI sites at St. Paulin and St. Edouard (Quebec, Canada), an 8-year old TBI site in St. Remi, Quebec, Canada and a 20-year old TBI site in Guelph, Ontario, Canada. At St-Paulin, the SOC pool was similar across the field. At St-Edouard, there was more SOC within 0.75 m of the hardwood tree row than near the hybrid poplar row and in the intercropped space. In St-Remi, there was more SOC within 0.75 m of the hybrid poplar row than in the intercropped space or near the hardwood row. At Guelph, there was no change in SOC at sampling points in hybrid

poplar TBI plots, but there was more SOC within 1 m of trees in the Norway spruce TBI plots. Results also indicate that St-Remi (8 yrs) contained 77% more SOC and Guelph (21 yrs) contained 12% more SOC than adjacent, conventionally managed agroecosystems. The SOC pool at these sites was correlated significantly (P <0.05, n = 53) with total N (r= 0.547), plant-available P (r= -0.515) and EC (r= 0.363). We conclude that TBI systems hold promise for maintaining or increasing the SOC pool, relative to conventionally managed agroecosystems.

Introduction

Atmospheric concentrations of carbon dioxide (CO_2) are increasing, with levels rising from 280 parts per million (ppm) in 1850 to 310 ppm in 1950, and increasing further to 380 ppm in 2005 (IPCC 2007; Smith et al. 1993). Two important anthropogenic factors contributing to the increase in atmospheric CO_2 concentrations are land use change and fossil fuel combustion. In Canada, the conversion of forests or grasslands to agriculture released considerable amounts of carbon (C) into the atmosphere by removing C-rich biomass and accelerating decomposition. It is estimated that in Canada, a mean of 25% of SOC was lost to the atmosphere following conversion of arable lands to agriculture following European colonization (Janzen et al. 1997). While land use change redistributes C to the atmospheric pool, fossil fuel burning takes C that was once inert in underground stores and adds it to the pools of exchangeable C already present in the atmosphere, terrestrial ecosystems and the ocean (Janzen 2005). In 2006, Canada released 721,000 kt of CO_2-equivalents into the atmosphere, with 8.5% from agriculture (including livestock production), with 48% of agricultural CO_2-equivalents coming from agricultural soils.

Fossil fuel combustion accounts for another 81% of emissions while the remaining 10.5% comes primarily from industrial processes (Environment Canada 2008a).

The Intergovernmental Panel on Climate Change (IPCC, 2007) proposed mitigation strategies to reduce the amount of CO_2 present in the atmosphere. First of all, the reduction of CO_2 emissions from fossil fuels is recommended. This can be achieved through increasing energy efficiency, decreasing energy use, and by substituting renewable biofuels for non-renewable fossil fuels (Flach et al. 1997). Another method is to increase the amount of C stored in terrestrial plant and soil pools by avoiding C-releasing practices, such as deforestation, or by adopting land management practices that increase the amount of C stored in plant and soil stocks, also known as C sequestration (Janzen 2005). Carbon sequestration is the difference in the amount of C gained through photosynthesis and C lost through respiration of plants and decomposers (Montagnini and Nair 2004).

A land management practice that can contribute to C sequestration in Canada is Tree-based intercropping (TBI), an agroforestry management system where crops are grown between permanent tree rows. These systems have long been promoted for their ability to diversify the rural landscape and provide economic returns by simultaneously producing food and high-value hardwoods; in addition, the C sequestered in trees and soils in a TBI system can offset CO_2 released to the atmosphere. Tree-based intercropping systems are expected to store more C than conventional cropping systems through two mechanisms: (1) TBI systems increase C storage in the biomass of planted trees (Peichl et al. 2006), and (2) TBI systems increase SOC storage through C inputs to the soil. These C inputs originate from leaf litter, root turnover and root exudates from the agricultural crops and trees, with those from trees generally contributing more recalcitrant C compounds that are slowly decomposed and thus stabilized in the SOC pool (Montagnini and Nair 2004). Thevathasan and Gordon (2004) estimated that annual net C input to soils was in the range of 400 to 600 kg ha^{-1} yr^{-1} in a maize monocropped field and 2400 kg ha^{-1} yr^{-1} in TBI systems. Another reason that TBI systems serve as a C offset is because they produce wood fiber and lignocellulose-rich crop residues that could be used as biofuels. The transformation of wood and agricultural residues into ethanol is underway in many parts of North America, and in Quebec, the provincial government plans to enforce a minimum of 5% ethanol in total fuel sales by 2012 (Gouvernement du Quebec 2008). This may suggest an important role for TBI systems in a future bio-based economy.

It is relatively simple to calculate the C storage in the above-ground biomass of trees and crops present in TBI systems and harvested for biofuel generation. Less is known about the SOC storage in TBI systems of Canada, since the available data comes from one study site in Guelph (Oelbermann and Voroney 2007; Oelbermann et al. 2004; Oelbermann et al. 2006; Peichl et al. 2006; Thevathasan and Gordon 2004). Researchers working in agricultural systems report considerable spatial variability in SOC pools due to factors such as soil texture, hydrology, vegetation and previous land use, even many years after a constant management regime has been implemented. In TBI systems, it is expected that the spatial distribution of trees and crops will be the most important factor controlling C storage in the SOC pool. This study is predicated upon two hypotheses. First, there will be horizontal variability in SOC storage, with a decline in the SOC pool with distance from the tree row because tree litter inputs are greater near the base of the tree (Peichl et al. 2006). Litterfall measurements by Thevathasan and Gordon (2004) showed that 84% of leaf biomass fell within 2.5 m of hybrid poplars (6 – 7 years old). However, the C input near trees should decline with time because larger trees will spread their litter more evenly in the intercropped area (Thevathasan et al. 2004). Second, there will be a significant gain in SOC storage in TBI systems compared to conventionally managed agroecosystems, due to recalcitrant C inputs from trees (leaves, branches and roots) (Smith 2008).

The objectives of this work are (1) to quantify the horizontal variability of the SOC pool in TBI systems and (2) to compare SOC pool in TBI systems with the SOC pool in nearby conventional agroecosystems, which addresses the hypotheses described above. A third objective of the work is to determine whether soil chemical properties, including the total N concentration, plant-available nutrient concentrations (mineral N, P, K), soil pH and EC were related to the SOC concentration in TBI systems.

Materials and methods

Site descriptions and experimental designs

The research sites included 4-year old TBI sites at St. Paulin and St. Edouard (Quebec, Canada), an 8-year old TBI site in St. Remi, Quebec, Canada and a 21-year old TBI site in Guelph, Ontario, Canada. A subset of plots from each site was selected for this study. A brief description of each site and the experimental designs are provided below, with additional details available from Peichl et al. (2006), Rivest et al. (2008) and Lacombe et al. (2008). All research sites were converted to TBI following conventional management except for St. Remi, which was previously a tree plantation.

The St. Paulin site (46° 27'N, 72° 59' W) was on a slightly acidic (pH 6.2) loamy sand (790 g sand kg^{-1}, 160 g silt kg^{-1} and 50 g clay kg^{-1}) with pockets of sandy loam soil (560 g sand kg^{-1}, 300 g silt kg^{-1} and 140 g clay kg^{-1}), mostly contained within one sampling block in the western section of the field. The soil was a Dystric Brunisol

(Agriculture and Agri-Food Canada 1998). The site had a rolling topography and moderate agricultural potential. Mean annual temperature at the site is 4^{o}C with annual precipitation of 1113 mm (Environment Canada 2008b). Treatments were established in 2004 according to a split-plot design, the two main-plot factors being a three-year annual crop rotation (oats-corn-corn) (*Avena sativa* L. - *Zea mays* L.), or fallow (a fallow that was mowed and harrowed during the growing season to control weeds). Sub-plot factors included two clones of hybrid poplar (*Populus deltoides* clone DN-3570, *Populus nigra* clone DN-3333), two high-valued hardwoods (red oak, *Quercus rubra* L. and black cherry *Prunus serotina* Ehrh.) and a conventionally managed agroecosystem with no trees. Tree rows were spaced 12 m apart along a north-west/south-east orientation, resulting in a tree-density of 208 poplar stems ha^{-1} and 139 hardwood stems ha^{-1}. Each treatment block measured 900 m^{2} and was replicated in four complete blocks. Data reported from this site comes from the crop-rotation plots with and without trees.

The St. Edouard site (46° 20' N, 73° 11' W) was on a slightly acidic (pH 6.3) loamy sand soil (860 g sand kg^{-1}, 120 g silt kg^{-1} and 20 g clay kg^{-1}) with less than 1% slope and moderate agricultural potential, having a mean annual temperature of 3^{o}C and annual precipitation of 1079 mm (Environment Canada 2008b). The soil was a Humo-Ferric Podzol (Agriculture and Agri-Food Canada 1998). Treatments were established with a similar design as the St. Paulin site, with the following differences: (i) high-valued hardwoods were planted in 2001, poplars in 2004 (both 1.5-2 m tall at planting); (ii) trees were established in alternating rows of hybrid poplar/red oak or hybrid poplar/white ash (*Fraxinus americana* L.); (iii) tree rows were 10 m apart; and (iv) the annual crop rotation consisted of buckwheat-oats-canola (*Fagopyrum esculentum* P. Mill. - *A. sativa* - *Brassica napus* L.). Tree rows followed a north-east/south-west orientation, resulting in a tree-density of 250 poplar stems ha^{-1} and 167 hardwood stems ha^{-1}. The conventional agricultural system was a cropped area within 10 m of the experimental site, which is considered statistically to be an unplanned control. Data for this site came from the crop-rotation plots grown between tree rows and the conventionally managed agroecosystem.

The St. Remi site (45°15′ N, 73°40′ W) was on a loamy soil (490 g sand kg^{-1}, 350 g silt kg^{-1} and 160 g clay kg^{-1}) (pH 7) with approximately 2% slope and high agricultural potential. The soil was a Melanic Brunisol (Agriculture and Agri-Food Canada 1998). At this site, the mean annual temperature is 6°C with an annual precipitation of 1027 mm (Environment Canada 2008b). Twelve treatments consisting of a factorial array of three tree species, two alley crops, and two row widths were organized in a completely randomized block design. Trees were established in 2000 and consist of 5 m tall hybrid poplar (*Populus trichocarpa x deltoids* TD-3230, *Populus nigra x maximowiczii* NM-3729 and *Populus deltoids x nigra* DN-3308), and 1.5-2 m tall white ash and black walnut (*Juglans nigra* L.). Alley crops followed a soybean-oat-wheat rotation (*G. max* - *A. sativa-Triticum aestivum* L.). Tree rows were spaced 6 m or 8 m apart and rows were oriented north-west/south-east on the research site. Following transition to TBI in 2000, there were 313 poplar stems ha^{-1}, but in 2006 they were thinned to 104 stems ha^{-1}. The hardwoods remained at a density of 208 stems ha^{-1}. Sampling locations were in the plots with 8 m spacing between tree rows. The conventional agricultural system used for comparison was an adjacent conventionally managed field within 20 m of the TBI site. Data from this site came from the crop-rotation plots grown between tree rows and the conventionally managed agroecosystem.

The Guelph site (43°32’28” N, 80°12’32” W) was on a sandy-loam soil (560 g sand kg^{-1}, 340 g silt kg^{-1}, 100 g clay kg^{-1}) (pH 7.4), located on a hillside with 2-4% slope, moderate agricultural potential and a slightly warmer, drier climate than the other sites, having a mean annual temperature of 7.2^{o}C and annual precipitation of 830 mm, with about 340 mm falling during the growing season (May to August). The soil is an Grey-Brown Luvisol (Peichl et al., 2006). Ten tree species were planted and annually intercropped with corn, soybean and winter wheat or barley (*Hordeum vulgare* L.) (Peichl et al. 2006). In 1987, hybrid poplar (*Poplus deltoides* x *nigra* clone DN-177) and Norway spruce (*Picea abies* L.) were planted along with a variety of 13 other tree species. Poplar trees are planted at a density of 0.0111 stems ha^{-1} as well as Norway spruce. Tree rows were spaced 12.5 m and 15 m apart and follow a north/south orientation. The conventional agricultural system was an adjacent agricultural field located at the top of the slope. Data from this site came from the all poplar and Norway Spruce TBI plots and the conventionally managed control.

Soil Sampling

Soil sampling was done in October and November of 2007. To allow for the possibility of assessing temporal changes in SOC pools, we collected samples for bulk density and other soil chemical analyses from the same sampling distances (although not the same sampling locations) as previous researchers. Non-decayed plant residues were brushed aside and not included in soil samples for this analysis, though these plant residues may have been included in previous soil sampling research on the study sites. In St-Paulin, soils were sampled at 0.75 m and 5 m from the hybrid poplar row, and then 0.75 m from the opposite hardwood row. At each sampling point, soils were collected from the 0-5 cm, 5-20 cm and 20-30 cm depths. Soil samples were taken with a shovel or trowel at 3-4 positions in the plot and mixed to form a composite sample that represented soil properties at each depth in the profile and each distance from the tree rows. The same procedure was followed to collect soil samples at the St-Edouard and St-Remi sites. At the Guelph site, soil samples were collected at 1 m, 3 m and 6 m distances from both hybrid poplar and Norway spruce trees. At each distance composite samples were taken from depths of 0-5 cm and 5-20 cm. It was not possible to get samples from the 20-30 cm depth as the substratum was very rocky. The St-Paulin site were tilled with a moldboard plow prior to sampling, while the St-Edouard, St-Remi and Guelph sites were untilled at the time of sampling.

Intact soil cores for bulk density assessment were also taken at each sampling distance and depth in each plot (8.5 cm diameter, 7.5 cm length). In St-Paulin, bulk density samples were collected at the 0.75 m distances alternatively from the poplar and hardwood row, depending on the direction of the pass of the moldboard plow prior to sampling, and also at a distance of 5 m from the hybrid poplars. In St-Edouard and St-Remi, bulk density cores were collected at 0.75 m and 5 m from the hybrid poplar row. In Guelph, bulk density cores were collected at 1 m, 3 m and 6 m from the hybrid poplar or Norway spruce trees at 0-5 cm and 5-20 cm depths. Soil samples at Guelph were always collected on the western side of poplar tree rows, where the effect of poplar shading on the intercropped row would be greater.

Soil Analysis

Bulk density was determined by drying the soil collected in a core (volume = 385.6 cm^3) to a constant mass at 60°C and weighing. Composite soil samples were passed through a 6 mm sieve, dried to a constant mass at a maximum of 40°C, ground in a mechanical soil grinder, then passed through a 1 mm sieve and glass-bottled (VandenBygaart 2006). Total C and N were analyzed using a ThermoFinnigan Flash EA 1112 CN Analyzer (Carlo Erba, Milan, Italy). Soils were tested for the presence of inorganic C, and the absence of carbonates in the samples permitted us to conclude that total C was equivalent to organic C. Dried, ground soils were also analyzed for mineral N (NO_3^- and NH_4^+) concentration in KCl extracts (Maynard et al. 2008), followed by colorimetric determination on a Lachat Quick-Chem AE autoanalyzer (Lachat Instruments, Milwaukee, WI, USA). Plant-available P and K concentrations in Mehlich-3 extracts (Ziadi and Sen Tran 2008) were determined by colorimetry and atomic absorption spectrometry. Soil pH and EC were measured in 1:2 soil:water solution (Hendershot et al. 2008).

Calculations

Soil bulk density was determined as:

$\rho_b = M_{soil} / V_{soil}$

where ρ_b is the soil bulk density (Mg m^{-3}), M_{soil} is the soil mass in the core (kg) and V_{soil} is the core volume (m^{-3})

The SOC and total N pools in the soil profile were calculated on an "equivalent mass basis", following the approach of Ellert and Bettany (1995). A hypothetical soil mass of 1.00 g cm^{-3} was chosen and the thickness of each soil layer in the field was adjusted to produce the hypothetical soil mass for each soil using the following equation:

$T_c = (T_n / \rho_b) - T_n$

where T_c is the soil thickness required to reach the hypothetical equivalent mass (m), T_n is the original thickness of the soil profile (m). This T_c value was then used to calculate the total SOC and N pools in the soil profiles in the following equation:

$M_{element} = conc * \rho_b * T_c * 10{,}000\ m^2\ ha^{-1} * 0.001\ Mg\ kg^{-1}$

where $M_{element}$ is the element mass per unit area (Mg ha^{-1}) and conc is the elemental concentration of total C or total N (kg Mg^{-1})

This permitted us to account for variation in soil density due to soil texture and cultural practices in research plots (Ellert and Bettany 1995). The SOC and total N pools were summed for the 0-30 cm depths in the Quebec sites, and presented as the SOC and total N pools in the 0-20 cm depth for the Guelph site.

Statistical Analysis

The effect of sampling distance from the tree row (distance) and comparison of treatments, including intercrops, fallows and controls, on the SOC pool were analyzed statistically using MANOVA repeated measures analysis with SAS software, with distance from trees and soil depth as repeated measures factors (SAS System 9.1, SAS Institute, Inc., Cary, NC). In the Guelph, St-Edouard and St-Remi sites where an unplanned control was used, one-way ANOVA was used to compare the average SOC pool of TBI and conventionally managed systems, following confirmation of the normality and independence of data points and the independence sample of variance. Correlation analyses with Pearson's correlation coefficients were used to determine if a relationship existed between the SOC pool and other soil parameters such as plant available P and K, total N and mineral N and soil EC and pH. In this analysis we pooled data from all sites (n = 53) and compared the SOC pool (0 – 20 cm or 0 – 30 cm) to the average value of the soil chemical parameter in the same depth. In all tests, values were considered significant at the 95% confidence level ($P < 0.05$).

Results and Discussion

Horizontal variability in the SOC pool

It was expected that the SOC pool would exhibit horizontal variability, with more SOC near the fast-growing hybrid poplar row and a declining SOC level in the intercropped alley. In St-Paulin, there was no change in the SOC pool in relation to distance from tree rows. At the St-Edouard site, there was more SOC near the hardwood row than beside the hybrid poplar row or within the intercropped space. At the St-Edouard site, hardwood trees were planted two years prior to the hybrid poplar and may have made a greater C input into the surrounding soil than hybrid poplars. This could be related to differences in litter decomposition rates of each tree species. At the St-Remi site, there was significantly more SOC ($P <0.05$) within 0.75 m of the hybrid poplar row than at other sampling locations (Table 1). At the Guelph site, there was no change in the SOC pool with increasing distance from the hybrid poplar tree row (Table 2). According to Thevathasan and Gordon (2004), the SOC pool varied with distance from the poplar tree row, with more SOC within 1 and 2 m of the poplar trees in 1993-1995, when the poplar trees were

6-8 years old. In 2002, this variation had diminished, probably because the trees had become quite tall (14 m) and spread their litter more evenly over the intercropped space (Peichl et al. 2006). This is supported by the observation of 82 -84% litterfall within 2.5 m of tree rows with 6 – 7 year old trees (Thevathasan and Gordon 2004), which declined to 71% litterfall in 12 year old hybrid poplars (Oelbermann et al. 2004). In addition, large trees would have a more uniform effect on the intercrop space (e.g. shading), which could affect the C input from annual crop litter. At the Guelph site, the SOC pool was greater within 1 m of the Norway spruce trees than further away, in the intercropped space (Table 2). Peichl et al. (2006) reported no variation in the SOC pool with distance from spruce trees in 2002. This suggests that variability in SOC due to spruce trees may not be detected until trees are 16-21 years old.

An Alabama study done by Polyakova and Billor (2007) showed that different deciduous tree species mixed with pine (Pinus taeda L.) litter (80% pine, 20% deciduous litter) have varying decomposition rates. Red oak (Quercus falcata L.) had a higher decomposition rate than yellow poplar (Liriodendron tulipifera L.), which in turn had a higher decomposition rate than water oak (Q. nigra L.). Laganiere et al. (2009) also found that in a study site in Quebec, the presence of trembling aspen (P. tremuloides Michx.) tree litter increased decomposition rates in black-spruce (Picea mariana Mill. BSP) plantations. The effect of varying decomposition rates could have an impact on SOC content in the TBI plots of this study.

TBI systems vs. conventional agroecosystems

We expected a significant gain in the SOC pools in TBI systems compared to conventional agroecosystems, and found this occurred at two of the four sites in this study. There was no difference in the SOC pool between TBI systems in St-Paulin and St-Edouard, likely because these sites are too young and trees too small to create variability in the SOC pool. In St-Remi, the SOC pool in the TBI system was 33.6 Mg C ha^{-1} or 77% greater than in the nearby conventionally managed agroecosystem (Table 3). The poplar TBI system in Guelph contained more SOC than both the Norway spruce TBI and conventionally managed agroecosystem (Table 4). The poplar TBI system at Guelph showed a 6.2 Mg C ha^{-1} or 12% increase in the SOC pool over the conventionally managed agroecosystem. This is more dramatic than the 0.6% increase in SOC of the poplar TBI system, compared to conventional agriculture, reported in 2002, after 17 years of TBI (Peichl et al. 2006).

The difference in the SOC pool of the TBI and conventionally managed systems was much larger in St-Remi than in Guelph, despite the fact that trees in Guelph are 15 years older. This is likely because the St-Remi site was a tree plantation prior to transition to TBI, whereas all other sites were conventionally managed agroecosystems prior to TBI establishment. Garten (2002) found that in seven agricultural plots converted to tree plantations, soil carbon levels rose from 0.4 to 1.7 Mg C ha^{-1} (0 – 40 cm pool) within 10 years of establishment. The prior presence of trees at St-Remi would have provided elevated background SOC pool to TBI management, through the inputs of tree litter and structural/coarse roots, some of which are slowly decomposed (Montagnini and Nair 2004; Sharrow and Ismail 2004).

More intensive sampling to compare intercropped plots to conventional management would be beneficial at all sites. This is especially true at St-Paulin where soils contained about 5 g clay kg^{-1} in three of four blocks, but had 14 g clay kg^{-1} in the other block and at Guelph, where C-rich pockets of soil created a large amount of variability in the field (Peichl et al. 2006). Also, the St-Paulin and Guelph sites were on slopes, which can influence SOC variability (Papiernik et al. 2005; Wei et al. 2008). Collecting more samples would help researchers to capture a broader picture of SOC variability in the field. In a grassland site, Don et al. (2007) recommended sampling along a 24 x 24 m grid to properly describe field variability in SOC. Whether this sampling intensity would be appropriate for TBI systems remains to be determined. It should also be noted that carbon inputs from tree roots in TBI systems are much deeper than the maximum sampling depths used in this study, the carbon sequestration potential of soils in these TBI systems are likely underestimated. For example, poplar and Norway spruce roots in the Guelph TBI site have been found at depths of 2.1 m (Peichl et al. 2006). To fully represent total SOC input from tree roots, one must dig soil sampling pits to the maximum depth of tree roots, but this time-consuming approach was not feasible in this study where a large number of samples were needed to capture horizontal SOC variability.

In carbon sequestration studies it is common for researchers to choose shallower sampling depths since deep sampling can be difficult and because fewer sampling sites in profiles allows for more samples to be collected horizontally to represent the full landscape (Don et al. 2007). There is a tradeoff between how many samples can be collected on a horizontal plane and how many deep soil pits can be sampled. Most research on soil C is restricted to the top 15 cm to 30 cm depth due to these constraints (Conant and Paustian 2002; Don et al. 2007). Soil C researchers in the tropics often need to dig deeper to characterize their soil C pools than researchers in other temperate or arctic/alpine ecosystems. This is because the depth of the pedosphere which biologically and chemically reacts with the atmosphere is much deeper in tropical areas (Lal et al.

1997). However, it is common for tropical studies on C sequestration to report the SOC pool to a depth of 20 cm (Oelbermann et al. 2004).

Correlation between the SOC pool and soil chemical properties

The SOC pool was positively correlated (P <0.05) with total N and EC, and negatively correlated with plant-available P and the P/Al saturation index (Fig. 1). It was expected that total N would be correlated with SOC because approximately 99% of total N in agricultural fields is present as organic N (Halvin et al. 1999). The positive relationship between EC and SOC could be related to the cation exchange capacity of the SOC and its ability to bind cations such as Na^{+}, K^{+}, Ca^{2+} and Mg^{2+} that contribute to soil salinity, but this remains to be confirmed. As plant-available P generally increases with SOC content (Halvin et al. 1999), a negative correlation between the two was unexpected. It is plausible that higher SOC levels stimulated microbial development (Iyyemperumal et al. 2007; Rees and Parker 2005) and increased microbial phosphorus intake, reducing the amount of plant-available phosphorus reported in the Mehlich III extraction process. The sites with the lowest P/Al saturation indices were the St-Edouard and St-Remi, which had a history of low input management. Low fertilizer additions likely account for their low P/Al saturation.

Conclusions

(1) Introducing trees into agricultural fields created significant horizontal variability in SOC after the site has been established for more than 4 years.

(2) In the older TBI site (> 21 years), horizontal variability in SOC was observed in the vicinity of Norway spruce (conifer) but not around hybrid poplar (deciduous).

This is probably because most spruce needles fall close to the spruce trees and are slowly decomposed, whereas the leaves of hybrid poplar are widely dispersed and more rapidly decomposed.

(3) TBI systems at Guelph and St-Remi tended to have more SOC than adjacent conventional agroecosystems, but this was not observed at the younger St-Paulin and St-Edouard sites. This suggests that the hypothesized C gain in these systems was not realized in the cultivated soil layers for a number of years after TBI establishment.

(4) Factors that control variability in SOC in TBI systems may also lead to variability in total N, P, EC and the P/Al saturation index.

Table 1. Mean SOC pool at increasing distance from hybrid poplars in a TBI system in St-Paulin, St-Edouard and St-Remi, Quebec, Canada (0 - 30 cm depth). The furthest sampling distance from hybrid poplar was within 0.75 m of a hardwood tree row.

St-Paulin (4 yrs)			St-Edouard (4 yrs)			St-Remi (8 yrs)		
Distance (m)	SOC (Mg C ha^{-1})	SE	Distance (m)	SOC (Mg C ha^{-1})	SE	Distance (m)	SOC (Mg C ha^{-1})	SE
0.75	60.3a	8.8	0.75	74.2a	4.5	0.75	81.9a	4.1
5	58.3a	7.2	5	72.6a	2.4	5	73.9b	3.6
11.25	81.5a	9.0	9.25	83.9b	2.8	7.25	75.4b	4.6

Mean values with the same letter are not significantly different ($P < 0.05$)

Table 2. Mean SOC pool (0 - 20 cm depth) at increasing distance from hybrid poplar and Norway spruce in a TBI system in Guelph, Ontario, Canada (21 yrs).

	Poplar		Norway spruce	
Distance (m)	SOC (Mg C ha^{-1})	SE	SOC (Mg C ha^{-1})	SE
1	58.4a	1.2	56.2a	1.7
3	57.0a	2.4	48.3b	2.2
6	55.7a	3.2	48.2b	1.4

Mean values with the same letter are not significantly different ($P < 0.05$)

Table 3. Mean SOC pool (0 - 30 cm depth) of a TBI and a conventionally managed agro-ecosystems in St-Paulin, St-Edouard, and St-Remi, Quebec, Canada.

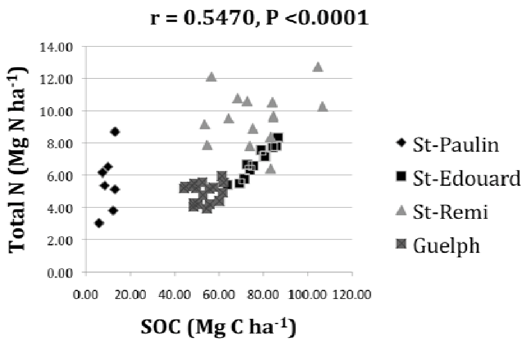
	St-Paulin (4 yrs)		St-Edouard (4 yrs)		St-Remi (8 yrs)	
Treatment	SOC (Mg C ha^{-1})	SE	SOC (Mg C ha^{-1})	SE	SOC (Mg C ha^{-1})	SE
TBI	66.9a	10.7	76.9a	2.0	77.1a	3.9
Conventional	66.3a	1.3	80.1a	6.0	43.5b	7.6

Mean values with the same letter are not significantly different ($P < 0.05$)

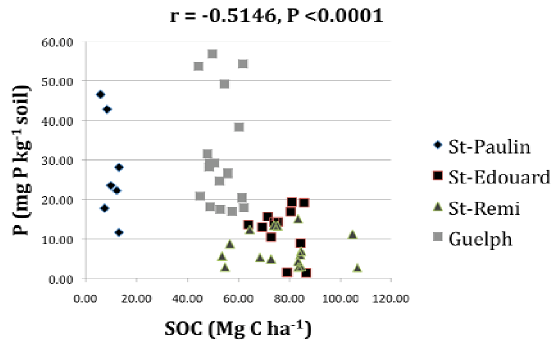
Table 4. Mean SOC pool (0 - 20 cm depth) of a TBI and a conventionally managed agro-ecosystems in Guelph, Ontario, Canada (21 yrs).

Treatment	SOC (Mg C ha^{-1})	SE
Poplar	57.0a	1.8
Norway Spruce	50.9b	1.4
Conventional	50.8b	1.8

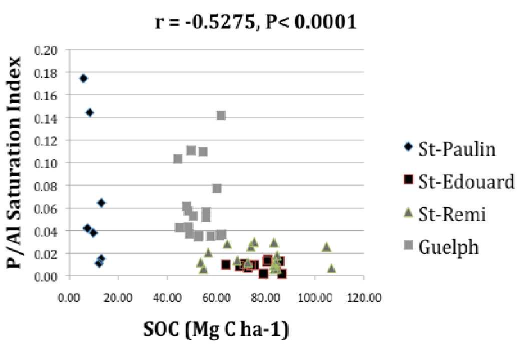
Mean values with the same letter are not significantly different (P < 0.05)



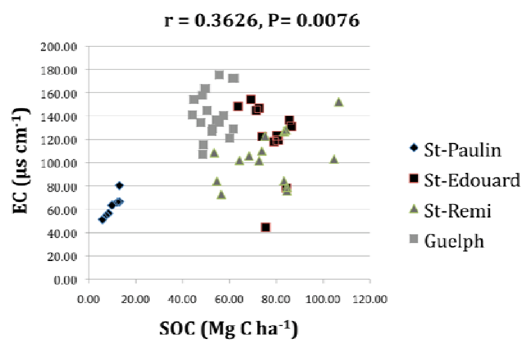
a)



b)



c)



d)

Figure 1. Scatterplots of SOC and soil chemistry properties that were significantly correlated (P < 0.05, n=53). Relationships between a) SOC and total N, b) SOC and Mehlich-3 extractable P, c) SOC and the P/Al saturation index and d) SOC and EC. All r values are Pearson correlation coefficients.

CONNECTING PARAGRAPH

It is clear that TBI systems can sequester carbon. Producers with TBI systems could collect financial reward for their efforts in the form of carbon trading. To make this possible, researchers must be able to generate reliable estimates of C sequestration in different TBI systems. Three parameters are needed to determine carbon sequestration amounts in TBI systems. These parameters are (1) net change in the amount of C in standing biomass, (2) net change in recalcitrant C remaining in the soil pool (3) the amount of carbon sequestered in products created from harvested wood. However, there is limited data available to generate these values. An environmental model such as *ecosys* could be used to make C sequestration estimates in a timely and cost-effective manner. Chapter 3 explores the use of *ecosys* to model the soil organic carbon pool in TBI systems.

CHAPTER 3: SOIL CARBON SEQUSTRATION IN TREE-BASED INTERCROPPING SYSTEMS: EXPLORATORY MODELLING WITH *ECOSYS*

Abstract

Although tree-based intercropping (TBI) systems are known to increase carbon sequestration in relation to conventional agricultural practices, actual carbon sequestration amounts are difficult to quantify. Difficulties in carbon sequestration quantification arise mainly due to changes in soil organic carbon (SOC) pools becoming masked by variability in SOC caused by the placement of tree rows in the field. Environmental modeling programs such as *ecosys* can prove useful to help predict field SOC levels, and could also be useful for affordable and timely prediction of carbon sequestration upon TBI conversion, allowing producers to benefit from potential carbon trading programs. In this study an actual poplar TBI system situated in Guelph, Ontario was simulated with a three-year soybean/winter wheat/corn crop rotation. *Ecosys* predicted a 5.0% decrease in SOC in the 0 - 20 cm soil layer following 21 years of TBI management while actual field measurements yielded a 12.6% increase in SOC in the 0 – 20 cm layer when compared to an adjacent conventionally managed field. Further investigation into the working of the model is needed to confirm the integrity of this result.

Introduction

Carbon sequestration refers to the storage of atmospheric CO_2 in plant biomass and soils of a particular ecosystem during a period of time. Tree-based intercropping (TBI) is a land management option that has C sequestration potential for two reasons. First, tree biomass contains more C than annual crops, leading to more C storage in TBI systems than conventional agricultural systems (Peichl et al. 2006; Sharrow and Ismail 2004). Second, TBI systems are expected to have more soil organic C (SOC) due to the greater annual C input from leaf litter, tree root turnover and tree root exudates, compared to agricultural crops. Organic residues from trees are lignin-rich and contain other resistant compounds (e.g., tannins) that are slowly decomposed and thus stabilized in the SOC pool (Montagnini and Nair 2004).

The establishment of North American agreements to reduce greenhouse gases using cap-and-trade systems, such as the Western Climate Initiative (WCI, 2009), and the Montreal Climate Exchange (MCeX, 2009) for carbon futures trading, will provide financial compensation to agricultural producers who increase C sequestration on their land. While TBI systems could be a viable land use in this context, there is scant information on the C sequestration potential of such systems and few established research sites where data can be obtained. According to Montagnini and Nair (2004), there are three parameters which are needed to quantify C sequestration in TBI systems, namely: (1) net change in the amount of C in standing biomass, (2) net change in recalcitrant C remaining in the soil pool (3) the amount of carbon sequestered in products created from harvested wood. Establishing a TBI site to measure these parameters represents a long-term (>20 years) investment in land, resources and human capital. Obtaining large amounts of data from field experiments requires a large investment of time and money (De Willigen 1991; Grant 1995). Producers require information on now to develop C sequestration strategies for maximum financial benefit. In this case, the *ecosys* model (Grant 2001) could be used to make C sequestration estimates for TBI systems in a timely and cost-effective manner.

Ecosys is a general purpose, research level model designed to anticipate behavior of various natural and managed ecosystems under varying environmental conditions (soils, climates, and land-use practices) (Grant 2001). This process-based environmental modeling program models the transformations and transfers of water, heat, C, nitrogen (N), phosphorous (P), and salts in the soil-plant system, based on user-defined conditions of climate, soil properties and ecosystem management. Thus, the *ecosys* model is an appropriate tool to predict changes in ecosystem functions such as C in standing biomass and the recalcitrant C in the soil pool (Grant, 1997). However, *ecosys* has not been tested to determine if it can accurately simulate C cycling in TBI systems.

The objective of this study was to use *ecosys* to model the change in SOC in a TBI system and to compare SOC estimates from the model with measured SOC values.

Materials and Methods

Site Information

Data used for model calibration and validation came from a long-term TBI site in Guelph, Ontario, Canada (43°32’28” N, 80°12’32” W). Established in 1987, this TBI system is the oldest of its kind in Canada and has been studied extensively (Oelbermann and Voroney 2007; Oelbermann et al. 2006; Peichl et al. 2006; Thevathasan and Gordon 1997; Thevathasan and Gordon 2004). Soil at the site was classified as an Albic Luvisol (Peichl et al., 2006) with a sandy-loam texture (560 g sand kg^{-1}, 340 g silt kg^{-1}, 100 g clay kg^{-1}) (pH 7.4), located on a hillside with 2-4% slope and moderate agricultural potential. The mean annual temperature is 7.2^{o}C and annual precipitation is 830 mm, with about 340 mm of rainfall during the growing season (May to August). Ten tree species were planted and annually intercropped with corn, soybean and winter wheat or barley (*Hordeum* *vulgare* L.). In 1987, hybrid poplar (*Poplus deltoides* x *nigra* clone DN-177) and Norway spruce (*Picea abies* L.) were planted along with 13 other tree species. Poplar and Norway spruce were planted at a density of 0.0111 stems ha^{-1}. Tree rows were spaced 12.5 m and 15 m apart and follow a north/south orientation. A conventionally managed agricultural field at the top of the slope, adjacent to the TBI site, was used as a benchmark of baseline conditions in the study area prior to the establishment of the TBI system.

Soil Sampling

Soil sampling was done in November 2007, after 21 years of TBI establishment. Soil samples were collected at 1 m, 3 m and 6 m distances from both hybrid poplar and Norway spruce trees. At each distance, composite samples were taken from depths of 0-5cm and 5-20 cm. It was not possible to get samples from deeper layers as the substratum was very rocky. Intact cores for soil bulk density were collected at 1 m, 3 m and 6 m from the hybrid poplar or Norway spruce trees at 0-5 cm and 5-20 cm depths. Soil samples were always collected on the western side of poplar tree rows, where the effect of poplar shading on the intercropped row would be greater. The site was untilled at the time of sampling.

Soil Analysis

Bulk density was determined by drying the soil collected in the intact core (volume = 385.6 cm^3) to a constant mass at 60°C and weighing. Composite soil samples were passed through a 6 mm sieve, dried to a constant mass at a maximum of 40°C, ground in a mechanical soil grinder, then passed through a 1 mm sieve and glass-bottled

(VandenBygaart 2006). Total C and N were analyzed using a ThermoFinnigan Flash EA 1112 CN Analyzer (Carlo Erba, Milan, Italy). Soils were tested for the presence of inorganic C, and the absence of carbonates permitted us to conclude that total C was equivalent to organic C. Dried, ground soils were also analyzed for mineral N (NO_3^- and NH_4^+) concentration in KCl extracts (Maynard et al. 2008), followed by colorimetric determination on a Lachat Quick-Chem AE autoanalyzer (Lachat, Milwaukee, WIThevathasan and Gordon 2004). Plant-available P and K concentrations in Mehlich-3 extracts (Ziadi and Sen Tran 2008) were determined by colorimetry and atomic absorption spectrometry. Soil pH and EC were measured in 1:2 soil:water solution (Hendershot et al. 2008).

Fundamental Principles of the *Ecosys* Model

The explanatory model, *ecosys*, was chosen for this study due to its proven versatility in various climates, soil and management conditions. The principles of the *ecosys* model were developed by Dr. Robert Grant (University of Alberta, Edmonton, Alberta, Canada) and guide the ongoing efforts to improve and upgrade the model. As described by Grant (2001), these principles are:

1. *Ecosys* parameters have a defined physical or biological meaning, and can be measured.
2. *Ecosys* parameters function at smaller spatial and temporal scales than the spatio-temporal scales at which the model can function.
3. Each ecosystem process is described with sufficient detail in the model that it can be isolated and constrained to test the model output.

4. *Ecosys* can function temporal scales from seconds to centuries, allowing users to validate and/or use data from experiments that range from short-term laboratory or long-term field studies
5. *Ecosys* integrates spatial scales ranging from mm to km in up to 3 dimensions. This permits researchers to extrapolate microscale phenomena to the landscape level.
6. *Ecosys* integrates biological scales from the organism to the entire community, allowing the representation of complex plant-microbial processes.
7. *Ecosys* simulates the transport and transformation of heat, water, C, oxygen (O), N, P, and ionic solutes through soil-plant-atmosphere systems. The atmosphere is used as an upper boundary of interactions and bedrock as a lower boundary.
8. *Ecosys* is constructed entirely in FORTRAN 77, allowing accessibility among different computers. Ecosys can be run on both high-performance and desktop computers.

In the *ecosys* interface, there are options available to simulate a wide range of site characteristics and management practices. One can specify hourly or daily weather data such as irradiance, air temperature, wind speed, humidity and precipitation amounts. General site topographic information must also be entered into the model. Information on soil physical, hydrologic, biologic, solution chemistry, solid chemistry and exchange chemistry properties must also be entered into the model for individual soil profile layers. Plants in a system can be described through their CO_2 fixation kinetics, phenology, morphology, grain and root characteristics, as well as plant-water relations and temperature sensitivity. Site management can be described according to tillage practices, fertilization and irrigation events, and plant management events such as planting, thinning and harvest (Grant 2001). In *ecosys*, all flux equations are solved in three dimensions (defined as row, column and layer in the model). This means that users can simulate ecological systems in up to three dimensions with any landscape length or width, soil depth, atmospheric height or slope. Any number of plant populations can be used in each modeled system. The availability of three dimensions for ecosystem simulation addresses a need for the ability to model systems up to a large landscape level (Grant 2001).

Ecosys Input Data: Climatic Variables

Weather data for the site was obtained from the Agrometerology group in the Department of Land Resource Sciences (University of Guelph, 2008). Hourly data on solar irradiance, air temperature, wind speed, humidity and precipitation from 2002, 2006 and 2007 was used to simulate weather conditions in the model. The rainwater pH level was set to 4.6 and rainwater deposition of NO_3^- and SO_4^{2-} was calculated at 0.42 mg N L^{-1} and 0.80 mg S L^{-1}, respectively (Table 1) (Meteorological Service of Canada 2004).

Ecosys Input Data: Topographical Variables and Soil Properties

The input data describing site topography and general field characteristics is shown in Table 2. The initial settings for general soil characteristics related to soil water potential and the depth of soil layers defined for the model run are given in Tables 3 and 4. For this simulation, the soil properties were described to a depth of 2 m, which corresponds to the maximum rooting depth expected for trees. The *ecosys* model then automatically adds two additional soil layers below the maximum rooting depth during the model run (Grant 2001). Soil properties up to a depth of 20 cm were the soil analysis results from field samples collected in the fall of 2007. The soil data for deeper depths was taken from the Soil Landscapes of Canada database (Agriculture and Agri-Food Canada 2008) or variables were set to the default *ecosys* soil properties suggested by Dr. Robert Grant. Soil water properties such as water content at field capacity, wilting point, and saturated hydraulic conductivity were calculated using Soil Texture Triangle Hydraulic Properties Calculator developed by the United States Department of Agriculture (Saxton and Rawls 2004; Saxton and Rawls 2006). The model also required initialization of soil describing physical, hydrologic, biological and chemical (solution, solid and exchangeable chemistry) properties for each soil layer. Input data for these soil properties can be found in Tables 5-10.

Ecosys Input Data: Crop Management

In the model simulation, poplar tree seeds were planted a density of 0.006 seeds m^{-2} at a depth of 0.05 m. Model equations were adjusted so the trees would have 1/3 of their foliage removed by pruning every three years. A three-year crop rotation (soybean - winter wheat - corn) was simulated for the intercropped space in the TBI systems. Soybean and corn were planted in the spring, whereas winter wheat was seeded in late summer. This three-year rotation was repeated 10 times in the model. One cropping year was added at the beginning and end of the model run to simulate the years of tree planting and harvest (both during the corn phase of the rotation) so the length of the simulation was 32 years (from 1987 to 2018). Details of the tillage practices, fertilizer applications, planting and harvesting dates in each phase of the rotation can be seen in Tables 11-15.

Ecosys Output

The model was set to provide output on soils and each plant species in the modeled TBI system. Soil outputs were requested for residue C, humus C, litter C, soil CO_2 flux, belowground autotrophic root respiration (R_a), net biome productivity (NBP), and total SOC for each user-defined soil layer (all soil outputs expressed as g C m^{-2}). Outputs for each plant species included: shoot C, leaf C, sheath C, stalk C, grain C, root C, grain number, leaf area index (LAI), root-exuded C, litter C, harvest C, soil organic C, and above + belowground autotrophic respiration. All plant outputs were expressed on a g C m^{-2} basis. For simplicity, the output reported in this chapter is limited to humus C (SOC in the entire 2 m profile) and SOC within user-defined soil layers. Although not reported here, the other model outputs were used to confirm proper functioning of the model. The *ecosys*-predicted soil C values from early November, 2007 were compared with measured SOC values from field sampling at this time. Although the model runs went to 2018, the last 11 years of data were not presented here.

Results and Discussion

The *ecosys* simulation predicted changes in SOC pools from the 0–20 cm layer and 0–2 m soil profile. The 0–20 cm soil layer provided SOC output that could be compared directly with measured values in soil samples collected in November, 2007. The 0 – 2 m provides additional information on the SOC storage and this soil depth coincides with the approximate rooting depth of poplars at the Guelph TBI site (Peichl et al. 2006).

During the first 21 years of the simulation period, *ecosys* modeling revealed a general decline in the SOC pool in both the 0 – 20 cm and 0 – 2 m soil depths (Table 16, Fig. 1). The SOC decline is cyclic, with slight increases in SOC every three years (Fig. 1).

The greatest SOC decline was predicted in 1990, 1993, and 1996 (Fig. 1). Since changes in the SOC pool are related to crop residue inputs and the transformation of plant C into recalcitrant soil C, it seems likely that the decline in SOC was related to cropping practices. As noted in Table 14, corn silage was harvested in early November of 1990, 1993 and 1996, a practice that leaves very little surface residue behind in the field. The removal of practically all of the above-ground plant biomass leaves little plant C that could be transformed into soil C, thus the decline in the SOC pool. The crop rotation years that show slight increases in the SOC pool (such as 1991, 1994, and 1997) are those in the soybean/winter wheat phase of the rotation. Soybeans are harvested for grain, which would leave stems, leaves and pods in the field to contribute to soil C. While fluctuations in the SOC pool are most notable in the 0 – 20 cm layer, they are also measureable to a depth of 2 m (Fig. 2). The decrease in SOC in the 0 – 2 m layer is more gradual, since it includes processes that occur below the tillage layer and crop root zone, thus is not as dramatically influenced by crop rotation effects. However, the SOC concentration at this site is greater in surface than subsurface soil layers, so the C losses occurring near the soil surface are reflected in the SOC pool of the 0 -2 m layer.

The *ecosys* simulation predicted a 5.0% and 11.6% decrease in SOC in the 0 – 20 cm and 0 – 2 m pools, respectively (Table 17). The measured values at this field site indicate a 12.6% increase in the SOC pool of the TBI system, compared to the adjacent conventionally managed agroecosystem, during the same time interval (Chapter 2). There are several reasons that could account for the model predicting a decrease in the SOC pool when measured values indicate that the SOC pool has increased, relative to the initial conditions. The most likely explanation is related to the fact that it was not possible to simulate the tree rows in the *ecosys* model, although this was how trees were planted in the field. Trees in the model were evenly spaced throughout the field with the crop, which could have led to a decline in the SOC pool for three reasons. First, the regular spacing of trees overshadowing the crop would increase competition for water, light and nutrients, effectively decreasing crop growth and therefore organic matter inputs from crops to soil. Second, since the trees were growing among the crop and caused shading, the poplar trees in the model had to be pruned more heavily (1/3 of the foliage removed every three years) than at the TBI field site, which likely decreased the C input from trees (leaf litter, branches) to the soil. Finally, *ecosys* was not also able to simulate the untilled area of the field (grass strip) associated with the tree rows. At the TBI field site, there was a 1-3 m buffer on either side of each tree row where no tillage operations occurred, mainly to protect the tree roots from mechanical damage. Untilled soils often exhibit an increase in SOC because organic residues are protected within soil aggregates and have less contact with decomposers like soil microorganisms (Grant 1997).

Further research is needed to devise a spatial algorithm for *ecosys* that could account for tree rows, including the untilled buffer strip around trees. This would provide a better representation of the actual configuration of trees and crops in TBI systems, and probably improve the model predictions.

Another difference between the model simulation and actual field management was related to the winter wheat crop. The *ecosys* input specified that the winter wheat would be harvested in mid-June and the field left bare until the next year. In reality, the farm manager would have planted a green manure crop or weeds would have filled the cropping space for the remainder of the growing season. However, the *ecosys* simulation indicates that no plants grew in the intercropped space during this time, which decreases the plant C inputs (e.g., from above-ground residues and roots) to the soil.

In future model runs, it would be beneficial to add a green manure crop to the soil following winter wheat harvest, which would be consistent with farm practices in this region (e.g., planting a green manure crop or allowing controlled weed regrowth to provide soil cover and avoid erosion).

Conclusions

The *ecosys* model is versatile and user-friendly. It possesses a variety of modules that can be initialized with climatic, soil and management data. Thus, *ecosys* can be calibrated to simulate biogeochemical cycling in the soil-plant system of agricultural, grassland and forest ecosystems. This is the first report of the use of the *ecosys* model for predicting changes in C storage in a TBI system, based on a long-term (21 year) field experiment in Guelph, Ontario. The *ecosys* model was able to predict changes in the SOC pool of this TBI system within a reasonable range of field measurements. However, the model predictions suggested sustained decline in the SOC pool at this site, whereas field experiments detected an increase in the SOC pool of the TBI system compared to a conventional agroecosystem. Several modifications to the *ecosys* model are suggested to improve the simulation of C dynamics in a TBI system and to achieve output that is more consistent with measured values.

Table 1. Rainwater pH, nitrate and sulfate deposition inputs

Site Characteristic	Input Value
pH	4.6
NO_3^- (mg N L^{-1})	0.48
SO_4^{2-} (mg S L^{-1})	1.4

Table 2. Model input settings for site topography and general field characteristics. Values in italics were estimated.

Site Characteristic	Input Value
Latitude (°)	43
Altitude (m)	328
Average annual air temperature (°C)	7.2
Depth to water table (m)	*3*
Depth to artificial drainage (m)	*3*
Slope aspect (°)	270
Slope inclination (°)	4
Surface roughness (%)	*0.025*
Initial depth of snowpack (m)	*0.3*

Table 3. General soil characteristic inputs for site. Values in italics were estimated.

Site Characteristic	**Input Value**
Water potential defined as field capacity (MPa)	*-0.033*
Water potential defined as wilting point (MPa)	*-1.5*
Wet soil albedo (%)	*0.35*

Table 4. Depth of each defined soil profile for model inputs

Soil Layer	Depth (m)
1	0.01
2	0.05
3	0.10
4	0.20
5	0.30
6	0.40
7	0.58
8	1.00
9*	2.00

* Plant roots reach down to final soil layer described by user. *Ecosys* adds two additional soil layers identical to the final layer, which is below the maximum rooting depth.

Table 5. Soil physical characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	**Bulk density ($Mg\ m^{-3}$)**	**Sand content ($g\ kg^{-1}$)**	**Silt content ($g\ kg^{-1}$)**	**Macropores (% vol.)**	**Coarse fragments (% vol.)**
1	1.39	569	342	*1×10^{-4}*	*0.01*
2	1.39	569	342	*1×10^{-4}*	*0.01*
3	1.50	558	346	*1×10^{-4}*	*0.02*
4	1.50	558	346	*1×10^{-4}*	*0.04*
5	1.25	406	454	*1×10^{-4}*	*0.08*
6	1.39	413	451	*1×10^{-4}*	*0.08*
7	1.38	421	330	*1×10^{-4}*	*0.15*
8	1.80	442	370	*1×10^{-4}*	*0.08*
9	1.80	442	370	*1×10^{-4}*	*0.08*

Table 6. Soil hydrologic characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	**Water content at field capacity (m^3 m^{-3})**	**Water content at wilting point (m^3 m^{-3})**	**Vertical saturated hydraulic conductivity (mm h^{-1})**	**Horizontal saturated hydraulic conductivity (mm h^{-1})**	**Initial water content (m^3 m^{-3}) ***	**Initial ice content (m^3 m^{-3}) ***
1	0.19	0.09	0.51	*20.4*	*-1*	*0*
2	0.19	0.09	0.51	*20.4*	*-1*	*0*
3	0.18	0.09	0.34	*20.4*	*-1*	*0*
4	0.18	0.09	0.34	*20.4*	*-1*	*0*
5	0.21	0.08	30.84	*20.4*	*-1*	*0*
6	0.21	0.08	30.84	*20.4*	*-1*	*0*
7	0.21	0.08	30.84	*4.5*	*-1*	*0*
8	0.21	0.08	30.84	*4.5*	*-1*	*0*
9	0.21	0.08	30.84	*4.5*	*-1*	*0*

* Initial water content and ice content values indicate that water and ice content are at wilting point

Table 7. Soil biological characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	Particulate organic C (g C kg^{-1})	Total organic C (g C kg^{-1})	Organic N (g N Mg^{-1})	Organic P (g P Mg^{-1})	Initial fine plant residue		
					C (g C m^{-2})	N (g N m^{-2})	P (g P m^{-2})
1	*1.0*	25.68	2340	*234*	*30*	*1.0*	*0.1*
2	*1.0*	25.68	2340	*234*	*30*	*1.0*	*0.1*
3	*1.0*	25.33	2230	*223*	*30*	*1.0*	*0.1*
4	*1.0*	25.33	2230	*223*	*30*	*1.0*	*0.1*
5	*1.0*	9.9	990	*99*	*30*	*1.0*	*0.1*
6	*1.0*	5.8	580	*58*	*0*	*0*	*0*
7	*0.0*	1.7	170	*17*	*0*	*0*	*0*
8	*0.0*	0	0	*0*	*0*	*0*	*0*
9	*0.0*	0	0	*0*	*0*	*0*	*0*

Table 8. Soil solution chemistry characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	**pH**	**NH_4^+ (g N Mg^{-1})**	**NO_3^- (g N Mg^{-1})**	**P (g P Mg^{-1})**	**Al (g Mg^{-1})**	**Fe (g Mg^{-1})**	**Ca (g Mg^{-1})**	**Mg (g Mg^{-1})**	**Na (g Mg^{-1})**	**K (g Mg^{-1})**	**S (g Mg^{-1})**	**Cl (g Mg^{-1})**
1	6.5	1.94	7.86	46.90	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
2	6.5	1.94	7.86	46.90	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
3	6.6	2.07	17.80	41.29	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
4	6.6	2.07	17.80	41.29	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
5	6.6	2.05	12.04	33.53	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
6	6.7	2.05	12.04	33.53	*938*	*0.01*	*2100*	*516*	*0.23*	*121.2*	*48.0*	*35.0*
7	7.0	2.05	12.04	33.53	*938*	*0.01*	*2031*	*18*	*0.23*	*126.2*	*48.0*	*35.0*
8	7.5	2.05	12.04	33.53	*938*	*0.01*	*2031*	*18*	*0.23*	*126.2*	*48.0*	*35.0*
9	7.5	2.05	12.04	33.53	*938*	*0.01*	*2031*	*18*	*0.23*	*126.2*	*48.0*	*35.0*

Table 9. Soil solid chemistry characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	Cation exchange	Anion exchange	Variscite (g P Mg^{-1})	Strengite (g P Mg^{-1})	Monetite (g P Mg^{-1})	Hydroxyapatite (g P Mg^{-1})	Aluminum hydroxide (g Al Mg^{-1})	Iron Hydroxide (g Fe Mg^{-1})	Calcite (g Ca Mg^{-1})	Gypsum (g Ca Mg^{-1})
1	*33*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
2	*33*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
3	*33*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
4	*9.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
5	*9.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
6	*9.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
7	*1.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
8	*1.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*
9	*1.0*	*2.0*	*0*	*0*	*0*	*100*	*0*	*0*	*0*	*0*

Table 10. Soil exchange chemistry characteristic inputs by soil layer. Values in italics were estimated.

Soil Layer	**Ca^{2+} - NH_4^+**	**Ca^{2+} - H^+**	**Ca^{2+} - Al^{3+}**	**Ca^{2+} -Mg^{2+}**	**Ca^{2+} - Na^+**	**Ca^{2+} - K^+**
1	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
2	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
3	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
4	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
5	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
6	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
7	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
8	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*
9	*0.01*	*0.25*	*0.25*	*0.60*	*0.16*	*3.0*

Table 11. Crop management in the first year of the model run (poplar planting and corn production, 1987)

Tillage		**Fertilizer**		**Planting**			**Harvest**		
Date	***Practice***	***Date***	***Application***	***Date***	***Species***	***Details***	***Date***	***Species***	***Details***
May 10	Harrow to 0.05 m	May 7	0.583 g urea m^{-2} and 1.25 g superphosphate m^{-2}	May 10	poplar	0.006 stems ha^{-1}			
				May 10	corn	6 plants m^{-2}			
		June 3	12.38 g urea m^{-2}						
							Nov 3	corn	Silage 0.05 m removal height
Nov 14	Harrow to 0.05 m	June 3							

Table 12. Crop management for year 1 of crop rotation (soybean/winter wheat)

Tillage		**Fertilizer**		**Planting**			**Harvest**		
Date	***Practice***	***Date***	***Application***	***Date***	***Species***	***Details***	***Date***	***Species***	***Details***
				May 15	Soybean	40 plants m^{-2}			
							Aug 25	Soybean	Grain 0.05 m removal height
Sept 27	Harrow to 0.05 m	Sept 27	0.876 g urea m^{-2} and 1.76 g superphosphate m^{-2}						
				Oct 1	Winter wheat	400 plants m^{-2}			

Table 13. Crop management for year 2 of crop rotation (winter wheat)

Tillage		**Fertilizer**		**Planting**			**Harvest**		
Date	***Practice***	***Date***	***Application***	***Date***	***Species***	***Details***	***Date***	***Species***	***Details***
							Apr 2	Poplar	2/3 of bole thinned
		Apr 24	10.35 g urea m^{-2}						
							June 15	Winter Wheat	Grain 0.05 m removal height
June 17	Harrow to 0.05 m								

Table 14. Crop management for year 3 of rotation (corn silage)

Tillage		**Fertilizer**		**Planting**			**Harvest**		
Date	***Practice***	***Date***	***Application***	***Date***	***Species***	***Details***	***Date***	***Species***	***Details***
		May 7	0.583 g urea m^{-2} and 1.25 g superphosphate m^{-2}						
May 10	Harrow to 0.05 m			May 10	Corn	6 plants m^{-2}			
		June 3	12.38 g urea m^{-2}						
							Nov 3	Corn	Silage 0.05 m removal height

Table 15. Crop management during the final year of the model run (poplar harvest and corn year, 2018)

Tillage		**Fertilizer**		**Planting**			**Harvest**		
Date	***Practice***	***Date***	***Application***	***Date***	***Species***	***Details***	***Date***	***Species***	***Details***
		May 7	0.583 g urea m^{-2} and 1.25 g superphosphate m^{-2}						
May 10	Harrow to 0.05 m			May 10	Corn	6 plants m^{-2}			
		June 3	12.38 g urea m^{-2}						
							Nov 3	Corn	Silage 0.05 m removal height
Nov 14	Harrow to 0.05 m								
							Nov 25	Poplar	Above ground harvest

Table 16. Soil organic carbon (SOC) content in a TBI system predicted by the *ecosys* model in the 0 – 20 cm layer and 0 - 2 m layer during the first 21 years of the simulation (1987 to 2007).

Year	**SOC 0-20 cm ($Mg\ C\ ha^{-1}$)**	**SOC 0–2 m ($Mg\ C\ ha^{-1}$)**
1987	70.05	90.05
1988	70.13	88.32
1989	69.54	87.56
1990	69.22	86.66
1991	69.59	85.94
1992	68.95	85.31
1993	68.45	84.53
1994	68.69	83.91
1995	68.12	83.43
1996	67.83	82.92
1997	68.15	82.50
1998	67.68	82.22
1999	67.46	81.88
2000	67.83	81.61
2001	67.39	81.46
2002	67.12	81.19
2003	67.45	80.97
2004	66.99	80.86
2005	66.72	80.64
2006	67.01	80.46
2007	66.57	80.38

Table 17. Soil organic carbon (SOC) values measured at the field site (actual) and predicted by the *ecosys* model for two soil layers (0 -20 cm and 0 – 2 m) at the time of TBI establishment (1987) and twenty-one years later (2007).

SOC pool	**1987**	**2007**	**Change in SOC (%)**
Actual SOC 0-20 cm (Mg C ha^{-1})	70.05	80.01	+ 12.6
***Ecosys* SOC 0-20 cm (Mg C ha^{-1})**	70.05*	66.57	- 5.0
***Ecosys* SOC 0-2 m (Mg C ha^{-1})**	90.05**	80.38	- 11.6

*Initial SOC value used by *ecosys* is the actual field value
**Value estimated from field measurements and Soil Landscapes of Canada database (Agriculture and Agri-Food Canada 2008)

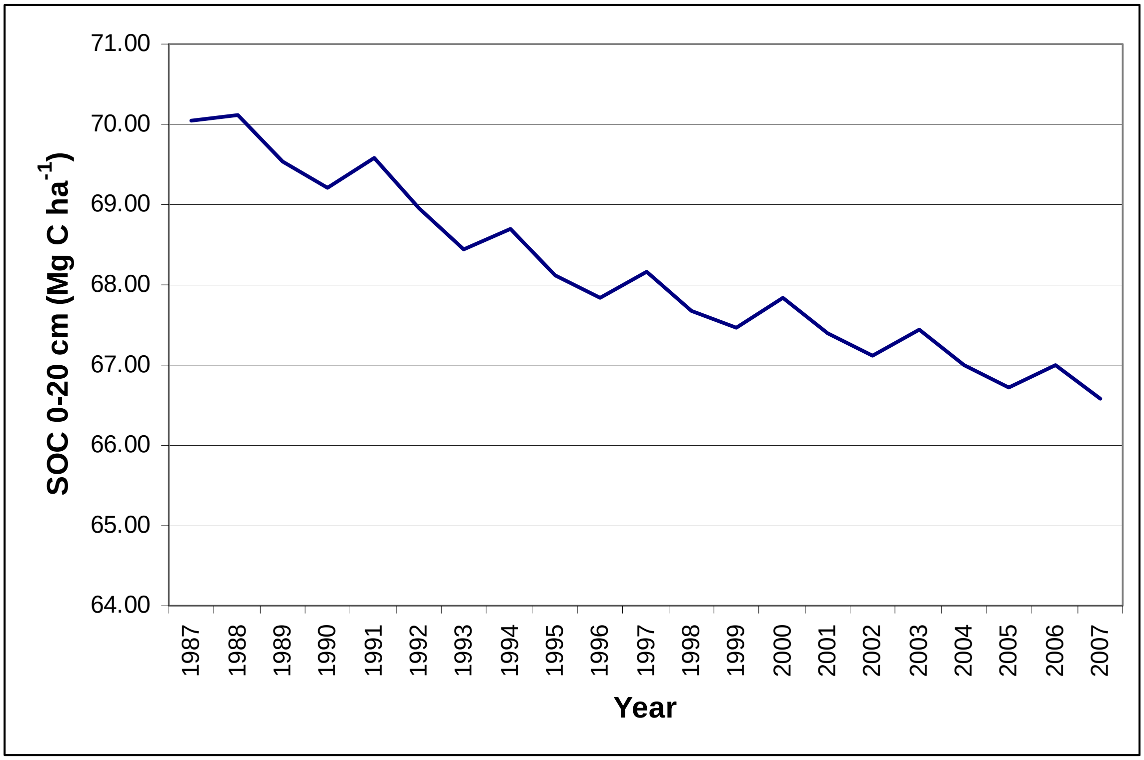


Fig.1 *Ecosys* predicted change in the SOC pool (0 – 20 cm depth) of a TBI system from its establishment in 1987 to 2007 (twenty-one years later).

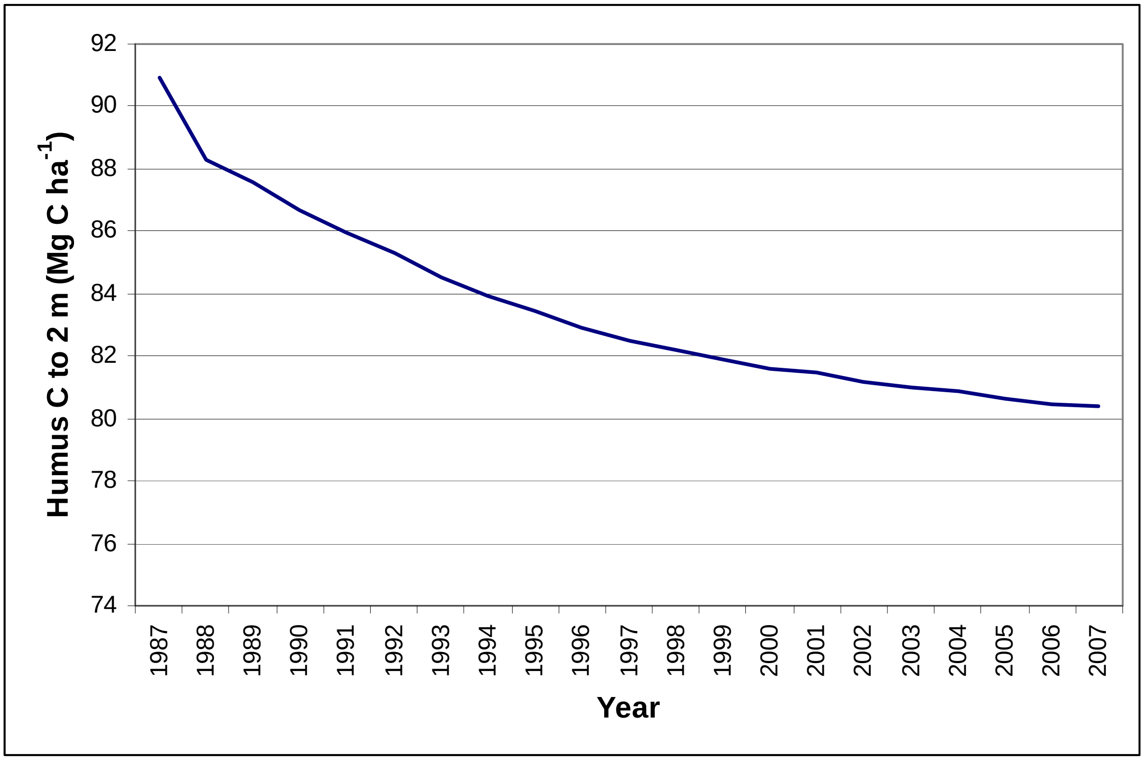


Fig 2. *Ecosys* predicted change in soil humus C (0 – 2 m depth) of a TBI system from its establishment in 1987 to 2007 (twenty-one years later).

GENERAL CONCLUSIONS

Field studies in TBI systems showed that introducing tree rows into agricultural fields caused variability in SOC within 4 years of establishment (St-Edouard). In the Guelph TBI site there was no variability in SOC with distance from poplar trees at the time of sampling, which was 21 years following TBI establishment. In earlier research on this same site it was found that there was variability in SOC in poplar TBI plots, indicating that poplar trees have become large enough to spread their litter evenly in the field now. The Guelph site did show variability with distance from Norway spruce trees however, likely because spruce trees were smaller and compact and were not able to spread their litter more evenly in the field.

It was determined that the Guelph and St-Remi TBI sites contained larger SOC pools than adjacent conventional agro-ecosystems, indicating that establishment of TBI systems increased SOC storage. In future studies, it would be recommended to dig soil samples below the general depth of agricultural influence (30 cm) so the effect of tree roots in these systems could be fully examined.

The *ecosys* model was used to simulate a long-term (21 year) TBI field experiment in Guelph, Ontario. The model predicted changes in the SOC pool, which were within a reasonable range of field measurements. The model predicted a decrease in the SOC pool however, while field measurements detected an increase in the SOC pool. Several modifications must be made to the *ecosys* model that may improve C simulation dynamics and show more consistent results with field measurement values.

If ecosys can be used to make reliable predictions on changes in SOC pools following transition to TBI, the model may be used to predict future carbon sequestration of new TBI systems in a timely and affordable manner. Such innovations would be beneficial to producers wishing to benefit from selling carbon credits on carbon-trading markets.

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