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Carbon and nitrogen in a temperate agroforestry system: Using stable isotopes as a tool to understand soil dynamics

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ABSTRACT

Natural exchanges of carbon (C) between the atmosphere, the oceans, and terrestrial ecosystems are currently being modified through human activities as a result of fossil fuel burning and the conversion of tropical forests to agricultural land. These activities have led to a steady increase of atmospheric carbon dioxide (CO_2) over the last two Centuries. The goal of this study was to determine the potential of temperate agroforestry systems to sequester C in soil. Therefore, changes in the soil organic C (SOC) and nitrogen (N) pools were quantified and the $\delta^{13}C$ and $\delta^{15}N$ stable isotope technique was applied to assess soil C and N dynamics in a 13-year old hybrid poplar alley cropping system in Southern Canada. Results from this study showed that after 13 years of alley cropping the SOC and N pools did not differ significantly ($p = 0.01$) with distance from the tree row, although a trend of a larger SOC and N pool near the tree row could be observed. Soil organic C after 13 years of alley cropping, was 19 mg C g^{-1} compared to 11 mg C g^{-1} upon initiation of agroforestry. Soil organic C and N were not evenly distributed throughout the plow layer. The largest C and N pool occurred in the top 20 cm, which is due to the accumulation of organic material in the upper horizons as a result of no-till cultivation. The entire soil, to a 40 cm depth, showed a $\delta^{13}C$ shift to that of C_3 residue. This shift reflects the greater input of residues from C_3 plants such as that derived from beans, wheat, and hybrid poplar leaf litterfall. The proportion of C derived from a C_3 source ranged from 64 to 69% to a 40 cm depth. The soil $\delta^{15}N$ signature of this study is similar to that of mineral soil, and reflect values characteristic of N mineralization processes. However, the entire soil shows a positive shift in $\delta^{15}N$ as a result of historical additions of manure and current use of mineral fertilizers, and ongoing processes of denitrification and nitrate leaching, which leads to an enrichment of the soil.

1. Introduction

The organic matter contained within the world's soil can act either as a sink or a source of atmospheric carbon dioxide (CO_2) (Bernoux et al., 1998; Liang et al., 1998). A reduction in soil organic carbon (SOC) and an increase in global atmospheric C arise when natural ecosystems such as forests and grasslands are replaced with agroecosystems (Bernoux et al., 1998; Collins et al., 1999; Huggins et al., 1998). For example, in Southern Canada most arable soils have been cultivated since the mid 1800s, which has resulted in a 25–35% loss of SOC (Liang et al., 1998).

Declining levels of SOC in agroecosystems coupled with an increased awareness of the potential role soil plays in the global C budget, has encouraged the development of soil organic matter (SOM) conservation practices (Huggins et al.,

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1998). Storage of SOC is a balance between C additions from non-harvested portions of crops and organic amendments, and C losses from the decomposition of organic matter which releases CO_2 to the atmosphere (Collins et al., 1999; Huggins et al., 1998). Additions and losses of C can also be regulated by practices such as crop rotations, residue and tillage management and the return of organic amendments such as manures and composts (Huggins et al., 1998).

Alternative land management practices like agroforestry, where trees are integrated into the agricultural landscape, are also considered as a land-use system that conserves soil C (Young, 1997; Watson et al., 2000). The practice of agroforestry leads to a more diversified and sustainable production system compared to treeless agroecosystems, and it also provides increased social, economic and environmental benefits for land-users at all levels (Sánchez, 1995; Fay et al., 1998). Agroforestry practices in temperate regions include planting trees at a wide spacing in combination with pastures or crops, which leads to an increase in C density (Buck et al., 1999).

For example, the incorporation of trees on farms affects C stocks differently compared to sole cropped areas because trees provide a tighter coupling of key processes such as nutrient cycling (Watson et al., 2000). However, to date little information is available on temperate agroforestry systems and their role in long-term soil C dynamics, including SOC turnover, residue stabilization efficiency and the size of the SOC pool (Diels et al., 2001, 2004; Oelbermann et al., 2006a).

Estimates of SOC pools and their turnover rates in natural and human-influenced systems, including agroforestry, is fundamental to our understanding of terrestrial C dynamics, and calculating C fluxes between the soil and atmosphere (Bernoux et al., 1998; Liang et al., 1998). Carbon isotope techniques are well suited to the study of soil C dynamics as they can be applied at various time scales ranging from a few years to several hundred years (Bernoux et al., 1998). Previous studies have used the δ^{13}C technique to generate quantitative information on long-term SOC dynamics in tropical and temperate agroecosystems (e.g. Veldkamp, 1994; Feigel et al., 1995; Gregorich et al., 1996, 2000; Collins et al., 1999; Huggins et al., 1998; John et al., 2003; Ludwig et al., 2003; Diels et al., 2004).

The δ^{13}C technique also has the potential to be used in more complex land-use systems such as agroforestry, or where the transition between vegetation types (C_3 and C_4) is not abrupt, where a pure C_3 or C_4 control vegetation is lacking, or when a mixture of C_3/C_4 occurs within the same cropped area (Diels et al., 2001). However, to date limited data are available on the application of the δ^{13}C technique in complex land-use systems, especially in agroforestry systems. Currently, some studies have assessed soil organic matter quality (Feigel et al., 1995), determined SOC turnover rates (Bernoux et al., 1998; Oelbermann et al., 2006a, 2006b), reconstructed vegetation history at the landscape scale (Boutton et al., 1998), measured the contribution of root vs. shoot tissue to soil organic matter formation (Balesdent and Balabane, 1992) and separated soil respiration into contributions from SOC and added green manure (Nyberg and Högberg, 1995) within the scope of agroforestry systems. However, the majority of these studies have focused on tropical agroforestry systems, and little information is available from temperate regions.

The objectives of our study were: (1) to determine changes in the SOC and N pools over a 13-year period of alley cropping in Southern Canada, (2) to investigate the usefulness of the δ^{13}C technique for a complex cropping system where organic material from C_3–C_4 sources is mixed in the SOC pool, (3) to evaluate changes in soil N using δ^{15}N, and (4) to determine the proportion of C in the soil derived from C_3 and C_4-plant material. A research goal was to provide insights into the potential of these land-use systems to sequester C to offset atmospheric CO_2 emissions and possibly be integrated into an environmental service system such as C trading.

2. Materials and methods

2.1. *Study site and design*

The study was conducted at the University of Guelph Agroforestry Research Station (43°16′N, 89°26′W), in Southern Canada, located 346 m above sea level. The area has an average annual temperature of 7.2 °C and a mean annual precipitation of 820 mm (Environment Canada, 2002). The soil at the research station is classified as a Gray Brown Luvisol with a sandy-loam soil texture (65% sand, 25% silt and 10% clay) to a depth of 30 cm.

The alley cropping system, using hybrid poplar (*Populus deltoids* × *nigra* DN-177) at a tree density of 133 trees ha^{-1}, was established in 1988 with trees spaced 12.5 m between rows and 6 m within rows. A 3-year rotation consisting of wheat (*Triticum aestivum* L.), soybeans (*Glycine max* L. (Merr.)) and maize (*Zea mays* L.) was maintained. The experimental design is a randomized complete block design with five replications.

Commercial N fertilizer was applied prior to crop seeding at 124 kg N ha^{-1} $year^{-1}$, 93 kg P ha^{-1} $year^{-1}$ and 46 kg K ha^{-1} $year^{-1}$ for maize; 117 kg N ha^{-1} $year^{-1}$, 45 kg P ha^{-1} $year^{-1}$ and 86 kg K ha^{-1} $year^{-1}$ for wheat; 30 kg K ha^{-1} $year^{-1}$ for soybeans. Tillage practices, before and after the establishment of the agroforestry system, included moldboard plowing to a depth of 20 cm each autumn, followed by seedbed preparation with a disc plow to a depth of 10 cm in the spring. In 1991 conservation tillage practices were initiated using a disc plow, but since 1996 the site has been under no-till cultivation.

2.2. *Sampling of tree litterfall and crop residues*

Litterfall from hybrid poplar was collected from September to December in 2000 and 2001, with litter traps of 0.32 m^2 placed at distances of 1.0, 3.5, 6.3, 9.0 and 11.5 m from the tree row; each sampling was replicated five times. Leaf litter and branches (≥2 cm diameter) were collected biweekly from the litter traps. Total C input from litterfall was integrated with distance from the tree row. Crop residue input from wheat, soybean and maize crops was determined at a distance of 1.0, 3.5, 6.3, 9.0 and 11.5 m from the tree row with a sample area 2.0 m in length and 0.4 m in width.

2.3. *Soil sampling*

Soils were sampled with distance from the tree row (1.0, 3.5, 6.3, 9.0 and 11.5 m) and at depths of 0–10, 10–20 and 20–40 cm