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Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada

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Abstract

Carbon (C) sequestration was quantified in two tree-based intercropping and in conventional agricultural systems in southern Ontario, Canada. In the intercropping systems, 13-year-old hybrid poplar (*Populus deltoides* × *Populus nigra* clone DN-177) and Norway spruce (*Picea abies* L.) were intercropped with barley (*Hordeum vulgare* L. cv. OAC Kippen). In the conventional agricultural system, barley was grown as a sole crop. Above- and below-ground carbon in trees, soil C, soil respiration and C leaching from each system were determined *in situ*. These data coupled with complementary data obtained from the literature were compiled and used to construct C cycle models, C pools and fluxes for each system. The total mean above- and below-ground C sequestered in permanent tree components was 15.1 and 6.4 t C ha^{-1} for poplar and spruce trees, respectively at 111 stems ha^{-1}. Soil C pools were 78.5, 66 and 65 t C ha^{-1} in poplar, spruce intercropping and in barley sole cropping systems, respectively. Soil respiration rates were 3.7, 4.5 and 2.8 t C ha^{-1} y^{-1} in poplar, spruce intercropping and barley sole cropping systems, respectively. Carbon leaching within the intercropping systems was greater below the tree row compared to the middle of the alley, but average values differed little from the sole cropping system. Total C pools (including an assumed barley C pool of 3.4 and 2.9 t C ha^{-1} within the sole cropping and the intercropping systems respectively) were 96.5, 75.3, and 68.5 t C ha^{-1} within poplar, spruce intercropping and in barley sole cropping systems, respectively. Estimated net C fluxes for the poplar and spruce intercropping systems and for the barley sole cropping system in 2002 were +13.2, +1.1, and −2.9 t C ha^{-1} y^{-1}, respectively. These results suggest that intercropping systems have a greater potential in reducing the atmospheric carbon dioxide concentration compared to sole cropping systems.

Introduction

Since 1750, atmospheric carbon dioxide (CO_2) concentration has risen by 30%, with a steep increase observed during the last 50 years (IPCC 2001a). With an annual increase of 0.5% or 3.6 Gt Carbon (C) y^{-1}, atmospheric CO_2 concentration is expected to double until the mid to late 21st century, which may cause a rise in temperature between 1.5 and 4.5 °C (Bouwman 1990; IPCC

2001a). Within anthropogenic emission sources, agricultural practices may account for one quarter of the contribution to the effect of global warming (Duxbury et al. 1993).

The International Panel on Climate Change (IPCC) has recommended a catalogue of remedial measures to mitigate increasing CO_2 emissions. Among these remedial measures, such as re-/afforestation, the conversion of agricultural land into agrosilvicultural systems has also been included (IPCC 2001b).

Agroforestry systems (including agrosilviculture) are commonly considered to be C sinks because the integration of trees results in greater CO_2 sequestration from the atmosphere and thus enhanced carbon storage in permanent tree components (Kürsten and Burschel 1993; Dixon 1995; Sampson 2001; Montagnini and Nair 2004). However, most studies on terrestrial carbon sinks in agroforestry do not distinguish between different agroforestry systems or only marginally include agroforestry within forest related research (Dixon et al. 1994a, b; Deying 1995). Only a few studies have demonstrated the potential of different agroforestry systems to function as carbon sinks in terrestrial ecosystems (e.g. Swisher 1991; Unruh et al. 1993; Dixon 1995).

In tropical latitudes, studies have estimated the C sequestration potential in agroforestry systems to be between 21 and 240 t C ha^{-1} within a cutting cycle of one or two decades, depending on tree species and density (Swisher 1991; Schroeder 1994; Dixon 1995; Adesina et al. 1999; Montagnini and Nair 2004). Within the temperate zone, agroforestry land use has been estimated to potentially sequester between 10 and 208 t C ha^{-1}. However, this is achieved over a longer cutting cycle of two to five decades (Dixon et al. 1994a; Schroeder 1994; Dixon 1995; Kort and Turnock 1999; Turnock 2001; Montagnini and Nair 2004).

The only known study examining *in situ* the potential of temperate intercropping systems to sequester C was conducted by Thevathasan and Gordon (2004). In this study C sequestration data for a 13-year old poplar intercropping system (111 trees) in southern Ontario, Canada, was collected. They concluded that the annual C sequestration in a hybrid poplar based intercropping field was four times higher than that found in sole cropping agricultural fields. Higher C sequestration in intercropping systems compared to sole cropping systems has been further supported by the model-based study by Zhou and Wang (1997) where CO_2 assimilation in a temperate *Paulownia*/winter wheat (*Triticum aestivum* L.) intercropping system was examined in the East China Plain.

However, all of the studies cited above are either based on biomass estimations and models, or failed to consider different cutting cycles and/or carbon losses via soil respiration and leaching, which may considerably modify the net C storage at a system level. Yet, it is necessary to quantify the net amount of C sequestration as a result from all C pools and fluxes within an intercropping system in order to best estimate its contribution and effectiveness in mitigating atmospheric CO_2 concentration and to compare intercropping systems as a possible land use system with other alternatives in future research activities.

This study is the first to examine and compare the majority of the carbon pools and fluxes within a temperate intercropping system to that of a barley sole cropping system in southern Ontario, Canada. All C pools and fluxes within the poplar- and spruce-based intercropping systems and the sole cropping system were determined and additional data was obtained from the literature where necessary, in order to create the C models for each system.

Material and methods

Site description and experimental design

The study was conducted in 2002 at the University of Guelph Agroforestry Research Station, established in 1987 on 30 ha of agricultural land (Canadian Land Index: 3) in southern Ontario, Canada (43°32′28″ N, 80°12′32″ W). Mean annual temperature is 7.2 °C, annual precipitation averages 830 mm, with approximately 340 mm falling during the growing season (May to August), and the average frost-free period is 136 days (Simpson 1999; Oelbermann 2002). The soils are Albic Luvisols, with a sandy loam texture having a pH of 7.4 (Thevathasan 1998; Oelbermann 2002). In 1987, among a variety of other tree species, hybrid poplar (*Populus deltoides* × *Populus nigra* clone DN-177) and Norway spruce (*Picea abies* L.) were planted in replicates of eight trees, with a within-row and between-row spacing of 6 and 15 m respectively, resulting in a density of 111 trees ha^{-1}. Trees were intercropped with a rotation of agricultural crops (crop alleys) including corn (*Zea mays* L.), soybean (*Glycine max* L.), and winter wheat or barley (*Hordeum vulgare* L. cv. OAC Kippen) (Oelbermann 2002). At the time of this study, mean tree height and tree diameter at breast height (DBH) was 17.6 m ± 0.05 (mean ± coefficient of variation) and 34.4 cm ± 0.07 for hybrid poplar, and 6.3 m ± 0.17 and 14.1 cm ± 0.17 for Norway spruce, respectively (Peichl 2003). Tree rows were 2 m wide at ground level. Based on this, the tree rows 'removed' 16% of the total area from crop production. From this intercropping system, six tree rows were chosen, with three replicates assigned to poplar and spruce, respectively.

For comparison, sampling was also undertaken from a barley sole cropping field located adjacent to the Agroforestry Research Field. During the study period, barley was the sole crop planted in both the sole cropping and intercropping site. Within the sole cropping site, three randomly distributed locations were chosen as replicates within an area of approximately 200 m^2.

Carbon content of intercropped hybrid poplar and Norway spruce trees

In order to determine the above and below-ground C sequestered in intercropped trees, three hybrid poplar and three Norway spruce trees were destructively sampled and their roots excavated to a depth of 2.1 m; roots having pencil thickness diameter or above were quantified. Sub-samples were collected from each tree component (stem, branches, litter, roots) and the moisture content (oven-dry weight basis) determined. Moisture content derived from these respective tree components was then used to convert the fresh weights of tree components to oven dry biomass, which was then converted to carbon content using data obtained with a LECO CR12 dry combustion Carbon Analyser (LECO Corporation, MI, USA).

Soil carbon

In order to determine the total soil carbon content within the upper 0–20 cm layer at different distances from the tree row, soil samples were collected in June 2002. Soil was collected from all three replicates assigned for poplar, spruce and sole cropping sites, respectively. At each intercropping replicate, soil samples were taken from both sides perpendicular to the tree row at 1 m intervals, from 1 to 12 m distance from the tree row at two depth classes (0–5 cm and 5–20 cm). Within the sole cropping site, soil samples were taken from each replicate at the same two depth classes. The soil samples were stored in a freezer until December 2002 and then air-dried, sieved through a 2 mm mesh and analyzed for total carbon using a LECO CR12 Carbon Analyzer following the dry combustion technique. A weighted average for the soil carbon content in the upper 0–20 of the soil profile was calculated based on the respective horizon depth and C-content.

Soil respiration

Measurements of CO_2 resulting from soil respiration, (both from roots and micro-organisms), were taken from both sites on 7 days during the year 2002 from July 18 until October 24 using the soda-lime method (Edwards 1982) from the poplar intercropping site and the sole cropping site. The time between each sampling day ranged from 1 to 4 weeks. Within poplar replicates, measurements were taken at three different locations: within the tree row, 1 m from the tree row (= 2 m from tree), and 4 m from the tree row. Within the sole cropping field, samples were taken from the three randomly distributed replicates.

Carbon concentration in leached soil solution

In order to determine the carbon concentration in soil solution leaching below the crop root zone (> 30 cm below soil surface) from the two sites, tension lysimeters were installed to a 30 cm depth and soil solution samples taken during June, July, September and October 2002. At each replicate, within the intercropping sites, one lysimeter was installed at each of the three locations: within the tree row, 1 and 6 m (= the middle of the alley) from the tree row. Within the sole cropping site, three lysimeters were installed at three random locations.

The lysimeters were installed 24 h prior to the sampling date, at a slight angle to a soil depth of 30 cm. In order to simulate 25 mm of rainfall, the areas around the installed lysimeters were irrigated with approximately 25 l of tap water and a suction of 85 kPa was created using a hand vacuum pump. 24 h later, the suction was released and the captured soil solution was mixed with LECO COM-AID powder in order to obtain a jelly-like solid substance, and analyzed using a LECO CR12 Carbon Analyzer for total carbon.

Model of carbon pools and fluxes within the sole cropping and the intercropping systems

The data of all C pools and fluxes within intercropping and sole cropping systems determined in this study were compiled and complemented by data from the literature, in order to develop carbon models for the barley sole cropping system and for both 13-year old poplar and spruce intercropping systems.

Respiration data for Norway spruce growing on the intercropping site is taken from Abohassan (2004). Data for poplar and spruce photosynthetic CO_2 uptake were calculated using studies from Bourdeau (1958), Larcher (1969), Schulze et al. (1977), Lyr et al. (1992), Landhäusser et al. (2001), and Thevathasan (pers. comm., 2003) assuming 12 h of photosynthetic CO_2 uptake per day. As these studies provide assimilation rates for optimum conditions, the real annual assimilation rates for poplar and spruce trees are likely to be lower than those presented in the models. Data for photosynthetic CO_2 uptake by barley, C storage and distribution in above and belowground barley biomass were developed in conjunction with data from Thevathasan (pers. comm., 2003) and from Keith and Oades (1986). For calculation details and assumptions please see the Appendix A.

Statistical analysis

All treatments were tested for statistical parameters using the software package SPSS v.10.0. Analysis of variance was conducted using the ANOVA procedure. Statistical significance ($p < 0.05$) was tested by applying independent sample *t*-tests (SPSS Science Inc 1989).

Results

Carbon content of intercropped hybrid poplar and Norway spruce trees

Above- and belowground carbon content of different tree components from the 13 year-old intercropped poplar and spruce trees are presented in Table 1.

For poplar, 85% of total tree C is stored as aboveground biomass, while 15% is stored within the roots. Together, leaves and branches store the same amount of C as the stem. For spruce, 82% of the total tree C is stored as aboveground biomass, similar to the situation for poplar. However, in contrast to poplar, 63% of the total C is stored in branches and needles (poplar – 44%) providing a potential C input to soil by litterfall and as result of branch pruning (in order to increase stem quality). Belowground, spruce roots stored the same amount of C as the aboveground stem, which is approximately 18% of the total C.

Table 1. Biomass and carbon content (mean ± standard deviation) of different tree components from 13-year old intercropped hybrid poplar ($n = 3$) and Norway spruce trees ($n = 3$).

Tree component	Hybrid poplar			Norway spruce		
	Biomass dry weight (kg)	C concentration (%)	C content (kg)	Biomass dry weight (kg)	C concentration (%)	C content (kg)
Leaves/needles	26.8 ± 7.5	43	11.5 ± 3.5	14.7 ± 6.9	51	7.5 ± 3.6
Branches	109.9 ± 21.2	45	49.5 ± 12	55.7 ± 16.8	51	28.5 ± 8.4
Trunk	135.9 ± 68.8	40	54.4 ± 33.5	21.7 ± 10.7	50	10.8 ± 5.6
Total aboveground	272.6 ± 43.6	42	115.4 ± 17.2	92.1 ± 33.9	51	46.8 ± 17.3
Roots	51.5 ± 10.9	43	22.1 ± 4.7	21 ± 9.2	51	10.5 ± 4.3
Total tree	324.1	42	137.4	113.1 ± 42.6	51	57.3 ± 21.2

After 13 years, the total tree C content of poplar is more than twice the amount found in that of spruce trees. For both tree species, a high degree of variability exists for measured parameters, as indicated by high standard deviations.

Soil carbon

The mean total soil C concentration of the barley sole cropping site (0–20 cm) was 2.4%, compared to 3 and 2.5% for the poplar and spruce intercropping sites (Figure 1).

Only within the poplar intercropping system total soil C increased compared to the sole cropping system; for the spruce intercropping site, soil C is only slightly higher at 1, 2, and 12 m (close to the next tree row). The total soil C concentration within the poplar intercropping system averaged across all distances is significantly higher than that of either the sole cropping system or the spruce intercropping system ($p < 0.05$). Distance from the tree row did not significantly influence soil total C concentration in either system.

Soil respiration

Soil respiration was found to have high spatial variation resulting in high standard deviations. CO_2 soil respiration from the sole cropping site and from the poplar intercropping site are presented in Figure 2.

Soil respiration from the barley sole cropping field remained constant at between 0.3 and 0.5 g CO_2 h^{-1} m^{-2} with mean summer values being slightly higher than those from fall sampling.

Compared to the barley sole cropping site, soil respiration was higher at all three locations (tree row, 1 and 4 m distance) within the poplar intercropping site on all days, except on July 18, and on October 24. Within the poplar row and at 1 m, this difference was significant ($p < 0.05$) on July 24, July 30, and September 24.

Soil respiration from the poplar intercropping system ranged from 0.3 to 0.8 g CO_2 h^{-1} m^{-2} and was visibly higher in summer than in fall, increasing from July 18 to July 30 and then decreasing constantly throughout the fall until October 24, with the exception of the low respiration noted

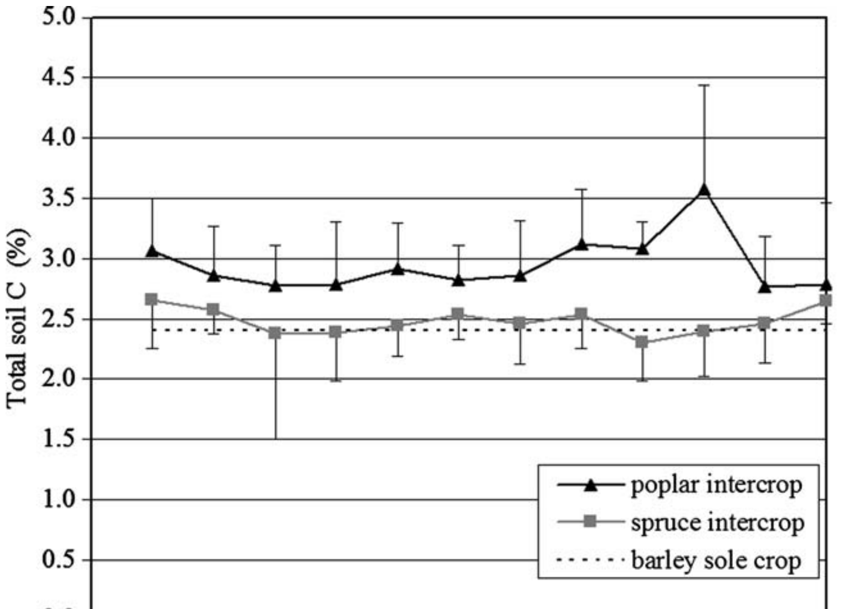


Figure 1. Total soil carbon (0–20 cm soil depth) at 1 m intervals from the tree row in the poplar/spruce intercropping systems. Total soil carbon within the barley sole cropping system is shown for comparison. Error bars indicate standard deviation; $n = 3$.

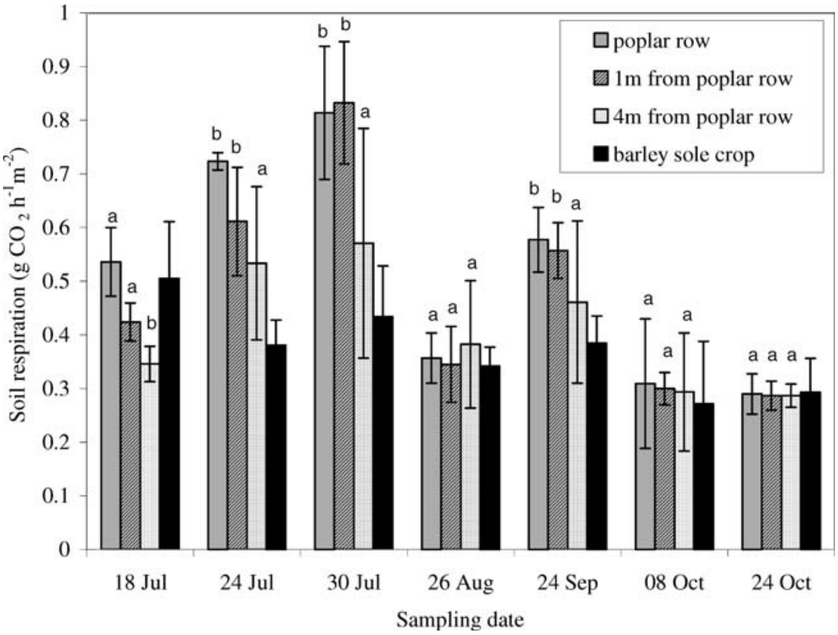


Figure 2. Soil respiration from the barley sole cropping site and from the three locations (tree row, 1 and 4 m from the tree row) within the poplar intercropping site between July and October, 2002. Within dates, respiration values denoted with a similar small-case letter are not significantly different at $p < 0.05$. Error bars indicate standard deviation; $n = 3$.

on August 26. Soil respiration tends to be the highest within the tree row, followed by slightly lower respiration rates at 1 m and with the lowest recorded 4 m from the row. However, this pattern was not observed on July 30 and August 26, nor on October 24 when values from all three locations were low and more or less equal. Irregularities within the trends mentioned above may be due to weather conditions.

An ancillary study, recently completed by Love (2005) in the poplar intercropping system, indicated winter (January–March) soil respiration rates to be in the range of 0.24 g CO_2 m^{-2} h^{-1}. As these studies were not carried out in the same year, we have not included this data in model development; however, researchers should be cognizant of the potential for soil CO_2 efflux under winter conditions.

Carbon concentration in leached soil solution

C concentration in leached soil solution from all sites remained within a narrow range (0.06% in September to 0.12% in October 2002). This quantified concentration is equal to 0.6 and 1.2 g C l^{-1}. C concentrations in soil solution showed only weak patterns between different sites, locations, and sample times. The mean C concentrations of leached soil solution as an average for the period June to October 2002 are presented in Table 2.

Table 2. Carbon concentration of leached soil solution from the barley sole cropping site and from the three locations (tree row, 1 m from row, and middle of the alley) within the poplar and spruce intercropping sites, averaged for the entire field season ($n = 8$–12 for different locations).

Carbon in soil solution	Barley sole crop	Poplar intercropping				Spruce intercropping			
		Row	1 m	Middle	Mean	Row	1 m	Middle	Mean
(%)	0.09	0.101	0.083	0.088	0.091	0.081	0.063	0.078	0.074
Standard deviation	0.02	0.02	0.01	0.02		0.01	0.01	0.01	

C concentrations in soil solution were similar when the sole cropping site was compared to the poplar intercropping site and the spruce intercropping site. When comparing the two intercropping systems by location (row, 1 m, middle) C concentrations in soil solution within the poplar site appear to be higher than concentrations from the spruce intercropping site at each location. However, statistical significance ($p < 0.5$) only exists when comparing average values across all locations from the poplar and spruce systems.

Discussion

Tree carbon content

The relatively high standard deviation (up to 37%) observed in the mean tree C contents implies that at the end of several decades, individual tree C content may vary considerably between individual trees of the same species, especially for slower growing species on a longer cutting cycle.

The observation that only 13 years after establishment poplar trees have already sequestered twice as much C compared to the similarly aged spruce is of further interest as this demonstrates the high sequestration potential of poplar and possible differences between tree species that need to be considered when accounting C pools in tree vegetation.

It is further important to note that poplar leaves, branches and roots store almost half of total tree C, as well as the fact that spruce branches and needles contribute two thirds of total tree C content, while spruce roots contain the same amount of C as the spruce stems. This is especially important as most studies have neglected to estimate the C content of roots and branches (Swisher 1991; Unruh et al. 1993; Turnock 2001). For example, Turnock (2001) assumed the belowground C content of trees to be within a broad range of 30–50% of the aboveground C content; this is higher than that reported within this study. Thus, in order to be able to accurately estimate the C pool in tree vegetation each component needs to be quantified and included in the total C budget.

Tree content data from this study are compared with that of other studies on spruce and poplar established in different temperate agroforestry systems in Table 3.

It is evident that the C content of trees may vary considerably depending upon tree age and type of agroforestry system. Tree C stock estimates also change considerably if all above and belowground tree components are included, which can be seen when comparing the C contents of poplar and spruce trees from this study with trees of similar age from the study by Turnock (2001).

In this study, it was not possible to determine the coincidental annual litterfall, decomposition and respiration rates. However, Zhang (1999), working in the same system 11 years after establishment estimated C inputs in litterfall to be ~600 kg ha^{-1} y^{-1} and Oelbermann (2002), also at the same site 12 years after establishment found a mean annual carbon input from litterfall to be 946 kg C ha^{-1}. Total decomposition times for spruce needles and poplar leaves in Chinese temperate agroforestry systems have been estimated to be 10 and 5 years, respectively (Deying 1995), and so annual inputs of C via litterfall will not immediately be sequestered into recalcitrant soil pools but may be lost as an atmospheric CO_2 flux, depending upon site and tillage conditions.

Soil carbon

Total soil C content varied greatly within the land-use systems. This variability may be explained by the heterogeneity of the soil and the presence of C-rich soil pockets. This observation has been previously made by Oelbermann (2002), working on the same study site.

The observation that soil C concentration within the upper 0–20 cm of the soil layer was only increased in the poplar intercropping system compared to the sole cropping and spruce intercropping system may be explained by the greater height, crown diameter and litterfall of poplar trees, resulting in a much higher C input to soil within the poplar intercropping system compared to the others.

Although C inputs were expected to be higher closer to the tree rows, the total soil C concentration was not significantly different in relation to the distance from the tree row. An earlier study on the same research site indicated that, 7 years after establishment, total soil C within the poplar intercropping site was significantly higher at 1 and 2 m compared to the middle of the alley

Table 3. Carbon content of spruce and poplar trees at different ages in different temperate agroforestry systems.

Tree species	Agroforestry type	Carbon content (kg C per tree)	Age (years)	Source
Picea abies	Intercropping	57	13	This study[b]
Picea glauca (Moench.) Voss	Shelterbelt	30	15	Turnock (2001)[a]
Picea glauca (Moench.) Voss	Shelterbelt	143	54	Kort and Turnock (1999)[a]
Hybrid poplar	Intercropping	128	13	This study[b]
Hybrid poplar	Shelterbelt	88	15	Turnock (2001)[a]
Hybrid poplar	Shelterbelt	272	33	Kort and Turnock (1999)[a]
Hybrid poplar	Agrosilviculture	170	9	Puri et al. (1994)[b]

[a]Only aboveground carbon.
[b]Above (including branches and litter) and belowground.

(Thevathasan 1998). However, more recent studies at the same site have indicated that the total soil C concentration is no longer significantly different with distance from the tree rows (Oelbermann 2002; Abohassan 2004). A likely explanation is that with the poplar trees now around 18 m in height, C input from litterfall is distributed more or less equally across the width of the crop alleys. This has positively impacted the total soil C in the middle of the cropping alleys. Within the spruce intercropping site, less litter input and smaller tree heights dictate little influence on soil carbon with distance from the tree row at this time.

Soil respiration

The likely reason for higher soil respiration within the intercropping field (up to 0.8 g CO_2 h^{-1} m^{-2}) compared to the sole cropping field (maximum 0.5 g CO_2 h^{-1} m^{-2}) is the presence of the trees in the system. Soil respiration in the poplar intercropping site was highest closer to the tree rows, and this may be due to higher tree root respiration and/or higher microbial respiration. Potentially higher C input in the form of litterfall closer to the tree rows creates favourable conditions for soil micro-organisms leading to enhanced microbial activity and CO_2 evolution (Brady and Weil 1996; Matteucci et al. 2000).

In another temperate intercropping system, Lee and Jose (2003) observed higher soil respiration from a pecan (*Carya illinoinensis*) – cotton (*Gossypium hirsutum*) alley cropping system compared to a cotton monoculture system. However, in contrast to the present study, they found that respiration did not change significantly with distance to tree rows. Soil respiration from forested ecosystems may be used and compared with respiration from sole cropped agricultural soils as tree density in intercropping systems may be somewhere between 25 and 75% of those in forests (Swisher 1991; Adesina et al. 1999). Within a review of several studies, Raich and Schlesinger (1992) noted that soil respiration from forested land compared to conventional agricultural land was up to three times higher. This again demonstrates the considerable influence that trees exert on soil respiration processes.

Carbon concentration of leached soil solution

The assumption that more carbon leaches from the intercropping than from the sole cropping site as a result of greater C input from trees was only verified for the poplar intercropping system. The higher C concentrations in leachate from the poplar site may be explained by the greater C input from leaves, branches, dead roots, and exudates from living roots (Brady and Weil 1996; Matteucci et al. 2000). Subsequently, it is not surprising that carbon losses are greater closest to the tree row. However, this pattern was not observed within the spruce system probably due to the small size of the spruce trees and their limited influence on soil properties. Lower C concentrations in leachate from the spruce system may also have resulted from the fact that spruce needles decompose more slowly than poplar leaves, releasing only small quantities of soluble carbon to the soil solution. Andersen and Gundersen (2000), for example, found more carbon in leachate at 25 cm depth from deciduous forests (5–25 g C l^{-1}) when compared to that sampled from conifer forests (5–15 g C l^{-1}). Depending upon the tree density of any given intercropping system, carbon concentrations in leached soil solution from intercropping systems may therefore vary considerably.

When comparing carbon losses via leaching from both intercropping and sole cropping systems, one needs to consider that in this study only the carbon concentration in the soil solution was determined, not the annual leaching rate. As well, artificial soil wetting occurred, whereas in reality, tree crowns can be expected to reduce rainfall close to the tree rows. Furthermore, tree roots are likely to reduce surplus soil water through increased uptake, and thus, the total amount of C leaching and loss from intercropping systems could be considerably lower than that found in sole cropping systems. Unfortunately, the annual leaching amount below 30 cm soil depth from both intercropping and sole cropping sites could not be determined in this study, although it is currently under investigation.

Model of carbon pools and fluxes within the sole and intercropping systems

In order to develop carbon models for the barley sole cropping system and for both 13-year old poplar and spruce intercropping systems, all C pool and flux data from the intercropping and the sole cropping system have been compiled and complemented by relevant data from the literature. The basic parameters for developing these C pool and flux models are given in Table 4.

Carbon models are presented for a temperate barley sole cropping system in Figure 3a, a temperate barley-poplar intercropping system in Figure 3b, and a temperate barley-spruce intercropping system in Figure 3c.

Carbon pools

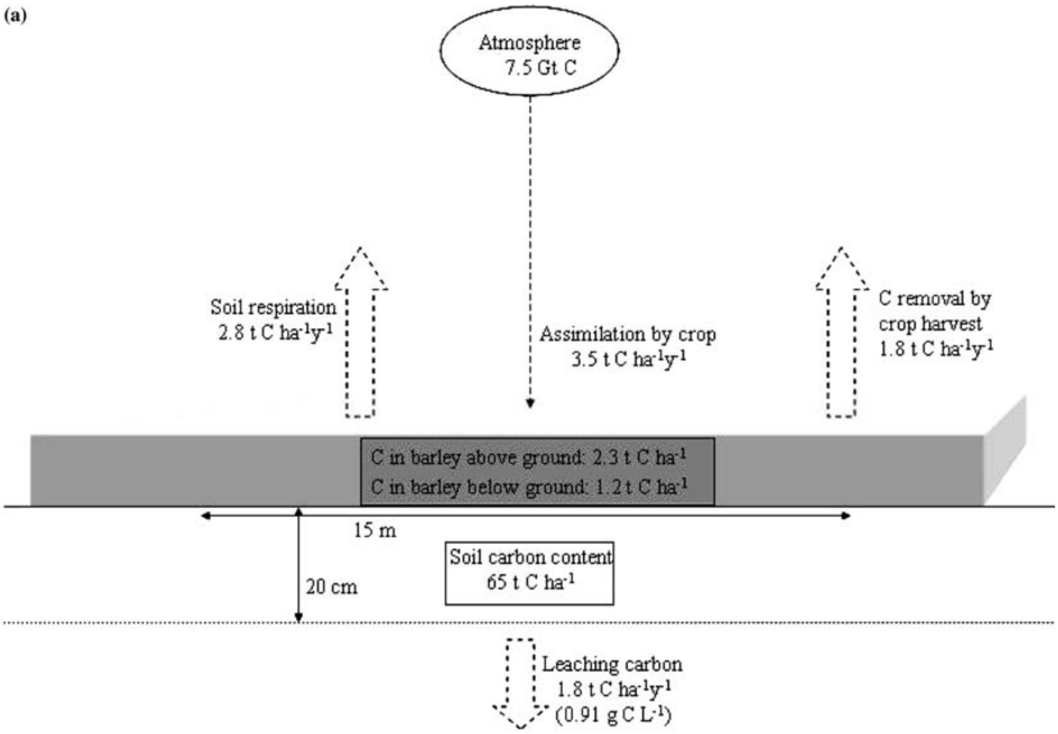
Summing all C pools in above/belowground vegetation and soil, yields a total C pool of 68.5, 96.5 and 75.3 t C ha^{-1} within the barley sole cropping system and the poplar and spruce intercropping systems, respectively. The ratio of above to belowground C pools is approximately 1:32, 1:6 and 1:10 for the sole cropping, the poplar intercropping and the spruce intercropping system, respectively. After 13 years, the total C pool of the poplar intercropping system is 41% greater than the sole cropping C pool and the C pool of the spruce intercropping system is 11% greater than the sole cropping C pool. The greatest contribution to the total pool is the soil pool which stores in each system 80–95% of the total. Note that data from this study (66–78.5 t C ha^{-1}) represent C storage in the upper 20 cm of the soil profile only and subsequently are likely to underestimate the total soil C pool, taken to a deeper depth. In an earlier study, for example, Oelbermann (2002) suggested that 121–125 t C ha^{-1} were stored in the upper 40 cm of the same poplar intercropping system.

The higher C pools within the intercropping systems compared to those from the sole cropping system were expected due to the additional C pool in trees and an increased soil C pool as a result of C input from litterfall and fine root turnover. The higher C storage within the poplar intercropping system can be explained by higher growth and assimilation rates compared to the spruce intercropping system. Compared to other temperate agroforestry systems, the total C storage indicated in this study (75–96.5 t C ha^{-1}) is within the reported range of 12–175 t C ha^{-1} for other recent studies (Schroeder 1994; Dixon 1995).

Table 4. Basic assumptions for calculating C pools and fluxes.

Parameter	Value[a]
Tree density	111 trees ha^{-1}
Soil bulk density	1.33 g cm^{-3}
Soil depth for C storage	0–20 cm
Leaching rate	200 mm ha^{-1} y^{-1}
Frost-free period for soil respiration	136 days
CO_2 assimilation by barley	C content of harvest = 52% of net assimilated C ha^{-1} y^{-1}
CO_2 assimilation by poplar	11.5 mg CO_2 h^{-1} g^{-1} leaf dry weight on 170 days y^{-1}
CO_2 assimilation by spruce	4 mg CO_2 h^{-1} g^{-1} needle dry weight on 260 days y^{-1}

[a] See Appendix for calculations and references.



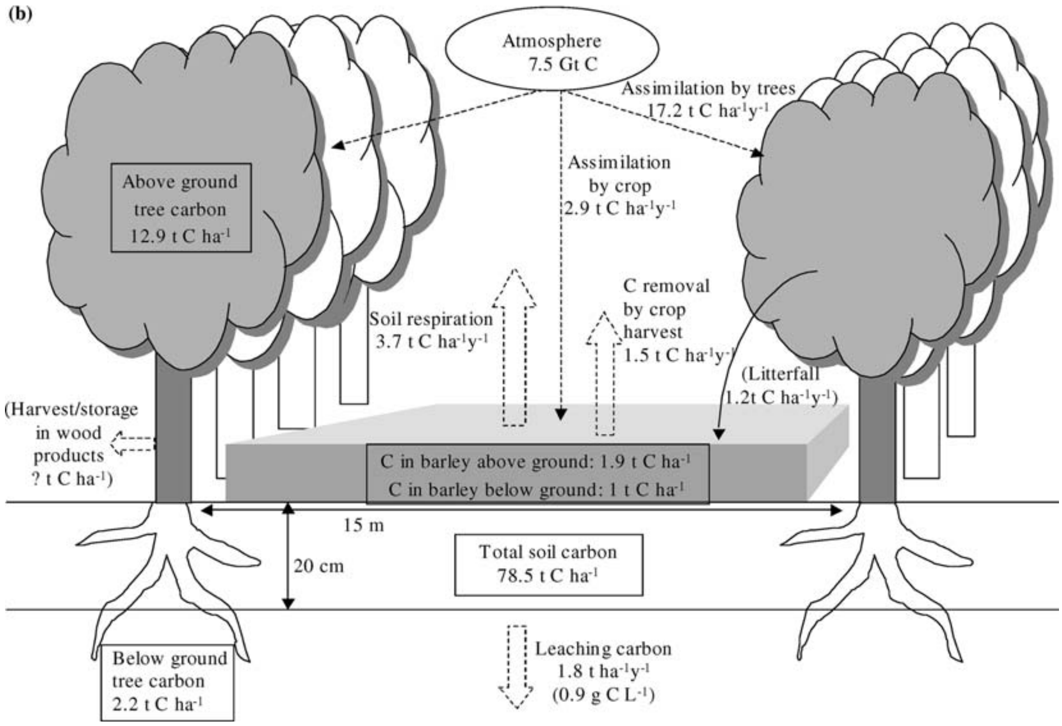


Figure 3. Model of all main C pools and C fluxes within (a), a temperate barley sole cropping system, (b), a 13-year old temperate barley-poplar intercropping system, and (c), a 13-year old temperate barley-spruce intercropping system. Boxes indicate C pools, arrows indicate C flux. See Appendix for calculations and references.

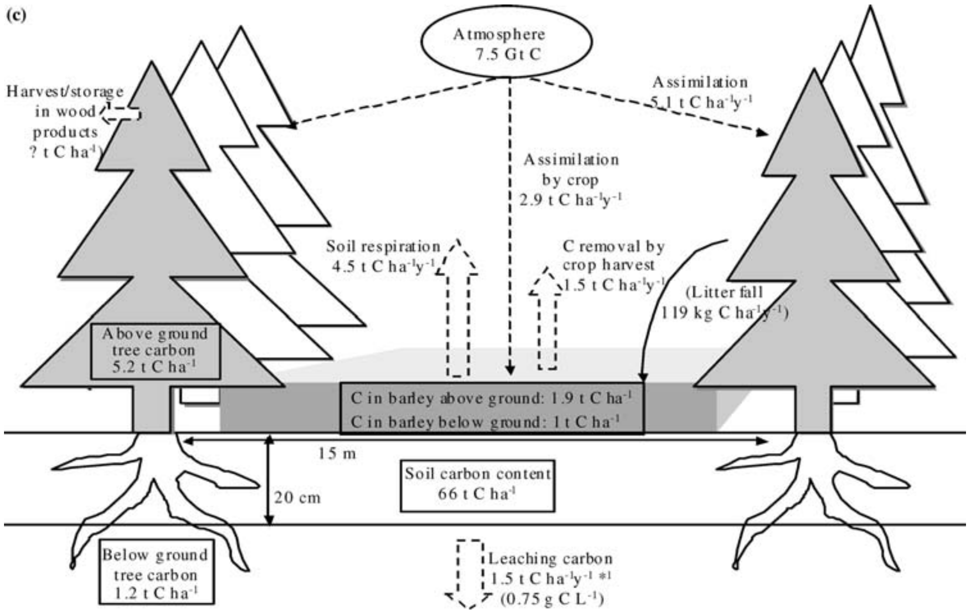


Figure 3. Continued.

Carbon fluxes

Summing all C fluxes of assimilation, soil respiration, C leaching and barley harvest within each system in 2002, the net C flux is -2.9 t C ha^{-1} y^{-1} for the sole cropping system, $+13.2$ t C ha^{-1} y^{-1} for the poplar intercropping system, and $+1.1$ t C ha^{-1} y^{-1} for the spruce intercropping system. Thirteen years after establishment, the C flux into the poplar intercropping system is five and four times greater than the C flux into the sole cropping system and the spruce intercropping system, respectively.

The higher C assimilation within the intercropping systems compensated for higher C losses via soil respiration and C leaching which resulted in net accumulation of carbon, compared to the barley sole cropping system. The C model developed for barley, shows a net loss of C from the system. However, the conventional crop rotation widely adopted in southern Ontario, is a corn-soybeans-barley and/or winter wheat rotation. Historical data on mean annual C additions from corn and soybeans residue, for this same site, ranged from 500 to 700 kg ha^{-1} y^{-1} (Thevathasan et al. 2004) and soil respiration did not differ significantly on an annual basis (Thevathasan 1998; Abohassan 2004). When a complete crop rotation is considered, it is likely that a small but net accumulation of C will be achieved, especially given the inputs associated with corn and beans over three growing seasons (Thevathasan, pers. comm., 2003).

Zhou and Wang (1997) found that the C assimilation rate in a Chinese *Paulownia*-wheat intercropping system was 57% higher than that of a wheat sole cropping system. They also found a much higher assimilation rate for wheat than that assumed for barley in this study. The net C flux into both intercropping and sole cropping systems may therefore be even higher than that indicated but would not change the absolute difference between the intercropping and the sole cropping systems.

Annual C loss via leaching appears to be a minor component in the overall C budget, but C loss from intercropping systems may increase depending upon tree species, age, stem density and annual leaching rate, and therefore, C loss via leaching may be underestimated in our model. It should also be noted that annual soil respiration is likely to be overestimated, as it was calculated only from summer and fall data, and did not include estimates from late fall and early spring, when soil respiration can be much lower. Considering this, an even greater flux into the intercropping system might be expected.

The atmospheric CO_2 reduction potential of intercropping

When evaluating atmospheric CO_2 reduction potentials through tree-based intercropping systems, it should be emphasized that this study only determined direct benefits in relation to C sequestration. However, intercropping systems also have indirect benefits that will aid in the reduction of CO_2 emissions by substituting wood for fossil fuel, reducing the need for forest clearing and fertilizer production, and enhancing C storage in wood products (Kürsten and Burschel 1993; Hall and House 1994; Schroeder 1994; Dixon 1995; Montagnini and Nair 2004). Kürsten and Burschel (1993) suggested that these indirect benefits may increase the amount of direct C storage by 2–15 times. Considering this, intercropping systems may possess a significant potential to mitigate atmospheric CO_2 concentrations.

However, in order to generate significant contributions, intercropping systems will need to be established on large tracts of land, which poses several problems including labour intensity, and the incentives for farmers to adopt temperate intercropping systems in general (Dabbert 1995). It is likely that incentives may be enhanced once carbon offset and credit schemes are developed.

This study demonstrates that intercropping systems using fast growing tree species such as hybrid poplar may result in significant short-term C storage, whereas the planting of slower growing conifers may instead contribute to long-term C storage. These results are supported by earlier studies that suggested that significant short-term reductions in atmospheric CO_2 concentrations can best be achieved with fast growing tree species (Van Kooten et al. 2001).

Conclusions

As tree C content can vary considerably between different intercropped tree species, this needs to be considered when accounting C sequestration by intercropped trees, and indeed, when establishing intercropping systems for C-sequestration purposes. It is therefore important to include all above- and belowground tree components when determining tree carbon pools in order to obtain realistic values that will provide accurate estimates over greater land areas. Further research is needed to quantify the above- and belowground C contents of mature intercropped trees at the end of their rotation period, which may be many decades depending on tree species. Together with specific growth models for different intercropping tree species, this will improve future tree C pool estimates.

Although annual C flux data may be slightly under- or overestimated, this study demonstrates that compared to the barley sole cropping system, both temperate barley-poplar and barley-spruce intercropping systems have a greater total C pool, a greater positive CO_2 flux into the system, and thus, a greater potential for reducing atmospheric CO_2. However, the difference is only significant when the sole cropping and the intercropping system with fast growing poplar are compared. C pools and fluxes within the intercropping system may vary with the growth rates of the intercropped tree species, tree density, and the length of the cutting cycle. Thus, further research in quantifying individual C pools and fluxes within intercropping systems and other agroforestry systems is warranted for different tree species, tree densities, cutting cycles, crop combinations, and soils in order to assess the effectiveness of carbon sequestration within intercropping systems.

Finally, atmospheric CO_2 reduction potentials through tree-based intercropping systems are greatly enhanced by its indirect benefits. Thus, intercropping systems should be considered a useful technology that used in combination with other tools, such as re-/afforestation and the use of alternative renewable energy sources, could contribute to a substantial greenhouse gas mitigation strategy globally.

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Appendix A

In order to develop a carbon pool and flux model of the 13-year old barley-poplar/spruce intercropping system and of the barley sole cropping system, the following calculations and assumptions were used:

(1) A tree density of 111 trees ha^{-1} is assumed for both intercropping models, and tree rows are considered to remove 16% of the area available for crop production.
(2) The above and belowground C pools per hectare within the poplar and spruce trees were calculated from the mean carbon content per tree determined within this study, multiplied by the tree density.
(3) Annual needle fall from the spruce trees was calculated from collected data and presented in order to demonstrate annual C inputs from needle fall, assuming the lifetime of a needle generation to be 7 years. Annual litterfall from the poplar trees is taken from Thevathasan (2002, unpublished data). Both needle and litter biomass are included in the tree C pool.
(4) The total soil C content ha^{-1} was calculated for the upper 0–20 cm soil layer, using an average value from all distances to the tree row (1–12 m), and assuming a bulk density of 1.33 g cm^{-3} (Thevathasan 1998).
(5) Carbon storage within barley was calculated from the harvested amount in 2002 (grain and straw) (Thevathasan 2002, unpublished data), assuming the carbon content to be 50% of the harvested biomass (dry weight). Further, it was assumed that the amount of C in total aboveground biomass represents two thirds of the total net assimilated C, while C content of the belowground biomass represents one third (Thevathasan, pers. comm., 2003). Keith and Oades (1986) found that C input into soil was 30% of yield C and 15% of total assimilated C. Based on these proportions, it was assumed that C content of harvested biomass is 52% of total net assimilation, while 14% of assimilated C remain in aboveground crop residues.
(6) Soil respiration data for the spruce intercropping system was taken from Abohassan (2004). Soil respiration from the poplar intercropping system was calculated from the respiration data obtained in this study. An average value for the period July–October was applied for the 136 frost free days in order to obtain annual soil respiration. This likely resulted in an overestimate as soil respiration during early spring and late fall months can be expected to be much lower. Within the intercropping systems, it was assumed that respiration within the tree row and 1 m from tree row 'accounts' for only one third of the spatial area, whereas respiration from the middle of the alley 'accounts' for two thirds of the area.
(7) The amount of carbon leaching was calculated assuming a leaching rate of 200 mm per year for both intercropping and sole cropping systems (Gisi 1997). As above, it was assumed that carbon leaching within the tree row and 1 m from the tree row accounts for only one third of the area, whereas carbon leaching from the middle of the alley accounts for two thirds of the area.
(8) The equation used for calculating the carbon storage in pools is:

$$C_{pool} = C_t + C_s + C_c, \qquad (1)$$

whereby C_{pool} = total carbon stored in pools, C_t = carbon pool in trees, C_s = carbon pool in soil, C_c = carbon pool in crop.
(9) The equation used to calculate the positive or negative C flux into or out of the system is:

$$C_{flux} = C_{at} + C_{ac} - C_{sr} - C_l - C_{ch}, \qquad (2)$$

whereby C_{flux} = net carbon flux, C_{at} = carbon input via net assimilation by trees, C_{ac} = carbon input via net assimilation by crop, C_{sr} = carbon loss via soil respiration, C_l = carbon loss via leaching soil solution below the crop root zone, C_{ch} = carbon loss through crop biomass removal after crop harvest.

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