Potential Greenhouse Gas Mitigation through Temperate Tree-Based Intercropping Systems

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Abstract: Increasing awareness of global climate change has pressured agricultural producers to reduce greenhouse gas (GHG) emissions while at the same time encouraging them to maintain food production needed for an increasing population. Tree-based intercropping (TBI) systems are believed to be useful in climate change mitigation, especially in temperate regions, due to their potential to reduce GHG emissions from agricultural practices. The purpose of this paper is therefore to review some of the research conducted on GHG mitigation in TBI in southern Ontario and Quebec, Canada. Research conducted at the University of Guelph Agroforestry Research Station (GARS) indicated that TBI systems had the potential to lower N_2O emissions by 1.2 kg ha^{-1} y^{-1} compared to a conventional agricultural field cropping system. Trees can assimilate residual nitrate (NO_3^-) left from nitrogen (N) fertilizer applications, thereby leaving less NO_3^- available for denitrification and subsequently reducing N_2O losses. Carbon sequestration is also enhanced in TBI systems as carbon (C) is stored in both above and below ground tree components. Soil Organic Carbon (SOC) is higher in systems incorporating trees because tree litter decomposes slowly, therefore reducing CO_2 loss to the atmosphere. The C sequestration potential of TBI systems and the possibility to include fast-growing tree species for bioenergy production in TBI systems make it a valid solution to mitigate climate change in temperate regions. The opportunity of C trading credits to offset the costs of implementing a TBI system and provide additional income to farmers could facilitate the adoption of TBI amidst agricultural producers in temperate regions.

Keywords: Agroforestry, greenhouse gas, intercropping, climate change, carbon sequestration, nitrous oxide.

INTRODUCTION

The effects of anthropogenic activities on nitrogen (N) and carbon (C) cycles have resulted in increased atmospheric concentrations of greenhouse gases (GHGs). This is largely a result of burning fossil fuel [1] and agricultural practices, including animal management systems [2]. Atmospheric concentrations of CO_2 have increased by 30% since 1750, with the majority of the increase occurring in the last 50 years [3]. By the mid to late 21st century, atmospheric CO_2 will increase by 0.5% or 3.6 Gt C y^{-1} and subsequently increasing temperatures by 1.5 to 4.5°C. On the other hand, N_2O emissions have increased by 15% since the pre-industrial era [3]. The Intergovernmental Panel on Climate Change (IPCC) [4] reported that N_2O accounted for 7.9% of the total GHGs emitted in 2004, compared to CO_2 at 76.7%. N_2O may have a relatively low abundance in the atmosphere (~ 310 ppbv), compared to CO_2 (370 ppmv); however, the global warming potential of N_2O is 296 times higher than of CO_2 [3].

The IPCC has provided a number of land-use alternatives for mitigating the impact of conventional agricultural practices on climate change [5, 6]. Tree-Based Intercropping (TBI) has been targeted as a potential remedial measure. Reynolds *et al*. [7] define TBI as “an approach to land use that incorporates trees into farming systems, and allows for the production of trees and crops or livestock from the same piece of land in order to obtain economic, ecological, environmental and cultural benefits”. After analyzing all of the possible agricultural land-use alternatives for mitigating climate change, the IPCC [5] reported that implementing TBI had the highest potential for C sequestration, as well as reducing emissions of other greenhouse gases such as N_2O.

TBI systems are generally considered to be C sinks because the integration of trees results in greater CO_2 sequestration from the atmosphere into tree biomass [8-11]. Soil organic carbon (SOC) is also higher in TBI systems compared to conventional monoculture systems as a result of the

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incorporation of litterfall and tree prunings into these systems [12]. This increases soil C storage and lowers C loss to the atmosphere.

The incorporation of litterfall and prunings can supply some of the N requirement of the agricultural crop, reducing the need of N fertilizers and preventing N_2O loss [13, 14]. Nitrogen losses in a TBI system are minimized because any loss of available N from the crop root zone can be captured by deep rooted trees. This can potentially inhibit denitrification in the soil profile, thus reducing N_2O emissions [13]. The results of tree shading affects the overall N cycle and can also potentially reduce N_2O emissions from the soil, since shading can decrease soil temperature, which in turn slows down microbial processes responsible for the conversion of plant available N to N_2O. However, shading can also prevent the evaporation of soil water, which can counteract the benefits of lowered soil temperature as high soil water content has been identified as a primary factor influencing N_2O emissions [15].

The purpose of this paper is to review some of the research that has been completed in temperate TBI systems in southern Ontario and Quebec, Canada emphasizing the potential of temperate TBI systems to limit GHG emissions. A review of the research completed in both temperate TBI and conventional agricultural systems in the areas of N_2O emissions, nitrate leaching, C sequestration and SOC storage is provided. These findings will then be used to demonstrate how TBI systems can potentially mitigate the effects of climate change, and support the establishment of TBI as a land-use alternative to conventional agricultural practices in temperate regions.

TBI Systems Reduce Nitrous Oxide Emissions from Soil

The application of N fertilizers, irrigation, tillage and the practice of leaving land fallow all facilitate soil microbial processes such as denitrification, responsible for the production of N_2O [16, 17]. This process is also regulated by the interactions between soil temperature, soil water content and carbon availability, as well as soil nitrate (NO_3^-) concentration due to nitrogen fertilizer inputs on agricultural land.

The N_2O emissions were compared between a TBI system and a conventional monoculture agricultural system between June 2007 and August 2008 e at the University of Guelph Agroforestry Research Station (GARS) in southern Ontario, Canada (44°32’28” N, 80°12’32” W), which is a 30 ha parcel of land established in 1987 [26]. The soil, for both sites, has been classified as a Gray Brown Luvisol (Granby sandy loam series) with a pH of 7.2. Mean annual precipitation is 830 mm, with 340 mm falling during the growing season (May to August), and the average frost free period is 136 days. (See Evers [18] for detailed methodology). Mean N_2O emission from June 2007 to August 2008 in the monoculture and TBI fields was 10.7 and 7.5 g ha^{-1} d^{-1}, respectively. Although the N_2O emission was numerically higher in the monoculture field, there was no significant difference between the two fields (p=0.5281). When analyzed by season (summer 2007, fall 2007/winter 2008, spring 2008 and summer 2008 harvesting and planting periods), the N_2O emission did not differ significantly between the two treatment types within or between seasons (Table **1**).

Correlation analysis was undertaken among soil parameters to determine the relationships between water-filled pore space (WFPS), rainfall, soil temperature, residual soil N and N_2O emission. Water-filled pore space did correlate positively with N_2O emission from summer 2007 to spring 2008 in both the monoculture and TBI fields (Table **2**). WFPS was negatively correlated with emission in the monoculture field and not statistically significant in the TBI field in summer 2008. Rainfall and soil temperature were not correlated with N_2O emission across all seasons. A significant correlation

Table 1. Mean N_2O Emission (g ha^{-1} day^{-1}) in the Monoculture and TBI Fields at the Guelph Agroforestry Research Station, Southern Ontario, Canada, During the Summer 2007, Fall 2007/Winter 2008, Spring 2008 and Summer 2008 Seasons

	N_2O Emission (g ha^{-1} day^{-1})			
Field	Summer 2007	Fall 2007/Winter 2008	Spring 2008	Summer 2008
Monoculture	4.5 a[†]	13.1 a	9.3 a	15.7 a
TBI	-2.8 a	6.8 a	9.3 a	16.7 a
P value	0.4116	0.7699	0.9972	0.8057

[†]Within columns, means followed by the same letter are not significantly different according to Tukey-Kramer means adjustment (p<0.05).

Table 2. Correlation between N_2O Emission and WFPS, Soil Temperature, and Soil Inorganic N in the Monoculture (Mono) and TBI Fields, at the Guelph Agroforestry Research Station, Southern Ontario, Canada

	Summer 2007 to Spring 2008		Summer 2008	
	TBI	Mono	TBI	Mono
WFPS	r = 0.19*	r = 0.20*	r = -0.40*	r = 0.01
Soil Temperature	r = -0.08	r = -0.14	r = 0.06	r = 0.18
Soil Inorganic N	r = 0.01	r = 0.27*	r = 0.57*	r = 0.18

*Indicates a significant correlation with N_2O emission (p<0.05).

was noted between residual N content and emission in the TBI field, but not in the monoculture field from summer 2007 to spring 2008. The opposite trend was found in the summer of 2008, where N_2O emission was correlated with residual soil N in the monoculture field but not in the TBI system. Similarly mixed results on the influence of these soil parameters on N_2O emission have been reported in the scientific literature [19]. These variations are due to many factors that influence N_2O emission from soils, as indicated above, and their interactions. Therefore, it becomes a challenge to associate N_2O emissions from TBI and agricultural fields to a single factor. For example, inconsistent relationships between soil variables known to affect denitrification could be due to the difficulty of isolating soil parameters that also influence each other. The addition of fertilizers, for example, can mask the effects of soil parameters on denitirification. As well, the lack of variation in N_2O between land management practices can be attributed to different soil parameters favouring N_2O production in each field. Generally, in a conventional monoculture, soil temperature is higher resulting in a greater soil microbial activity, where as N uptake is lower and NO_3^- leaching is more likely to occur, thereby facilitating the production of N_2O deeper within the soil profile. In a TBI system, WFPS is higher, due to a reduction in evaporation from both soil and plants as a result of shading, which could enhance denitrification. Choudhary *et al*. [19] also found extreme variability in N_2O emissions within treatments as a result of variability of soil parameters, which makes measuring N_2O emissions very difficult in complex agricultural systems like TBI.

Overall, the N_2O emission in the monoculture and TBI systems was 3.9 and 2.7 kg ha^{-1} y^{-1}, respectively. A model developed by Thevathasan and Gordon [14] suggested that TBI systems could potentially reduce N_2O emissions by 0.69 kg N_2O ha^{-1} $year^{-1}$. This study found that annual N_2O emission was reduced by 1.2 kg ha^{-1} $year^{-1}$ in a TBI system compared to a conventional monoculture, although this difference was statistically insignificant. The estimated N_2O emissions at this research site were in the lower ranges of N_2O emissions reported in other studies. Syväsalo *et al*. [20] found that annual N_2O emissions ranged from 3.7 to 7.8 kg ha^{-1} from clay soil and 1.5 to 7.5 kg ha^{-1} from sandy loam soil. Emissions ranged from 1.9 to 8.0 kg ha^{-1} over 10 months in grazed grassland, whereas emissions from arable land were lower ranging from 0.3 to 1.4 kg ha^{-1} over the same time period [15]. Williams *et al*. [21] calculated large variations in N_2O emission in grassland, where the range was 0.2 to 9.2 kg ha^{-1} y^{-1} and at one sampling point emissions reached 61.4 kg ha^{-1} y^{-1}. Emissions are affected by rainfall events and WFPS, soil temperature and the number of freeze/thaw events, carbon content, as well as soil management practices such as fertilization rates, all of which can cause variation in emissions from year to year

The incorporation of trees into agricultural systems can also reduce nitrate (NO_3^-) leaching through the soil profile, below the rooting zones of arable crops. The "safety-net hypothesis" suggests that tree roots capture and take up NO_3^- that would normally be leached past the crop rooting zone. Lacombe [22] tested the safety-net hypothesis in a TBI system located in St. Rémi, Quebec using lysimeters and root trenching system (see Lacombe *et al*. [22] for methodology). The TBI system consisted of soybean (*Glycine max* L.) and alternating rows of hybrid poplars or black walnut (*Juglans nigra* L.) and white ash (*Fraxinus Americana* L.). Lacombe *et al*. [22] expected the TBI system to reduce NO_3^- leaching to subsurface water, despite the young age of the system.

During the 2007 growing season, by sampling on 11 dates and modelling water infiltration in the system, Lacombe *et al*. [22] was able to estimate NO_3^- leaching beyond the reach of tree roots for 10 time intervals in 2007 (Fig. **1**). For eight of these intervals, NO_3^- leaching was found to be

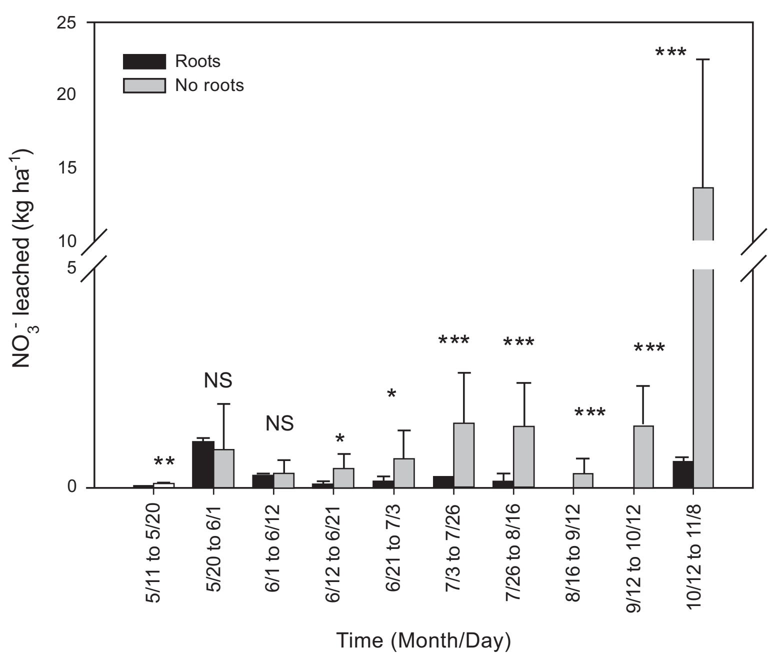

Fig. (1). Average NO_3^- kg ha^{-1} leached per sampling step (n=18) in trench vs. non-trench plots. Error bars represent standard deviation. T-test significance levels are indicated by *(p<0.05), **(p<0.01), ***(p<0.001) and NS (p>0.05, not significant). Tests were performed on log-transformed data [22]. Study site, Saint-Rémi, 2007, Québec, Canada.

significantly higher in the no roots treatment, however, the net NO_3^- leaching reduction for the roots treatment zone was 4.7 kg ha^{-1}. This is equivalent to an 81% NO_3^- leaching reduction for the TBI system segment that had intact roots.

One possible confounding factor in the study of Lacombe *et al*. [22] was the presence of dead tree roots, which may have contributed to NO_3^- levels in the no roots section. Fertilizers were added to the study site to override this effect. A C flush due to dead roots could have had an impact on the soil's N cycle, but Lavoie and Bradley [23] observed no detectable C flush in a southern Quebec forest floor trenching study. In addition, on some of the mid-summer sampling dates, it was found that water did not even reach many of the lysimeters in the roots treatment. Thus, water usage by the trees and a reduction in NO_3^- leaching was evident for those dates. This last point may raise questions with respect to the availability of water for the agricultural crop. However, Reynolds *et al*. [7] showed evidence that light may be a more important factor than water when it comes to competition between trees and agricultural crops.

Dougherty [24] also tested the safety-net hypothesis in a TBI system. This study was completed between April and November in 2005 and 2006 at GARS and measured NO_3^- leaching from both a TBI system and a conventional monoculture using tile drain monitors (see Dougherty [24] for full methodology). The authors found that NO_3^- leaching was consistently greater in the monoculture than in the TBI system, but this difference was not significant ($p>0.05$) in 2005, with a cumulative total of 57.37 and 54.74 kg ha^{-1} from the monoculture and TBI system, respectively (Table **3**). However, in 2006 a significant difference was seen where NO_3^- leaching was 164.67 and 88.59 kg ha^{-1} in the monoculture and TBI systems, respectively (Table **4**). This accounted for a reduction of 43% in NO_3^- in the TBI system compared to the conventional monoculture.

In both studies, the authors confirmed the safety-net hypothesis in both temperate TBI systems, whereby tree roots take up soil water, thus reducing the volume of water and NO_3^- percolating through the soil profile beyond the crop-tree root zone. Allen *et al*. [25] showed similar results where at a depth of 0.3 m there was 121.94 and 63.84 kg NO_3^--N ha^{-1} leached from the barrier (no roots) and non-barrier (roots) treatment, respectively. At 0.9 m depth leaching was 45.56 and 13.05 kg NO_3^--N ha^{-1} in the barrier and no barrier treatments, respectively. Allen *et al*. [25] calculated a reduction in NO_3^- leaching between 48% and 71%, which is consistent with the results found in Lacombe *et al*. [22] and Dougherty [24].

In all cases, the authors speculated that lower NO_3^- leaching in a system where trees are present compared to conventional agriculture systems because tree roots are able to take up large amounts of water compared to agricultural crops and with it more NO_3^- is taken up [22, 24, 25]. Tree rooting systems also extend to deeper soil regions, where roots of agricultural crops may not be present [24]. Lower NO_3^- leaching in agro-ecosystems where trees are present may also be attributed to the longer growing season of trees in which water is taken up for a longer period of time compared to where just agricultural crops are grown [24].

As a result of the increase in NO_3^- uptake by trees in a TBI system, there will be less NO_3^- available for denitrifica-

Table 3. Mean Daily and Total Loss (kg ha^{-1}) of NO_3-N *via* Leaching for Three Time Periods During 2005, at the Guelph Agroforestry Research Station, Southern Ontario, Canada [24]

Date	Mean Daily Loss *via* Leaching (kg ha^{-1})			Total Loss *via* Leaching (kg)	
	Monoculture	TBI	p-value	Monoculture	TBI
April 7th – May 21st	1.05a†	0.93b	< .001	44.46	43.73
Aug 18th – Sept 30th	0.09a	0.02b	< .001	0.71	0.19
Nov 8th – 31st	0.87a	0.76b	< .001	12.20	10.81
Total				57.37	54.74

† Within rows (Date), means followed by the same letter are not significantly different according to T-test ($p<0.05$).

Table 4. Mean Daily and Total Loss (kg ha^{-1}) of NO_3-N *via* Leaching for Four Time Periods During 2006, at the Guelph Agroforestry Research Station, Southern Ontario, Canada [24]

Date	Mean Daily Loss *via* Leaching (kg ha^{-1})			Total Loss *via* Leaching (kg)	
	Mono	TBI	p-value	Mono	TBI
Mar 21st – Apr 30th	1.09a†	0.59b	< .001	44.33	24.67
May 1st – June 12th	1.16a	0.58b	< .001	44.52	22.20
July 4th – Aug 7th	0.76a	0.54b	< .001	14.66	9.86
Sept 28th – Nov 21st	1.11a	0.58b	< .001	61.16	31.86
Total				164.67	88.59

† Within rows (Date), means followed by the same letter are not significantly different according to T-test ($p<0.05$).

tion and subsequently less production of N_2O compared to conventional monocultures. Evers [18] found that soil NO_3^- concentrations were significantly lower in a TBI system than in a conventional monoculture at GARS in spring and summer 2008. Soil NO_3^- concentration was 2.1% and 1.1% in spring and 0.60% and 0.21% in summer in the conventional monoculture and TBI systems, respectively. Overall NO_3^- leaching may be lower in a TBI system than in a conventional monoculture, thereby reducing N_2O emissions from these systems.

TBI Systems Contribute to Above- and Below-Ground C Sequestration

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 [26], and (2) TBI systems increase SOC storage through C inputs to the soil. TBI systems are generally considered to be C sinks because the integration of trees into these systems allows for greater CO_2 sequestration from the atmosphere and subsequently higher carbon storage in permanent tree components.

Peichl *et al*. [26] examined and compared C pools and fluxes between a TBI system (13 year old poplar (*Populus deltoides* x *Populus nigra* clone DN-177)-based intercropping system) and a barley (*Hordeum vulgare* L. Cv. OAC Kippen) conventional monoculture system at the GARS located in southern Ontario, Canada (See Peichl *et al*. [26] for methodology). Mean total soil carbon concentration at 0-20 cm depth was significantly lower, 2.4%, in the conventional monoculture system compared to 3% in the poplar intercropping system. Soil respiration rates were between 0.3 and 0.5 g CO_2 h^{-1} m^{-2} in the barley conventional monoculture system and were slightly higher in the poplar intercropping system at a rate between 0.3 and 0.8 g CO_2 h^{-1} m^{-2}. Carbon concentration in leached soil solution between the conventional monoculture and poplar intercropping system was the same at 0.09%. The total C pool of above and below ground components yielded 68.5 and 96.5 t C ha^{-1} in the barley conventional monoculture and poplar intercropping systems, respectively. The total soil carbon pool was 41% higher in the poplar intercropping system than in the conventional monoculture C pool. This can be attributed to the increase in C inputs into the poplar system as a result of litterfall and fine root turnover (note: crop residue inputs in the TBI system is low due to the space (15%) occupied by the trees). The rate of decomposition of tree and crop residues is also an important factor to the overall soil C pool. Slowly-decomposing tree residues have a longer residence time in the soil than rapidly decomposable crop residues (e.g., N-rich soybean residues) [27].

Soil C and C leaching are heterogeneous within the site depending on proximity to the tree row and the physical property of the poplars, even at the same age [26]. Carbon leaching may be closer to the tree row as a result of C inputs from leaves, branches, dead roots and exudates from living roots compare to the middle of the crop alley or in a conventional monoculture system [26, 28, 29]. Pockets of high soil C in the intercropping system can be attributed to the height, crown diameter and litterfall differences of the poplar trees even at the same age; however, the leaf litter input on its own explains the higher soil C content in an intercropping system compared to the conventional monoculture system [26]. Even though soil respiration was equivalent in the conventional monoculture and TBI systems, there was higher variability in respiration rates in the TBI system compared to the conventional monoculture system further demonstrating the heterogeneity of C inputs and outputs in a TBI system. Respiration rates were higher closer to the tree rows likely due to higher tree root respiration and / or soil microbial respiration. Leaf litter decomposition at the tree row increases microbial biomass and subsequently microbial activity, thereby increasing CO_2 respiration [26, 28, 29]. Based on the above measurements from [26], overall C fluxes were -2.9 t C ha^{-1} y^{-1} for the conventional monoculture system and +13.2 t C ha^{-1} y^{-1} for the poplar intercropping system (Fig. **2**). The higher C assimilation in the poplar intercropping system balanced the higher soil respiration rate, which facilitated the net accumulation of C compared to the barley conventional monoculture system.

TBI systems may also increase the SOC, compared to conventional agriculture practices. Not only does an increase in SOC enhance soil fertility, reduce erosion and nutrient leaching, but also increases soil C storage, which reduces the atmospheric CO_2 concentration, thereby demonstrating the ability of soils to buffer climate change effects. The C inputs in TBI systems 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 [30]. In the fall of 2008, soil organic carbon (SOC) storage was compared between four TBI and conventional agricultural systems by Bambrick [31]. 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. Rémi, Quebec, Canada and a 23-year old TBI site in Guelph, Ontario, Canada (see Bambrick [31] for methodology).

A significant gain in the SOC pools in TBI systems compared to conventional agroecosystems was anticipated, and this occurred at two of the four sites in the study. There was no difference in the SOC pool between TBI systems in St. Paulin and St. Edouard, likely because the sites were too young and trees too small to generate a measureable change in the SOC pool. In St. Rémi, the SOC pool to a depth of 15 cm in the TBI system was 33.6 Mg C ha^{-1} or 77% greater than in the nearby conventionally managed agroecosystem (Table **5**). The poplar TBI system in Guelph contained more SOC than both the Norway spruce TBI and conventionally managed agroecosystem (Table **6**). 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 substantial than the 0.6% increase in SOC of the poplar TBI system, compared to conventional agriculture, reported in 2002, after 17 years of TBI [26].

The difference in the SOC pool of the TBI and conventionally managed systems was much larger in St. Rémi than in Guelph, despite the fact that trees in Guelph are 15 years older. This is likely because the St. Rémi site was a tree plantation prior to transition to TBI, whereas all other sites were conventionally managed agroecosystems prior to TBI establishment (note: Soil textures for both sites, St. Rémi, loamy soil (490 g sand kg^{-1}, 350 g silt kg^{-1} and 160 g clay kg^{-1})

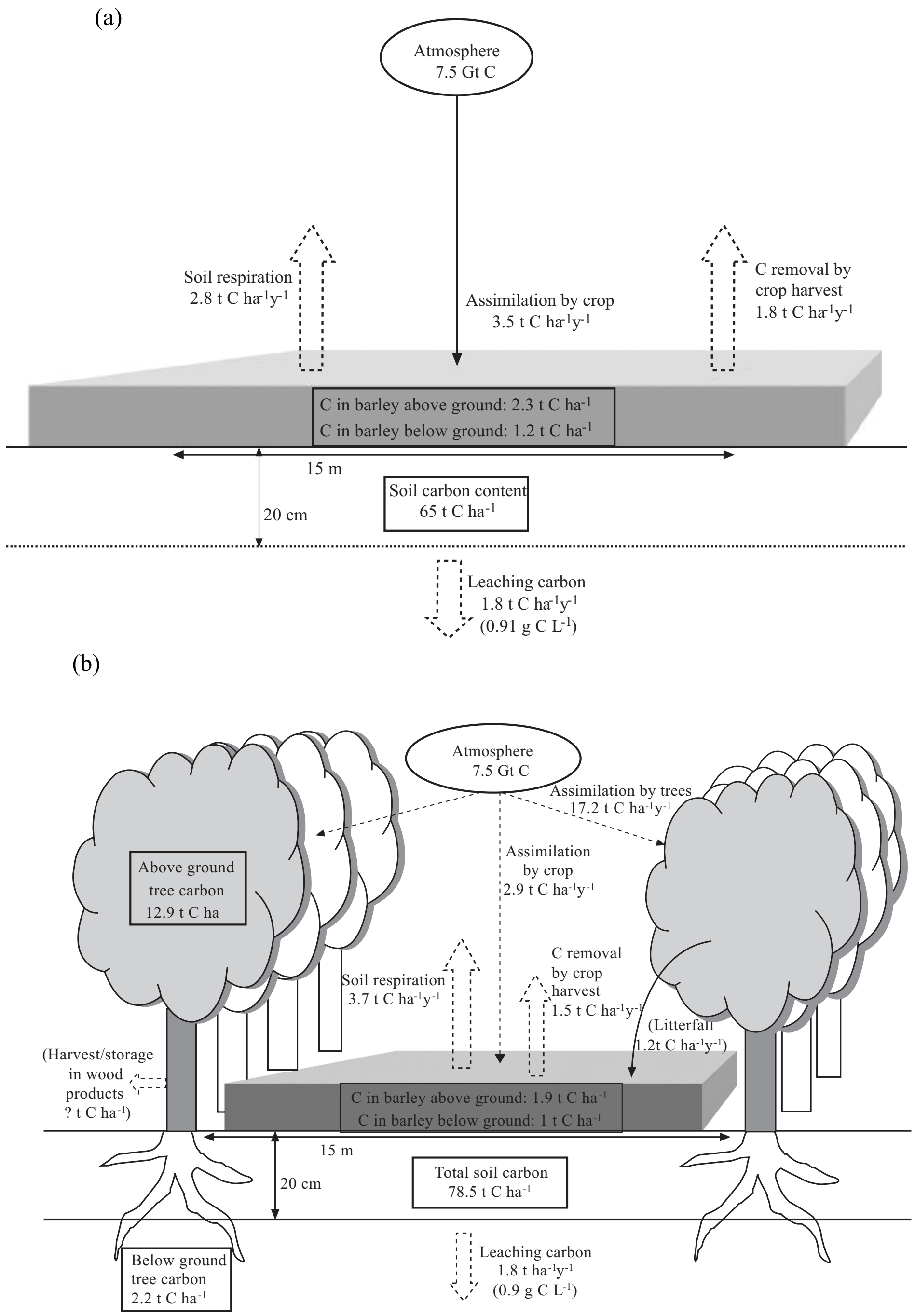

Fig. (2). Model of all main C pools and C fluxes within a) a temperate barely conventional monoculture system, and b) a 13-year old temperate barely-poplar intercropping system, at the Guelph Agroforestry Research Station, southern Ontario, Canada. Boxes indicate C pools and arrows indicate C flux [27].

Table 5. Mean SOC Pool (0 - 30 cm Depth) of TBI and Conventional Monoculture in St. Paulin, St. Edouard and St. Rémi (Quebec, Canada) [31]

Treatment	St. Paulin (4 yrs)	St. Edouard (4yrs)	St. Rémi (8yrs)
	SOC (Mg C ha^{-1})	SOC (Mg C ha^{-1})	SOC (Mg C ha^{-1})
TBI	66.9a†	76.9a	77.1a
Monoculture	66.3a	80.1a	43.5b

† Within columns, means followed by the same letter are not significantly different according to Tukey-Kramer means adjustment ($p<0.05$).

Table 6. Mean SOC Pool (0 - 20 cm Depth) of a 23-yr Old TBI System and Conventional Monoculture in Guelph (Ontario, Canada) [31]

Treatment	SOC (Mg C ha^{-1})
Poplar	57.0a†
Norway Spruce	50.9b
Monoculture	50.8b

† Within columns, means followed by the same letter are not significantly different according to Tukey-Kramer means adjustment ($p<0.05$).

(pH 7), Guelph site, sandy loam, sand 67%, silt 25% clay 8%). Garten [32] found that in seven agricultural plots converted to tree plantations, soil C 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. Rémi 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 [27, 33]. The TBI systems at Guelph and St. Rémi 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. It was concluded that TBI systems hold promise for maintaining or increasing the SOC pool, relative to conventionally managed agroecosystems.

The Role of TBI in Climate Change Mitigation

TBI systems are generally considered to be C sinks because the incorporation of trees into farming systems increases the sequestration of atmospheric CO_2, as shown in the studies by Peichl *et al*. [26] and Abohassan [29]. Implementing TBI systems in temperate regions may not only just sequester CO_2, but also reduce other GHG emissions such as N_2O. Evers [18] found that a TBI system in southern Ontario lowered N_2O emissions by 1.2 kg $ha^{-1}y^{-1}$ compared to a conventional monoculture. This difference was not significant statistically, but over time, due to numerically lower N_2O emission, could contribute towards climate change mitigation. When converting N_2O sequestered in a TBI system to a common unit of C sequestered, the value of N_2O sequestered is equivalent to 0.1 t C ha^{-1} y^{-1}. The actual C sequestered in a temperate poplar TBI system is 13.2 t C ha^{-1} y^{-1} and adding this to the N_2O potential equivalent, the total becomes approximately 13.3 t C ha^{-1} y^{-1}. If there is a net C loss of 2.9 t C ha^{-1} y^{-1} from a barely conventional monoculture system [26], the C sequestration potential of a poplar intercropping system is 16 times higher than in a conventional monoculture system.

Even though the above example shows a significant difference in C sequestration potentials between a temperate poplar TBI system and a conventional monoculture system, many factors need to be taken into consideration that could change both C and N_2O sequestration potentials in an individual system. N_2O is influenced by a variety of below ground interactions, such as soil temperature, water content and available N content, which could increase or decrease emissions from year to year. The addition of fertilizer is another contributing factor to N_2O emissions because the timing, rate and type of fertilizer can influence N_2O losses [16, 17]. However, TBI systems generally require less fertilizer as a result of leaf litter inputs and less N_2O is lost due to the increase in N uptake by the trees [34].

Physical properties of individual tree species, such as crown diameter, tree height, and litter production can all influence the actual C sequestration potential of a temperate TBI system. The C sequestration potential is also largely dependent on the crop in a conventional monoculture system and the tree species in a TBI system. Peichl *et al*. [26] found that in a Norway spruce (*Picea abies* L.) intercropping the C sequestration potential was 1.1 t C ha^{-1} y^{-1}, which is still 4 times higher than in the barely conventional monoculture system but is 12 times lower than the poplar system. When considering what species to use in an intercropping system the farmer must bear in mind the value of lumber compared to the C sequestration potential. Poplar species produce lower quality lumber compared to oak species *Quercus spp*. L); however, the C sequestration potential, in a short time period (less than 15 years), is much higher in poplar species compared to oak.

TBI systems could be implemented on agricultural land classes from 3 to 4 from the Canada Land Inventory (CLI) [14]. The CLI ranks agricultural land from 1 to 7 according to its suitability for agriculture, 1 being the highest suitability for supporting agriculture and 7 being the lowest. Therefore, roughly 45.5 million hectares of marginal land (classes 3 to 4) in Canada could be converted to TBI, which could have a significant effect on GHG mitigation in temperate regions.

The use of TBI systems in Short Rotation Woody Crops (SRWC) for the production of biomass in temperate regions has recently been explored with previous success in many tropical locations [35]. This exploration has been facilitated by rising fuel costs and the need to reduce the dependence on fossil fuels contributing to climate change. Bioenergy production is a viable option in Canada for climate change mitigation due to the success of establishing TBI and SRWC on marginal land [35, 36]. Although fossil fuels are used in the establishment and maintenance of TBI systems and SRWC production, the consumption of fossil fuels may be off-set by the amount of C that is sequestered in these systems. Carbon storage occurs in both above and below ground tree components contributing to overall C sequestration. These systems also provide a variety of other ecosystem services such as enhancing biodiversity [37], preventing soil erosion [38] and reducing water pollution [39].

Clinch *et al*. [36] conducted a study from 2006 to 2007 at GARS and found that willow (*Salix spp*.) yields were significantly higher when grown in a TBI system than in conventional plantations. Yields for the TBI and control fields were 0.78 and 0.54 oven dried tons ha^{-1}, respectively, in 2006, and 3.00 and 1.11 oven dry t ha^{-1}, respectively, in 2007. The authors also found that survival rates of willow trees were significantly higher in the TBI system. They attributed this to the ability of a TBI system to buffer against changes in microclimatic conditions, where the TBI system had higher soil water and lower soil temperature as a result of shading from the trees. This is important in dryer seasons, where shading can significantly reduce the evaporation of water from both the soil and crops allowing for better survival and yield under a TBI system.

Some European countries such as the UK and Sweden have incorporated the production of renewable energy sources in their policies for the mitigation of climate change. The UK was required to produce 6.7% of their energy from renewable resources in 2006 and 2007, with an increase to 15% by 2015 [39]. In Sweden, SRWC are mainly used in municipalities to prevent water pollution by reducing N and P inputs of up to 95% [40, 41]. Therefore, it is evident that SRWC systems can play a major role towards climate change mitigation, while providing ecosystem services.

There are large financial obstacles for farmers implementing TBI in terms of preparation, labour, establishment and maintenance; therefore, some monetary incentive may be needed to encourage farmers to establish a TBI system on their own land. The Kyoto Protocol allows for emitting nations to purchase C credits from other countries if they cannot accomplish projected GHG mitigation goals. This C 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 occur 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 C-emitting industries. The industries must then reduce their C emissions to the required amount, or purchase C credits from an outside agency as another way to meet CO_2 mitigation targets [31]. As a general trend, C trading has allowed developed countries to offset their CO_2 emissions by investing in C sequestration practices in developing countries. Developing countries have been able to invest this payment towards the establishment of ecologically friendly land-use practices in their respective countries. Costa Rica was the first developing country to take advantage of this system by selling C credit bonds to European countries to fund rainforest conservation and reforestation projects in 1997 [42]. In Canada, C-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 GHG levels through the market-based cap-and-trade system [43]. The Montreal Climate Exchange was established in 2006 in partnership with the Chicago Climate Exchange and has recently introduced carbon futures trading in Canada [44].

CONCLUSIONS

Alternative land-use systems are currently needed that can address issues related to climate change, while maintaining food production, environmental services and alternative (bioenergy) fuel crops. Tree-based intercropping could address these concerns by limiting GHG production while supporting annual crop production and providing woody biomass for fuel. It is difficult to measure the impact of TBI system on N_2O emission reductions as a result of heterogeneity in soil variables. However, the extensive rooting system of trees enhances the uptake of NO_3^-, leaving less NO_3^- available for denitrification and subsequently lowers N_2O emissions. Proper management practices, such as incorporating tree prunings and leaf litter inputs reduce the need for N fertilizers, which may also lower the potential for N_2O losses.

Incorporating trees into farming systems can also increase C sequestration potentials. Carbon sequestration is enhanced in both above and belowground tree components and in soils. However, the extent of the C pools and fluxes can vary among tree species, tree planting density, cutting cycles, crop combinations and even within species as a result of tree height, and crown diameter. Along with C sequestration potentials of TBI, the possibility of growing bioenergy crops between permanent tree rows could also contribute substantially to GHG mitigation in temperate regions. A C trading system could provide the financial incentive to farmers considering the adoption of TBI systems in the temperate regions.

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REFERENCES

[1] Paustian K, Six J, Elliot ET, Hunt HW. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 2000; 48: 147-63.

[2] Intergovernmental Panel on Climate Change. IPCC Special Report on Emissions Scenarios. Available at http://www.grida.no/climate/ipcc/emission/078.htm [Online October 2, 2009].

[3] Intergovernmental Panel on Climate Change. In: Houghton JT, Ding Y, Griggs DJ, *et al*, Eds. Climate change 2001: the scientific basis. Cambridge: Cambridge University Press 2001; p. 251.

[4] Intergovernmental Panel on Climate Change. IPCC Fourth Assessment Report, Climate Change (AR4) 2001; p. 14.

[5] Intergovernmental Panel on Climate Change. Land-use, land-use change and forestry. Special report of the intergovernmental panel on climate change. Cambridge University Press, UK 2000; pp. 375.

[6] Intergovernmental Panel on Climate Change. Climate Change 2001: Mitigation [cited 2009 Oct 2]. Available from http://www.grida.no/climate/ipcc_tar/wg3/pdf/TAR-total.pdf.

[7] Reynolds PE, Simpson JA, Thevathasan NV, Gordon AM. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecol Eng 2007; 29: 362-71.

[8] Kürsten E, Burschel P. CO_2-mitigation by agroforestry. Water Air Soil Pollut 1993; 70: 533-44.

[9] Dixon RK. Agroforestry systems: sources or sinks of greenhouse gases? Agroforest Syst 1995; 31: 99-116.

[10] Sampson RN. Agroforestry as a carbon sink. In: Schroeder W, Kort JK, Eds. Temperate agroforestry: adaptive and mitigative roles in a changing physical and socio-economic climate. Proceeding of the 7th Biennial Conference on Agroforestry in North America and 6th Annual Conference of the Plains and Prairie Forestry Association, August 13-15, 2001, Regina, Saskatchewan, Canada 2001; p. 342.

[11] Montagnini F, Nair PKR. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agroforest Syst 2004; 61: 281-98.

[12] Oelbermann M, Voroney RP, Gordon AM. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agric Ecosyst Environ 2004; 104: 359-77.

[13] Kang BT, Caveness FE, Tian G, Kolawole GO. Longterm alley cropping with four hedgerow species on an Alfisol in southwestern

Nigeria – effect on crop performance, soil chemical properties and nematode population. Nutr Cycl Agrosyst 1999; 54: 145-55.

[14] Thevathasan NV, Gordon AM. Ecology of tree intercropping systems in the North temperate region: experiences from southern Ontario, Canada. Agroforest Syst 2004; 61: 257-68.

[15] Smith KA, Thomson PE, Clayton H, McTaggart IP, Conen F. Effects of temperature, water content and nitrogen fertilization on emissions of nitrous oxide by soils. Atm Environ 1997; 32: 3301-9.

[16] Hénault C, Devis X, Lucas JL, Germon JC. Influence of different agricultural practices (type of crop, form of N-fertilizer) on soil nitrous oxide emissions. Biol Fertil Soils 1998; 27: 299-306.

[17] Hénault C, Devis X, Page S, Justes E, Reau R, Germon JC. Nitrous oxide emissions under different soil and land management conditions. Biol Fertil Soils 1998; 26: 199-207.

[18] Evers AK. N_2O Emissions from a tree-based intercropping system compared to a conventional monoculture in Southern Ontario, Canada. M.Sc. Dissertation. Department of Environmental Biology. University of Guelph. Guelph, Ontario, Canada 2009; p. 146.

[19] Choudhary MA, Akramkhnov A, Saggar S. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agric Ecosyst Environ 2002; 93: 33-43.

[20] Syväsalo E, Regina K, Pihlatie M, Esala M. Emissions of nitrous oxide from boreal agricultural clay and loamy sand soils. Nutr Cycl Agroecosyst 2004; 69: 155-65.

[21] Williams DL, Ineson P, Coward PA. Temporal variations in nitrous oxide fluxes from urine-affected grassland. Soil Biol Biochem 1999; 31: 779-88.

[22] Lacombe S, Bradley RL, Rivest D, Cogliastro A, Olivier A. Significant reduction of soil nitrate leaching in a six-years old tree-based intercropping system, in southern Québec. In: Lacombe S. Diminution des pertes du nitrate par lixiviation et augmentation de la diversité microbienne dans les systèmes agroforestiers. Mémoire de maîtrise, Département de biologie, Université de Sherbrooke, Sherbrooke, QC 2007.

[23] Lavoie M, Bradley RL. Short-term increases in relative nitrification rates due to trenching in forest floor and mineral soil horizons of different forest types. Plant Soil 2003; 252: 367-84.

[24] Dougherty MC. Nitrate, ammonium and *Escherichia coli* NAR levels in mixed tree intercrop and monocrop systems. M.Sc. Dissertation. Department of Environmental Biology. University of Guelph. Guelph, Ontario, Canada 2007; p. 143.

[25] Allen SC, Jose S, Nair PKR, Brecke BJ, Nkedi-Kizza P, Ramsey, CL. Safety-net role of tree roots: evidence from a pecan (Carya illinoensis K. Koch)-cotton (Gossypium hirsutum L.) alley cropping system in the southern United States. Forest Ecol Manage 2004; 192: 395-407.

[26] Peichl M, Thevathasan NV, Gordon AM, Huss J, Abohassan R. Carbon sequestration potentials in temeperate tree-based intercropping systems, southern Ontario, Canada. Agroforest Syst 2006; 66: 243-57.

[27] Abohassan RA. Carbon dynamics in a temperate agroforestry system in Southern Ontario, Canada. M.Sc. Dissertation. Department of Environmental Biology. University of Guelph. Guelph, Ontario, Canada 2004; p. 122.

[28] Brady NC, Weil RR. The nature and properties of soils, 11^{th} ed, Prentice Hall, Upper Saddle River, NJ 1996; p.740.

[29] Schulze ED, Ed. Carbon and nitrogen cycling in European Forest Ecosystems. Ecological Studies 142, Springer-Verlag, Berlin, Heidelberg 2000; pp. 217-36.

[30] Montagnini F, Nair PKR. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agroforest Syst 2004; 61: 281-95.

[31] Bambrick A. Soil organic carbon in tree-based intercropping systems of Quebec and Ontario Canada. M.Sc. Dissertation. Department of Natural Resource Sciences, McGill University, Montreal, Quebec, Canada 2009; p. 81.

[32] Garten CTJ. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass Bioenergy 2002; 23: 93-102.

[33] Sharrow SH, Ismail S. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agroforest Syst 2004; 60: 123-30.

[34] Kass DCL, Sylvester-Bradley R, Nygren P. The role of nitrogen fixation and nutrient supply in some agroforestry systems in the Americas. Soil Biol Biochem 1997; 29: 775-85.

[35] Gruenewald H, Brandt BKV, Schneider BU, Bens O, Kendzia G, Hüttl RF. Agroforestry systems for the production of woody biomass for energy transformation purposes. Ecol Eng 2007; 29: 319-28.

[36] Clinch RL, Thevathasan NV, Gordon AM, Volk TA, Sidders D. Biophysical interactions in a short rotation willow intercropping system in southern Ontario, Canada. Agric Ecosyst Environ 2009; 131: 61-9.

[37] Christian DP, Hoffman WJ, Hanowski M, Niemi GJ, Beyea J. Bird and mammal diversity on woody biomass plantations in North America. Biomass Bioenergy 1998; 14: 395-402.

[38] Wilkinson AG. Poplars and willows for erosion control in New Zealand. Biomass Bioenegy 1999; 16: 263-274.

[39] Dimitriou I, Aronsson P. Willows for energy and phytoremediation in Sweden. Unasylva 2005; 56: 47-50.

[40] Rowe RL, Street NR, Taylor G. Identifying potential environmental impacts of large scale deployment of dedicated bioenergy crops in the UK. Renewable Sustain Energy Rev 2009; 13: 271-90.

[41] Berndes G, Borjesson P. Low cost biomass produced in multifunctional plantations - the case of willow production in Sweden. 2nd World Conference on Biomass for Energy, Industry and Climate Protection, Rome, Italy 2004.

[42] Oelbermann M, Voroney R, Gordon A. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agric Ecosyst Environ 2004; 104: 359-77.

[43] Western Climate Initiative (WCI). Western Climate Initiative [cited 2009 January 19] Available from http://www. westernclimateinitiative.org/

[44] Montreal Climate Exchange (MCeX). Montreal Climate Exchange [cited 2009 January 19]. Available from http://www.mcex.ca/ index_en

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