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Ecology of tree intercropping systems in the North temperate region: Experiences from southern Ontario, Canada

N.V. Thevathasan* and A.M. Gordon
Department of Environmental Biology, University of Guelph, Guelph, Ontario, Canada N1G 2W1
**Author for correspondence: email: nthevath@uoguelph.ca*

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Abstract

Agroforestry practices in northern latitudes, although less diverse than those in warmer regions, have unique advantages over conventional land-use systems in the region in terms of water-quality enhancement, carbon sequestration, and biodiversity conservation. Tree intercropping, especially, is a potentially promising agroforestry option in the region. Understanding the ecological interactions between trees and crops in such intercropped systems provides the basis for designing efficient systems with potential for wider applicability. With this objective, the experience from several years of research on this aspect at the University of Guelph, in southern Ontario, Canada are presented. Yields of C3 crops intercropped with trees, as well as growth of trees, did not differ from those in corresponding sole-stand (conventional) systems of crops and trees. But, soil organic carbon content and bird and insect diversity increased in the intercropped area. The abundance and distribution of earthworms were higher closer to the tree rows indicating improved soil health. The C sequestration potential in fast-growing tree (hybrid-poplar)-based intercropping systems was four times more than that reported for conventional agricultural fields in the region. Because of reduced fertilizer use and more efficient N-cycling, the tree-intercropping systems could also lead to the reduction of nitrous oxide emissions from agricultural fields by about 0.7 kg ha^{-1} yr^{-1}. Marginal or degraded land that is suitable for agroforestry is estimated to be 57 million ha in Canada. Tree/crop intercropping is one agroforestry system that shows great potential for this region. We suggest that this land-management option can be placed above conventional agriculture in terms of long term-productivity and sustainability.

Introduction

Out of the estimated 140 million ha of marginal or degraded land that is considered to be available for agroforestry establishment in North America (Dixon et al. 1994), 50 million to 57 million are in Canada (McKeague 1975). Although many different types of agroforestry including windbreaks and shelterbelts, silvipastoral systems, integrated riparian forest systems, forest farming systems, and tree–crop intercropping systems have historically been practiced in North America (Garrett et al. 2000; Gordon et al. 1997; Gordon and Newman 1997), the vast potential for economic and environmental benefits attributed to agroforestry is yet to be realized on a large scale. Compared to the diverse and extremely complex agroforestry systems that exist in warmer parts of the world, the types of agroforestry applications could be limited in the northern latitudes. Even so, agroforestry is being practiced in many areas in Canada including southern Ontario (Table 1), and research at the University of Guelph, Ontario, Canada, during the past 15 years has shown the vast potential for agroforestry in terms of such benefits as water-quality enhancement, carbon sequestration, and biodiversity conservation. The integration of trees into the agricultural land-base via tree/crop intercropping systems has indeed shown great potential for the region (Thevathasan et al. 2004). Given the recent ratification of the Kyoto Protocol by Canada and the role of agroforestry in carbon sequest-

Table 1. Summary of research trials undertaken on different agroforestry technologies in southern Ontario, Canada.

Agroforestry technology	Reference
Windbreaks and shelterbelts	Kenney 1987; Loeffler et al. 1992
Integrated riparian forest systems	O'Neill and Gordon 1994; Oelbermann and Gordon 2000, 2001
Forest farming systems	Matthews et al. 1993; Christrup 1993[6]; Williams et al. 1997
Tree-based intercropping systems	McLean 1990[8]; Ball 1991[9]; Gordon and Williams 1991; Williams and Gordon 1992, 1994, 1995; Ntayombya 1993; Ntayombya and Gordon 1995; Kotey 1996[10]; Thevathasan and Gordon 1995, 1997; Thevathasan 1998; Price and Gordon 1999; Dyack et al. 1999; Price 1999[7]; Simpson 1999[3]; Zhang 1999[2]; Gray 2000[4]; Middleton 2001[5]
Silvipastoral systems	Bezkorowajnyj et al. 1993

ration (Montagnini and Nair 2004), agroforestry as a land-use approach is more important now than ever before. When carbon trading becomes effective, as it is poised to be soon, industries that emit greenhouse gasses (GHG) may be required to purchase C credits and agroforestry land-use practices may become an attractive land-use option.

The low adoption rate of tree/crop intercropping systems in southern Ontario is in part due to current tax policies that do not take into consideration the numerous nontangible, societal-level benefits associated with agroforestry systems (Dyack et al. 1999). It is also true that the traditional farming community in many areas of the region is not entirely aware of the intricacies of adopting and practicing intercropping (Matthews et al. 1993). Nevertheless, from a scientific perspective, a clear understanding of the ecological foundations of agroforestry is essential for promoting the practice and extending it to potential sites. With that background, this chapter synthesizes the ecological information generated from 15 years of tree/crop intercropping research at the University of Guelph and in other parts of Canada, and discusses the application potentials and management implications of these results in terms of long-term production and sustainability of the resource base in the north temperate region, with particular focus on Canada. We hope that this chapter will complement well with the two companion chapters in this volume, by Jose et al. (2004) and Garcia-Barrios and Ong (2004) that discuss interspecific interactions in temperate and tropical agroforestry systems respectively, in providing the ecological foundations for agroforestry in a wide range of conditions.

The results presented here are from a long-term tree-based intercropping research project that was initiated in 1987 on a 30-ha field at the University of Guelph Agroforestry Research Station, Ontario, Canada (43°32′28″ N latitude, 80°12′32″ W longitude). Ten tree species, namely *Acer saccharinum* (silver maple), *Corylus avellana* (hazelnut), *Fraxinus americana* (white ash), *Juglans nigra* (black walnut), *Picea abies* (Norway spruce), *Populus* sp. (poplar – hybrid), *Quercus rubra* (red oak), *Robinia pseudoacacia* (black locust), *Salix discolor* (willow) and *Thuja occidentalis* (white cedar) were planted and annually intercropped with maize (corn) (*Zea mays*), soybean (*Glycine max*), and winter wheat (*Triticum aestivum*) or barley (*Hordeum vulgare*). Tree rows were spaced at 12.5 m or 15 m apart with within-row spacing of 3 m or 6 m. The soil type is sandy loam (Typic Hapludalf). Crops were planted between the tree rows every year according to local 'standard' cultural practices.

Plant-to-plant interactions for growth resources

Interactions in agroforestry systems are defined as the effect of one component of the system on the performance of another component and/or the overall system (Nair 1993). The study of interactions requires the examination of a number of complex processes, including processes related to soil fertility, competition, microclimate, insect pests and diseases, soil conservation and allelopathy (Rao et al. 1998). Exploitation of positive interactions between the woody (tree) and nonwoody (agricultural or annual crop) components and the minimization of negative interactions is the key to the success of tree-based intercropping systems. This paper will therefore deal mainly with the identification and quantification of these interactions that could be used in designing management strategies that promote complementary interactions and reduce or eliminate the negative ones.

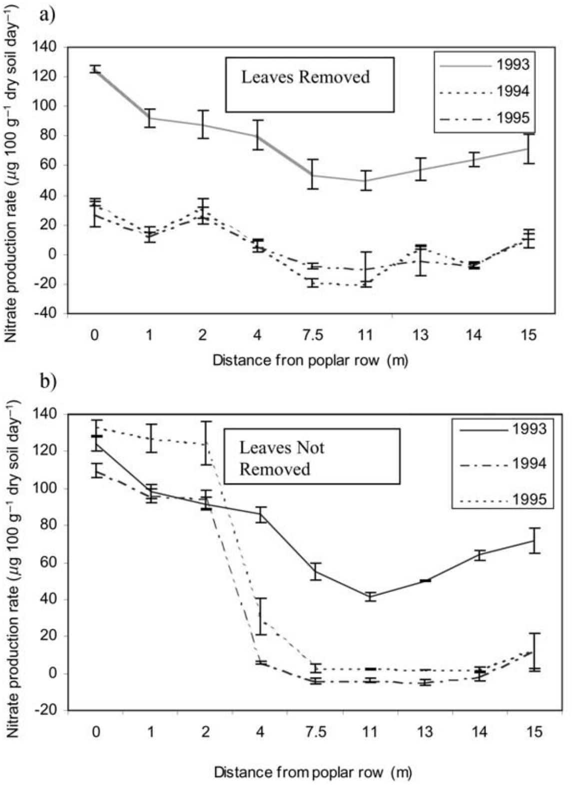

Figure 1. Effects of removing or retaining poplar-tree-leaf on soil N mineralization near the tree row (up to 2.5 m horizontal distance) in the tree-intercropping study during 1993–1995 in southern Ontario, Canada; (a) Leaves removed; (b) Leaves not removed. Source: Thevathasan (1998).

Soil carbon and nitrogen

The effects of litterfall distribution of poplar (hybrid clone DN 177; *Populus deltoides* x *Populus nigra* 177) on soil nitrogen (N) transformations and soil organic carbon (SOC) was studied from 1993 to 1995 and then again in 2002. The associated crop was barley; the poplar trees were 6 years old in 1993 (15 yr in 2002). In field experiment 1 (Figure 1a), poplar leaves were removed after leaf senescence in 1993 and 1994; in experiment 2 leaves were not removed (Figure 1b). Poplar litterfall distribution on the ground showed a distinct pattern, with almost 80% of the leaves falling within 2.5 m from the tree-row (Table 2).

Differing rates of poplar-leaf biomass input across the alleyways created distinct regions with respect to the accumulation of soil nitrogen and carbon. Based on the abundance of these resource pools, the intercropped alley can be divided into three zones: the area close to the poplar tree row (0 m to 2.5 m on either side of the tree row), the middle of the crop alley (2.5 m to 8.0 m from the tree-row), and the area furthest away from the tree-row (8.0 m to 15.0 m)[1]. Observed mean soil nitrate production in the aforementioned zones during June to August 1993 was 73.1, 41.0 and 34.0 μg 100 g^{-1} dry soil day^{-1} respectively (Figure 1a). The higher nitrate production rates in 1993 were due to the presence of 1992 fall-shed poplar leaves. In 1995, as a result of the removal of poplar leaves from the field for two consecutive years (1993 and 1994), nitrate production rates decreased to 17.6, −2.8 and −1.7 μg 100 g^{-1} dry soil day^{-1} in the same zones, respectively (Figure 1a). In experiment 2 (June to August 1995, leaves not removed), however, mean nitrate production in the same zones was 109.4, 15.4 and 5.7 μg 100 g^{-1} dry soil day^{-1}, respectively (Figure 1b).

Table 2. Poplar litterfall distribution in a poplar–barley intercropping system during the 1993 and 1994 growing seasons when trees were 6 and 7 years old respectively, Guelph, Ontario, Canada.

	Litterfall biomass (Mg ha^{-1} yr^{-1})	
Distance from the poplar tree row (m)	1993	1994
0–2.5	2.67 ± 0.04	2.76 ± 0.14
2.5–6.0	0.52 ± 0.05	0.61 ± 0.06

Source: Thevathasan and Gordon (1997).

There is much information available on tropical hedgerow intercropping systems where nutrient release occurs through the mineralization of recently added hedgerow prunings and root decay (Rao et al. 1998). In these systems, considerable labour input is required to bring about this desirable complementary interaction. In the temperate region, and especially with tree species that have the potential to produce high leaf biomass (e.g., hybrid poplar), no special effort is made for soil incorporation of leaf biomass. Nitrogen release from annual poplar litterfall at the University of Guelph Agroforestry Research Station has been estimated to be equivalent to 7 kg N ha^{-1} yr^{-1}. This implies that rates of inorganic N fertilizer rates in the poplar-based crop alleys could be reduced by this amount, which in turn can directly reduce input costs.

Soil organic carbon did not change significantly ($P > 0.05$) in the three indicated zones from 1993 to 1995 with recorded SOC zone means of 3.25%, 2.32% and 2.50% respectively (Figure 2). This was to be expected as only 15% to 35% of added organic residue is actually incorporated into the permanent organic pool (humus) (Brady and Weil 2002).

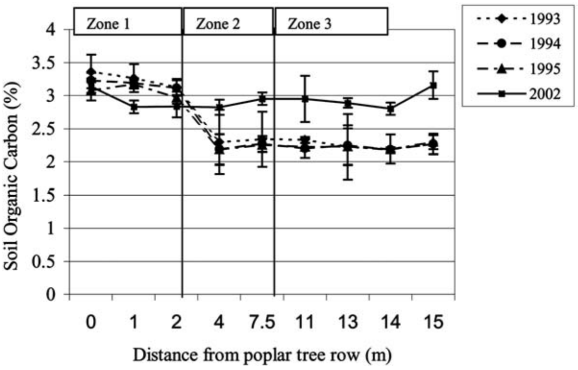

Figure 2. Soil organic carbon content at various distances from the poplar tree-row in 1993, 1994, 1995 and 2002, when the trees were 6, 7, 8 and 15 years old, in the tree-intercropping experiment in southern Ontario, Canada. Error bars that overlap indicate that associated values are not significant at $P < 0.05$. Source: Thevathasan and Gordon (1997).

The high rate of poplar leaf biomass addition (1 Mg C ha^{-1} yr^{-1}) over the total period of 8 years resulted, however, in an increase of SOC of approximately 1% close to the tree-row, and this effect extended into the alley for up to approximately 4 m. This is about a 35% relative increase (percentage difference between 3.25 and the mean of 2.32 and 2.50) in SOC close to the tree-rows over the given period of time, and reflects leaf biomass inputs in the early 1990s, when trees were small and the major portion of litterfall was distributed close to the tree row (2 to 3 m) (Table 2). By 2002, poplar trees were 14 m tall and leaf biomass was evenly distributed across the crop alley up to distances of 15 m. This resulted in a slow but inexorable increase in soil C in the middle of the crop alley, as illustrated in Figure 2.

It appears that the addition of poplar leaves significantly ($P < 0.05$) affected nitrate production rates, especially in regions close to the tree row and in the middle of the crop alley. It also appears that the major portion of nitrate was released from the labile organic pool (recently added poplar leaf biomass) rather than from the recalcitrant organic pool, since the removal of poplar leaves from the field did not significantly change the soil organic carbon pool over the three-year period (Thevathasan and Gordon 1997).

Zhang (1999)[2] has shown that trees can significantly influence nutrient additions to associated crops through throughfall (rainwater falling through tree canopies) and stemflow (rainwater falling down the branches and stems). Hybrid poplar and silver maple contributed 10.99 and 15.22 kg N ha^{-1} yr^{-1} respectively, through these combined pathways. The addition of N and other nutrients through these pathways could potentially reduce nutrient deficiencies that might arise because of tree–crop competition close to tree rows.

The build-up of SOC under tree canopies in tropical hedgerow intercropping systems and the positive influence of this on many soil physical, chemical and biological properties has been well reported (Nair 1993; Young 1997; Rao et al. 1998). Even though indirect results obtained at Guelph (e.g., increases in SOC, nitrate mineralization from fall-shed poplar leaves, and enhanced earthworm populations) indicate that the above-mentioned soil parameters are likely to have been positively influenced, no empirical data for temperate systems currently exist. Given the results obtained from tropical systems (Rao et al. 1998) and the complementary interactions that have been observed in temperate tree/crop intercropping systems (Table 1), we suggest that the adoption of tree/crop intercropping systems may ameliorate components of the degraded temperate land-base that have come about as a result of poor farming practices.

Light

The effects of shading by poplar and silver maple on the productivity of intercropped maize (C4 plant) and soybean (C3 plant) were studied during the 1997 and 1998 growing seasons, when the trees were 10 and 11 years old (Simpson 1999[3]). Generally, tree competition reduced the growth of individual plants significantly up to 2 m and often to a moderate degree up to 6 m from the tree rows in comparison with those in the control treatment (Table 3). Daily rates of C assimilation were generally lower near the trees where competition for photosyntheticallyactive radiation (PAR) was the greatest, resulting in lower crop yields. Growth characteristics (height, leaf area, weight) of individual plants were significantly correlated with available PAR (r = 0.87 for soybeans; r = 0.87 to 0.95 for maize) and net assimilation (r = 0.73 to 0.83 for soybeans and r = 0.92 to 0.96 for maize), but not significantly correlated (r = 0.02 to 0.16) with midday water potential. It was concluded that competition for light, and not water, within 6 m of the tree rows was the main factor that detrimentally affected maize and soybean yields (Simpson 1999[3]). Pooled observations from all the treatments of this study revealed that all ten tree species detrimentally affected the yields of C4 plants more than those of C3 plants. Based on this observation, it seems prudent to

Table 3. Growth of soybeans and maize in sole cropping and intercropping with 10-year-old poplar or maple at Guelph, Ontario, Canada.

Crop	Parameter	Control (sole cropping)		Intercropping with poplar		Intercropping with maple	
		2 m	6 m	2 m	6 m	2 m	6 m
Soybean	Height (cm)	75.6a	82.7a	45.6b	67.5a	44.4b	69.4a
	Leaf area (cm^2 plant^{-1})	796.2b	1070.1a	317.4b	630.8a	247.1b	766.3a
Maize	Height (cm)	196.0b	209.3a	103.8b	177.2a	126.2b	198.8a
	Leaf area (cm^2 plant^{-1})	5386.9a	5389.3a	3769.2b	5026.5a	3758.5b	5302.0a

By parameter and similar treatment, values in each row followed by the same letter are not significantly different (Tukey's HSD, $P > 0.05$). Source: Simpson (1993)[3].

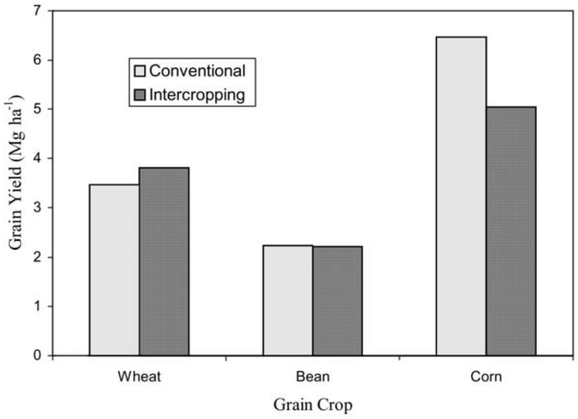

Figure 3. Overall yields of intercropped grain crops in 1999 across 10 tree species when the trees were 12 years old compared with yields obtained from an adjacent conventional sole crop field at Guelph, Ontario, Canada.

recommend alternative management strategies such as pruning and crown thinning of tree canopies to reduce shading impacts from tree rows and to ensure acceptable economic yields in the zone closest to the tree row.

We have documented (on average) a 20% to 25% yield reduction per unit land area for maize when compared to the yield recorded in conventional system from an adjacent field (control). Yields of C3 crops such as soybean and wheat were higher in intercropping or generally on par with yields in the conventional system, especially under dry weather conditions. In the former scenario, effects of microclimate modification by trees in terms of lowered crop evapotranspiration rates and reduced soil temperatures might have helped to enhance yields in the intercropping system (William and Gordon 1995; Zhang 1999[2]).

Results reported on competition for light, or shade effect, in tropical hedgerow systems have been varied. The factors governing the shade effect on crops grown in the alleys are reported to be climate, management, soils, tree, and crop species (Nair 1993; Ong and Huxley 1996). The hedgerows generally had no shading effect on crop yields when the alley spacing exceeded 4 m in humid tropics (Rao et al. 1998). Even at wider spacings, however, tree shade is reported to have negatively impacted C_4 crops such as maize more than C_3 crops such as beans (*Phaseolus* sp.) (Rao et al. 1998). A similar trend on the effect of tree shade on crop yields has been observed in the intercropping trials at the University of Guelph irrespective of row spacing (12.5 m or 15 m) (Figure 3).

Water

The site receives a total of 833 mm of precipitation per year out of which 334 mm falls during the 105-day crop-growing season (Simpson 1999)[3]. During the first three to five years after planting of trees, soil water content under the associated wheat declined rapidly to a depth of 60 cm until harvest in early August. This period also corresponds to the critical growth phase of young trees when demand for water is high. At that stage, roots of the young trees exploit a relatively small and shallow soil zone. The early demand for water by the winter wheat crop detrimentally affected the growth and development of young trees. When maize was grown in association with the trees, a temporal change in water demand was observed: water demand for maize was low early in the season and hence young trees experienced little competition for water. This positively influenced the height growth of trees in association with maize (Williams and Gordon 1995). An extensive survey of the rooting habits of hybrid poplar trees (Figure 4), indicated, however, that 15 year-old trees competed less for surface water because of penetration of roots into deeper soil horizons (Gray 2000)[4].

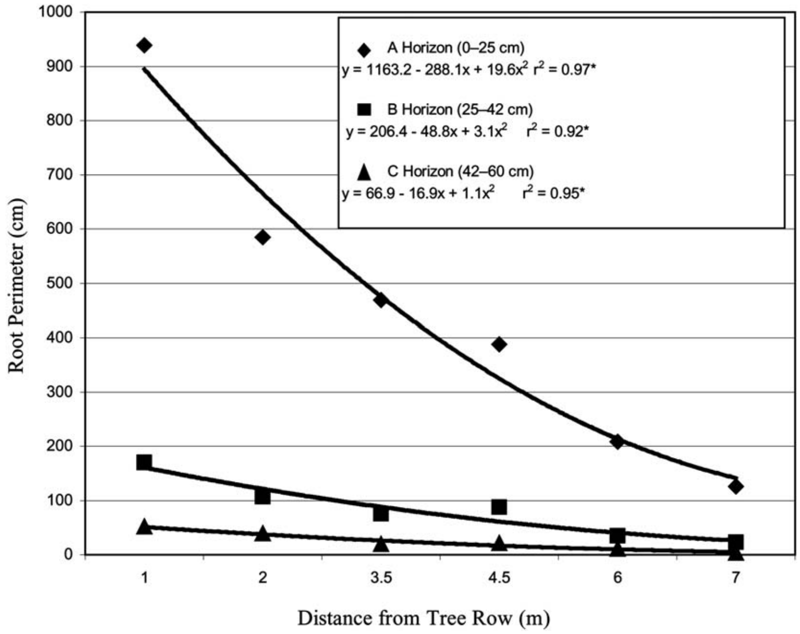

Figure 4. Mean root perimeter at various horizontal distances from a row of 12-year-old poplar trees at different soil horizons, Guelph, Ontario, Canada. Source: Gray (2000)[4].

Biological interactions

Soil fauna

Earthworm population dynamics in soil was also studied at the above research site in 1997 and 1998 (Price and Gordon 1999). Tree species played an important role in determining the spatial and temporal distribution of earthworms within the intercropping system (Table 4). Earthworm densities were greatest next to poplar and white ash tree-rows, possibly due to greater litter contributions. Although earthworm numbers decreased during the summer period, their populations in agroforestry system were still significantly greater than those from a comparable conventionally cropped field.

Earthworm activity in the soil profile has been proven to be beneficial for soil structure and stability (Lawton 1994; Edwards and Lofty 1977). A wide range of benefits is attributed to earthworms; these include decreased soil bulk density, increased decomposition of soil organic matter, and improved soil stability in cropped fields (Scheu 1995; Edwards and Bohlen 1997; Edwards and Lofty 1977). Strong correlations between higher soil organic matter levels within poplar (*Populus trichocarpa*) rows and earthworm activity have been established (Park et al. 1994). Enhanced decomposition of soil organic matter and nutrient release as influenced by earthworms have also been reported in tropical agroforestry systems (Tian 1992). The most important role played by earthworms is, however, in the comminution and mixing of organic matter within the soil. The ingestion and subsequent excretion of organic matter by earthworms throughout the soil profile, and on surface as casts, are important processes in the transformation of mineral nutrients into forms available for uptake by plant roots (Tian 1992). This process is positively correlated with soil organic matter levels and earthworms are believed to significantly contribute to soil chemical processes such as cation exchange capacity (CEC) (Brady and Weil 2001)

Birds

Williams et al. (1995) investigated the extent to which birds ‘used’ or visited an intercropped maize field, a conventional maize field and an old-field site. The old-field site had various tall grasses and weeds including goldenrods (*Solidago* spp.), asters (*Aster* spp.) and milkweed (*Asclepias* spp.). Only one species of bird nested in the maize field, but 10 species foraged in the intercropped plots compared to four species in the maize field and six in the old-field site (Table 5). The study revealed that intercropping provided opportunities for birds to nest and forage that were not

Table 4. Mean biomass and populations of earthworms in intercropping and sole maize measured in 1998 when the trees were 11 years old at Guelph, Ontario, Canada.

	Earthworm population (No. m^{-2})				Earthworm Biomass (g m^{-2})			
	Poplar	Maple	Ash	Maize	Poplar	Maple	Ash	Maize
1997								
Spring	394 a(a)	257 a(b)	379 a(a)	11 a(c)	457 a(a)	440 a(a)	735 a(b)	6.07 a(c)
Summer	119 b(a)	42 b(b)	61 b(b)	4 a(c)	245 b(a)	89 b(b)	153 b(b)	4.54 a(c)
Fall	257 c(a)	196 c(a)	268 c(a)	30 b(b)	345 c(ab)	263 a(b)	437 c(a)	45.96 b(c)
1998								
Spring	90 b(a)	63 b(a)	46 b(a)	3 a(b)	181 b(a)	144 b(a)	161 b(a)	3.12 a(b)

Values followed by the same letter within a column are not significantly different (LSD, $P > 0.05$).
Values followed by the same letter across a row, within brackets, are not significantly different (LSD, $P > 0.05$).
Source: Price (1999)[7].

available in the monocropped maize field. The diversity of the breeding population in the intercropped field approached that found in the nearby old-field site, although some of the species were different. The intercropped field also provided foraging opportunities for other species whose diversity and numbers clearly demonstrated the value of the site to local and migrating bird populations. The direct impact of the increased presence of birds on alley-crop yields appeared to be neutral although there was no actual study conducted on this (cf., Figure 3). It can be speculated, however, that birds can reduce insect pest populations as they feed on them. Research in this area is lacking in the temperate region.

Insect pests

Studies on arthropod abundance and diversity in the study site showed that taxons such as the Opiliones, Dermaptera and Carabidae, which are associated with organic litter and areas that provide shelter during the day, were significantly higher in the intercropped system than in the monoculture system. Significantly higher numbers of parasitoids and detritivores were also recorded in the intercropped system compared to the monoculture system; the intercropped treatment also supported a significantly higher ratio of parasitoids to herbivores (Figure 5). We surmise that trees grown with crops such as maize may improve insect pest management options by providing habitat that will foster populations of natural enemies (Middleton 2001)[5]. More specific research on these aspects is required for many temperate regions.

Interactions affecting the environment

Carbon sequestration and greenhouse gases

The potential of agroforestry systems to sequester carbon is examined in a companion chapter in this volume (Montagnini and Nair 2004). Additionally, tree-based intercropping systems can reduce emissions of greenhouse gases (GHG) such as nitrogen oxides (NO_x), and therefore, may potentially have a significant impact on climate change mitigation. Thirteen-year-old poplar trees were sampled in this study (Table 6). During the 13-year duration of the study, the permanent tree component of the intercropping system (hybrid poplar clone DN-177) sequestered 14 Mg C ha^{-1}; C contribution to soil from leaf litter and fine root turnover was estimated at 25 Mg ha^{-1}; thus the total C sequestration was approximately 39 Mg C ha^{-1} during the 13-year period. This amounts to the immobilization of 156 Mg ha^{-1} of CO_2 in 13 years. About 70% of the C added via leaf litter and fine roots will, however, be released back into the atmosphere through microbial decomposition processes. Hence, the net sequestration potential of trees alone is 1.65 Mg C ha^{-1} yr^{-1} or approximately 7 Mg ha^{-1} yr^{-1} of CO_2. It is also interesting to note that based on the known growth rate of this particular hybrid poplar clone, it is estimated that more than 43 Mg ha^{-1} of C will be sequestered by age 40.

Impact of tree-based intercropping systems on C sequestration in woody components and in soil

The above studies illustrate the extent to which trees that are introduced into agricultural fields can contribute to enhanced C sequestration in the system.

Table 5. Number of birds observed foraging in intercropped, maize-only, and old field plots at Guelph, Ontario, Canada.

Bird species	Intercrop	Maize field	Old field
Song Sparrow (*Melospiza melodia*)	0	0	12
Eastern Kingbird (*Tyrannus tyrannus*)	0	0	6
Tree Swallow (*Tachycineta biocolor*)	12	2	2
Red-winged Blackbird (*Arelaius phoeniceus*)	2	0	17
Savannah Sparrow (*Passerculus sandwichensis*)	20	0	15
Horned Lark (*Eromphila alpestris*)	2	2	0
Eastern Meadowlark (*Sturnella neglecta*)	0	0	2
Eastern Bluebird (*Sialia sialis*)	8	0	0
American Robin (*Turdus migratorius*)	2	1	0
Kildeer (*Charadrius vociferus*)	4	1	0
American Goldfinch (*Carduelis tristis*)	12	0	0
Indigo Bunting (*Passerina cyanea*)	3	0	0
European Starling (*Sturnus vulgaris*)	16	0	0
Total Species	10	4	6

Source: Williams et al. (1995).

Table 6. Carbon content of different components of a 13-year-old poplar tree in tree–crop-intercropping system at Guelph, Ontario, Canada[a].

Tree component	Carbon content per tree (kg)
Leaves	11.7 ± 3.5
Twigs	6.3 ± 2.3
Small branches	15.0 ± 6.2
Large branches	28.0 ± 17.3
Trunk	54.3 ± 33.5
Roots	19.7 ± 1.5
Total	135.0 ± 15.73

[a] Data are reported on per tree basis, as planting densities vary considerably in temperate intercropping scenarios (average tree density used at the University of Guelph Agroforestry Research Station, Ontario, Canada is 111 trees ha^{-1}).

The possible scenarios could be summarized as follows. 1) In a maize monocropped field, annual net C input to the soil is in the range of 400 to 600 kg ha^{-1} yr^{-1} as compared to annual net C inputs as high as 2400 kg ha^{-1} C yr^{-1} in a tree-based intercropping system. 2) Tree-based intercropping systems can potentially be adopted in agricultural land classes from 1 through 4. Therefore, the land base in Canada that could be brought under tree-based intercropping is estimated at more than 45.5 million hectares; if intercropped, this would have a significant effect on C sequestration and GHG emission reduction. 3) The tree component in intercropping occupies a part of the land area and proportionately reduces the area under annual crop and consequently the need for supplemental nitrogen for crop production. 4) The decrease in nitrogen moving out of the rooting zone will lead to reduced NO_x emissions as a result of denitrification in surface water resources. 5) If the tree species are deciduous, annual litterfall will cycle some nitrogen back to the soil reserve. While this nitrogen is localized to the area close to the tree, it does constitute a quantifiable contribution to the agricultural crop. Reduced application rates of inorganic N can result in reduced environmental losses. Apart from reduction in GHG emissions, C sequestration in agricultural fields can also be augmented through this type of land-use practice, since annual leaf litter input and fine root turnover can significantly influence long-term soil organic C dynamics.

The Canadian national target of a 20% reduction in GHG emissions could be achieved if at least 200 kg C ha^{-1} is sequestered annually over the next 10 to 15 years on the aforementioned 45.5 million hectares of cropped land in Canada. Thus, the adoption of tree-based intercropping systems in geographically suitable regions of Canada could not only diversify farm income, bring about changes in biodiversity, and enhance other environmental benefits, but could also contribute towards fulfilling the national requirements of the Kyoto Protocol (Thevathasan 1998).

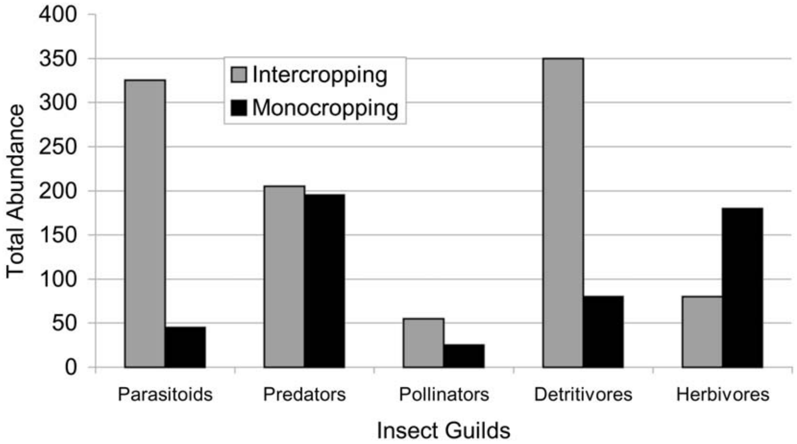

Figure 5. Total arthropod abundance in June samples (1999) in the tree-intercropped plots (12-year-old trees) and sole crop sites, Guelph, Ontario, Canada. Source: Middleton (2001)[5].

Impact of tree-based intercropping systems on reducing nitrous oxide (N_2O) emission

Tree-based intercropping systems alter the nitrogen balance compared to conventional agricultural systems in the following ways: (1) There is less N fertilizer addition as a result of reduction in the area under annual crop due to tree occupation (10%) (Table 7); (2) the decomposition of leaf litter (in both deciduous and coniferous tree species) in the litterfall zone can supply some nitrogen to the agricultural crop (Thevathasan 1998). However, it requires special agricultural management to vary the rate of nitrogen application within this zone of enhanced nitrogen cycling (e.g. Variable Rate Technology). About 1.25% of applied fertilizer N is lost as N_2O (Cole et al.1996) (Table 7). (3) In agricultural production areas with high rainfall, a portion of the applied nitrogen is lost through leaching below the rooting zone of the agricultural crops. In fact, the Intergovernmental Panel on Climate Change (IPCC) methodology estimates a 30% loss from this source.

Modeled data from our research site indicates that nitrate leaving the intercropping site can be potentially reduced by 50% compared with a conventional monocropped field (Thevathasan 1998). A portion of the nitrate leached below the agricultural rooting zone will also be denitrified and lost as N_2O. Oenema (1999), for example, estimates that 2.5% of the leached N is lost as N_2O. Based on the above assumption and from the modeled data it can be assumed that, as a result of reduced leaching, N_2O emissions in tree-based intercropping systems could be potentially reduced by 0.69 kg N_2O ha^{-1} relative to emissions from conventional agricultural fields (Table 7). In order to meet the terms of reference of the Kyoto Protocol, N_2O emissions from Ontario agricultural fields need to be reduced by approximately 2 kg N_2O ha^{-1} over the next 10 years (2008–2012 first reporting period). In this context, our research suggests that tree-based intercropping systems could potentially reduce N_2O emissions by 0.69 N_2O kg ha^{-1} yr^{-1}, 7 to 9 years after establishment of a fast-growing fibre tree species-based intercropping system in southern Ontario. As trees age and N-inputs in litterfall increase, N_2O emissions could be further reduced.

Conclusions and lessons learned

Among the various environment-friendly agricultural practices currently under consideration in southern Ontario and other parts of the temperate region, tree-based intercropping systems seem to be a viable option. The ameliorative effects of trees in terms of soil fertility, productivity and nutrient cycling can be exploited through tree-based intercropping systems on both marginal and prime agricultural lands. The success of intercropping depends mainly on the ability of the system components to maximize resource utilization while at the same time maintaining ‘complementary’ interactions between them.

The complexity of agroforestry systems often results in constant changes in spatial patterns, as tree growth proceeds in both horizontal and vertical dimensions. As the temporal dimensions of the system keep changing, the patterns of interaction are also likely to change. Therefore, the beneficial interactions ob-

Table 7. The potential for annual N_2O-N reduction, eight years after establishment of trees, based on a hypothetical N cycling budget developed for a fast-growing hybrid poplar-based intercropping system, Guelph, Ontario, Canada.

Causes of N_2O reduction	N fertilizer saved (kg ha^{-1})	N_2O emission reduction (N_2O-N kg ha^{-1})
10% less land area	8[a]	0.1[b]
N cycling in tree-based intercropping	7	0.09[c]
Reduction in N leaching	20	0.5[d]
Total N_2O reduction potential		0.69

(Source: Thevathasan and Gordon, personal communication, 2003).

[a] maize, bean, wheat rotation, average annual N fertilizer application = 80 kg ha^{-1}.

[b] $8 \times 0.0125 = 0.1$ (1.25% of the applied fertilizer N is lost as N_2O).

[c] $7 \times 0.0125 = 0.09$.

[d] $20 \times 0.025 = 0.5$ (2.5% of the leached N is lost as N_2O).

served in this study may also change over time as tree canopies become larger and/or when lateral tree roots further extend into the rooting zone of the cropping alley. This may result in many competitive interactions with respect to light, water and nutrients. The ameliorative effects of poplar may also get masked as a result of these possible competitive interactions. When competitive interactions are observed, however, alternative management strategies may be considered so that competitive interactions between components are delayed, reduced, or completely eliminated from the system. Agroforestry research in the tropics has shown that the proper selection of system components and adoption of proper management techniques are the two most important steps that should be considered while designing agroforestry systems to reduce or avoid competitive interactions among components (see, for example, Rao et al. 1998; Garcia-Barrios and Ong 2004).

Several alternative management strategies could be considered for poplar-based intercropping systems in southern Ontario to maintain the viability and sustainability of these systems. These strategies can also be applied to other parts of temperate regions. The effectiveness of any alternative management strategy requires, however, testing in the field on a long-term basis and to be scientifically proven before any recommendations are made. The following alternative management strategies are suggested as worthy of future research:

1. Planting of fast growing tree species such as poplar in concert with hardwood tree species in alternate rows. This will also reduce shading effects and delay crown closure. More knowledge (research) is also needed on the effects of shading on crop productivity. Closure of stomata during noon or early afternoon hours is an adaptive mechanism that plants often exhibit to overcome temporary water stress. When stomata are temporarily closed, photosynthesis does not proceed and hence shading during this time might have little effect on crop productivity. This area needs more research.
2. Pruning lateral roots of trees: Root competition can be significantly reduced if tree roots and crop roots utilize nutrients and water from different layers of the soil profile. This can be achieved by pruning tree lateral roots (if any) in the first 20 cm to 30 cm of the soil profile. Research on competition brought about by tree shading versus tree root competition is also required.
3. Continuous monitoring of root distribution of intercropped trees: This will yield a better understanding with respect to tree root pruning practices, although, as usual, there are technical research challenges associated with below-ground processes.
4. Evaluation of short-term as well as long-term costs and benefits: Various types of tree-intercropping strategies may help maintain the system economically profitable; more research is needed in this area as well.

In conclusion, on a biological level, the increased range of faunal activity is a clear indication of ecosystem ‘health’ within an intercropping system relative to that associated with conventional agricultural practices. From an ecological perspective, intercropping systems trap larger amounts of energy at different trophic levels, demonstrating higher energy utilization efficiency. In relation to carbon sequestration and greenhouse gas (e.g., N_2O) emission reductions, tree-based cropping systems have the potential to contribute greatly to climate change mitigation. The tangible benefits that are derived from the above described eco-biological processes, along with combined yields obtained from the trees and crops, place this land-use practice above conventional agricultural systems in terms of long term overall productivity. The economics of tree-based intercropping systems need to be examined in more detail, however. Investigation into policy measures, and/or tax incentives and cost-share programs should be initiated in order to increase adoption rates of the practice in southern Ontario in particular and other potential regions in general.

As we step into the next millennium, a change is warranted in current agricultural practices and land use options so that priority is given to the stewardship of soil and water resources. The results from our intercropping research in southern Ontario have shown much promise in this regard. The long-term viability and sustainability of tree-based intercropping systems in the temperate region needs to be examined, however, before recommendations on the use of these systems can be made to the farmers.

End Notes

1. The experiments were designed with the poplar tree row as the middle row; the two adjacent tree rows did not have any poplar trees, but did have small white ash and black walnut trees. These trees were less than 2 m high at age 6 and did not contribute any sizable quantity of leaf biomass (Thevathasan and Gordon 1997).
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