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Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada

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ABSTRACT

In 1987, the University of Guelph established a large tree-based intercropping system on 30 ha of prime agricultural land in southern Ontario, Canada. The purpose was to investigate various aspects of intercropping trees with prime agricultural crops. In this study, objectives were to investigate tree competitive effects (i.e., shading and competition for soil moisture) on under-story crop net assimilation (NA), growth, and yield. The effects of tree competition on corn (C4 plant) and soybean (C3 plant) photosynthesis and productivity in the intercropped system were studied during the 1997 and 1998 growing seasons. Corn and soybeans were intercropped with hybrid poplar (*clone-DN-177*) and silver maple (*Acer sacharrinum*) at a within-row spacing of 6 m and between-row spacing of 12.5 or 15 m. Trees were absent from control rows. Tree rows were oriented approximately north and south. Twelve crop locations were sampled around each tree. These were at 2 and 6 m east and west of the tree, located along a primary axis running through the tree trunk and perpendicular to the tree row, and at 2 m north and south of each location along the primary axis. Net assimilation and plant water deficit measurements were made three times daily (morning, noon, afternoon) on sampling days in July. Generally, tree competition significantly reduced photosynthetic radiation (PAR), net assimilation (NA), and growth and yield of individual soybean or corn plants growing nearer (2 m) to tree rows in both years and soil moisture in 1998. NA was highly correlated with growth and yield of both crops. These correlations were higher for corn than soybeans in both years, with corn, rather than soybeans being more adversely impacted by tree shading. In 1997, poplar, rather than maple, had the greatest competitive effect on NA. In 1997, the lowest plant water deficits, for soybeans and for corn, were observed for the maple treatment. Nonetheless, in both years, daily plant water deficits were non-significantly and poorly correlated with NA and growth and yield of both crops. However, soil moisture (5 and 15 cm depth) was significantly correlated with soybeans yield in 1998. Possible remediation strategies are discussed to reduce tree competitive interactions on agricultural crops.

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1. Introduction

Agroforestry can be defined 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" (Thevathasan et al., 2004; Gordon and Newman, 1997). Traditionally, agroforestry has had its origins in developing nations where high population densities coupled with scarce land resources have required that concurrent food and wood production often occur on the same land base. In North America, where population densities are often low and arable land resources frequently vast, the potential benefits of agroforestry practices are yet to be realized (Gordon et al., 1997). Agroforestry practices that are currently being researched in North America include shelterbelts, windbreaks, silvopastoral systems, forest farming systems, integrated riparian forest systems, and tree-based intercropping systems—also known as alley cropping (Thevathasan et al., 2004; Gordon and Newman, 1997; Garrett et al., 2000).

A properly designed and managed tree-based intercropping system can create a dynamic agroecosystem resulting in increased and diversified farm income (Dyack et al., 1999), enhanced wildlife habitat, reduced soil erosion, and lower nutrient loading to waterways (Williams et al., 1997). Furthermore, tree-based intercropping systems can result in more diversified economies for both short- and long-term products and provide a market for both agronomic and forest crops (e.g., corn, wheat, soybeans, cereals, Christmas trees, nut crops, e.g., walnuts, etc.). Intercropping systems can also play a vital role in sequestering carbon (C) within below- and above-ground plant components, thereby addressing present and critical societal concerns about global climate change (Brandle et al., 1992; Kort and Turnock, 1999; Schroeder, 1993; Thevathasan et al., 2004; Unruh et al., 1993).

With these potential benefits of tree-based intercropping systems in mind, a number of interactions within agroforestry systems can arise that may be neutral, beneficial, or potentially detrimental (Ong, 1996). To maximize the potential benefits of tree-based intercropping systems, competitive interactions need to be avoided in order to properly design and manage intercropping systems (Thevathasan et al., 2004; Nair, 1993). In an earlier review of biophysical interactions in tropical agroforestry systems, Rao et al. (1998) advocated that studies of interactions in agroforestry systems necessitates the evaluation of several complex processes, including those related to soil conservation, soil fertility, allelopathy, pests and diseases, plant competition (i.e., for light, water, and nutrients), and microclimatic modifications. According to Thevathasan et al. (2004), successful tree-based intercropping systems will minimize competititve interactions between non-woody (annual agricultural crop) and woody (tree) components while exploiting beneficial interactions between these components. Increasing our understanding of these interactions will provide a scientific basis for both improvement and adoption of tree-based intercropping systems.

Investigations over the past 10 years of a tree-based intercropping system in southern Ontario have revealed several beneficial (complementary) biophysical interactions for this temperate agroforestry system (Thevathasan et al., 2004). These include improved nutrient inputs, reduced greenhouse gas (GHG) emissions, greater carbon (C) sequestration, and enhanced species biodiversity. It is not feasible to explain all the beneficial interactions observed in southern Ontario studies in this paper. However, the reader is encouraged to refer to the paper by Thevathasan et al. (2004) for a detailed review.

This contribution will deal mainly with plant competition related interactions for these tree-based intercropped systems. Thevathasan et al. (2004) state "tree-influenced microclimatic modifications may act in such a way as to increase the overall productivity of the associated agricultural crop". However, they also acknowledge that in certain tree–crop combinations, the trees chosen may adversely affect availability of soil water, available light for crop photosynthesis, and available nutrients for use by the adjoining agricultural crop. This paper examines differing tree–crop combinations, provides advise on which are best for maximizing crop yields, and offers possible solutions where yields of agricultural crops are impaired in temperate tree-based intercropping systems, as primarily influenced by tree shading.

In this study, the agricultural crops chosen were corn (*Zea mays* L.), a shade intolerant C4 species, and soybeans (*Glycine max* L. Merr.), a shade tolerant C3 species. The two selected tree species, chosen to compare their shading effects on corn and soybeans, were hybrid poplar and silver maple. Hybrid poplars are tall and elliptical (columnar), and only moderately dense with few interior leaves relative to other tree species used at the site. Therefore, a significant amount of light was expected to penetrate through the canopy to the under-story crop, and the elliptical symmetry of the canopy was thought to block less sunlight penetration to the under-story. This *Euramericana* type hybrid (*Populus deltoids x nigra* DN177) is also characterized with strong lateral roots near the surface with secondary roots plunging vertically (Demerritt, 1990), thereby potentially reducing plant water competition with the intercropped agricultural crop. Silver maple (*Acer sacharrinum* L.), by contrast, has a shorter, broad dense crown with many interior leaves, which allow very little light to pass directly through the canopy. This canopy architecture was expected to provide maximum interception of sunlight, and to result in maximum shading of the under-story agricultural crop. Silver maple is also characterized by a shallow, fibrous root system (Gabriel, 1990), which was thought to potentially compete with under-story agricultural crops for water resources.

Therefore, the two major objectives of this study were as previously stated by Simpson (1999). First, "provided that the shading does not limit the light levels beyond the threshold of light saturation, no reduction in net assimilation should occur". "Second, if direct competition for soil moisture is limiting to growth and yield of the under-story crop, empirical measurements of plant water use should indicate differences based on relative location and proximity to the tree".

2. Experimental

2.1. Site description

The Agroforestry Research Station (ARS) is located on a 30 ha parcel of prime agricultural land within the city limits of

Guelph, Ontario (Wellington County, Ontario, 43°32′28″N longitude, 80°12′32″W latitude). In 1988, a long-term tree-based intercropping research experiment was initiated at the University of Guelph ARS by planting different hardwood (genera *Juglans*, *Quercus*, *Fraxinus*, *Acer*, and *Populus*) and coniferous (genera *Picea*, *Thuja*, and *Pinus*) trees species that were annually intercropped with corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), winter wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.). The various agricultural crops are grown in rotation between tree rows. All agricultural crops are planted using a no–till planter.

The landform is a drumlin oriented approximately north/south with the lowest point approximately 334 m above sea level. Tree rows were oriented along the long axis (N–S) of the drumlin, and on the west side of the drumlin, with each species planted in groups of eight with two within row tree spacing (3 m or 6 m) distances. Tree rows were either 12.5 or 15 m apart, and initially approximately 1 m in width (i.e., 8.0 or 6.7% of the available land area). In 1997, larger tree crowns approximately doubled the width of the tree rows or fallow strips from what they were in 1988. In 1997, the canopies of most trees were relatively uniform within each species, and only a few trees had begun to overlap.

The soil is from the Guelph Loam series and the texture ranges from silt loam to loam (Order: Alfisols, group: Typic Hapludalf; Thevathasan et al., 2004). Drainage is naturally imperfect to moderately well drained, although, much of the site is now tile drained.

Climate at the site was variable during the 2-year period (1997–1998) when this study was conducted. Despite year-to-year temperature and precipitation variations, the average frost-free period is 136 days (May 15–September 28), and constant. On average, annual precipitation averages 833 mm and approximately 334 mm falls during the growing season. The mean annual corn heat units received are 2740.

2.2. *Site location within the ARS and sample location*

Trees and crops for this experiment were selected as previously discussed. Allowing for annual crop rotations of annual agricultural plants, the best available areas for the various combinations (i.e., poplar–soybeans, poplar–corn, maple–soybeans, and maple–corn) were selected at the start of the 1997 and 1998 growing seasons. In addition, control areas were selected for measurements within the ARS where tree plantings within the rows had failed, and no trees existed. These represent a reasonable estimate of productivity and crop response within a mono-crop management system.

The characteristics of selected poplar and silver maple trees intercropped with soybeans and maize in 1997 and 1998 varied (Table 1). In general, the poplars were taller and had larger stem diameter than the maples. Crown dimensions also differed for the two species, with crown depths of poplar being greater than those for maple. Crowns also began closer to the ground for the maples. Crown widths were similar.

Twelve sample locations around each tree at plot center were selected. The tree rows were oriented approximately north/south. Twelve locations around the tree, at 2 and 6 m east and west of the tree (primary axis perpendicular to the tree row) and at 2 m north and south of each location of the primary axis, were identified as sampling points. At each time of sampling, a single leaf from the upper crop canopy was selected within a 0.5 m radius of the identified sample point.

Table 1 – Characteristics of trees intercropped with soybeans or corn in 1997 and 1998 at the University of Guelph Agroforestry Research Site (ARS)

Measurement	Poplar		Maple	
	1997	1998	1997	1998
Soybeans				
Tree height (m)	12.1	11.1	7.6	8.5
DBH (cm)	22.3	21.5	15.6	17.6
Depth of live crown (m)	9.9	8.9	5.1	6.0
Mean radius of crown (m)	3.1	2.1	3.2	3.0
Maize				
Tree height (m)	12.3	13.3	10.1	7.8
DBH (cm)	25.3	24.7	15.5	17.6
Depth of live crown (m)	10.0	10.9	8.0	5.9
Mean radius of crown (m)	2.9	2.7	2.7	3.2

Adapted from Simpson (1999).

2.3. *Net assimilation (NA) measurements*

Gas exchange, using the LiCor 6200 Portable Photosynthesis Unit (LiCor, Lincoln, Nebraska), was measured on a fixed area of a single leaf from the upper canopy of the crop using a l Liter (L) chamber. Measurements were repeated at three locations at each distance from the tree row (2 and 6 m from the tree in both the east and west direction) three times daily, in the morning (before noon, 09:00–11:00 h), at midday (12:00–14:00 h), and afternoon (after 15:00 h). During each measurement period, all three treatments (poplar, maple, control) were visited. These treatments for soybeans were measured on July 29, and for corn on July 30 in 1997 and again on July 15 for soybeans and July 18 for corn in 1998. Sampling of both crops on the same day was not feasible. Fortunately, all sample dates were near identical days, with similar temperatures, relative humidity, and partly cloudy sky conditions.

The LiCor 6200 simultaneously measures a number of environmental variables, including photosynthetically active radiation (PAR). Using these measured variables, estimates of the rates of photosynthesis (i.e., net assimilation: NA) and other gas exchange parameters are calculated. These are then corrected for the specified leaf area exposed in the measurement chamber.

2.4. *Soil moisture and plant water deficit*

Soil moisture content was determined gravimetrically at two depths, for all sample locations, at two depths, 5 and 15 cm on July 17, 1998. No intervening rain occurred between July 15 and July 18. No soil moisture measurements were made in 1997.

In both years, a single leaf from each plant was excised (AM, Noon, PM), and stored in a polyethylene bag, with a piece of damp paper towel, and the bag stored in a chilled cooler. Samples were analyzed for plant water deficit using a Plant Water Console (Soil Moisture Corporation, Santa Barbara, CA)

Table 2 – Treatment differences (control, poplar, maple) for soybean or maize intercrops: July 1997 and July 1998

Parameter ($N=4$)	Soybeans			Maize		
	Control	Poplar	Maple	Control	Poplar	Maple
1997						
Photosynthetically active radiation ($\mu mol\, s^{-1}\, m^{-2}$)	1525.0 a	1251.8 a	1301.8 a	1553.5 a	1179.3 a	1300.2 a
Daily plant water deficit (MPa)	−0.99 a	−0.94 a	−1.11 b	−0.78 a	−0.96 ab	−1.08 b
Daily net assimilation ($\mu mol\, m^{-2}\, s^{-1}$)	18.6 a	14.8 a	14.7 a	37.7 a	22.6 b	29.6 ab
Yield (t/ha)	2.59 a	1.50 b	1.67 b	4.52 a	3.75 a	3.33 a
Height (cm)	79.1 a*	56.5 b*	56.9 b*	202.7 a*	140.5 b*	162.5 ab*
Whole plant leaf area (cm^2)	933.2 a*	474.1 b*	506.7 b*	5388.1 a	4397.8 a	4530.2 a
Whole plant leaf weight (gm)	3.6 a	1.8 b	1.9 b	31.1 a	21.6 b	22.9 ab
Total above-ground biomass (gm)	9.2 a	4.6 b	5.0 b	NA	NA	NA
1998						
Photosynthetically active radiation ($\mu mol\, s^{-1}\, m^{-2}$)	1352.8 a	1097.8 a	937.8 a	1450.3 a	1179.8 a	956.1 a
Soil moisture, 5 cm (%)	6.940 a	5.495 b	7.512 a	9.480 a	7.192 b	7.678 b
Soil moisture, 15 cm (%)	6.998 ab	5.610 b	7.960 a	9.922 a	7.080 b	7.580 b
Daily plant water deficit (MPa)	−1.06 b	−0.78 a	−0.85 a	−1.00 a	−0.85 a	−0.87 a
Daily net assimilation ($\mu mol\, m^{-2}\, s^{-1}$)	22.0 a*	13.9 b*	15.8 b*	23.1 a	16.9 a	20.4 a
Yield (t/ha)	2.24 a*	1.39 b*	2.14 a*	5.79 a	2.99 b	5.43 a

Values are means of 6W, 2W, 2E, and 6E locations. Within each crop, values in each row followed by the same letter are not significantly different (Tukey's HSD, $P<0.05$).

* Significant at 10% level.

pressure bomb in the field. Daily plant water deficits were then calculated.

2.5. *Measurements of soybean and corn growth, biomass, and crop yields*

A single soybean or corn plant was sampled at each of the 12 locations (i.e., poplar, maple, control treatments) on July 31, 1997. A total of 36 soybean and 36 corn plants were harvested. Plants were returned to the lab, where leaf areas and oven-dried (70 °C) weights were determined. Leaf areas were determined using a LiCor 3100 Leaf Area Meter (LiCor, Lincoln, Nebraska). For soybeans and corn, plant height (cm), whole plant leaf area (cm^2), and whole plant leaf weight (gm) were determined.

In September 1997 and October 1998, samples for yield determination were collected from the soybean and corn plots. An 18 cm × 14 m grid was laid out with the long axis perpendicular to the tree rows. Sub-samples (1 m × 1 m), were collected from approximately one-third of the area. Yield samples were stored in paper bags and kiln-dried. The grain or oilseed were mechanically separated from the non-economic plant parts. Samples were weighed and mass per unit area was corrected to constant moisture content. Yield values were reported on a per hectare basis and do not represent land lost due to tree production.

2.6. *Data visualization and analysis*

Contour maps of environmental, physiological, and growth/yield parameters were produced for each treatment (i.e., control, poplar, maple) and/or time-of-day combinations. The maps were produced using CSS Statistica software. Collectively, the maps allow for visualization of how these parameters change in reference to location within the treatment plots or diurnally for certain environmental or physiological parameters. For example, changes in photosynthetically active radiation (PAR) or photosynthesis (NA) can be observed as the sun's rays traverse the plots from east to west each day. The sun's rays shine on the eastern portion of the plot before noon, are directly over the tree rows at noon, and shine on the western portion of the plot in late afternoon.

One-way ANOVA's were performed for each crop (soybeans or corn) to determine treatment differences (i.e., control, poplar, maple) for environmental, physiological, and various crop productivity parameters. Significant differences were assessed using Tukey's HSD at $P<0.05$ and at $P<0.10$. Within treatment (i.e., control, poplar, maple) differences for crop productivity parameters, daily (i.e., average of morning, midday, afternoon readings) environmental parameters, and daily physiological parameters for two major locations (2 and 6 m, i.e., near trees and center of inter-row strip) were also analyzed using one-way analyses of variance (ANOVA), according to Snedecor and Cochran (1967). Mean daily net assimilation or crop growth, biomass, and yield values for soybean and maize plants were correlated with environmental or physiological parameters to determine to what extent tree shading or competition for water affected net assimilation or crop productivity. Values ($N=6$) used in these analyses included means of the 2 and 6 m locations within the control, poplar, and maple treatments.

3. Results

Treatment differences were similar, but somewhat variable from 1997 to 1998 (Table 2). For corn, treatment differences were observed for net assimilation (NA) in 1997, but not in 1998. Similarly, for soybeans, treatment differences for NA were not observed in 1997, but were in 1998. In 1997, and for corn, the only true significant difference for NA was between

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Table 3 – Effects of tree competition on (1) within plot environmental parameters; (2) physiological parameters (daily mean) of agricultural crops; and (3) crop yield, growth, and biomass

Parameter (N = 6)	Crop	Control		Poplar		Maple	
		2 m	6 m	2 m	6 m	2 m	6 m
1997	Soybeans						
Photosynthetically active radiation (μmol s^{-1} m^{-2})		1464.0 a	1586.0 a	1133.0 a	1370.0 a	1045.0 b	1558.0 a
Daily plant water deficit (MPa)		−0.93 a	−1.05 a	−0.90 a	−0.98 a	−1.09 a	−1.15 a
Net assimilation (μmol m^{-2} s^{-1})		19.6 a	17.5 a	12.1 b	17.5 a	11.4 b	17.9 a
Yield (t/ha)		2.51 a	2.59 a	1.04 b	1.97 a	1.29 b	2.00 a
Height (cm)		75.6 a	82.7 a	45.6 b	67.5 a	44.4 b	69.4 a
Whole plant leaf area (cm^2)		796.2 b	1070.1 a	317.4 b	630.8 a	247.1 b	766.3 a
Whole plant leaf weight (gm)		3.2 b	4.1 a	1.3 b	2.3 a	1.0 b	2.9 a
Total above-ground biomass (gm)		7.6 b	10.7 a	3.4 b	5.8 a	2.6 b	7.4 a
1998	Soybeans						
Photosynthetically active radiation (μmol s^{-1} m^{-2})		1405.0 a	1158.0 a	746.0 b	1296.0 a	670.0 b	1336.0 a
Soil moisture, 5 cm (%)		6.612 b*	7.266 a*	5.598 a	5.862 a	7.348 a	7.915 a
Soil moisture, 15 cm (%)		6.403 b*	7.590 a*	5.397 a	5.824 a	7.294 b*	8.626 a*
Daily plant water deficit (MPa)		−1.07 a	−1.04 a	−0.70 a	−0.86 b	−0.84 a	−0.86 a
Net assimilation (μmol m^{-2} s^{-1})		22.0 a	19.6 a	11.0 b	19.1 a	10.1 b	22.5 a
Yield (t/ha)		2.24 a	2.25 a	1.15 b	1.67 a	1.55 b	2.85 a
1997	Maize						
Photosynthetically active radiation (μmol s^{-1} m^{-2})		1528.0 a	1579.0 a	952.0 b*	1407.0 a*	1075.0 b*	1525.0 a*
Daily plant water deficit (MPa)		−0.71 a	−0.91 a	−0.90 a	−1.01 a	−1.04 a	−1.14 a
Net assimilation (μmol m^{-2} s^{-1})		36.9 a	38.5 a	17.1 b	28.1 a	21.6 b	37.5 a
Yield (t/ha)		4.21 a	4.83 a	2.89 b	4.61 a	2.07 b	4.64 a
Height (cm)		196.0 b	209.3 a	103.8 b	177.2 a	126.2 b	198.8 a
Whole plant leaf area (cm^2)		5386.9 a	5389.3 a	3769.2 b	5026.5 a	3758.5 b	5302.0 a
Whole plant leaf weight (gm)		30.2 a	32.0 a	17.3 b	26.0 a	17.6 b	28.2 a
1998	Maize						
Photosynthetically active radiation (μmol s^{-1} m^{-2})		1422.0 a	1200.0 a	794.0 b	1117.0 a	481.0 b	1420.0 a
Soil moisture, 5 cm (%)		10.049 a	8.913 b	6.653 a	7.562 a	7.017 b	8.279 a
Soil moisture, 15 cm (%)		10.545 a*	9.303 b*	6.708 a	7.454 a	7.150 b	8.007 a
Daily plant water deficit (MPa)		−0.89 a*	−1.10 b*	−0.84 a	−0.85 a	−0.86 a	−0.88 a
Net assimilation (μmol m^{-2} s^{-1})		20.3 a	22.1 a	10.8 b	19.1 a	12.0 b	26.9 a
Yield (t/ha)		5.70 a	5.88 a	0.69 b	5.29 a	3.79 b	7.07 a

Soybean and maize intercrops, July 1997 and July 1998. Within each treatment (control, poplar, maple), values in each row followed by the same letter are not significantly different (Tukey's HSD, $P < 0.05$).

* Significant at 10% level.

the control and the poplar treatment, with poplar, rather than maple, having the greatest competitive effect on NA. In 1998, by contrast, NA for both poplar and maple treatments, differed (i.e., was lower) from the control treatment for soybeans. Despite widely ranging mean values for PAR in both years, no treatment differences for PAR were observed in either year. In 1997, the lowest plant water deficits, for soybeans (−1.11 MPa) and for corn (−1.08 MPa), were observed for the maple treatment. In 1998, no treatment differences for daily plant water deficit were observed for the maple and poplar treatments. However, in 1998, soil moisture (5 and 15 cm depth) did differ (i.e., was lower) from the control treatment for both of these treatments intercropped with corn, and for the poplar treatment intercropped with soybeans. Corn and soybeans growth or yield for the poplar and maple treatments differed from the control treatment in both years. In 1997, yield of soybeans intercropped with poplar or maple was lower than for mono-cropped soybeans (control treatment). In 1997, no differences in corn yield were observed among treatments, despite widely ranging values. In 1998, corn and soybeans yields were lower for the poplar treatment only. In 1997, all other growth parameters for soybeans were lower for the poplar and maple treatments compared with the control treatment. In 1997, only corn height and whole plant leaf weight differed from the control treatment.

Generally, presence of trees significantly reduced PAR, net assimilation (NA), and growth and yield of individual soybean or corn plants growing nearer (2 m) to tree rows in both years and soil moisture in 1998 (Table 3; Figs. 1–3). Within plot differences in these parameters were significantly correlated (Table 4). In both years, PAR was highly correlated with net assimilation (NA) and growth and yield of both agricultural crops. Similarly, NA was highly correlated with growth and yield of both crops. For both parameters (i.e., PAR and NA),

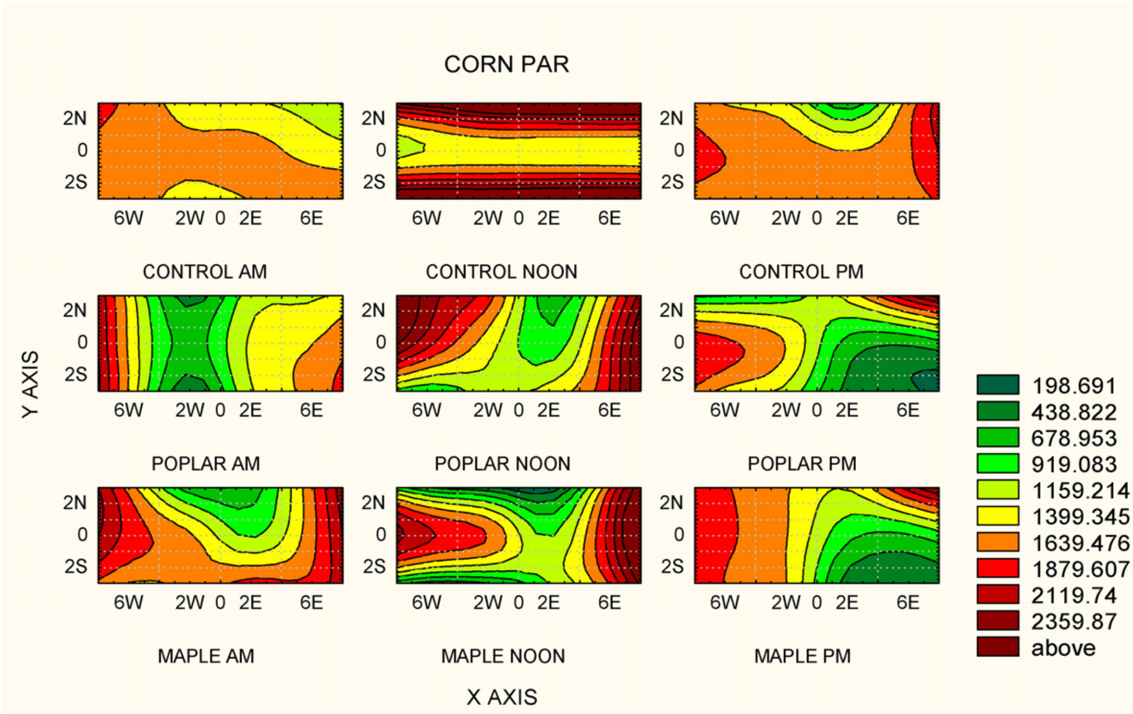

Fig. 1 – Diurnal (AM, noon, PM) PAR (photosynthetically active radiation) within corn plots for control, poplar, and maple plots.

correlations were higher for corn than soybeans in 1997, with corn, rather than soybeans, being more adversely impacted by tree shading. In 1998, PAR was better correlated with NA and yield for soybeans, whereas NA was better correlated with yield for corn. In both years, daily plant water deficits were non-significantly and poorly correlated with NA and growth and yield of both crops. However, soil moisture (5 and 15 cm depth) was significantly correlated with soybeans yield in

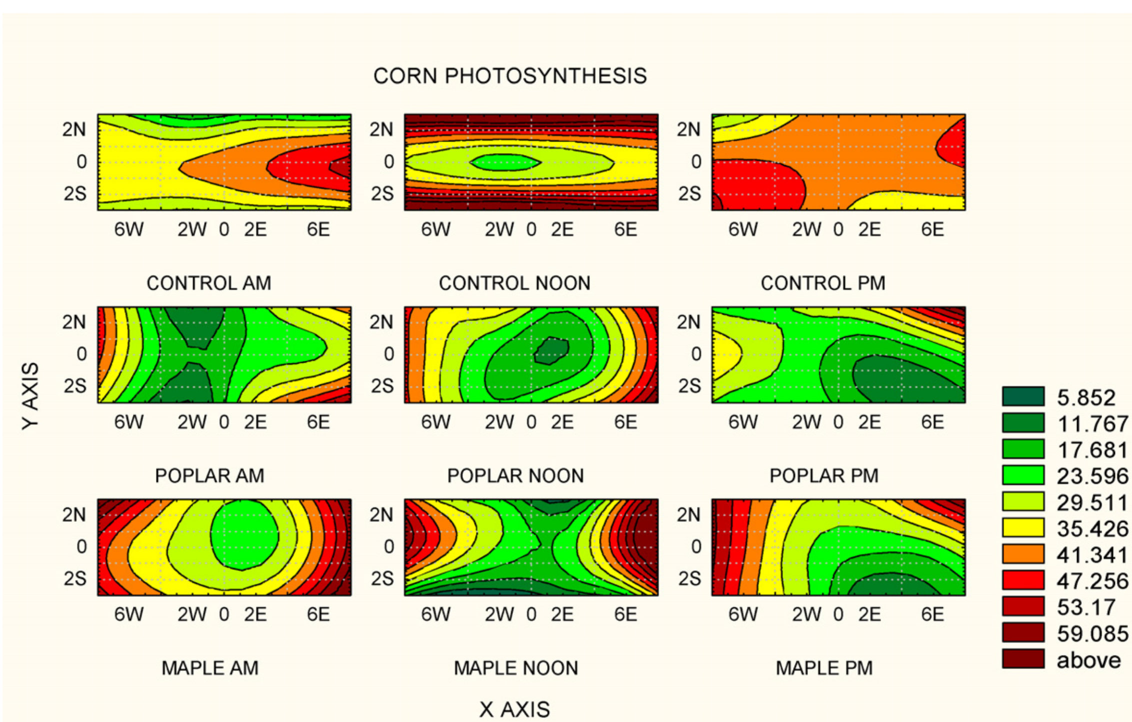

Fig. 2 – Diurnal (AM, noon, PM) NA (net assimilation) within corn plots for control, poplar, and maple plots.

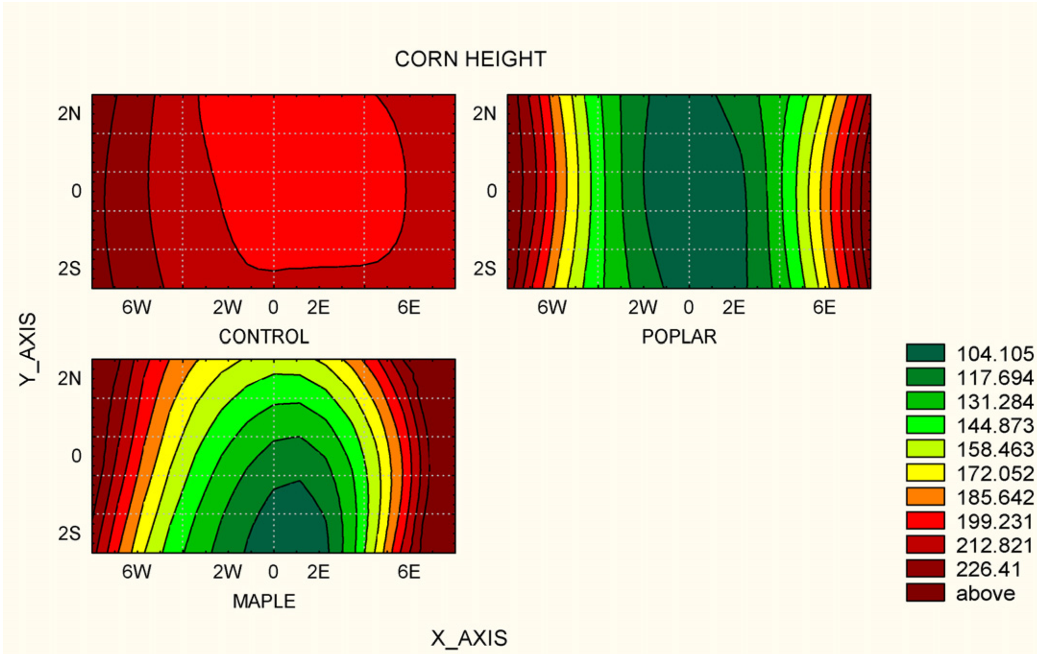

Fig. 3 – Height growth of corn in relationship to plot location for control, poplar, and maple plots.

Table 4 – Correlation of soybean and maize net assimilation, yield, growth, and biomass with environmental or physiological parameters measured in July 1997 and July 1998

Independent variable	Dependent variable ($N = 6$)					
	Net assimilation (μmol m^{-2} s^{-1})	Yield (t/ha)	Total above-ground biomass (gm)	Leaf weight (gm)	Leaf area (cm)	Height (cm)
Soybeans 1997						
Photosynthetically active radiation (μmol s^{-1} m^{-2})	0.90**	0.89**	0.94**	0.95**	0.96**	0.95**
Plant water deficit (MPa)	−0.03	−0.12	−0.18	−0.15	−0.18	−0.12
Net assimilation (μmol m^{-2} s^{-1})		0.91**	0.81**	0.85**	0.85**	0.92**
Soybeans 1998						
Photosynthetically active radiation (μmol s^{-1} m^{-2})	0.98**	0.74*				
Soil moisture, 5 cm (%)	0.32	0.76*				
Soil moisture, 15 cm (%)	0.39	0.81**				
Plant water deficit (MPa)	−0.67	−0.59				
Net assimilation (μmol m^{-2} s^{-1})		0.85**				
Maize 1997						
Photosynthetically active radiation (μmol s^{-1} m^{-2})	0.98**	0.90**		0.98**	0.99**	0.999**
Plant water deficit (MPa)	0.12	0.05		0.24	0.17	0.08
Net assimilation (μmol m^{-2} s^{-1})		0.83**		0.96**	0.95**	0.98**
Maize 1998						
Photosynthetically active radiation (μmol s^{-1} m^{-2})	0.88**	0.72*				
Soil moisture, 5 cm (%)	0.66	0.69				
Soil moisture, 15 cm (%)	0.55	0.59				
Plant water deficit (MPa)	−0.41	−0.38				
Net assimilation (μmol m^{-2} s^{-1})		0.91**				

Values used in analysis include daily means of 2 and 6 m locations within control, poplar, and maple treatments.

* Significant at 10% level.

** Significant at 5% level.

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1998. In 1998, soil moisture was slightly more correlated with soybeans yield than PAR, but large differences in correlation values were not notable. By contrast, soil moisture was not significantly correlated with corn yield in 1998. And, soil moisture was not significantly correlated with either soybeans or corn NA in 1998.

4. Discussion

In this, one of the first studies to examine competition effects in a temperate tree-based intercropping system, two crop species (corn, a C4 plant and soybeans, a C3 plant) and two tree crops (hybrid poplar, a tall, columnar-shaped tree with a sparse canopy and silver maple, a shorter, broad-based canopy, with dense foliage) were examined for their potential competitive interactions. Of the two crops, corn was the most detrimentally impacted by tree competition. Poplar appears to have had a greater shading impact then maple—probably because this taller tree casts a longer shadow on the intercrop. In this study, competition for water was of lesser importance than competition for light.

Within tree-based intercropping systems, a number of factors can influence tree shading of adjoining agricultural crops. The potential limitations to productivity in the under-story due to shading may be addressed through appropriate over-story species selection and plantation design. This is partly so in selecting C3 or C4 plants as annual agricultural crops in the under-story. C3 plants (e.g., soybeans, winter wheat) become light saturated at approximately 50% of full sunlight, whereas C4 plants (e.g., corn) become light saturated at near full sunlight. If shading by the tree crop does not reduce light levels below the threshold of light saturation, then no reduction in photosynthesis (net assimilation), or ultimately crop growth or yield, should occur. The degree of light reduction would depend upon the extent and duration of shade produced by the trees. This in turn would depend upon the tree species, the shape and height of its crown (i.e., crown architecture), and the density of its foliage. Deciduous trees should have a temporary shading impact on the crop, dependent upon the start (i.e., leaf emergence) and the finish (i.e., leaf senescence) of the tree's growing season, whereas evergreen trees would have a permanent shading impact, with the extent of shading dependent upon their crown size. An over-story tree species that reduces light levels by no more than 50% of full sunlight should allow an under-story C3 species to operate at near full photosynthetic potential, with no resulting loss of crop yield compared with the same plants grown in full sunlight. By contrast, tree species reducing light levels even slightly would be expected to reduce photosynthesis for under-story C4 plants, ultimately resulting in reduced crop yields.

Other key deciduous trees being grown at the University of Guelph Agroforestry Research Station (ARS) include *Juglans*, *Quercus*, and *Fraxinus* genera. These species have crown architectures that fall between the two species selected for this study. However, canopy heights of the five ARS hardwood species may differ significantly, and *Juglans*, allowing for possible allopathic chemicals, is currently the most valuable crop. Therefore, future studies to determine and comparatively quantify daytime shading for the five species would be a first step for further study. Coniferous trees planted at the ARS include *Picea*, *Thuja*, and *Pinus*. These species, particularly *Picea* and *Pinus*, if grown for Christmas trees, another valuable crop, would have comparatively small conical crowns on relatively short trees, and would likely pose little shading impact on the agricultural crops.

Other factors, in addition to tree species and their crown architecture, influencing tree shading in tree-based intercropping systems, include tree row orientation, distance between tree rows, and the timing of tree leaf emergence and leaf senescence. Orientation of tree rows can significantly affect the degree and duration of annual crop shading. With tree rows oriented north/south, shading at noon falls primarily on the tree row. This becomes more prominent in higher latitudes. Typically, rates of photosynthesis are maximized around noon where the solar angle is at or near its azimuth. Latitude controls the angle of incidence of solar radiation.

Working with temperate tree-based intercropping systems in China, Wu and Zhu (1997) also observed that inter-row spacing was a significant factor influencing tree shading. To reduce shading, they recommended that spacing be dependent upon the relative value of the crop and the tree. They recommended 5–10 m spacing where wood from the tree is more valuable (not likely for most ARS trees, except *Juglans*), 15–20 m where both crops are equally valuable (this is similar to current ARS spacing), and 30–50 m where the under-story agricultural crop is the most valuable. Based upon this study, it would suggest that the latter spacing is the most appropriate when grain and oil seed prices are high. However, commodity prices in Canada are currently depressed which may influence a decision to move to closer spacing and more intensive management of the tree crop. The decision making process is a great challenge given annual market fluctuations for the annual crops.

Where shading occurs in tree-based intercropping systems, a 'parabolic effect' on crop height and yield has been observed within the intercropped agricultural crop (Newman et al., 1998). The apex of the parabola (i.e., greatest growth) occurs in the middle of the crop strip, with growth reduced nearest the tree edge. They also observed that leaf weight and inter-node distance were also highest in the middle of the crop strip. Similar results were observed in this study. They also reported that shade tolerant crops benefit from intercropping. Ginger, a shade tolerant C3 plant, when intercropped with *Paulownia*, had a 34% increase in yield as compared with yields when mono-cropped. *Paulownia* is a temperate tree species, characterized by a sparse crown, and favorable late-season leaf emergence and early-season leaf senescence relative to potential under-story agricultural crops (Wu and Zhu, 1997). In previous studies at this southern Ontario site with barley (Thevathasan and Gordon, 1997), another C3 plant, no detrimental competitive interactions of trees, including poplar and maple, on wheat yields were observed. In fact, like ginger, an average increase of 8.4% in barley yields was observed in intercropped systems compared with mono-cropped wheat (Zhang, 1999; Thevathasan et al., 2004), suggesting that winter wheat (or other cool season crop) is a much better choice than soybeans for intercropping with trees in a temperate tree-based intercropping system.

However, as is normally the case, this study also suggests that additional experiments would be worthwhile. It is clear that corn, a C4 plant, or other C3 plants such as soybeans cannot be eliminated from consideration, since both crops are too important in North America to consider this option, and the goal is to promote this agroforestry practice in North America—not to discourage it. Therefore, what it is needed are other design options for these intercropping systems that might ultimately improve crop yields for both C4 and C3 plants, accepting some potential, but acceptable levels of tree competition. If tree competition can be reduced to acceptable levels so that crop yields for these important crops are not seriously or detrimentally impacted, then it should still be possible to promote this intercropping practice.

Despite the advantages of intercropping C3 species such as winter wheat with other desirable tree species, including poplar and maple at this site, this approach may not always be possible. For example, maize (corn) is a valuable agricultural crop grown around the world. Under such circumstances the issue becomes one of quantifying possible yield losses, and developing possible strategies to either neutralize or minimize these losses. Elsewhere in the world, some previous experience exists with this scenario. This is especially so in tropical agroforestry, and to a lesser extent in temperate agroforestry. Rao et al. (1998) reported on intercropping of corn with *Peltophorum*, a slow-growing tree with a small compact canopy, where a positive interaction was observed, and corn yield was positively affected. However, in most recorded instances, corn yields have been reduced or were not sustainable throughout the growing season. Haggar and Beer (1993) reported on attempts to grow corn intercropped with pollarded (heavily pruned) *Gliricidia* and *Erythrina*, in an attempt to minimize detrimental shading impacts resulting from late-season leaf expansion of the two pruned tree species. In both instances, corn biomass was reduced after 60 days, once late-season leaf expansion of the two trees began. Elsewhere, Newman et al. (1998) reported that corn yields and field beans yields were reduced by 63 and 68%, respectively, when intercropped with *Paulownia*, a temperate tree species with desirable crown characteristics. To avoid these possible yield losses, Simpson (1999) has suggested that the canopies of trees be pruned to reduce shading and that the trees also be root-pruned to reduce possible competition for soil moisture. Additionally, thinning of trees, removing alternate trees in rows, or even removing alternate tree rows, should help to reduce shading effects and possible competitive effects for soil moisture.

Growing a temperate tree-based intercropping system to take advantage of potential federal government carbon (C) credits, resulting from Canada's signature of the international the Kyoto Protocol Agreement (treaty) on climate change, could be yet another way to compensate for or even eliminate potential economic losses resulting from agricultural yield losses in these systems. In a recent review of temperate tree-based intercropping systems, Thevathasan et al. (2004) state, "The United Nations has also estimated that agroforestry based land-use practices on marginal or degraded lands could sequester 0.82–2.2 Pg C year^{-1}, globally, over a 50-year period (Dixon et al., 1994)." They concluded, "the land base in Canada that could potentially be brought under tree-based intercropping is substantial (20–25 million ha) which in turn, can have a significant effect on C sequestration and GHG (greenhouse gas) emission reduction". For all of these reasons, they concluded, "The tangible benefits that are derived from properly designed and managed tree-based intercropping systems place this land management option above conventional agriculture in terms of long-term productivity and sustainability" (Thevathasan et al., 2004).

Canada is yet to formally approve C credits, in compliance with this treaty agreement, but is expected to do so soon. Enabling legislation would likely compensate farmers for growing crops, including agroforestry systems, where C credits could be obtained to compensate for Canadian air emissions resulting from manufacturing and other sources. Under a government approved system of carbon credits, farmers could benefit doubly from participating in the growing of tree-based intercropping systems—first from conventional short- and long-term economic yields from both agronomic and tree crops, and second, from monies (or tax credits) received from the government for C credits. The latter could potentially more than compensate for any economic yield losses attributable to tree competition in these systems. Such C credits would apply to fertile sites already being farmed, but could also apply to less fertile sites that are not currently in agricultural or forestry production, for example, abandoned or fallow fields. The potential for such a system could be enormous, and most beneficial to farmers willing to participate. Potential economic losses from yield losses on fertile sites could be overcome by these credits, and in addition, farmers could benefit from bringing abandoned, less fertile sites, back into agroforestry production.

Under this hypothetical, but probable system, careful determinations of actual C fixed by various tree-based intercropping systems would need to be determined as quickly as possible. This would result in an additional boost to researchers qualified to make these determinations. Actual amounts of C being sequestered by the trees (differing species) and the intercropped agricultural crops would need to be determined on an area basis for differing site classes. Using these data, C sequestration for agroforestry systems could then be scaled up to a landscape basis across Canada. The key to these determinations – yet to be done – would be to properly couple plant population levels with reasonable estimates of C cycling both above- and below-ground. Much of this information is already existent for fertile temperate intercropping systems, and merely needs to be refined and verified. When this is done, it could very well turn out for many prospective systems, that total C being sequestered by the intercropping system would exceed C sequestered by either crop grown separately as mono-crops (agricultural crops) or as trees (plantations). This land-equivalent ratio (LER) concept has been previously expressed and verified for conventional crop yields (Willey, 1979; Marshall and Willey, 1983; Rao et al., 1990, 1991), but has not yet been applied to C sequestration. However, since C sequestration is closely paralleled by plant biomass acquisition, similar results are expected.

In summary, we conclude that there is great potential for temperate tree-based intercropping systems in North America, which could have both domestic and international (global) impacts. If properly designed, these systems could increase crop yields, and economic profits, on both fertile and previously abandoned (relatively infertile) farm-lands. In terms of the world's commitment to abate detrimental climate change, these systems also offer great potential to act as C sinks in sequestering C emissions.

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