Defining competition vectors in a temperate alley cropping system in the midwestern USA

1. Production physiology

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Abstract. With renewed interest in the use of ecologically-designed, sustainable agricultural systems for temperate regions of the world, agroforestry is being proposed as an alternative to intensive production of crops in monocultures. However, the knowledge-base for understanding and managing complex, multi-strata systems worldwide is limited, particularly so for temperate regions. We examined an alley cropping system in the midwestern US where maize (*Zea mays* L.) is grown in alleys between tree rows of either black walnut (*Juglans nigra* L.) or red oak (*Quercus rubra* L.). During a course of ten years, crop yields in rows adjacent to tree rows declined by 50% or more. With the experimental introduction of barriers to separate tree and crop root systems, yields in the rows near trees were equal to those of the center row (and monoculture). Irrespective of a high correlation between photosynthetically active radiation and net photosynthesis, shading did not have a major influence on crop yield. At this stage of system development (11 year old trees), influence of incident PAR on crop yield seems to be minimal. Subsequent papers in this series examine the sharing of belowground resources between trees and crops to quantify the competitive interactions that impact crop yields and their implications for economic return to the farmer.

Introduction

Renewed interest in perennial agriculture and ecologically-designed agricultural systems (Moffat, 1997; Matson et al., 1997) is evidence of a search for highly productive yet sustainable agricultural practice. Agroforestry systems, the planting of perennial trees and/or shrubs with annual agronomic crops or pasture, have been proposed as more environmentally benign, alternative systems for agricultural production in temperate North America (Gold and Hanover, 1987; Garrett and Buck, 1997). In addition to environmental pressures, the economic benefits of multiple crops within agroforestry systems have also generated interest in their adoption by farmers (Gordon and Newman, 1997). Despite intense interest in these food and fiber production systems worldwide, the knowledge-base for research and implementation is only just developing (Sanchez, 1995; Garrett and Buck, 1997), particularly for the temperate regions of the world. These multi-storied, multi-component

plant and animal systems are more complex than single-species cropping systems, varying in temporal and spatial ecological interactions. A number of positive and negative interactions have been postulated for the tree and crop components of these systems, and the direction and magnitude of these interactions are determined by the patterns of resource sharing and the time scale at which these patterns are measured. In this series of papers, we report on an investigation into the ecological mechanisms defining crop yields over time and space in a combined tree-crop alley cropping agroforestry system in the midwestern US (Figure 1). In contrast to tropical alley cropping, temperate alley cropping has come to mean the cropping of alleys between rows of trees that are grown to maturity and not repeatedly coppiced for mulch or green manure.

This paper reports on the spatial and temporal changes in crop yield and tree growth in our alley cropping system of maize and fine hardwoods. Further, the role of light in determining crop yield through its influence on photosynthesis is also addressed. Although the role of environmental factors in controlling crop yield has been studied rather extensively in agroforestry systems in recent years, the underlying physiological processes have yet to be understood (Ong and Huxley, 1996). Alley cropping structure has been cited as causing shade and thereby reducing yield of associated crops in both tropical (Ong et al., 1991), and temperate systems (Chirko et al., 1996). Hence, it is critical to test the hypothesis of light as a limiting factor when separated from below-ground limitations. Understanding the temporal patterns of light distribution in alleys and subsequent crop photosynthesis will significantly enhance our ability to design alley cropping systems to reduce competitive effects.

Materials and methods

System description

Alley cropping, as defined in the US, is the planting of row crops or pasture in alleys formed by single or multiple rows of trees (Garrett and Buck, 1997). Design of these systems is flexible to meet different objectives or constraints. Our systems, established in 1985, incorporate black walnut trees (*Juglans nigra* L.) in rows spaced 8.5 m apart (currently 2.4 m intra-row tree spacing) interplanted with six rows of maize (*Zea mays* L.) in the alleys and an identical trial using northern red oak trees (*Quercus rubra* L.). In our plantings, the tree rows and alleys have a north-south orientation. The study site is located in southern Indiana, USA (39°03′ N, 85°30′ W) at the Purdue University Southeastern Agriculture Center. The area is characterized by a Parke Silt Loam soil (fine-loamy, mixed, mesic Ultic Hapludalf), a well-drained loess over loamy glacial till, underlain by sand and gravel. This soil has moderate permeability and high water-holding capacity, with the subsoil

Figure 1. Maize grown within rows (alleys) of black walnut trees in an alley cropping agro-forestry system in the midwestern USA.

extending to 175 cm. Diameter of the walnut and oak trees at age 10 averaged 11.43 and 12.95 cm, respectively. Height for both species averaged 7.42 m. During 1996, the mean annual temperature was 10.8 °C with an annual rainfall of 2120 mm.

Standard maize production methods for the midwestern USA have been utilized for the trial. A planting density of 65,000 maize plants ha^{-1} was used within the alleys with rows 0.76 m apart. In initial years, the crop alleys were tilled, but no-till management was undertaken after the system was eight years old. Standard pesticide and fertilizer regimes were also used with 168 kg N ha^{-1} added annually as anhydrous NH_4 (knifed in to the crop alleys) before 1985. Ammonium nitrate was surface-applied (broadcast) at the same rate in subsequent years due to experimental plant and soil-sampling equipment in alleys.

For each tree species trial, initial tree spacings were 1.2 m within a row (again, 8.5 m between rows). Trees were thinned to the current intra-row spacing of 2.4 m in 1995, and will soon be thinned to a final intra-row spacing of 4.8 m. Constant thinning to maximize diameter growth is critical in fine hardwood tree plantings when veneer-quality logs are the production objective. Similarly, pruning is critical to attain a clear bole for veneer, and these trials have been pruned annually. Alternate objectives, such as nut production in walnut, would not require this intensity of management. Annual pruning, however, has facilitated the use of farm machinery in the tree alleys, quickly raising branches above the level of planters and harvesters.

From inception, crop alleys were machine-harvested by row to determine the spatial patterns of yield. The pattern of yield in initial years while the trees were small showed enhanced yields of maize in outer rows of the alley adjacent to trees. The higher yield of outer rows probably resulted from increased light availability and less competition for moisture and nutrients. However, as trees grew in size, yields of the outer rows decreased relative to center rows (Figure 2). This led to the establishment in 1995 of an experimental trial to define the mechanisms by which maize yields were impacted by tree rows. The experimental design for each tree species trial included a randomized complete block design with 12 plots. Each plot was 100 m long and 11 m wide with two rows of trees. In the spring of 1995, three root pruning treatments were superimposed with four replications in an attempt to separate above- and below-ground tree-crop interactions. The treatments were as follows:

1. Root barrier: polyethylene barriers, 1.2 m deep, were installed on both sides of both tree rows in a plot, 1.2 m from the trunks of the trees. These barriers were used to prevent tree roots from growing into the alley and thus to eliminate below-ground competition to a 1.2 m depth.
2. Trench: roots were pruned by trenching on both sides of both tree rows to a depth of 1.2 m, 1.2 m from the base of trees. These trenches, although minimizing the below-ground interactions of trees and crops, allowed the roots to regrow into the alley.
3. No barrier: control in which tree and maize roots interacted.

With this design, crops grown with reduced below-ground interaction with trees could be compared to the intact system where the annual and perennial
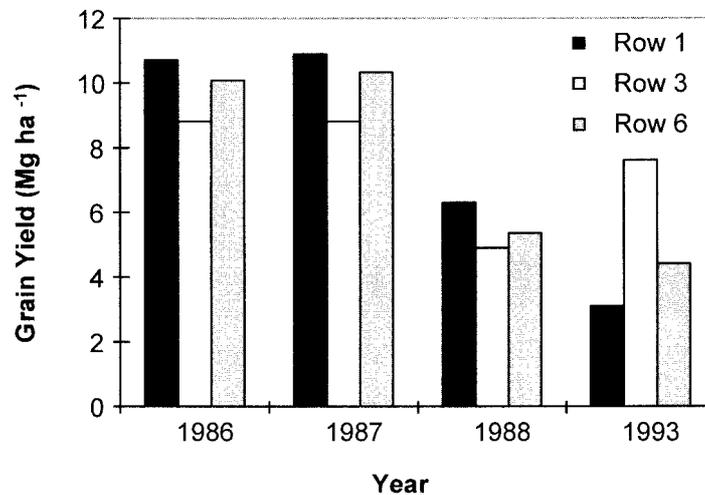
Figure 2. Historical Indiana, USA alley cropping maize yields by row with shift in outer row production due to high resource availability when young and competition for resources with age.

root systems intermingled (Singh et al., 1989; Ong et al., 1991). Components of carbon, nutrient, and water gain were measured over two growing seasons (years 11 and 12) to understand the competitive relationships within this mixed agricultural system. System biomass production (maize grain yield and tree biomass) and partitioning over time, and patterns of incident light and maize photosynthesis are reported in this paper. Three companion papers describe competition for water between trees and crops (Jose et al., this issue, a), system nutrient dynamics (Jose et al., this issue, b) and economic modeling (Benjamin et al., this issue).

Tree growth and maize yield

Diameter at breast height (DBH) was measured from 1993 through 1997 on each individual tree for both tree species to determine treatment impacts on diameter growth rates. Standing woody biomass was calculated for both black walnut and red oak using published allometric equations (Smith, 1985). Tree leaf biomass was quantified using equations developed by Jose (1997). Tree and crop root biomass was determined as described in Jose et al. (this issue, a). Maize grain yields were monitored by row from 1986 through 1996.

Photosynthetically Active Radiation (PAR) and photosynthesis

PAR (400–700 nm) was measured using LI-COR LI-190SZ quantum sensors (LI-COR, NE, USA) placed in the alley just above maize plants in the first (eastern row), third (middle row), and sixth (western) rows. Readings were collected at half hour intervals using a LI-1000 datalogger (LI-COR, NE,

USA). Hourly PAR readings in the open were obtained from a nearby automated weather station (Campbell Scientific Inc., Utah, USA) throughout the growing season (from June through October) in 1996.

Net photosynthesis was measured using a portable infra-red gas analyzer (LCA-3, Analytical Development Corporation, Hoddesdon, UK) operated in differential mode. Photosynthesis measurements were made four times during the growing season on the two upper-most, fully developed leaves of two plants each in the first, third, and sixth rows of maize using a Parkinson leaf chamber (PLC) (Analytical Development Corporation, Hoddesdon, UK). All measurements were taken between 11:00 am and 1:00 pm on clear sunny days. Further, the diurnal course of photosynthesis was measured once in all treatments during 1996. Net photosynthesis was calculated as described by Long and Hallgren (1985).

Data analysis

Tree growth data were analyzed using ANOVA within a randomized complete block design. Maize yield and net photosynthesis data were analyzed using a split block design where distance (row position) was considered as a subunit of the main block (Little and Hills, 1978). Daily integrated PAR data from the weather station were used to calculate the total weekly incident PAR during the growing season (June through October, 1996). Data from the LI-COR LI-190 SZ sensors were used to calculate the percentage of total PAR incident on maize rows, and to model the spatial variation in growing season PAR in the crop alley.

In each analysis, main effects and interactions were tested for significance using the appropriate error terms. If significant treatment effects were revealed at $\alpha = 0.05$, then Tukey's range test was used for mean separation. Regression analysis was used to define relationships between PAR and net photosynthesis.

Results and discussion

Grain yield and tree growth

Ecological interactions between trees and crops in alley cropping systems have been the subject of numerous experiments in the tropics (e.g., Singh et al., 1989; Ong et al., 1991). Comparable attempts are only beginning in temperate alley cropping systems (e.g., Williams and Gordon, 1995). These above- and below-ground interactions define the resource sharing patterns of component crops and trees and thus control system productivity. Maize, having the C_4 photosynthetic pathway, is sensitive to shading and earlier investigation in different agroforestry systems attributed decline in crop yields to competition for light (Karim et al., 1993; Chirko et al., 1996). However, the relative effect of limited resources (light, water, and nutrients) leading to yield declines

over time has been undocumented for agroforestry systems in temperate regions.

In our study, with the restriction of below-ground competition, striking differences in crop yield were observed during both 1995 and 1996. Grain yield of maize exhibited significant differences between treatments in both black walnut ($P = 0.0001$) and red oak alley cropping systems ($P < 0.0024$) (Figure 3). In general, the red oak system had a lower yield than the black walnut system. In the black walnut system, average grain yield ranged from 5.0 mg ha^{-1} for the 'no barrier' treatment to 8.3 mg ha^{-1} for the 'trench' treatment, with the 'barrier' treatment having a grain yield of 7.7 mg ha^{-1}. Average grain yields within the red oak system were 4.2 mg ha^{-1}, 6.3 mg ha^{-1}, and 6.2 mg ha^{-1} for the 'no barrier', 'trench', and 'barrier' treatments, respectively. Inter-row variation in grain yield was significant for the 'no barrier' treatment in both the black walnut ($P = 0.028$) and red oak systems ($P = 0.024$) (Figure 3). Other treatments (except the 'trench' treatment in the black walnut system), however, did not exhibit any significant differences in grain yield among different rows. The yield of maize grown in monoculture on an adjacent field was 7.4 mg ha^{-1}.

Long-term economic viability of this system will be impacted by diameter growth rates of trees, and diameter growth is closely linked to water availability during the growing season, a below-ground resource. For our trial, there were no significant differences among treatments for either species prior
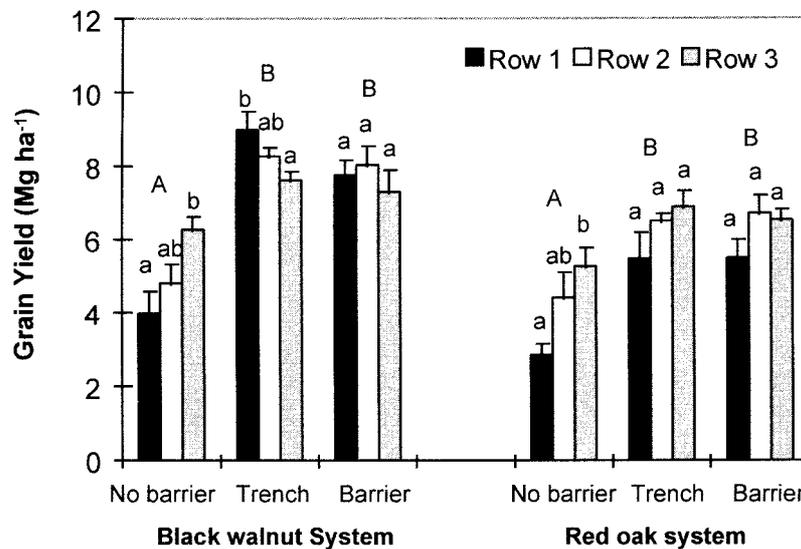

Figure 3. Grain yield of maize by row (row 1 is the closest row to the tree row, and row 3 is the farthest) during 1996 for different treatments in the black walnut and red oak alley cropping systems in Indiana, USA (Bars with the same lower case letters are not significantly different within each treatment. Similarly, upper case letters indicate significant differences between treatment means. Tukey's range test at alpha = 0.05).

to root pruning in 1995 (Figure 4). In the three years following the below-ground treatments, black walnut diameter growth in the 'no barrier' treatment was significantly greater than the 'trench' and 'barrier' treatments ($P = 0.0001$). Comparison of means showed no significant diameter growth difference between black walnut 'trench' and 'barrier' treatments. In the red oak system, the situation was different. There were no significant growth differences between 'no barrier' control plots and the 'trench' or 'barrier' treatment plots for any of the years. Growth rates were nearly the same in all plots, even following root pruning. Annual variations in diameter growth were significant for both species ($P = 0.0001$) due to the annual fluctuations in precipitation, temperature, and other growing conditions.

The pruning of roots in both red oak and black walnut was hypothesized to have a potentially negative impact on annual diameter increment. Diameter growth in black walnut was significantly reduced following the root pruning treatment. However, the effect was less with red oak. The observed difference may be due to differences in root structure. Both species develop large taproots, which make them beneficial trees for an agroforestry system. Red oak roots tend to be shorter and more fibrous. Therefore, they can sustain pruning at some distance from the stem without an effect on water uptake. Walnut roots tend to be longer and less fibrous, making it more difficult to
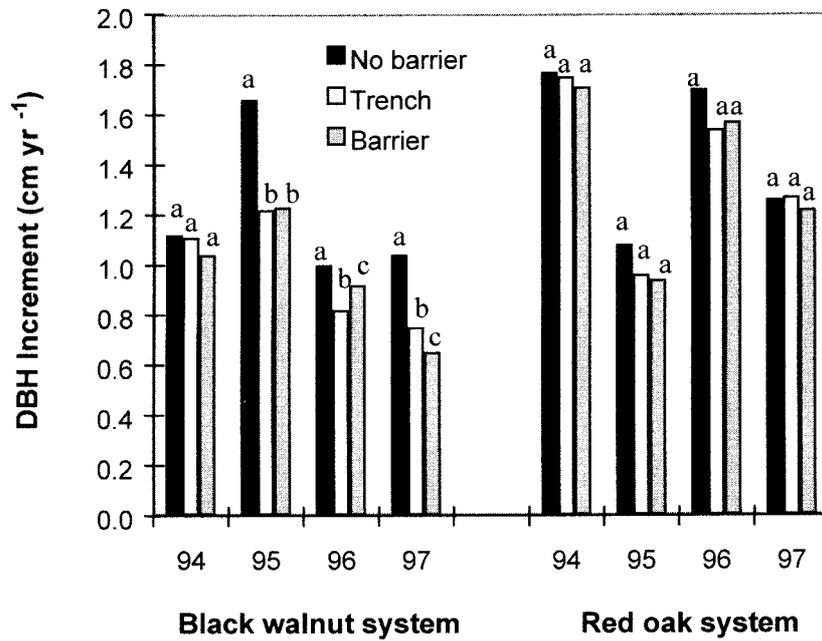

Figure 4. Annual diameter increment by root zone treatment for black walnut and red oak trees within the alley cropping systems by root zone treatment in Indiana, USA (Bars with the same lower case letters are not significantly different within a given year. Tukey's range test at alpha = 0.05).

root-prune this species without affecting root function. With a reduction in soil volume available for rooting as a result of trenching, root morphology appears to affect the ability to manage below-ground competition. This experimental trial is also an extreme example of root-pruning. If shallower trenches were cut (down to 10–30 cm), it is possible there would be little to no diameter growth reduction in the trees.

The distribution of standing biomass (Figure 5) indicates that red oak trees have a greater proportion of their biomass in roots as well as a greater total biomass in comparison to black walnut. The different root to shoot ratios for the two tree species indicate that oak may be more efficient in water and nutrient uptake. As the ratio is uniform across all treatments, it is probably a species characteristic rather than a treatment response. Standing maize biomass shows that total production was essentially equal between the systems though grain production was slightly higher under black walnut (Figures 3 and 5). Proportional root production of maize, however, appears unaffected by tree species, and stover biomass compensates for differences in production where grain yield varies by treatment. Thus, root competition reduces total biomass production for maize, but red oak more sharply reduces biomass allocation to grain yield. Red oak produces more total biomass but is more adversely affected by the presence of root barriers. A more detailed analysis of the below-ground resources and their impacts will be undertaken in the following papers of this series.

Spatial variation in incident PAR

Competition for light between trees and associated crops has been studied rather intensively in tropical alley cropping systems (Lawson and Kang, 1990; Corlett et al., 1992). Many of these studies have concluded that shading is a major factor causing crop yield reductions in these tree-crop systems (e.g. Lawson and Kang, 1990). We also observed shading of maize plants in our alley cropping system. Incident PAR was greatly reduced for eastern and western rows in comparison with the middle rows in both black walnut and red oak systems (Figure 6). Maize plants in the western row received most of their PAR during the morning hours when the eastern row was shaded. However, this pattern was reversed in the afternoon with western rows being shaded and eastern rows receiving a greater amount of PAR. During mid-day, all three rows were receiving similar levels of PAR.

According to Fisher and Palmer (1984) above-ground shading is detrimental to maize growth from two weeks before to two weeks after flowering. These authors reported a 15–30% grain yield reduction in 50% shade. Shading in our experiment was not as high as 50%, although a 41% reduction in PAR was observed for external rows in red oak alley cropping (Figure 6). Shading in red oak and black walnut alley cropping, however, resulted in no apparent yield reductions. Rather, preventing below-ground competition increased grain yields in external rows relative to the center row in the black walnut alley
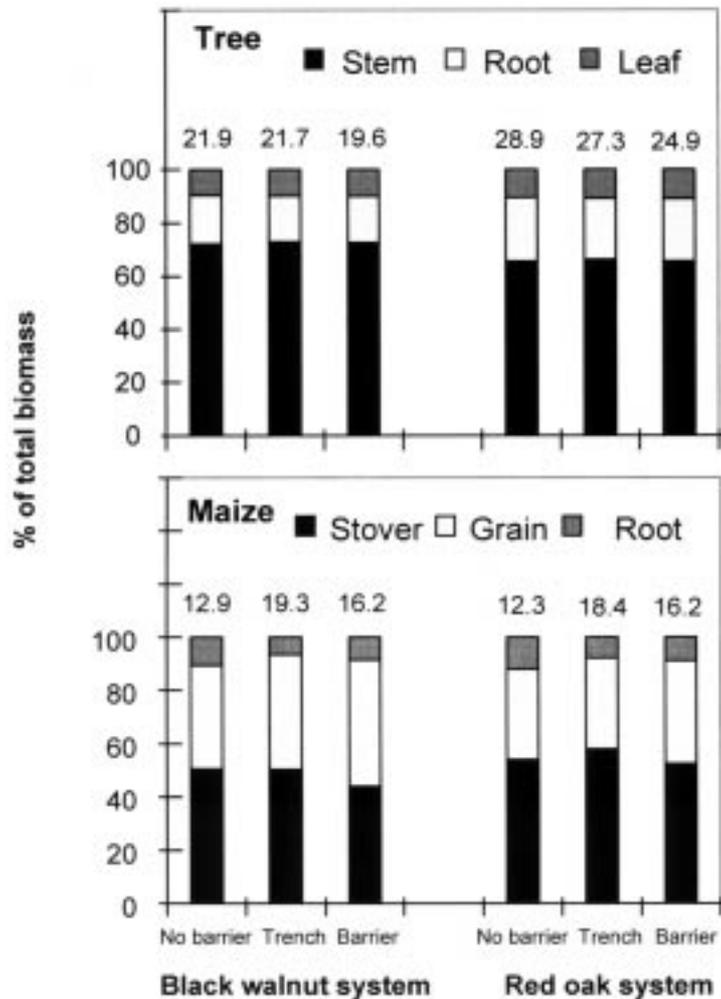
Figure 5. Standing biomass one year after root-zone treatment for tree and maize components in alley cropping systems in Indiana, USA. Total production (Mg ha^{-1}) to a depth of 90 cm is shown at the top of each bar.

cropping system (Figure 3). The greater reductions in yield in both black walnut and red oak systems when tree and maize roots interact indicates a higher degree of below-ground competition for water and/or nutrients than for light.

Similar results have been reported for alley cropping in the tropics where preventing root competition resulted in normal grain yield irrespective of shading by tree rows (Singh et al., 1989). For example, irrespective of intense shading by *Leucaena leucocephala* Lam. De Wit tree rows (as much as 85%), sorghum (*Sorghum bicolor* Moench.) yield was as high as the monoculture
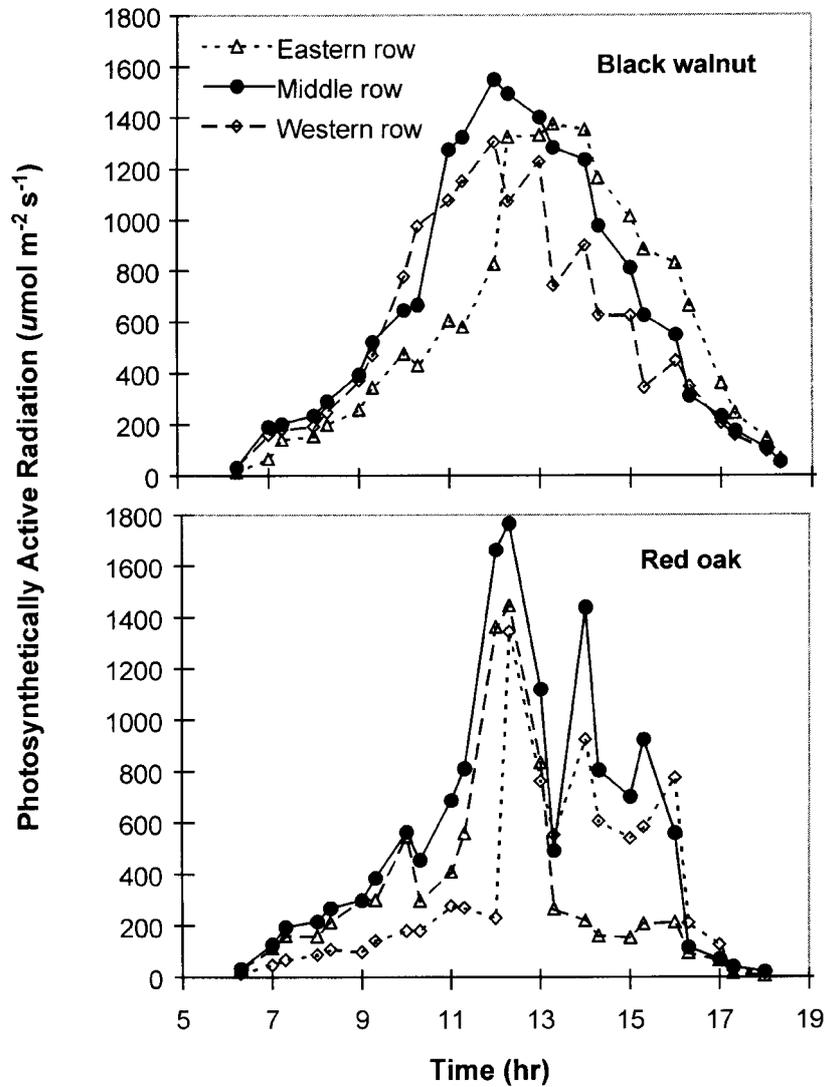
Figure 6. Typical spatial pattern of incident PAR in black walnut and red oak alleys by row position (eastern row, middle row, and western row) during the course of the day in midwestern USA alley cropping systems.

(control) when below-ground competition was prevented by a root barrier in semiarid India (Singh et al., 1989). In a more recent study in the tropics, Leihner et al. (1996) reported similar results for maize. These authors concluded that shading played only a minor role in competition at the tree-crop interface. However, a study conducted in a temperate alley cropping system in China showed significant influence of PAR on grain yield of winter wheat

(Chirko et al., 1996). Since the wheat was irrigated and fertilized, these authors attributed the yield reductions to reduced PAR, which accounted for 93% of the variation in yield. Since no attempt was made to separate the effects of below-ground interaction, some of this variation might be due to competition for water and/or nutrients.

Net photosynthesis

As suggested by Monteith (1972), a reduction in incident and absorbed PAR can cause reduced crop photosynthesis and thereby a decrease in crop yield. However, photosynthesis is only one of the determinants of dry matter production. Plant leaf area, leaf area density, leaf area duration, and losses of assimilate by dark respiration are also important aspects of crop production (Lawlor, 1995). In this study, mid-day net photosynthesis (P_{net}) of maize exhibited significant temporal differences ($P < 0.001$) during the growing season (Figure 7). Maize P_{net} was higher early in the growing season and decreased with the aging of plants. The root-zone treatments exhibited no significant effects on maize P_{net} in either black walnut ($P = 0.245$) or red oak (0.078) alley cropping systems under similar PAR. Further, P_{net} exhibited no significant spatial differences among plants in the eastern, middle, and western rows during mid-day when light availability was uniform across the alley ($P = 0.604$ for black walnut and $P = 0.693$ for red oak). However, P_{net} increased as PAR increased and reached a plateau at about 1700 μmol m^{-2} s^{-1}
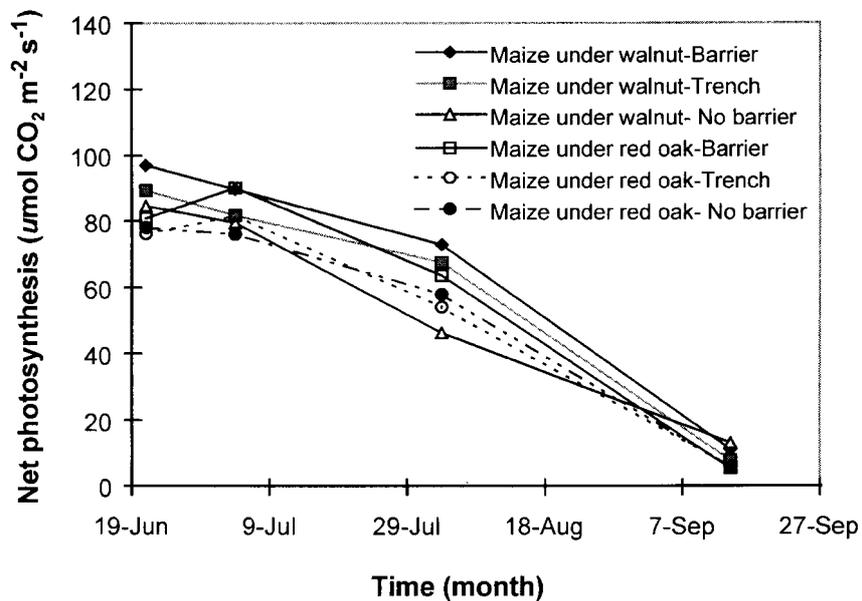

Figure 7. Temporal changes in P_{net} of maize during the 1996 growing season in a midwestern USA alley cropping system.

(Figure 8a), a typical C_4 photosynthetic response to PAR. This pattern is further evident in diurnal P_{net} measurements of maize (Figure 8b) where P_{net} responds to PAR patterns. Since maize P_{net} is greatly reduced at lower PAR, it is reasonable to expect less dry matter production and a decline in grain
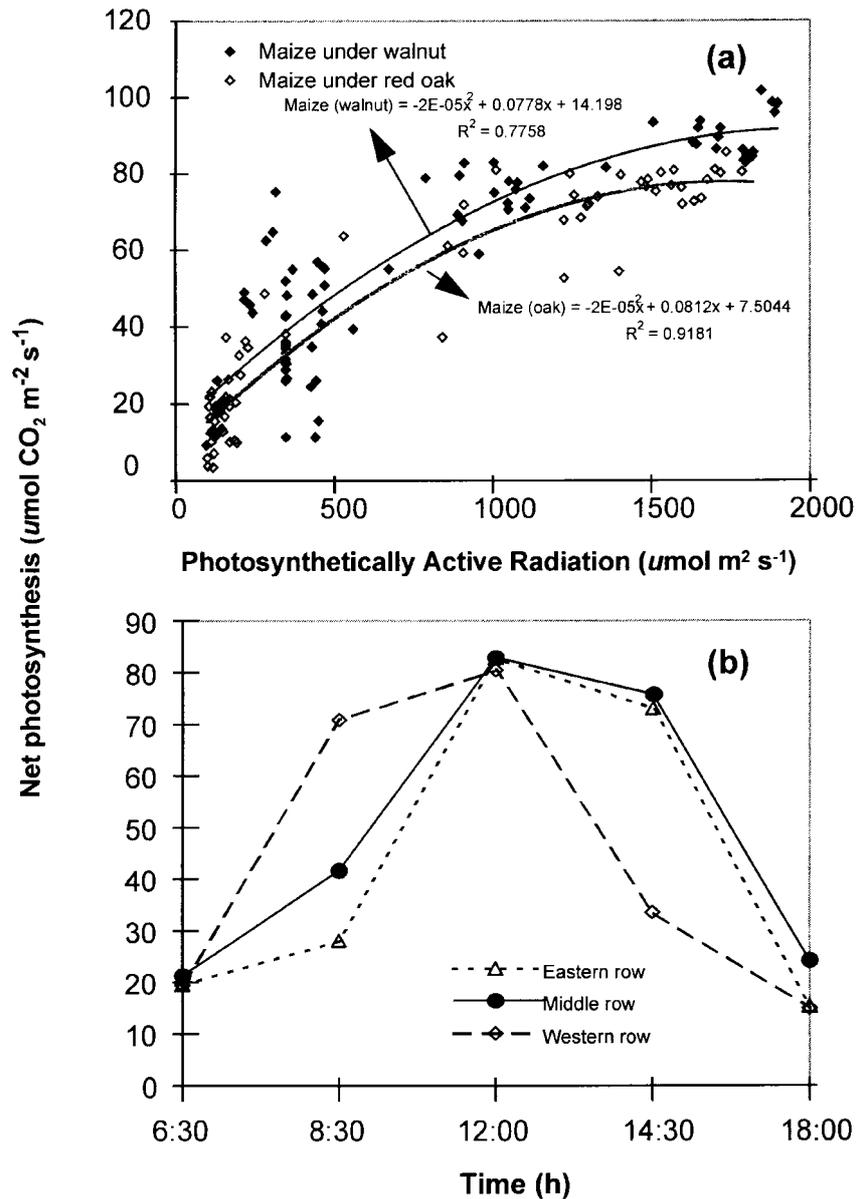

Figure 8. (a). P_{net} as a function of PAR in maize and (b) typical diurnal pattern of maize P_{net} by row position in a midwestern USA alley cropping system.

yield as a result of shading of outer rows. However, we did not observe any significant yield reductions in the external rows of maize in comparison to the middle rows when isolated from below-ground interactions (Figure 3).

Since preventing below-ground root interaction resulted in maize yields comparable to monoculture yields, competition for light can be assumed to be minimal at this stage of system development. Below-ground competition for water (Jose et al., in press, a) and to a limited extent nutrients (Jose et al., in press, b) appears likely in our alley cropping system. It is possible that competition for these below-ground resources has led to reduced leaf area in maize plants (Table 1) which results in lower light interception and thereby lower P_{net} on a canopy basis. The absorbed PAR and the resultant canopy P_{net} has a stronger influence on growth and grain yield than the diurnal differences in P_{net} in response to incident radiation. Otherwise, we would have seen similar inter-row grain yield in all the three treatments due to similar spatial and temporal patterns of incident PAR. Shorter leaf area duration in water stressed plants may be another possible mechanism causing lower canopy P_{net} and thereby lower yields. For black walnut, potential allelopathic interaction can impact interplanted crop yields. In allied research, we have shown that, though maize can be injured by the allelochemical juglone, soil concentrations are low enough to have little impact in our soil type (Jose and Gillespie, 1998a,b).

Conclusions

In our alley cropping trial, maize grain yield varied both spatially (within the alley) and temporally. In general, maize in the black walnut alley cropping had a higher grain yield than the red oak system. Grain yield also varied significantly between the treatments. Although tree biomass and biomass allocation varied by tree species, no treatment differences were observed.

Table 1. Average leaf area (and standard error) of maize (102 days after planting) in three different root-zone treatments for black walnut and red oak alley cropping systems in the midwestern USA.

Treatment	Row	Corn leaf area (m^2 $plant^{-1}$)	
		Black walnut[a]	Red oak[b]
Barrier	1	0.62 (0.02)	0.54 (0.02)
	3	0.59 (0.03)	0.57 (0.02)
Trench	1	0.60 (0.03)	0.58 (0.01)
	3	0.58 (0.02)	0.56 (0.02)
No barrier	1	0.50 (0.02)	0.41 (0.03)
	3	0.52 (0.03)	0.52 (0.02)

[a] Significant treatment effect ($P < 0.001$).
[b] Significant treatment effect ($P < 0.001$) and row effect ($P = 0.011$).

However, maize biomass and biomass allocation varied by tree species and by root zone treatments. At this stage of system development, shading of the external rows does not seem to be critical in controlling grain yield in our alley cropping system. Where root systems of the trees had been isolated from root systems of the maize crop, maize yields were uniform across the alley and comparable to those in adjacent fields where corn was grown with traditional monocultural practices. This uniformity occurred despite the measured shading effect of the trees, now 7 to 8 m tall, and associated photosynthetic response of maize plants. Where root systems were unrestricted, the pattern of reduced yields in outside rows remained, indicating a negative interaction among the perennial and annual plants, an interaction that was below-ground rather than above-ground. Thus, the ecological potential of this system is defined by below-ground processes and resources, and light, at least at this stage plays only a secondary role. However, light may become a limiting factor as the trees grow larger with denser canopies. These trees are managed for veneer production with annual pruning. And pruning significantly lowers canopy leaf area while raising the height of the canopy, allowing better light penetration into the alley. Thinning of trees to the desired number may also periodically increase light availability in the alleys. Root pruning resulted in reduced diameter growth in black walnut but less so in red oak. Currently, diameters have only been measured for three years after root pruning. Long-term studies may show that there is an initial drop in growth but a return to normal growth once roots find new places to grow within the severed zone.

Acknowledgements

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