Production of soybean associated with different hybrid poplar clones in a tree-based intercropping system in southwestern Québec, Canada

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ABSTRACT

In tree-based intercropping systems, trees, especially hybrid poplars (HP), can compete with crops for light, water and nutrients, resulting in a decrease in crop production. Some tree management characteristics, such as plantation density and tree species selection, may help to partially control this competition. The aim of this study was to analyse the effect of HP competition on yield and yield components of a soybean intercrop. Soybean was added to a HP–hardwood plantation which was established in 2000 and composed of alternate rows spaced 6 m (field A) and 8 m (field B) apart. The experimental design permitted the comparison of the combined effects of HP clones (TD-3230, DN-3308, NM-3729), orientation with respect to HP row (East, West) and distance from the HP row. A thinning was performed at the beginning of 2006 to increase the initial 2 m-spacing between HP within each row to a final 6 m-spacing. Percent total light transmittance (PTLT) was measured from soybean emergence to grain filling (VE-R6). Soil water content (WC) and soil N mineralisation (NMIN) were determined at two different periods corresponding to distinct soybean reproductive stages: (1) from flowering to pod formation (R1–R4) and (2) during grain filling (R5–R6). In 2005, PTLT, soil WC, soil NMIN (for R1–R4), soybean yield and yield components were significantly reduced near the HP row (2 m). The number of pods per m² contributed more to the variation in soybean yield than did the 100-seed size. Yield and number of pods per m² were highly correlated to PTLT, soil WC (R1–R4) and NMIN (R1–R4). An interaction between clone and orientation was found for field A. On the east side of the HP row, soybean yield with NM-3729 or DN-3308 was significantly higher than that with TD-3230, whereas it did not differ from that with the clone on the west side of the field. In field B, a significant interaction between orientation and distance was observed for PTLT and the number of pods per m². PTLT and number of pods per m² showed less variability on the west side compared to the east side. In 2006, a more regular PTLT distribution with respect to different orientations and distances from the HP row was observed and compared with that in 2005. Similarly, soil WC, soil NMIN, soybean yield and yield components were more uniform in 2006. These results suggest that HP clone selection, tree spacing within the rows, row spacing, orientation, and silvicultural treatments such as thinning may be useful to control the negative effects of HP competition on the intercrop.
develops, as well as the age and species composition of the system.

In a study of a TBI association of 9- to 10-year-old HP (P. deltoides Bartr. ex Marsh × P. nigra L.) and soybean (Glycine max (L.) Merr.) established in Guelph, Canada, Reynolds et al. (2007) concluded that competition for light was the principal factor limiting soybean yield. However, their study did not distinguish the effects of this TBI system on the yield components so that the critical phases in which soybean is more sensitive to the availability of resources could be identified. According to Brun (1978) and Jiang and Egli (1995), canopy photosynthesis has a greater effect on soybean yield during the reproductive period [R1–R8 stages (Fehr et al., 1971)] than during the vegetative period (emergence to R1). Several studies have shown that light interception by artificial shade structures, at different times during the reproductive period, reduces soybean yield, principally by influencing pod number. Seed size remains unaffected (Schou et al., 1978; Board et al., 1995; Kakiuchi and Kobata, 2006). These results suggest that yield is more sensitive to shading during flowering and pod formation (R1–R4) than during seed filling (R5–R6). With respect to competition for water, Sionit and Kramer (1977) observed that water stress, when applied during seed filling, resulted in a greater reduction in yield and seed size when than a comparable stress applied during flowering. The authors emphasised that pod number was negatively affected when the water stress occurred at the beginning of pod formation.

Despite the fact that soybean productivity in TBI systems tends to decline as competition from trees increases, certain silvicultural treatments, such as the choice of tree species and clones (Dhyani and Tripathi, 1999; Puri et al., 2002; Reynolds et al., 2007) as well as plantation density (Yin and He, 1997; Shanker et al., 2005), may limit the competitive effect. Plantation density depends on the spacing between the trees as well as the initial spacing of the trees within the same row. Density can also be adjusted by thinning. The association of HP and hardwood species arranged in alternate rows (Thevathasan and Gordon, 2004) appears to be a very promising system, which may help to reduce shading effects and delay crown closure.

In this study, due to the duration of time necessary for trees to grow in temperate regions, the TBI system was created by sowing soybean in an already existing tree plantation. Soybean yield and yield components were measured in 2005 at low HP spacing (2 m) in the same row. Although such a low spacing is unusual in TBI systems, we reasoned that it could help to detect quickly the possible effects of HP clone and tree row orientation, and to better understand the relative importance of HP competition for light and belowground resources. Soybean yield and yield components were re-evaluated in 2006 at higher HP-row spacing (6 m), following a HP thinning. The objectives of the present study consist of: (i) comparing the effects of three HP clones (TD-3230, DN-3308 et NM-3729), two orientations (East and West from the HP row) and various distances with respect to the HP row on the percent total light transmittance (PILT), as well as soybean yield and the individual soybean yield components; (ii) comparing the effects of various distances with respect to the HP row on the soil water content (WC) and nitrogen mineralisation (NMIN), at two different periods corresponding to distinct soybean reproductive stages (R1–R4 and R5–R6); and (iii) determining the relationship between environmental factors (PILT, soil WC, NMIN) and the soybean yield variables.

2. Materials and methods

2.1. Site characteristics

The study was conducted in St-Rémi (45°14′N, 73°40′W; altitude, 53 m), in southwestern Québec. Between 1971 and 2000, an average annual temperature of 6 °C, an average annual number of degree-days (above 5 °C) totalling 2031 and an average annual precipitation of 1027 mm were recorded in the St-Rémi region (Environment Canada, 2008). Over the two years of the study, in 2005 and 2006, average monthly temperature between June and October represented 100 and 103% of the 30-years monthly average (15.4 °C), respectively. Average monthly precipitation between June and October represented 107 and 94% of the monthly average (96 mm) in 2005 and 2006, respectively. The soil is classified as an orthic melanic brunisol (Agriculture Canada Expert Committee on Soil Survey, 1987) with a loam soil texture (19% clay, 34.5% silt and 46.5% sand) with moderate to imperfect drainage, a cation exchange capacity of 20.6 cmolc kg⁻¹, a total N content of 3 g kg⁻¹, a total C content of 30 g kg⁻¹, and a pHwater of 6.9 in the 0–15 cm layer.

2.2. Vegetative material, experimental design and treatments

The original experimental design, established in 2000, was composed of two adjacent fields (A and B) separated by a distance of 20 m. The fields differed in the spacing between rows of hardwoods and HP (A = 6 m and B = 8 m). Each of the fields contained five HP rows and four rows of hardwoods. A row of HP was present on both sides of each hardwood row. The rows of trees were oriented at 310° (NW–SE), which corresponds to the orientation of the fields in the study region. Each field (A and B) was divided into four experimental blocks perpendicular to the direction of the slope. Each block consisted of three plots arranged in the direction of the slope. Each plot contained one of the three clones being evaluated: TD-3230 (P. trichocarpa Torr. & Gray × P. deltoides cv. Boelare), DN-3308 (P. deltoides × P. nigra cv. Regenerata Bårdät H’auerime), NM-3729 (P. nigra × P. maximowiczii Henry cv. Max S). Typically, TD-3230 clone has a dense, narrow crown of moderately rising branches. DN-3308, in contrast, is characterised with a narrowly cylindrical crown of short rising branches, but often tends to be broadly rounded and irregular as it grows. NM-3729 has a large, narrowly egg-shaped crown of long, gently to sharply rising branches (Eckenerwalder, 2001). The clones were randomly assigned to the plots. From 2004 to 2006, a soybean crop was integrated into the plantation. In the present study, each experimental plot was bounded on each side by a row of hardwood species, with two alleys separated in the middle by one row of HP (Fig. 1).

In each row, 20-cm long rooted cuttings of HP were planted at 2 m spacing. Nine cuttings of each clone were planted adjacent to each other. The HP were pruned twice (2003 and 2005) with the goal of releasing the top third and top half of their boles in 2003 and 2005, respectively. A thinning, in the winter of 2006, permitted the spacing between HP in each row to be increased from 2 to 6 m, thereby decreasing their density from 417 to 139 stems ha⁻¹ in field A and from 313 to 104 stems ha⁻¹ in field B. The hardwood tree species, black walnut (Juglans nigra L.) and white ash (Fraxinus americana L.), were planted at 3 m spacing in the rows, in groups of 3 seedlings per species. However, given that the hardwoods were smaller (average height of 2.4 and 3.2 m in 2005 and 2006, respectively) than the HP, their influence was considered to be negligible over the course of this study. For this reason, the treatment combinations were planned to isolate the effects of the HP clone, the orientation with respect to the HP row and the distance from the HP row.

The soybeans (cv. S03-W4) were sowed on June 11, 2005 and July 3, 2006. The 2006 sowing was delayed because of abundant precipitation in June. Following superficial (0–10 cm) soil preparation, the soybeans were sowed with a no-till planter at a density of 50 plants m⁻² with spacing of 38 cm between rows.
Before sowing, the soil was amended with a N–P₂O₅–K₂O fertiliser, (300 kg ha⁻¹ of 5–27–24 in 2005 and 275 kg ha⁻¹ of 9–24–21 in 2006). A conventional herbicide (mixture of cloroanisulam-methyl, quizalofop-p-ethyl and thifensulfuron-methyl) was applied to the soybean at the 2–3 trifoliate leaf stage. An uncultivated strip, 2.3 m in width, was maintained along each row of trees. Repression of herbaceous vegetation in this strip was assured by a continuous band of black polythene-film mulch and a localised application of glyphosate at the mulch–soybean interface at the end of May.

2.3. Measurements

2.3.1. Percent total light transmittance (PTLT)

The PTLT was measured using hemispherical image analysis, which permitted a precise estimate of percentage photosynthetically active radiation (PAR) (Gendron et al., 1998). In August 2005 and 2006, hemispherical photographs were taken at 120 locations in field B. These locations were distributed in transects perpendicular to the rows of trees in such a manner that each combination of block (n = 4) × clone (TD-3230, DN-3308, NM-3729) × orientation (East, West) × distance (2, 3, 4, 5 and 6 m) was represented (Fig. 1). The hemispherical photographs were taken with a digital camera (Nikon Coolpix 990, Tokyo, Japan), equipped with a hemispherical lens (Nikkor fisheye converter FC-E8). The camera was positioned on a tripod 1 m above the soil surface. The colour photos were converted into binary mode using image editing software (Photoshop®, Adobe Systems Inc., San Jose, CA, USA), thus enabling the light flecks appearing on the leaves and tree trunks to be removed manually (Paquette et al., 2007). These binary images were then analysed with Gap Light Analyser software (Frazer et al., 2000), using correct sun and sky parameters for the region (Canham, 1988). A magnetic correction of 50°W was applied to correct the orientation of the rows of trees (310°) with respect to true north. PTLT calculations, which integrate the fractions of diffuse and direct light, were made for the period between June 15 and September 30, at a temporal resolution of 1 min and a spatial resolution of 36 azimuth by 18 zenith sky regions. This permitted estimation of the average PAR during the soybean growing season between VE (emergence) and R6 (full seed).

2.3.2. Soil water content (WC)

A previous study showed that soil WC in the fields studied was not affected by either HP clone or orientation with respect to HP row (Rivest et al., 2005). The soil WC was therefore only studied as a function of the effect of distance from HP row. Soil WC (10-cm depth) was measured in field B, in the plots containing clone NM-3729, east of the HP row, in such a manner that each combination of block (n = 4) × distance (2 and 5 m) was represented (Fig. 1). On two of the four sampling dates of each year, soil WC was characterised gravimetrically (ca. 10 g subsample oven-dried at 105°C for 24 h) from soil samples collected for the determination of soil NMIN (July 20 and September 6, 2005; July 30 and September 21, 2006). The soil WC was characterised using a time-domain reflectometry (TDR) sensor (Delta-T, Burwell, Cambridge, UK) on the other two sampling dates (July 31 and August 26, 2005; August 18 and September 27, 2006). In both years the average soil WC on the first two sampling dates (one by gravimetry and the other by TDR) was calculated to characterise soil WC during flowering and pod formation (R1–R4), when the pod number was determined. In the same manner, the measurements on the last two sampling dates were used to estimate soil WC during seed filling (R5–R6), when the 100-seed size was determined. The soil WC measurements were always preceded by a period of at least 72 h without precipitation.

2.3.3. Soil nitrogen mineralisation (NMIN)

The rate of net soil NMIN (ammonification + nitrification) was determined from laboratory-based aerobic incubations, a reliable method for estimating soil N fertility (Pare´ and Van Cleve, 1993). The soil sampling dates (July 20 and September 6, 2005; July 30 and September 21, 2006) and the duration of the incubations (28 days) permitted to estimate soil nitrogen availability during the R1–R4 period and the R5–R6 period. The observations were made in the same plots as those used for soil WC measurements (four blocks, clone NM-3729, eastern orientation, 2 m and 5 m) (Fig. 1). Each observation consisted of a homogeneous composite sample of 8 soil cores (10 cm depth x 3.3 cm diameter), which were roughly screened (5-mm mesh). Before and after incubation, NH₄⁺ and NO₃⁻ were extracted from subsamples (ca. 20 g) mixed with
100 ml of aqueous KCl (1 M), shaken for 1 h, and then filtered (Whatman No. 5). NH\textsubscript{4}\textsuperscript{+}–N and NO\textsubscript{3}\textsuperscript{−}–N concentrations of the extracts were analysed colorimetrically using a Technicon Autoanalyzer (Pulse Instrumentation, Saskatoon, SK, Canada). The soil samples were incubated in darkness at a constant temperature of 22 °C, in 500 ml Mason jars covered with polyethylene film to minimise evaporation. The soil NMIN rate was calculated by subtracting the NH\textsubscript{4}\textsuperscript{+} and NO\textsubscript{3}\textsuperscript{−} concentrations measured before incubation (t\textsubscript{o}) from those measured after incubation (t\textsubscript{28}). The soil sampling dates were considered to be (t\textsubscript{0}).

2.3.4. Morphological characteristics of the HP clones

Total height and crown diameter of the three HP clones were assessed in both fields in 2005 and 2006. Total height of the HP was determined by calculating the average of the height at the beginning and the end of each growing season. This represents a reasonable estimate of average height of the HP during the soybean growing season. Heights were calculated with the Vertex III hypsometer (Haglof, Sweden). Crown diameter was calculated taking into account four measures per tree of the crown base projected radius (in mid-July) in the cardinal NE, SE, SW and NW directions. Crown base projected radius was obtained using a measuring tape.

2.3.5. Soybean yield and yield components

In each sampled distance plot (1.14 m × 12 m), soybeans were manually harvested at full maturity (October 19, 2005 and November 1, 2006) in two 4 m\textsuperscript{2} quadrats (1.14 m × 3.51 m) in 2005, and in two 3 m\textsuperscript{2} quadrats (1.14 m × 2.63 m) in 2006 (Fig. 1). Each quadrat (sub-sample) contained three consecutive rows of soybean. After a manual threshing of the samples, the seeds were cleaned and dried at 40 °C for 72 h. The yield and 100-seed size were then determined. In each sampled distance plot, the number of pods per m\textsuperscript{2} was determined before harvesting in two 1 m\textsuperscript{2} quadrats (1.14 m × 0.88 m). The number of pods per m\textsuperscript{2} was measured by multiplying the average number of plants per m\textsuperscript{2} by the average number of pods per plant measured from 15 plants per quadrat. In each field (A and B), 4 to 8 quadrats (2 per block; 4 blocks (A and B) in 2005; 2 blocks (A) and 3 blocks (B) in 2006) were sampled for each of the combinations of clone (TD-3230, DN-3308, NM-3729) × orientation (East, West) × distance (A: 2, 3 and 4 m; B: 2, 3, 4, 5 and 6 m (2005) or 2 and 5 m (2006)) (Fig. 1). This corresponds to a total of 144 samples for field A and 240 samples for field B in 2005, and 72 samples in each field in 2006. To obtain the reference values (without the influence of trees), 12 (2005) or 8 (2006) plots were also sampled at a distance of more than 12 m from both the northern and southern ends of the rows of trees in field A as well as the southern ends of the rows in field B.

2.4. Statistical analyses

The two fields (A and B) and the two study years (2005 and 2006) were evaluated independently. Analysis of variance (ANOVA) using the Proc Mixed procedure of SAS 8.2 for Windows (SAS Institute, Cary, NC, USA) was performed in accordance with the experimental design. For the PTLT, soybean yield and yield components, the sources of variation were: block, HP clone, orientation with respect to HP row, distance with respect to HP row and the interactions among these factors. Block and distance were sources of variation for soil WC and NMIN. For simplicity reasons, block effect and interactions containing it are not shown in Tables 1 and 2, and Figs. 2 and 3. However, all significant effects of interactions with blocks are reported in Section 3. When the normality and homogeneity of variance were not respected, data non-parametric (rank) transformation was employed. Tukey’s test was used to compare means. A significance level of 5% was retained for all analyses. An analysis of the correlation between environmental parameters (PTLT, soil WC, NMIN) and the different soybean yield variables was conducted. Values (n = 6–8 per distance) spatially common to each of the sampled parameters (clone NM-3729, eastern orientation, 2 and 5 m) were used for correlation analyses.

3. Results

3.1. Percent total light transmittance (PTLT)

In 2005, the PTLT was significantly affected by the interaction between distance and orientation of the crop with respect to the HP row (Fig. 2a). Throughout the study area, for distances between 2 and 5 m, PTLT increased significantly from one distance to the next, stabilising between 5 and 6 m. This variation in PTLT was smaller on the west side of the HP row than on the east side. In addition, at all distances, PTLT on the west side of the HP row was significantly greater than on the east side (results not presented). Although not significant (p = 0.08), a tendency for an effect of the interaction between orientation and HP clone was also detected: east of the HP row, PTLT was 70% with DN-3308, 66% with

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Stage growth</th>
<th>P value</th>
<th>Distance (m) from hybrid poplar row</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
<td>5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil water content (X%)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>R1–R4</td>
<td>0.014</td>
<td>20.0 (5.0) a</td>
</tr>
<tr>
<td></td>
<td>R5–R6</td>
<td>0.003</td>
<td>18.2 (3.3) a</td>
</tr>
<tr>
<td>Net N mineralisation (mg kg&lt;sup&gt;−1&lt;/sup&gt; d&lt;sup&gt;−1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>R1–R4</td>
<td>0.021</td>
<td>0.91 (0.24) a</td>
</tr>
<tr>
<td></td>
<td>R5–R6</td>
<td>0.996</td>
<td>0.98 (0.35) a</td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil water content (X%)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>R1–R4</td>
<td>0.230</td>
<td>27.1 (2.8) a</td>
</tr>
<tr>
<td></td>
<td>R5–R6</td>
<td>0.724</td>
<td>30.9 (1.5) a</td>
</tr>
<tr>
<td>Net N mineralisation (mg kg&lt;sup&gt;−1&lt;/sup&gt; d&lt;sup&gt;−1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>R1–R4</td>
<td>0.271</td>
<td>0.41 (0.14) a</td>
</tr>
<tr>
<td></td>
<td>R5–R6</td>
<td>0.158</td>
<td>0.84 (0.10) a</td>
</tr>
</tbody>
</table>

R1–R4, from flowering to pod formation; R5–R6, during grain filling. Values in each row followed by different letters are significantly different at p < 0.05 (Tukey’s multiple means comparison test). Standard deviations are given in parentheses.

<sup>a</sup> n = 16 per distance.

<sup>b</sup> n = 10 per distance.
NM-3729 and 60% with TD-3230 (Fig. 2a). In 2006, although a significant interaction between HP clone, orientation and distance was noted, PTLT was more uniform among distances (in comparison with 2005), particularly for clones NM-3729 (east side) and TD-3230 (west side), for which no significant difference was measured (Fig. 2b).

3.2. Soil water content (WC) and soil nitrogen mineralisation (NMIN)

In 2005, soil WC at 5 m was 23 and 30% greater than that at 2 m during the R1–R4 and R5–R6 periods, respectively (Table 1). However, a significant interaction between block and distance (p < 0.0001 for R1–R4, and p = 0.001 for R5–R6) limits inference of this result. Soil NMIN at 5 m was significantly greater by 20% than that at 2 m, during the R1–R4 period, but distance had no effect during the R5–R6 period. In 2006, no effect of distance was noted for soil WC or soil NMIN, for either reproductive period.

3.3. Morphological characteristics of hybrid poplars

In both fields (A and B), HP height did not differ among clones in either 2005 or 2006 (Table 2). Crown diameter of clone TD-3230 was significantly greater than that of clone DN-3308, in field A, in 2005. No significant difference was observed in field B in 2005, or in field A and B in 2006.

3.4. Soybean yield and yield components

In 2005, the interaction between HP clone and orientation significantly affected yield in field A (Fig. 3a). East of the HP row, soybean yields with HP clones NM-3729 and DN-3308 were significantly greater by 28 and 17%, respectively, than that with clone TD-3230. West of the row, there was no difference in soybean yield among the clones. In field B, yield with NM-3729 and DN-3308 tended to be higher than that with TD-3230 (p = 0.11) (Fig. 3g). However, inference of this result is limited by a significant

**Table 2**

<table>
<thead>
<tr>
<th>Tree height (m)</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD-3230</td>
<td>8.4 (0.6)</td>
<td>11.4 (1.1)</td>
</tr>
<tr>
<td>DN-3308</td>
<td>8.6 (0.8)</td>
<td>10.6 (0.7)</td>
</tr>
<tr>
<td>NM-3729</td>
<td>8.6 (0.8)</td>
<td>10.8 (0.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crown diameter (m)</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD-3230</td>
<td>4.0 (0.1)</td>
<td>3.7 (0.3)</td>
</tr>
<tr>
<td>DN-3308</td>
<td>4.2 (0.1)</td>
<td>3.6 (0.3)</td>
</tr>
<tr>
<td>NM-3729</td>
<td>4.2 (0.1)</td>
<td>4.0 (0.7)</td>
</tr>
</tbody>
</table>

Field A, spacing = 6 m; field B, spacing = 8 m. For each year, values in each row followed by different letters are significantly different at p < 0.05 (Tukey’s multiple means comparison test). Standard deviations are given in parentheses.

a n = 36 (2005) and 12 (2006) for each clone.

b n = 20 (2005) and 12 (2006) for each clone.

**Fig. 2.** Percent total light transmittance in 2005 (a) and 2006 (b) as influenced by hybrid poplar clone, orientation and distance (m) from the hybrid poplar row, in a hybrid poplar-hardwood-soybean intercropping system in southwestern Québec, Canada. The means were calculated from observations made in field B (spacing = 8 m). Vertical lines indicate the standard deviations. The significant ANOVA probability values (p) are indicated in the upper right corner. For each of the combinations of clone, orientation and distance, the means with different letters are significantly different at p < 0.05 (Tukey’s multiple means comparison test).
### Field A: spacing between tree rows = 6 m

(a) Yield (g/m²) in 2005

<table>
<thead>
<tr>
<th>Clone</th>
<th>Orientation</th>
<th>Distance</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD</td>
<td>a</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>DN</td>
<td>a</td>
<td>3</td>
<td>0.0005</td>
</tr>
<tr>
<td>NM</td>
<td>a</td>
<td>3</td>
<td>&lt;0.0001</td>
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</table>

(b) Yield (g/m²) in 2006

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Distance</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>3</td>
<td>0.02</td>
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</table>

(c) Number of pods per m² in 2005

<table>
<thead>
<tr>
<th>Distance</th>
<th>p-value</th>
</tr>
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<tbody>
<tr>
<td>3</td>
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</table>

(d) Number of pods per m² in 2006

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<th>Orientation</th>
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<tbody>
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(e) 100-seed size (g) in 2005

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<th>p-value</th>
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(f) 100-seed size (g) in 2006

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</thead>
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<tr>
<td>3</td>
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### Field B: spacing between tree rows = 8 m

(g) Yield (g/m²) in 2005

<table>
<thead>
<tr>
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</tr>
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<tbody>
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(h) Yield (g/m²) in 2006

<table>
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<th>p-value</th>
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(i) Number of pods per m² in 2005

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(j) Number of pods per m² in 2006

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(k) 100-seed size (g) in 2005

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(l) 100-seed size (g) in 2006

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**Fig. 3.** Yield and yield components of soybean in 2005 (a, c, e, g, i, k) and 2006 (b, d, f, h, j, l) as influenced by hybrid poplar clone, orientation and distance (m) from the hybrid poplar row, in a hybrid poplar-hardwood-soybean intercropping system in southwestern Quebec, Canada. TD, TD-3230; DN, DN-3308; NM, NM-3729; W, west; E, east; 2, 3, 4, 5 and 6: distance (m) from hybrid poplar row. Each result is presented in the form of an absolute value and a relative value (in parentheses), which indicates the absolute value as a function of the reference value (without the influence of trees, 100%). The significant ANOVA probability values (p) are indicated in the upper right corner. For each of the treatment combinations presented, the means with different letters are significantly different at p < 0.05 (Tukey’s multiple means comparison test). NS, not significant.

Despite a non-significant result (p = 0.13), a tendency for an effect of the interaction between orientation and distance was noted for field B, in 2005. At a distance of 2 m, soybean yield on the west side (113 g m⁻²) tended to be greater than that on the east side (101 g m⁻²), while yield remained uniform between east and west at other distances (3 to 6 m) (results not presented). In addition, a significant interaction between orientation and distance was observed in field B: the pod number per m² was more regular for west than for east of the HP row (Fig. 3i), which

Interaction between block and clone (p = 0.02). In the two fields (A and B), pod number per m² with NM-3729 was significantly greater than that with TD-3230 (Fig. 3c and i). In field B, the 100-seed size followed the inverse tendency observed for pod number per m²: it was significantly higher with TD-3230 than with NM-3729 (Fig. 3k). As was observed by Schonbeck et al. (1986), this result suggests that 100-seed size partially compensated for the reduction in pod number per m². In 2006, the soybean yield and yield components did not differ significantly among HP clones.
was also the case for PTLT (Fig. 2a). The same year, in field A, the pod number per m² for west of the HP row also tended to be superior to that for east of the row, although no significant difference was found (p = 0.11). A significant effect of orientation on 100-seed size was measured in field B in 2005. The 100-seed size was highest on the eastern side (Fig. 3f). A similar tendency was also measured in field A (p = 0.06). In 2006, an interaction between orientation and distance was observed in field A: at 2 m, the yield west of the HP row was 13% higher than that east of the row, while there was no difference between orientations at 3 and 4 m (Fig. 3b). The pod number per m² west of the HP row was significantly superior by 21% relative to the number east of the row in field A (Fig. 3d).

In 2005, maximum variation in soybean yield was observed under the effect of distance from the HP row (Fig. 3a and g). Yield was generally lowest at 2 m from the HP row and highest at 4 m (Field A) or 5–6 m (Field B). In 2006, a significant interaction between HP clone and distance in field B was noted. Yield between 2 and 5 m differed only for NMG-3729 (Fig. 3h). Overall, although significant, the effect of distance on yield was marginal in field B in 2006, considering that at 2 m, the yield represented 94% of that obtained at 5 m. In field A, there was no effect of distance on yield. In the two fields (A and B), both pod number per m² and 100-seed size did not differ with distance in 2006.

3.5. Relationships between soybean yield components and environmental parameters

In 2005, where the availability of resources was the lowest, that means at 2 m from the HP row (Table 1, Fig. 2a), yield was most highly correlated with PTLT, soil WC and soil NMIN during the R1–R4 period (Table 3). Pod number per m² was significantly correlated with PTLT, soil WC and soil NMIN during the R1–R4 period, while 100-seed size was not significantly correlated with any of these variables (Table 3). At 5 m from the HP row, the yield was significantly correlated with PTLT and soil WC measured during the R5–R6 period (Table 3). The two yield components were generally weakly correlated with the environmental parameters measured at 5 m, with the exception of 100-seed size which showed a strong negative correlation with PTLT. In 2006, the yield was only weakly correlated with the different environmental parameters at both 2 and 5 m from the HP row (Table 3). Similar results were also obtained for pod number per m², with the exception of a significant positive correlation with PTLT, at 5 m. 100-seed size exhibited a strong negative correlation with PTLT (2 m), soil WC (2 and 5 m) and soil NMIN (2 m) measured in the R5–R6 period (Table 3).

4. Discussion

4.1. Hybrid poplar-soybean interactions for growth resources under dense tree cover

In 2005, the greatest reduction in soybean yield was observed in proximity to the HP (2 m), where PTLT and soil WC were the lowest. Because aboveground interactions were not isolated from belowground interactions, the relative importance of the effects of competition for light and water cannot be identified with any degree of certainty. Nevertheless, despite the fact that it was correlated with soybean yield, it is worth mentioning that average soil WC, which was never less than 18.2% during the study, did not reach the permanent wilting point (−1.5 MPa). Indeed, other measurements (September 7, 2006) showed that an average daily (i.e. average of predawn and midday) plant water deficit of only −1.17 MPa was associated with a soil WC as low as 17.2%. In a TBL system similar to the one of the present study, Reynolds et al. (2007) also found that soil WC was significantly correlated with soybean yield. However, the authors emphasised that even though yield was correlated with PAR and net assimilation, it was not correlated with daily plant water deficit, indicating that competition for light was more limiting than competition for water. In their study, soil WC at 2 m from the HP row was only 5.6% (silt-loam to loam, mid-July, 5 cm depth), which is much lower than that measured in the present study, even though the soil texture was similar. On the other hand, although, in the present study, soil WC differed significantly between 2 and 5 m during seed filling (R5–R6), this was not the case for 100-seed size. This indirectly suggests that water availability did not reach a critical threshold during this period. According to Sionit and Kramer (1977), 100-seed size is very sensitive to water stress during the seed filling period.

At the HP–soybean interface, comparable results of PTLT, soybean yield and yield components to the effect of orientation, also lead to the conclusion that competition for light was more important than competition for water in 2005. An asymmetry of water availability as a function of orientation is not very plausible (Rivest et al., 2005; Chirko et al., 1996b). Even though soybean is a plant with a C₃ metabolism with relatively low light compensation...
and light saturation points, many studies have shown the importance of maximising light interception to optimise canopy photosynthetic rate and C accumulation (Sinclair, 2004). Egli and Yu Zen-wen (1991) found that soybean yield under an artificially imposed shade of 63% (applied from R1 to maturity), was reduced to 55% of the yield of the control treatment. In the present study, the yield obtained 2 m east of the HP row, where the shade of the trees (56%) (Fig. 2a) was the greatest, was 62% lower than the yield measured in the reference plots. In addition, as expected, under conditions of high tree shading, the pod number per m² contributed more to the variation in yield than did 100-seed size. For example, yield, pod number per m² and 100-seed size at 2 m of the HP row represented 45, 50 and 98% of those at 5 m, respectively (Fig. 3g, i and k). This suggests that soybean was clearly more affected by light interception during the R1–R4 period, when pod number is determined, than during the seed filling period (R5–R6).

Jiang and Egli (1993) also observed a significant reduction in pod number (per plant) under the effect of a 63% shade treatment applied between R1 and maturity. They indicated that this reduction in pod number was attributable to both increased flower and pod abortion and fewer flowers per plant. The reduction in other yield components, either vegetative (branch dry matter and branch node number) or reproductive (branch reproductive nodes and main stem pods per reproductive node) (Board et al., 1996), is probably also responsible for the decrease in pod number in the present study.

Since no tree-less control was included in the experimental design, competition for N cannot be proven. However, in 2005, during the R1–R4 period, soil NMIN was substantially reduced close to the HP row and closely correlated with the yield (r = 0.71, p = 0.11) and pod number per m² (r = 0.79, p = 0.06). Although N nutrition is not that important for soybean yield, the assimilation of soil nitrates could be critical during the flowering period (R1–R2) (Heatherly and Elmore, 2004). In temperate TBI systems, low rates of N mineralisation associated with low crop yield would indicate competitive interactions for N resulting in a decreased N uptake by the intercrop (Allen et al., 2005).

4.2. Tree management considerations

In 2006, a greater uniformity in PTLT, soybean yield and its components was observed. More uniform soil WC and NMIN in the alley were also measured. Although there was no unthinned control to infer the formal effects of thinning, there is considerable evidence that an important part of this greater uniformity in environmental and soybean yield variables could be attributed to the thinning performed in winter 2006. In fact, 66% fewer HP individuals were intercepting light and making demands on belowground resources, particularly close to the HP row. Overall, the 2006 results highlight the interest to further test the effect of thinning on crop yield, which is not well known in the temperate TBI systems because most experimental sites are still too young to perform that kind of test. There is also reason to believe that the HP pruning treatment at the end of 2005 (the second since establishment) also contributed to the increase in PTLT, especially close to the HP. In a TBI system containing HP (P deltoides × P nigra) approaching maturity, Dupraz et al. (2005) observed that, 2 m from the HP row, the PTLT associated with HP pruned to a height of 10 m (51%) was 24% greater than that associated with trees pruned to a height of 6 m (41%).

A significant effect of HP clone on soybean yield parameters was observed in 2005. In the context of optimising productivity of the intercrops, this result emphasises the importance of selecting the appropriate tree species and clones as suggested in other studies on TBI systems associating fast-growing tree species and soybean (Dhyan and Tripathi, 1999; Puri et al., 2002; Reynolds et al., 2007). In 2005, the yield and the number of pods per m² were generally lower with clone TD-3230, which was the one that tended to intercept the most light. Given that the crown diameter and tree height in field B, where PTLT was measured, did not differ among clones (Table 2), it is highly probable that TD-3230 developed lower crown porosity than the other two clones. Nevertheless, findings by Paquette et al. (2008), who implemented simulations of hybrid poplar growth at the St-Rémi site, suggested that clone TD-3230 moved from low light transmission at age 7, to moderate light transmission at age 12, and finally to most light being let through at age 20. The authors also emphasised that clone NM-3729 tended to intercept the most light at age 20. While assuming that HP and soybean compete for soil nutrients, it is also necessary to consider that resource use may vary among clones, as noted by Berthelot et al. (2000).

In the TBI system studied, the rows of trees were oriented at 310°, which is approximately mid-way between a north/south and an east/west orientation. As previously mentioned, near the HP, the PTLT, yield and number of pods per m² were lower east of the HP row than west of the row in 2005. These results are similar to those obtained by Dupraz et al. (2005), who observed that the availability of light and the yield of winter wheat 2 m from the HP row was lower on the east side of a row of trees with a north/south orientation and on the north side of a row oriented east/west. However, the authors mentioned that it is preferable to orient the row of trees in a north/south direction. This orientation is advantageous because, at mid-day, when the rate of photosynthesis is highest, only the row of trees is shaded (Reynolds et al., 2007). However, factors such as field orientation and drainage may present constraints when selecting how to orient the tree rows.

The experimental design of this present trial did not permit formal comparisons between field A and field B, or between the reference plots (without trees) and those of the TBI system. The observed differences in the response to treatments may nevertheless be considered to be indicative of general tendencies. Notably, the average yield of soybean in field B, which had a lower density of trees, was 30% higher (all years combined) than that of field A. These results compare favourably with those obtained by Yin and He (1997). Given that the height of the HP in field B was slightly less than that in field A (Table 2), the variation in yield between the two fields cannot be attributed totally to the density of the trees. Yet, the yield in field B was less variable among distances and orientations with respect to the HP row, being closer to those of the reference plots. In their synthesis on temperate TBI systems, Rivest and Olivier (2007) emphasised that plantation density is an important criterion to consider when light is the principal factor limiting the productivity of the intercrops. In this context, it appears desirable to favour TBI systems with wide spacing between trees in the same row, as suggested by the results of the present study in 2006. Wide spacing (15–30 m) between rows of trees is also desirable, because it decreases the proportion of non-productive land, facilitates the movement of agricultural machinery and may be better adapted to fields with subsurface drainage systems. However, optimal tree spacing should take into account the sum of intercrop and tree productivities, as well as environmental benefits. Row spacing in the present study (6 or 8 m) was initially chosen for the purposes of forest research and, therefore, should not be considered as a convention to follow in TBI systems.

The arrangement of the hardwood tree species and the HP in alternating rows constitutes, in its own right, a novel system. Through the incorporation of HP, this system offers the advantage of creating environmental conditions that are beneficial to the hardwoods (Gardiner et al., 2001) which, in exchange, allow the
field to remain open, thus favouring the intercrops. This was clearly illustrated in the present study since soybean yield in proximity of the hardwoods was similar to that of the reference plots. Furthermore, this type of system permits wood harvesting over the medium term (15–20 years) because of the presence of HP, which is not the case in TBI systems that incorporate only slow-growing hardwood species.

5. Conclusions

In the present study, the maximum reduction in soybean yield was observed at the HP–soybean interface under dense tree cover. Competition for light appeared to be more important than that for water. This is supported, among others, by a comparable response of PTLT, and of soybean yield and its components, to the effect of orientation with respect to HP row. Nonetheless, the effect of competition for water may be more evident during periods of prolonged drought. Certain results also indicate that competition for soil nitrogen in proximity of the HP row may be impart responsible for the observed reduction in soybean yield. Under intense competition for resources, the period of flowering and pod formation appears to be more critical than the seed filling period. The results obtained also suggest that it is possible to control the negative effects of competition for resources by the trees, particularly competition for light, by paying special attention to the selection of HP clones, tree spacing both within- and between-rows, row orientation, and silvicultural treatments such as thinning and pruning. However, intercropping and its associated interventions may also have a significant influence on the tree component and, consequently, on the overall productivity of the TBI system. So that a complete evaluation can be made of the HP-hardwood–soybean system, the influence of soybean (and its cultural practices) on tree growth, as well as on soil quality, must be studied further. This would provide the fundamental knowledge necessary to quantify the environmental and economic benefits of TBI systems in Canada.

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References


