Agroforest Syst (2015) 89:237–246
DOI 10.1007/s10457-014-9758-6

Maize yield patterns on the leeward side of tree windbreaks are site-specific and depend on rainfall conditions in eastern Canada

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Received: 24 July 2014 / Accepted: 24 October 2014 / Published online: 29 October 2014

Abstract Tree windbreaks may offer a range of potential advantages in terms of increased crop productivity and stability under climate change while providing multiple external benefits to society. The effects of windbreak on maize yields have not been assessed in a well-documented manner in eastern Canada, which is a major influential barrier limiting their adoption by farmers. In this study, we investigated the spatial distribution of maize grain yield in the leeward side of mature (average age, 30-years-old) single-tree row windbreaks that were located on four farm sites in southern Québec, Canada. We determined whether the sign and magnitude of windbreak effects on spatial patterns of maize yield varied across contrasting years with respect to rainfall conditions. The greatest yield variation was observed at the tree-crop interface (within 0.5–1H, where H = tree height), where substantial yield reductions occurred. In two sites, the magnitude of negative windbreak effects on maize yield at the tree-crop interface decreases in the wetter years. We found important maize yield variation among sampling positions between 2H and 20H (here considered as the shelter zone), with yield values often significantly higher than at 24H (here considered as a control zone with negligible tree shelter effects). The magnitude of this yield variation in the shelter zone generally decreased in the wetter years. In most cases, we estimated that the net effect of windbreak on maize yield (0.5–20H vs. 24H) was negligible. Significant net positive (16 %) or negative (−6 %) effects of windbreaks on maize production were found at one site only and occurred on two different years. We conclude that the sign and magnitude of windbreak effects on spatial patterns of maize grain vary considerably across farms and depend upon temporal variation in rainfall conditions in eastern Canada.

Keywords Tree-crop interaction · Shelterbelt · Crop production · Spatial yield variability · Climate change · Temperate agroforestry

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Introduction

An increasingly important challenge that is facing agriculture is the need to maintain or even increase crop yields in the face of climate change, while providing other ecosystem services such as maintaining or restoring biodiversity (Howden et al. 2007; Rey Benayas and Bullock 2012; Pretty et al. 2010). In North America and elsewhere in the temperate zone, tree windbreaks may offer a range of potential advantages, from increased crop productivity and stability under climate change, to optimization of inputs and resilience to disruption, to ecological sustainability (Brandle et al. 2004; Schoeneberger et al. 2012). Windbreaks are the most important and widespread agroforestry systems in Canada, where they have been readily adopted in the Prairie Provinces compared to eastern Canada (Thevathasan et al. 2012). Windbreaks provide high-value public benefits, particularly in terms of protecting soil, water, air and biodiversity (Kulshreshtha and Kort 2009). Windbreaks can also offer important benefits to farmers, especially through the improvement of agricultural production (Baldwin 1988; Kort 1988; Nuberg 1998). With respect to agricultural yields, windbreaks can moderate microclimate conditions, for example, through reductions in wind speed and turbulent air mixing, thereby increasing the efficient use of soil moisture by reducing evaporation from the soil surface leaving more water for crop growth; windbreaks can also protect crops from physical damage that can be incurred through aeolian transport of mineral soils (Armbrust 1982; Brandle et al. 2009). However, these potential microclimatic benefits can be offset by substantial yield reductions that result from intense tree competition with the crops for above- and belowground resources in the zone that is closest to the windbreak (Sudmeyer et al. 2002; Hou et al. 2003; Ding and Su 2010). This competition at the tree-crop interface appears to be a major factor causing reluctance among North American farmers to divert even a small proportion of their fields to windbreaks (Marchand and Masse 2008; Valdiva et al. 2012).

Although different literature syntheses have highlighted a global positive net effect of temperate zone windbreaks on crop yield (Kort 1988; Nuberg 1998; Brandle et al. 2009), a closer reading of several individual studies reporting these beneficial effects has revealed great variability in yield results. Indeed, crop yield response to windbreak shelters seems to be strongly dependent upon the edaphic and climatic context of the study and to vary widely with crop species, windbreak design, and geographic location (Brandle et al. 2004). In contrast, studies in temperate Australia concluded yield gains that could be attributed to the effects of shelter on microclimate were smaller than expected, especially for cereals, which was most likely due to the low soil water holding capacity of Australian soil (Cleugh et al. 2002). According to the temperate windbreak literature that we have amassed, the shelter effect on crop yield is equivocal. In eastern Canada, the inconsistent nature of the shelter effect on crop yield and the lack of information for this region are perceived as major barriers to the adoption of windbreaks by farmers (Tartera et al. 2012; Thevathasan et al. 2012). In this region, together with several other regions of North America, maize (*Zea mays* L.) is one of the most widely planted crops. Realistic estimates of the effects of windbreaks on maize yields are clearly needed if the widespread adoption of windbreaks is to occur in eastern Canada. Filling this knowledge gap would provide scientific support that would help improve decision-making with respect to the implementation of windbreaks in intensive agricultural systems of eastern Canada.

Maize has a C_4 photosynthetic pathway, therefore, is shade-intolerant. Previous studies in different temperate agroforestry systems had suggested that the shading imposed by trees is the principal factor limiting maize yield at the tree-crop interface (Reynolds et al. 2007; Ding and Su 2010), although belowground competition for water may also have a substantial effect as drought pressure increases crop water stress (Jose et al. 2004). However, maize yield reduction in the narrow zone that is adjacent to the windbreak (usually within 1H, where 1H = tree height) may be compensated by slight yield increases in the larger area that is created by the shelter effect, which usually occurs on the leeward side between 2 and 20H for a near-permeable windbreak (Kort 1988; Zhang and Brandle 1996; Nuberg 1998; Helmers and Brandle 2005). The intensity of windbreak effects on spatial variation in maize yield productivity may also differ according to temporal fluctuations in climate conditions. For example, using a modelling approach, Easterling et al. (1997) showed that the positive effects of shelter on maize yield decrease as precipitation levels increase. The authors also showed that windbreaks can compensate for climate change except in the most severe cases. Other agroforestry experiments have suggested that the decreases in maize yield across the tree-crop interface are less important in wetter growing seasons (Miller and Pallardy 2001).

In this study, we investigated the spatial distribution of maize grain yield in the leeward side of mature windbreaks that were located on four farms in southern Québec, Canada. Since the study area is characterized by considerable inter-annual variation in precipitation that may strongly affect maize yield (Almaraz et al. 2008), a second objective was to determine whether the sign and magnitude of windbreak effects on spatial patterns of maize yield varied across contrasting years with respect to rainfall conditions. We hypothesized that the magnitude of windbreak effects on maize yield patterns would decrease in wetter years. Our study is relevant because it was conducted at the farm level under operational conditions, which clearly fills a need that has been identified by different agricultural stakeholders, especially the farmers, in eastern North America (Strong and Jacobson 2005; Tartera et al. 2012). Our work will provide reliable data that could feed economic models for assessing costs of windbreak development in eastern Canada.

Materials and methods

Study sites

The study was conducted on four farms (hereafter referred to as sites). The first three sites (Les Cèdres, St-Polycarpe, St-Télésphore) were located near Montréal (i.e., within a 50 km radius), within close proximity to one another (i.e., within a 30 km radius). The regional climate that was typical of these three sites is characterized by an average growing season (May to October) temperature of 16.3 °C and 978 mm of annual precipitation (Valleyfield station, 1981–2010 records; Environment Canada 2014a), and an average annual homogenized surface wind speed (at 10 m level) of 15.7 km h^{-1} (Montreal station, 2001–2011 records; Environment Canada 2014b). The fourth site (St-Prime) was located near the town of Saint-Félicien (i.e., within 20 km), which was about 3° of latitude north of the other sites and, therefore, situated in a colder climate zone. The St-Prime site is characterized by an average growing season temperature of 13.3 °C, 833 mm of annual precipitation (St-Prime station), and an average annual homogenized surface wind speed of 13.3 km h^{-1} (Roberval station). All of the study sites were located on flat terrain and included a windbreak (minimum length of 250 m) that was composed of a single tree row of planted mature trees (optical porosity of ca. 20–40 % in vegetative period). The sites were selected based on their relatively spatially homogenous soil properties (assessed visually using pedons). Maize (2,800 corn heat units at Les Cèdres, St-Polycarpe, and St-Télésphore; 2,100 corn heat units at St-Prime) was grown next to the tree row on all sites during the study (2010–2013). Maize was sown between May 8 and 26 at 74×10^3 plants ha^{-1} in rows (0.76 m between rows) that were parallel to the tree line. The crop was grown using conventional tillage practices, which consisted of one mouldboard plough operation in the autumn after crop harvesting to a depth of 20 cm, followed by disking and harrowing to 10 cm each spring before seeding. Herbicides, cultivars and fertilization levels that were used in the study were based on local recommendations (CRAAQ 2000, 2010). Relevant soil and windbreak characteristics for each site have been summarized in Table 1, while rainfall conditions during each maize growing season of this study are provided in Table 2. At Les Cèdres, St-Polycarpe and St-Télésphore, the rainfall that had accumulated in each growing year (2010, 2011 and 2012) represented 126, 114 and 94 % of the 30-year average, respectively. For these three sites, 2010 was considered as a wet year, while 2011 and 2012 were considered as near-normal years. At St-Prime, the rainfall that had accumulated in each growing year (2012 and 2013) represented 144 and 104 % of the 30-year average, respectively. For the last site, 2012 was considered as a wet year and 2013 was a normal year. In each site, monthly average temperature during the growing season was similar among the different study years (data not shown).

Maize grain yield

Maize was harvested at maturity in October 2010 (Les Cèdres, St-Polycarpe), 2011 (Les Cèdres, St-Polycarpe, St-Téléspore), 2012 (St-Polycarpe, St-Téléspore, St-Prime), and 2013 (St-Prime). On each site, five transects that ran perpendicular to the leeward side of the windbreak were established. Each transect was

Table 1 Main characteristics of the four windbreak sites sampled (Québec, Canada)

Les Cèdres	
Location	45°18′N, 74°30′W
Soil type	Sandy loam (in the Ap horizon), Dystric Gleysol (Typic Endoaquent) of the Courval series
Tree age, average height and species	40 years, 11 m, white spruce (*Picea glauca* (Moench) Voss)
Tree spacing and row orientation	3.5 m, north–south
Dominant wind direction	West
Sampling position	At east from the tree row at 0.5, 1, 2, 4, 8, 12, 16, 20 and 24 H[a]
St-Polycarpe	
Location	45°18′N, 74°18′W
Soil type	Silty clay, Orthic Humic Gleysol (Typic Humaquepts) of the Ste-Rosalie series
Tree age, average height and species	12 years, 10 m, white spruce and green ash (*Fraxinus pennsylvanica* Marsh.)
Tree spacing and row orientation	2 m, northeast–southwest
Dominant wind direction	West
Sampling position	At southeast from the tree row at 0.5, 2, 4, 8, 12, 16, 20 and 24H
St-Télésphore	
Location	45°18′N, 74°23′W
Soil type	Sandy loam, Dystric Gleysol (Typic Endoaquent) of the Courval series
Tree age, average height and species	40 years, 13 m, Scots pine (*Pinus sylvestris* L.)
Tree spacing and row orientation	3.5 m, northeast–southwest
Dominant wind direction	West
Sampling position	At southeast from the tree row at 0.5, 1, 2, 4, 8, 12, 16, 20 and 24H
St-Prime	
Location	48°37′N, 72°25′W
Soil type	Sandy loam, Gleyed Humo-ferric Podzol (Typic Cryaquod) of the Pelletier series
Tree age, average height and species	25 years, 8 m, tamarack (*Larix laricina* (Du Roi) K. Koch) and white spruce
Tree spacing and row orientation	1.5 m, northeast–southwest
Dominant wind direction	Northwest and west
Sampling position	At southeast from the tree row at 0.5, 1, 2, 4, 7, 11, 14, 17 and 24H

[a] H = windbreak height in m

Table 2 Monthly average precipitation (mm) on the four windbreak sites (Québec, Canada)

Month	Les Cèdres, St-Télésphore and St-Polycarpe sites[a]				St-Prime site[b]		
	2010	2011	2012	30-year average	2012	2013	30-year average
May	50.4	142.2	105.8	82.9	79.4	131.3	65.4
June	179.1	50.6	82.3	94.7	142.4	79	75.9
July	85.2	51.4	93.4	97.6	50.8	39	118.3
August	97.2	191.6	46.2	92.5	172.4	44.4	79.2
September	177.2	87.6	100.7	82.6	147.2	123	84.2
October	94.4	94.8	80.9	90.6	107.6	92.3	64.3
Total	683.5	618.2	509.3	540.9	699.8	509.0	487.3

[a] Data from 2010 to 2012 were recorded at Les Cèdres station (45°18′N, 74°30′W), while 30-year averages were recorded at the Valleyfield station (45°17′N, 74°06′W)

[b] All data were recorded at the St-Prime station (48°37′N, 72°25′W)

separated from the next by 10 m and was manually harvested, at distances that were parallel to the tree row ranging from 0.5 to 24H, where H was the mean tree height (Table 1). At each sampling location, maize grain yield was determined by harvesting plants in a 3 m-long maize single-row. Grain was threshed and weighed, and yields were adjusted to 15 % moisture content (CRAAQ 2010).

Statistical analyses

Differences in maize yield at different distances from the tree row were assessed using a mixed-effects model ANOVA, including two factors: replicate transect (random) and sampling position (fixed). Separate ANOVAs were conducted for each site and year. Plots of fitted and observed values and residuals were examined for deviations from normality assumptions. Data were transformed, when necessary, prior to analysis to comply with ANOVA assumptions of normality and homoscedasticity. In all post hoc analyses, we used least significant difference (LSD) tests to separate treatment means when ANOVA showed significant effects.

On each site, we estimated an integrated maize yield value for all the positions within 20H from the windbreak (hereafter referred to as the windbreak system) to contrast with the position at 24H (referred to as agricultural system). Indeed, we assumed that the "sheltered zone" was within 20H and that the sampling position at 24H reflected field conditions with negligible tree effects on airflow, microclimate and crop yield (Cleugh 1998). The purpose of this approach was to compare maize yield for the whole leeside area of windbreak protection vs the agricultural system without trees. The yield data were weighted proportionally to the area that each sampling position represented within each site (from 0.25 to 20 H). For example, the integrated maize yield value in the windbreak system at the Les Cèdres and St-Télésphore sites was calculated according to the sum of the following proportions that were allocated to each sampling position: 0.5H (0.25–0.75H; 2.5 %); 1H (0.75–1.5H; 3.8 %); 2H (1.5–3H; 7.6 %); 4H (3–6H; 15.2 %); 8H (6–10H; 20.3 %); 12 H (10–14H; 20.3 %); 16 H (14–18H; 20.3 %); and 20H (18–20H; 10.1 %). Differences in maize yield between windbreak and agricultural systems were analyzed using a Student's t test. Statistical significance of all analyses was declared at $\alpha = 0.05$. Analyses were conducted in SAS (version 9.2, SAS Institute, Cary, NC).

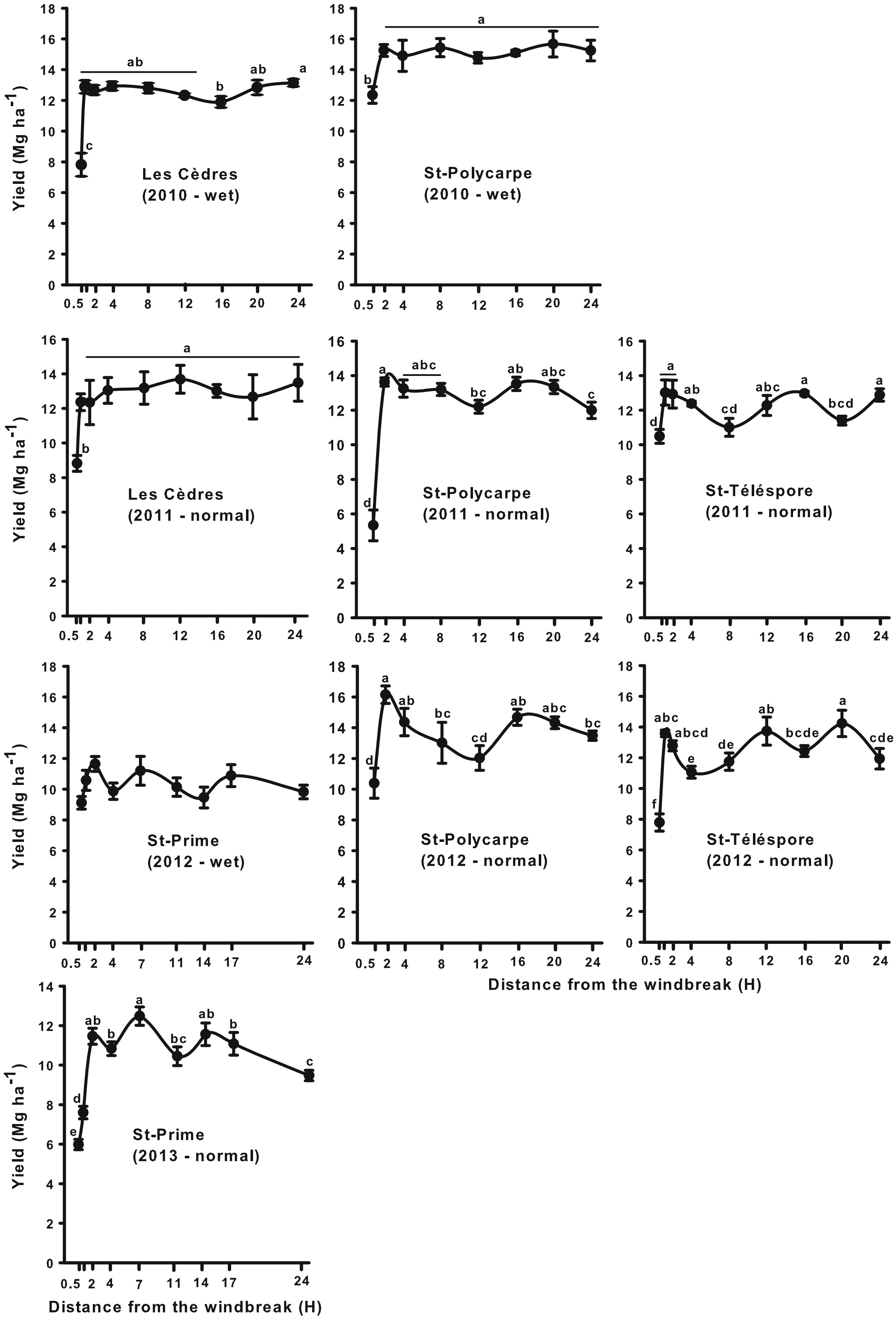
Results

Spatial and temporal patterns of maize grain yield within sites

At the Les Cèdres site, maize grain yield at 0.5H was significantly lower than that for all the other positions (Fig. 1; $P < 0.0001$ in 2010, and $P = 0.0036$ in 2011). Yield between 1 and 24H was generally uniform in both years. Mean yield at 0.5H relative to yield beyond 1H was respectively, 62 and 68 % in 2010 and 2011.

At the St-Polycarpe site, a significant effect of sampling position on maize yield was found in the three study years (Fig. 1; $P = 0.0253$ in 2010, $P < 0.0001$ in 2011, and $P = 0.0012$ in 2012). Grain yield at 0.5H was markedly lower compared to all other sampling positions between 2 and 24H (except 12H in 2012). The greatest yield variation between two adjacent positions was observed between 0.5 and 2H during the three study years. Mean yield at 0.5H relative to yield at 2H was 81, 39 and 64 % in 2010, 2011 and 2012, respectively. Yield between 2 and 24H was uniform in 2010. In contrast, yield between 2 and 24H varied significantly among sampling positions and showed different spatial patterns in 2011 and 2012, with the highest means occurring at 2H from the windbreak.

At the St-Télésphore site, a significant effect of sampling position on maize yield was found in the two study years (Fig. 1; $P = 0.002$ in 2011, and $P < 0.0001$ in 2012). The lowest means of maize yield were found at 0.5H. The highest yield variation between two adjacent positions was observed between 0.5 and 1H in both study years. Mean yield at 0.5H relative to yield at 1H was 81 and 57 % in 2011 and 2012, respectively. Yield varied significantly among sampling positions in both years. The spatial distribution of yield between 1 and 24H from the windbreak was not consistent in 2011 compared to 2012. In 2011, maize yield at 1, 2, 16 and 24H was significantly higher than that at 8 and 20H. In 2012, yield at 12 and 20H was significantly higher than that at 4, 8, 16 and 24H.


Yield (Mg ha-1)
Les Cèdres
(2010 - wet)
St-Polycarpe
(2010 - wet)
Les Cèdres
(2011 - normal)
St-Polycarpe
(2011 - normal)
St-Téléspore
(2011 - normal)
St-Prime
(2012 - wet)
St-Polycarpe
(2012 - normal)
St-Téléspore
(2012 - normal)
St-Prime
(2013 - normal)
Distance from the windbreak (H)

◀**Fig. 1** Grain yield of maize plants relative to distance to tree row in mature windbreaks on four sites (Québec, Canada) in different years. *H* windbreak height. Study years with rainfall conditions (normal or wet) are given in parentheses (see Table 1). *Vertical lines* represent $\pm$ 1 SE. Means not sharing the same letter are significantly different at $P < 0.05$ (LSD)

At the St-Prime site, a significant effect of sampling position on maize yield was found in 2013 only (Fig. 1; $P = 0.0933$ in 2012, and $P < 0.0001$ in 2013). In 2013, maize yield was the lowest at 0.5H. Grain yield at 0.5 and 1H was significantly lower compared to all other sampling positions between 2 and 24H. The highest yield variation between two adjacent positions was observed between and 1 and 2H. Mean yield at 1H relative to yield at 2H was 61 %. Maize yield at 2, 4, 7 14 and 17H was significantly higher than at 24H.

Maize grain yield in windbreak versus agricultural systems

We estimated an integrated yield value for all positions between 0.5 and 20H (i.e., windbreak system) relative to the 24H position (i.e., agricultural system), which is likely the position that would be most marginally affected by the trees (see the statistical analysis section). At the Les Cèdres site in 2010, maize yield in the windbreak system was significantly lower by 6 %, compared to the agricultural system (Fig. 2; $P = 0.0263$). At the St-Prime site in 2013, maize yield in the windbreak system was significantly higher by 16 % than that in the agricultural system ($P = 0.001$). At St-Polycarpe in 2010 and at all sites between 2011 and 2012, maize yield did not differ significantly between windbreak and agricultural systems (P values ranging from 0.1 to 0.7762).

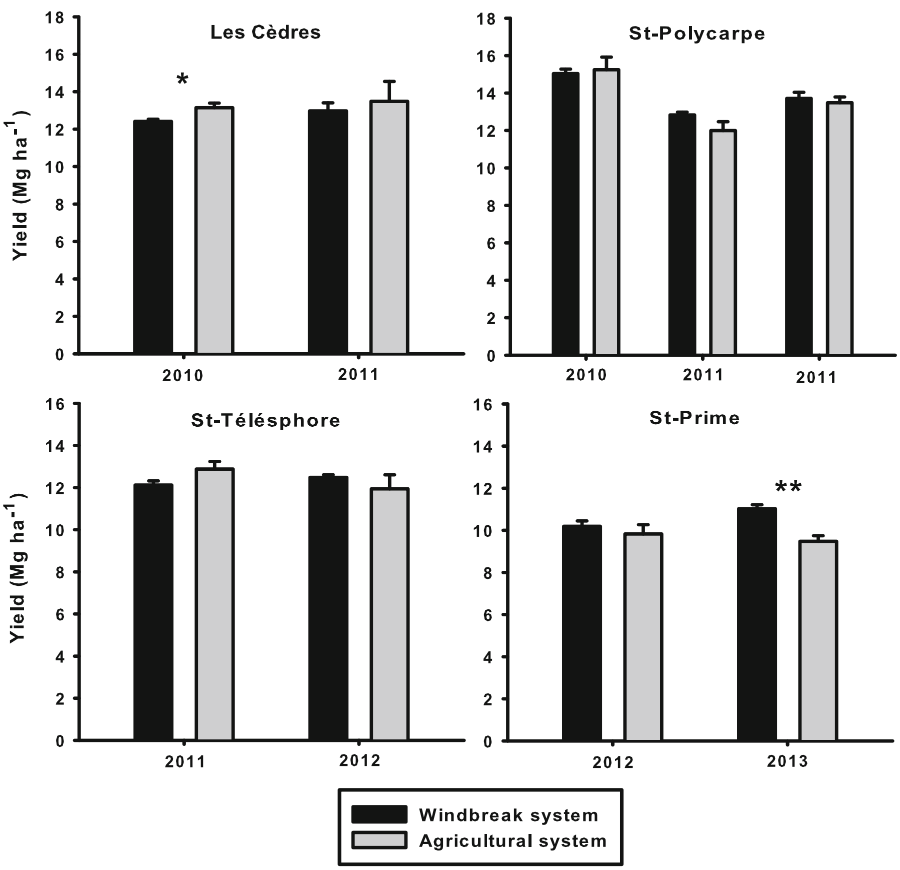


Fig. 2 Effect of windbreak versus agricultural systems on grain yield of maize plants in mature windbreaks on four sites (Québec, Canada) in different years. *H* windbreak height. Study years with rainfall conditions (normal or wet) are given in parentheses (see Table 1.). *Vertical lines* represent + 1 SE. Asterisks indicate significant differences between systems (*t*-tests: $^{*}P \leq 0.05$, $^{**}P < 0.001$)

Discussion

Important maize yield decreases at tree-crop interface: management implications

Across all sites and years (except St-Prime in 2012), we found a significant competitive effect of trees on maize yield, with markedly lower production within 0.5–1H from the tree row than beyond 1–2H. Maize has a C_4 photosynthetic pathway and becomes light-saturated at near full sunlight. Consequently, maize may be very sensitive to windbreak shading. For example, Ding and Su (2010) showed that lower incident photosynthetically active radiation (PAR) and air temperature, and higher atmospheric CO_2 concentrations that were caused by windbreak shading resulted in lower daily mean transpiration rates, 100-grain weights and yields of maize. Previous research in eastern Canada has suggested that competition for light is likely the most important resource limiting maize yield at the tree-crop interface throughout this cold temperate region (Reynolds et al. 2007). Within windbreak systems, a number of factors may alter tree shading of adjacent agricultural crops. The potential drawbacks to crop production in the understory that are due to overstory shading may be addressed through tree management during the mature phase of windbreaks. For example, tree pruning and thinning have been found to periodically increase light availability and crop yield at the tree-crop interface (Sudmeyer and Flugge 2005; Rivest et al. 2009), with likely positive effects on wood quality (Grado et al. 2001; Cutter et al. 2004). In Eastern Canada, widespread implementation of tree management in mature windbreaks remains, however, a fundamental concern that needs to be resolved. Indeed, there is a lack of appropriate subsidy programs covering tree management of windbreaks after the establishment phase, which seems to be a source of major reluctance by farmers to include trees in their farm practices (Tartera et al. 2012; Thevathasan et al. 2012). Long-term studies may analyze whether the benefits of tree shading management could be greater than the benefits of wind protection.

Another factor that may influence crop yield response to tree shading is crop cultivar selection. Some studies have helped gain greater insight into the shade-tolerance of different forage crop species and cultivars with potential for application in temperate agroforestry systems (e.g., Lin et al. 1999). Little knowledge is available, however, regarding crops of high economic importance, such as maize. We recommend that future research be guided towards selecting maize and other cash-crop cultivars that are best suited to the shading conditions originating from effects of a tree overstory in temperate windbreaks.

In this study we found that the magnitude of negative windbreak effects on maize yield at the tree-crop interface decreased at the St-Polycarpe and St-Prime sites in the wet years (2010 and 2012, respectively). Therefore, our data suggest that maize yield in the zone closest to the windbreak can also be limited by water availability in the specific climatic context of eastern Canada. However, a companion study, which investigated the extent and distribution of tree roots in fields adjacent to mature windbreaks, suggested that tree root competition for water would be likely to occur predominantly within 0.5–0.75H and would be more intense in light-textured soils (Plante et al. 2014). Future research should attempt to determine whether maize production is likely to be periodically limited by windbreak competition for water in eastern North America, especially in dryer years, and whether root pruning may limit this belowground competition in the vicinity of trees.

Windbreaks had near-neutral net effects on maize yield

Under different circumstances (i.e., St-Polycarpe and St-Télésphore in 2011 and 2012, and St-Prime in 2013), we found marked variation in yield among positions ranging from 2 to 20H (here considered as the shelter zone, sensu Nuberg 1998), with yield values often significantly higher than those at 24H (here considered as a control zone with negligible tree shelter effects). Considerable efforts have been invested in studying the mechanisms underlying the shelter effect, i.e., a windbreak that alters the mean wind speed, wind direction and turbulence of the airflow (see, for example, reviews by Cleugh 1998; Nuberg 1998; Brandle et al. 2004). Briefly, positive tree shelter effects include crop protection from physical damage, soil quality improvement, reduction in soil evaporation that contributes to higher water use efficiency, and enhancement of the crop energy balance and plant water relations. Also, the period from grain emergence to maturation may be lengthened in the shelter zone due to the increase in day time temperatures and the greater number of heat units accumulated, thereby allowing the crop to achieve greater grain fill than in the unsheltered zone. In our study, the spatial variation of crop yield in the shelter zone likely tracked the complex spatial and temporal interplay among these mechanisms.

In seven out of our nine case studies, we estimated that the net effect of windbreaks on maize yield was negligible (Fig. 2). Windbreaks had a net positive effect on maize production at St-Prime (2013), while having a net negative effect only at Les Cèdres (2010). Our results are not consistent with those reported by Kort (1988). This author had summarized the effect of windbreaks on maize yields over 209 sites and reported an overall mean yield increase of 12 %. Most of these data originated from an extensive study that had been conducted in the semiarid prairies of North America. Accordingly, it seems that the net positive effects of windbreaks would be expressed preferentially in regions where plant growth is limited by water shortages. This conjecture was partly supported by our results, which revealed less variation in maize yields among sampling positions within the shelter zone in wetter years. Because no dry years had occurred during our study, we were not able to test windbreak effects on maize yield under dry conditions. However, a modelling study provided evidence that maize yield enhancement in the shelter zone is more important in dry years than in wet years (Easterling et al. 1997). Windbreaks should be fully investigated as a potentially important tool for the adaptation of agroecosystems to climate change in eastern Canada, especially those including intensive maize production. Future field experiments in eastern North America could be designed to determine whether windbreaks may help mitigate extreme weather events such as drought and strong winds, which are detrimental to agriculture (Motha and Baier 2005).

Conclusions

We conclude that the sign and magnitude of windbreak effects on spatial patterns of maize grain vary considerably across farms and depend upon temporal variation in rainfall conditions in eastern Canada. The greatest yield variation was observed at the tree-crop interface, where substantial yield reductions occurred. However, our results suggest that these reductions may be compensated by slight yield increases in the large area that is affected by the shelter effect. Indeed, in most of our case studies, we found a neutral net effect of windbreaks on maize yield in years with normal or above normal rainfall. We believe that the net effects of windbreaks on maize yield could be increased through appropriate management of tree competition, but these practices need further research. We also consider that institutional recognition of ecosystem services that is provided by trees through economic incentives offered to farmers may significantly increase the overall economic soundness of windbreaks.

Acknowledgments We would like to thank Stéphane Gariépy and the numerous landowners who have collaborated to this experiment. This study was supported by grants from Agriculture and Agri-Food Canada (AF-10-114, AF-11-155, AF-12-219). We are grateful to Yves Perrault for technical assistance. We thank Drs. William F. J. Parsons and Miren Lorente for their useful comments and for improving the language of this paper.

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