Scientia Horticulturae 232 (2018) 127–138

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

High productivity of soilless strawberry cultivation under rain shelters

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A R T I C L E I N F O

Keywords:
Fragaria × ananassa
Sawdust
Peat
Umbrella shelters
Powdery mildew
Botrytis fruit rot
Early forcing
Capillary mat

A B S T R A C T

The effect of rain shelters on the performance of the day-neutral strawberry (*Fragaria* × *ananassa*) Monterey cultivar was studied in northern Québec in trials extending over 2 years. The main objective of the study was to evaluate the benefits of growing strawberry crops under plastic rain shelters in terms of yield, fruit quality, disease incidence and economical returns for soilless strawberry production. Five treatments were carried out and these included four − under rain shelters cultivation (T1 to T4) and one under open-air conditions (the Control, C). Under rain shelters conditions, plants were grown in either peat (PE; T1 treatment) or peat-sawdust (PS25; T2 treatment) substrates. Early forcing of bare-root plants (T3) in combination with a rain shelter cover was also carried out in an attempt to generate consistent early yields by the end of July as such would allow producers to capture a niche market for strawberries in Québec. Finally in T4, the PE substrate was laid onto a capillary mat to determine the potential of sub-surface water retention technology to minimize water use. In comparison to the Control treatment, protected cultivation led to a significantly lower incidence of strawberry mildew [*Sphaerotheca macularis* (Wall. ex Fries)] and consistently higher marketable yields which largely compensated for the initial costs associated with the rain shelters. When grown under greenhouse conditions, forced plants had a significant production peak earlier, coinciding with the period of high prices for fresh strawberries in 2013. However, the economical analysis revealed that this method was not always profitable. Balancing economical and environmental considerations, the conditions of the T4 treatment were found to be best for generating both consistent water savings and profits (CAD $ 724–1356 per 0.1 ha) compared to the Control. Taken together, our results highlight the potential for rain shelters for soilless strawberry production, and should be a more profitable and environmentally friendly cultivation method for strawberry producers.

1. Introduction

From 22 to 27 thousand metric tons of fresh strawberries (*Fragaria* × *ananassa*) are produced each year in Canada (2012–2016 period; Statistical overview of the Canadian fruit industry, 2016). Quebec is the top producing province in Canada (274,822 metric tons), representing 28.8% of commercial strawberry production (Statistical overview of the Canadian fruit industry, 2016). Strawberries are generally produced in open-field systems on raised beds. However, soilborn strawberry diseases are currently a major limiting factor that severely impacts the plant agronomic performance and generates economic losses in conventional production fields (Koike et al., 2010). Recently, and in response to increasing regulatory constraints on all fumigants, soilless culture has dramatically increased in Europe (Neri et al., 2012). While many studies have shown that soilless strawberry production may be a suitable alternative growing system in North America (Kempler, 2002; Paranjpe et al., 2008), there is still a need to expand this crop production system to a commercial scale.

For decades, peat has been widely marketed in due to its great productivity potential and its lower price than alternative inorganic substrates (Parent and Ilnicki, 2002). In spite of its high availability in North America, northern Asia and Europe, peat is not readily renewable, which is a problem in a long-term perspective of sustainable production (Joosten and Clarke, 2002). With respect to peatland conservation, researchers are trying to develop a rational use of this resource by developing and testing horticultural mixes made of peat and

Abbreviations: AFP, air-filled porosity; K_{sat}, saturated hydraulic conductivity; K(θ), unsaturated hydraulic conductivity; BD, bulk density; EC, electrical conductivity; ET, evapotranspiration; PS25, peat-sawdust; θ, volumetric water content; θ_e, estimated water content; WHC, water holding capacity; WP, water productivity; WRC, water retention curves

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https://doi.org/10.1016/j.scienta.2017.12.056
Received 2 May 2017; Received in revised form 19 December 2017; Accepted 22 December 2017
0304-4238/

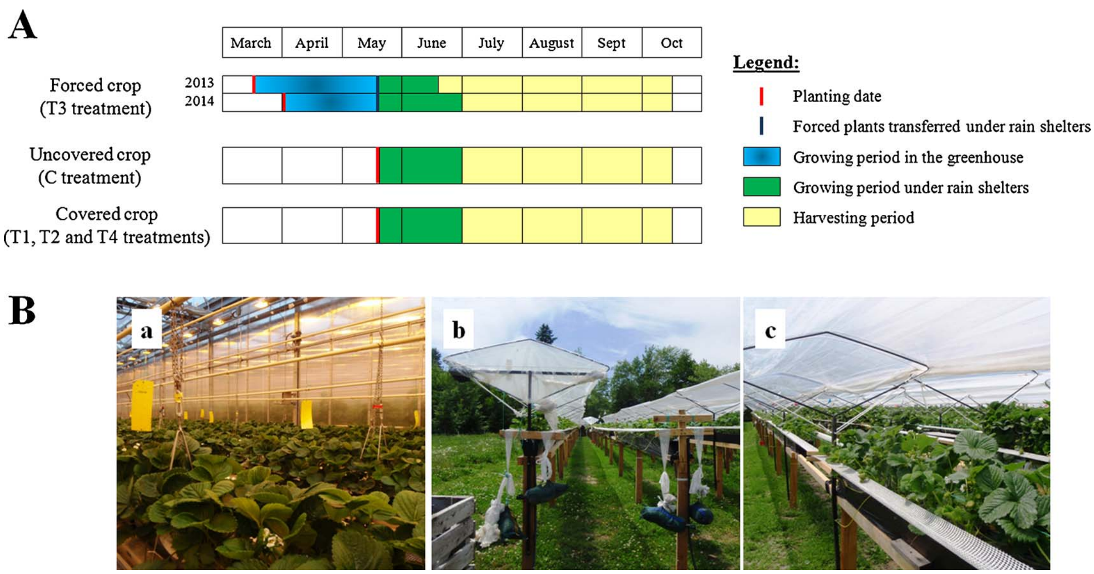

Fig. 1. Experimental design used during the two-year trial. (A) Schematic representation of the experimental design used for the forced plants (T3), the unprotected (Control, C) and protected (T1, T2 and T4) cultivation of strawberries. For T3, the two different strategies adopted for the two years are represented. (B) Photos of soilless strawberry cultivation for forced crop under greenhouse (a), under rain shelter conditions (b, left line) or unprotected (b, right line) with 1.5 m spacing within rows and a final pole density of 243 poles.ha^{-1}. Growing strawberries under rain shelter covers (c). Nets were placed horizontally on either side of the troughs to sustain the flowering stems and facilitate fruit ripening.

wood industry by-products such as bark and sawdust (Clarke and Rieley, 2010; Aubé et al., 2015). Improved performances using bark-based substrates and peat-bark mixes have been previously demonstrated for soilless strawberry production (Jarosz and Konopinska, 2010; Depardieu et al., 2016). In contrast, even when added in small proportions to peat-based growing media, sawdust can affect strawberry plant growth (Jarosz and Konopinska, 2010). Previous studies showed that specific, precise irrigation and fertigation strategies need to be defined to reach the full productivity potential of peat-sawdust substrates (Lemay et al., 2012). Although the suitability of such mixes has been demonstrated for protected (high tunnel) strawberry culture (Depardieu et al., 2016), their performance needs to be further confirmed in a context of open-air rain shelter fruit production.

In northern areas where the season for strawberry production is especially short, expanding the berry production season is particularly important and can be achieved by day-neutral varietal innovation (Taghavi et al., 2016), forcing an early spring crop (Demchak, 2009; Kadir et al., 2006), or using tunnels (Ballington et al., 2008; Medina et al., 2009; Janke et al., 2017). Although several studies have reported attempts to force strawberries in greenhouses, until now a successful summer commercial production has never been reported (Deyton et al., 2009; Neri et al., 2012; Paparozzi, 2013; Takeda, 2000). At present, most marketed cultivars are not adapted to winter climate (Khanizadeh, 2002) and-or highly susceptible to the most destructive and economically important pathogens of strawberry worldwide, including *Botrytis cinerea*, *Phytophthora sp.*, *Sphaerotheca spp.* and *Verticillium spp.* (Elmhirst, 2005; Barboza et al., 2017; Hancock et al., 2008).

Protected culture systems such as greenhouses and tunnels are becoming more popular for frost protection (Neri et al., 2012; Maughan, 2013), extension of the harvesting period, increased yields (Lieten and Baetes, 1991; Grijalba et al., 2015), and fruit quality improvement (Kadir et al., 2006; Xiao et al., 2001) as well as the control of several major plant diseases (Evenhuis and Wanten, 2006; Kennedy et al., 2013). However, warm and dry conditions and the absence of rainfall in these production systems favor the development of strawberry mildew [*Sphaerotheca macularis* (Wall. ex Fries)] (Amsalem et al., 2006; Xiao et al., 2001). Until now, protected strawberry production has remained highly dependent on the intensive use of chemicals to control this plant disease (Pertot et al., 2007). Numerous trials have shown that mildew was persistent under tunnels (Daugaard, 2008; Prémont, 2015) and has had significant adverse economic impact on soilless strawberry production. Botrytis fruit rot caused by *Botrytis cinerea* is another major limiting factor in berry production under high-tunnel environment (Grijalba et al., 2015). Even with weekly applications of fungicides, up to 15% of fruit loss has been observed for cultivars susceptible to *Botrytis cinerea* (Legard and Chandler, 1998). Alternatively, crop cultivation under rain shelters has the potential to achieve economic benefits due to the low cost of these structures combined with the better fruiting performance of crops than in open-field production (Latifah et al., 2014; Xu et al., 2013). These protected structures effectively reduce fruit damage due to rain, frost and disease occurrence, while creating a more favorable microclimate in terms of ventilation and relative humidity than do greenhouses and tunnels (Inada et al., 2005). Furthermore, such growing system appears to be a viable alternative cultivation system in northern America where significant rainfalls occur during the production season.

The main purpose of this study was to evaluate the benefits of growing strawberry plants in substrate under rain shelters in terms of yield, fruit quality and disease incidence. By protecting strawberries from rain while reducing infection risks associated to the *Sphaerotheca macularis* and *Botrytis cinerea* pathogens, we hypothesized that this growing system would increase marketable yields. We further aimed to optimize the seasonal fruit yields and water use under the rain shelter and soilless production conditions by using (1) greenhouse-forced plants, (2) a low cost and locally produced peat-sawdust mixture and (3) a capillary mat under the peat substrate.

2. Methodology

2.1. Treatments

The five treatments consisted of one group of strawberry plants cultivated under open-field conditions (C, control treatment) and four different cultivation systems/conditions with strawberry plants grown using the rain-shelter cultivation technology (T1, T2, T3, T4; see Fig. 1 for details). T1 and T2 corresponded to plants grown in PE and PS25, respectively. Under T4 conditions, the PE substrate was laid on a capillary mat (AQUAMAT®, Soleno Textiles, Laval, QC, Canada) to minimize water use (Caron et al., 2005a). The T3 treatment involved bare root plants that were forced in the greenhouse during spring and then transferred under shelters at the time of plant implantation under T1-T4 conditions.

2.2. Growing media composition and preparation

A peat-sawdust substrate (PS25) and a commercial peat substrate (PE) were used in this study. The peat-sawdust substrate was a mixture of 30% white spruce sawdust [*Picea glauca* (Moench) Voss.] sieved to less than 6 mm, and 70% brown sphagnum peat (FIBRO MOSS®; Fafard et Frères ltée., Saint-Bonaventure, QC, Canada). Because nutrient immobilization was previously observed for this particular mixture (Depardieu et al., 2016), PS25 received an initial fertilizer load to fulfill initial plant requirements (Appendix D in Supplementary material; 12:5:20 N:P:K, Fafard et Frères ltée., Saint-Bonaventure, QC, Canada). The commercial substrate PE was a mixture of peat, gypsum and limestone (AGRO MIX® G10; Fafard et Frères ltée., Saint-Bonaventure, QC, Canada). In the preparation for use, the substrates were pH adjusted to 5.8 and saturated with nutritive solution.

2.3. Physical characteristics of growing media

2.3.1. Bulk density and particle-size distribution

The initial bulk density was determined based on the volume of the substrate after drainage and the dried mass of the substrate (70 °C until a constant mass was reached), whereas the final bulk density was determined according to the core method. Particle-size distribution (PSD) was obtained according to the method described by Parent and Caron (2008).

2.3.2. Hydraulic conductivities

Both saturated and unsaturated hydraulic conductivities (K_{sat} and K (θ), respectively) were determined on initial substrate material using the Laval tension disk method for water potential values ranging from 0 to −15 kPa (Caron and Elrick, 2005). In parallel, K_{sat} was also determined according to a method described by Conseil des Productions Végétales (1997). Subsequently, K(θ) was determined using the instantaneous profile method for water potential in the range of −15 to −80 kPa (Naasz et al., 2005). Critical irrigation thresholds (i.e. substrate water potentials at which the irrigation was initiated) were further deduced from initial unsaturated hydraulic conductivity profiles of the substrates, according to a methodology described by Rekika et al. (2014). Briefly, predicted water fluxes in the growing media were first calculated using the Buckingham-Darcy equation. Then, the critical irrigation thresholds were determined from K(θ) curves. Based on previous observations at Laval University (unpublished data), an evapotranspiration (ET) value of 6 mm d^{-1} (maximum ET observed for mature plants) was used to determine the critical irrigation thresholds.

2.3.3. Water retention curves and predicted oxygen levels during plant growth

Water retention curves (WRC) were generated as previously described by Depardieu et al. (2016). For T1, T2 and T4 treatments, final measurements of K_{sat} and WRC were determined using extracted blocks of final substrate material. Curve-fitting parameters including the air volume content or air-filled porosity (AFP; corresponding to water losses between 0 and −1 kPa) and the water holding capacity (WHC; defined for the range of *h* from −1 to −10 kPa) were then estimated with the van Genuchten model (van Genuchten et al., 1980). To estimate oxygen levels and water contents during plant growth, values of water content (θ_e) and AFP were determined from observed water potential values in each block of substrates (one datum point per hour) using final WRC data. Minimum and maximum values of these parameters were determined using sorption and desorption curves, respectively.

2.4. Chemical characteristics of the substrates

During cultivation, substrate solution was extracted in triplicate at mid-height of a container using a suction lysimeter (Model Soil water sampler 1905, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Subsequently, the pH_{lys} and EC_{lys} of the collected solutions were measured using a pH meter (Symphony SB70C; VWR, Mont-Royal, QC, Canada) and a conductivity meter (Symphony, 11388-382 Epoxy: VWR, Mont-Royal, QC, Canada). Final pH_{SSE} and EC_{SSE} values were measured on Substrate Saturated Extracts of the growing media which were divided into three equal parts along the containers' depths. pH_{SSE} and pH_{lys} values observed during the two trials remained in an acceptable range for strawberry plant growth (data not shown).

2.5. Plant growth conditions and experimental design

2.5.1. Greenhouse-forced plants growing conditions

Bare root strawberry plants were grown from March 14th to May 21th in 2013 and from March 31th to May 16th in 2014, in the high performance EVS greenhouses at Université Laval, Québec City, Canada (lat. 46°77′56" N, long. 71°28′29" W). Five bare root plants cultivar "Monterey" were transplanted into troughs (8 L; 50 cm x18 cm x16 cm; Bato Plastics B.V., Zevenbergen, Netherlands) containing the commercial PE substrate. In the greenhouse, a PRIVA system (Priva B.V., Vineland Station, ON, Canada) controlled the climate, with a day/night temperature of 19/15 °C and a relative humidity of 43/58% in 2013 and a day/night temperature of 18/14 °C and a relative humidity of 41/56% in 2014. Daily, artificial lighting provided by high vapour pressure sodium lamps (600 W; PL Light Systems Canada Inc., ON, Canada) was automatically switched on at 10:30 and switched off at 16:00. However, supplemental lighting was turned off when the photosynthetically active radiation (PAR) exceeded 1200 µmol m^{-2} s^{-1}. To maximize root development, the first flowers were cut until April 23th and April 25th in 2013 and 2014, respectively. Flowers were hand-pollinated with a hair dryer set at the cool setting. Irrigation started one day after plant transplantation. The irrigation solution was distributed using a drip-tape system (RO-DRIP™ Drip Tape, Dubois Agrinovation Inc., Saint-Rémi, Québec, Canada) with drippers of nominal discharge at 2.27 L h^{-1} installed at a space of 10.16 cm between them. One hundred and sixty-five healthy plants having a homogeneous developmental stage were chosen and transferred to the study site under umbrella-like shelters.

2.5.2. Plant growth conditions under rain shelters

The two-year study (2013 and 2014) was conducted in an umbrella-like structure (100 m x 620 m) located at the Onésime Pouliot farm on the Orleans Island in Québec (46°54′06.1"N 70°56′13.7'W). The experimental design included 4 blocks and a total of 20 experimental units (EU). Within each block, 5 EU were randomly assigned to the 5 treatments. Each EU was composed of 33 containers (8 L; 50 cm x 18 cm x 16 cm; Bato Plastics B.V., Zevenbergen, Netherlands) with a total of 165 plants. Five bare root plants cultivar "Monterey' were transplanted (in May 22th 2013 and May 10th 2014) into troughs that were supported by wooden structures at 1 m above ground and arranged in rows of 100 m with a spacing within containers' rows of 1.4 m. The final planting density was 10 plants m^{-1}. Shelters were built along with containers' rows before berries coloration, and were 3.0 m high and covered with transparent polyethylene film of 1.7 m wide (Fig. 1B). Poles with an arc structure were spaced 3 m apart, for a final pole density of 243 poles ha^{-1}. Plants were micro-irrigated using a drip-tape system (RO-DRIP™ Drip Tape, Dubois Agrinovation Inc., Saint-Rémi, QC, Canada). Containers were individually irrigated by one line of drip tape, with a discharge rate of 2.27 L h^{-1}. All cultural operations (planting, harvest, management of pest and diseases, weed control, pruning of flowers and runners as well as general maintenance) were performed according to the local producer's procedures.

2.6. Precision irrigation and fertigation management

Irrigation scheduling was based on substrate moisture measurements using tensiometers inserted vertically in the rooting zone. For each treatment, three tensiometers were installed into three independent blocks. Real time acquisition of matric potential measurements was performed by the IRROLIS 3 wireless system (Hortau, Lévis, QC, Canada). Irrigation was manually triggered once the matric potential threshold was reached. Fertigation was conducted as previously described by Depardieu et al. (2016). During the plant establishment period, an irrigation threshold (IT) of −1.5 kPa was applied to all blocks during the first 15 days after planting, under greenhouse and rain shelters conditions. During the fruiting and fruit production periods, a progressive decrease in IT at a rate of 0.2 kPa per day was applied to strawberry plants until −5 kPa was reached. Independent irrigation systems were used to provide a nutrient solution adapted to plant growth for each treatment. Water consumption was measured weekly by water meters. In this study, the water productivity (WP) was calculated as the marketable yield divided by the total amount of irrigation water used.

2.7. Growth parameters, crop yield and fruit quality

Plant vegetative growth was evaluated weekly by measuring crown stem diameter on three plants per treatment. Every 3–4 days, fresh fruits were harvested and classified into marketable or unmarketable groups to determine yields. For each treatment, the final leaf dry masses of 5 plants per block were determined after drying in a thermo-ventilated oven at 60 °C until constant dry mass was reached. The average fruit size was calculated as the ratio of marketable fruit weight to fruit number. Fruit quality parameters including firmness (penetrometer FT02, QA Supplies LLC, Norfolk, VA, USA) and total fructose level (Brix index; refractometer PAL-1, Atago) were measured weekly on two randomly chosen fruits per EU.

2.8. Evaluation of disease incidence

Disease incidence (number of infected plants, percentage of infection) for *Botrytis* fruit and strawberry mildew were evaluated four times on a total of 15 plants per treatment during plant growth. At the end of the harvest season, the proportion of roots affected by root rot was evaluated by three independent experimenters according to Zhang and Tu (2000). The root systems did not show any symptoms of soil born diseases (data not shown).

2.9. Economic study

Given that the five treatments of this study received identical management, a partial budget analysis was used to compare their respective economic effectiveness (Kay et al., 2008). This economic analysis was based on a production area of 0.1 ha, a reference area commonly used in a context of soilless culture (Latifah et al., 2014; Engindeniz and Gül, 2009; Grafiadellis et al., 2000). The cost items for the soilless crop production under rain shelters included determining both variable costs and fixed costs. In our study, variable costs included those of growing media, fertilizers, electricity, labour for harvesting and maintenance associated with the placing and removing of the transparent polyethylene covers on the shelters. These costs were based on current input prices and current labour costs. Fixed costs included interest on total initial investment costs (rain shelters), depreciation of the initial investment as well as the cost of electricity in the greenhouse. Depreciation of the initial investment was estimated using the straight-line method (Penson et al., 2002), assuming that the useful life of rain shelters was 10 years. An interest rate of 5% was charged and used to calculate the interest on total initial investment. Gross revenue was calculated as the product of weekly marketable yield by the market price. Net return was obtained by subtracting total costs from gross revenue. Additional information regarding the estimation of treatment-related costs and summary of data sources are reported in Appendix A (in Supplementary material).

2.10. Statistical analysis

Data were analysed with the MIXED procedure of SAS 9.3 (SAS Institute, Inc., Cary, NC). Non-normally distributed data were transformed using either square root or log functions. Following statistical analysis, normality of residuals was checked by Shapiro-Wilk tests ($P > 0.05$) and visual inspection of Q–Q residuals plots. The least square means were compared when the ANOVA model was significant at $P = 0.05$. Scripts are available upon request.

3. Results

3.1. Physical characteristics of the substrates

3.1.1. Predicted critical irrigation thresholds and water potential variations during cultivation

When considering an ET of 6 mm d^{-1}, critical irrigation thresholds of −4.0 and −4.4 kPa were determined for PE and PS25, respectively (Fig. 2). Previous studies performed at Laval University showed that applying irrigation thresholds from −2 to −5 kPa had no significant impact on strawberry plants growth in PE (Appendix E in Supplementary material), consistent with these estimates. Seasonal estimated AFP ranged 0.31-0.45 $cm^3 cm^{-3}$ for PS25 and 0.29–0.42 $cm^3 cm^{-3}$ for PE, which falls in the range of (1) adequate air-filled porosity levels generally reported for substrates (0.20–0.30 $cm^3 cm^{-3}$) and (2) recommended values of 0.30–0.45 $cm^3 cm^{-3}$ at container capacity (−0.3 kPa) for growing medium constituents with intense microbial activities (Naasz et al., 2009). In 2014, similar average water potentials were observed among all treatments that exhibit adequate air-filled porosity levels ranging 0.20–0.50 $cm^3 cm^{-3}$. The presence of the capillary mat allowed maintaining significantly higher oxygen levels in

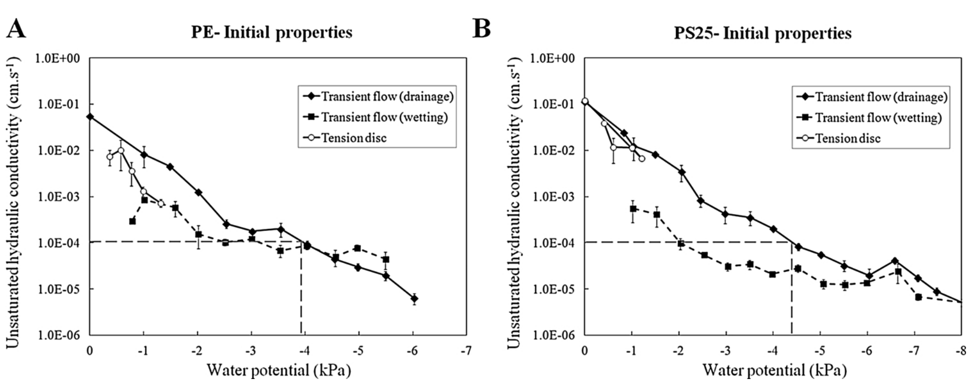

Fig. 2. Unsaturated hydraulic conductivity measurements of the two different substrates used during the two growing seasons. Data reported are the mean (n = 4) with SE.

Table 1
Physical properties of the T1, T2 and T4 treatments tested in this study. Parameters such as total and air-filled porosity, water availability as well as water buffering capacity were estimated after fitting the van Genuchten model to the WRC data. Means (n = 3) and SD are presented. The PE-PS25 contrast which is reported for final values of the different parameters tested corresponds to the T1-T2 contrast. –: variable not measured. Significant P-vales are indicated in bold.

Year	Treatment	Substrate	Estimated AFP		Saturated hydraulic conductivity (Ksat, cm s^{-1})		Bulk density (BD, g cm^{-3})		Water holding capacity (WHC, cm^3 cm^{-3})		Air-filled porosity (AFP, cm^3 cm^{-3})	
			Sorption	Desorption	Initial	Final	Initial	Final	Initial	Final	Initial	Final
2013	T1	PE	0.42 (0.01)	0.29 (0.02)	0.055 (0.009)	0.129 (0.11)	0.114 (0.002)	0.107 (0.011)	0.39 (0.07) ab	0.35 (0.02) bc	0.31 (0.01) a	0.12 (0.12) ab
	T2	PS25	0.45 (0.01)	0.31 (0.03)	0.116 (0.008)	0.699 (0.748)	0.126 (0.002)	0.114 (0.004)	0.47(0.06) a	0.29 (0.021) c	0.12 (0.03) b	0.21 (0.11) b
	T4	PE	–	–	0.055 (0.009)	0.448 (0.615)	0.114 (0.002)	0.11 (0.014)	0.39 (0.07) ab	–	0.31 (0.01) a	–
	P value- GLM											
	Treatment (T)	–	0.2286	0.5177	**0.0123**		0.4779		0.724		0.1986	
	Date (D)	–	–	–	**0.0057**		**0.0488**		**0.0005**		0.2769	
	T*D	–	–	–	0.5312		0.551		**0.0087**		**0.0076**	
	Contrasts											
	PE vs PS25	–			**0.0013**		0.097		0.724		0.2275	
2014	T1	PE	0.20 (0.07) c	0.25 (0.01) b	0.055 (0.009)	0.08 (0.039)	0.114 (0.002)	0.109 (0.018)	0.31 (0.05) b	0.24 (0.01) b	0.38 (0.06) a	0.23 (0.04) bc
	T2	PS25	0.31 (0.01) b	0.21 (0.02) b	0.116 (0.008)	0.176 (0.076)	0.126 (0.002)	0.158 (0.026)	0.46 (0.06) a	0.24 (0.01) b	0.12 (0.03) c	0.25 (0.04) b
	T4	PE	0.50 (0.01) a	0.37 (0.02) a	0.055 (0.009)	0.105 (0.093)	0.114 (0.002)	0.123 (0.007)	0.31 (0.05) b	0.27 (0.09) b	0.38 (0.06) a	0.28 (0.12) ab
	P value- GLM											
	Treatment (T)	–	**0.0027**	**< 0.0001**	**0.0094**		**0.0004**		**0.0428**		**0.0076**	
	Date (D)	–	–	–	0.4082		0.2746		**0.0016**		0.2997	
	T*D	–	–	–	0.9374		0.0525		**0.0249**		**0.0104**	
	Contrasts											
	PE vs PS25		**0.0345**	**0.0203**	**0.0003**		**< 0.0001**		**0.015**		**0.0026**	

treatment T4 than in T1, due to the additional suction created by the mat in contact with the substrate (Caron et al., 2005b).

3.1.2. Changes in physical properties of peat substrates after plant growth

A comparison of substrate specificities [PE (T1) versus PS25 (T2)], the effect of using a capillary mat (T4) on changes in physical properties of PE, and the hydraulic parameters associated to T1, T2 and T4 are reported in Table 1. Additional information regarding particle size distributions can be found in Appendix F (in Supplementary material). Since the bulk density (BD) of substrate PE remained unaffected after cultivation, the decrease in AFP of T1 was most likely the result of root growth in peat macro-pores, leading to a decrease in pore numbers, thus restricting aeration in the growing media. In 2014, a marked increase in AFP was observed after cultivation for PS25, as previously observed for this mixture (Depardieu et al., 2016).

Compared to T1, the presence of the capillary mat (T4) resulted in (1) the maintenance of higher air-filled porosity; and (2) limited changes in water hydraulic properties in 2014 (Table 1, Appendix B in Supplementary material) and particle size distribution (Appendix F in Supplementary material). These results demonstrate that, when properly used, capillary mats can limit the extent by which substrate physical properties may be affected during cultivation by significantly reducing the wetting and drying cycles induced by irrigation events.

3.2. Water use and salinity control

As expected, the amount of nutritive solution used under Control conditions was overall 63% lower than in treatments under rain shelters (Fig. 3A). By using a capillary mat under the peat substrate (T4), a significant amount of water was saved, as the leachate is temporarily stored into the mat before moving back into the container through a capillary rise process. In 2013, the volume of water used in T4 was 3.8% lower than that under T1, thus increasing WP by 9.6% (Fig. 3). These water savings were substantially lower than those reported under nursery conditions using the Aquamat System ™ (Colombo et al., 2005). The poor efficiency of the capillary mat for that particular year was explained by a low drainage rate of the irrigation water combined with short irrigation events. In 2014, we corrected this situation by irrigating plants in T4 for longer periods to fill the capillary mat efficiently. As a result, T4 conditions generated 39.0% more water and nutrient solution savings and increased WP by 81.9% in 2014 (Fig. 3).

During the two cropping seasons, the EC_{lys} was within an acceptable range for plant growth for all growing systems under protected culture (Fig. 3B; Guérineau, 2003). Lower values of EC_{lys} and EC_{SSE} were observed for the open-air cultivation (C), which was attributed to rainfall causing nutrient leaching, thus decreasing the amount of nutrients in the substrate. While similar values of EC_{SSE} and EC_{lys} were observed between T1 and T4 during the first trial, the highest values of EC_{SSE} for T4 the next year may be explained by an efficient nutrient leaching catch-up within the capillary mat and subsequent capillary rise properties into the peat substrate.

3.3. Plant growth, fruit quality and yields

Plant growth characteristics, seasonal yields as well as fruit quality parameters are reported in Table 2. Covering strawberry plants with shelters improved the seasonal total and marketable yields by 15–24%, in comparison with those of the unprotected crop. Fruit quality parameters remained unaffected by the growing system type, in line with previous observations for the 'Clery', "Elsanta", "Darselect" and "Sonata" strawberry cultivars (Klein and Linnemannstöns, 2011). Under protected conditions, plants grown in PS25 (T2) exhibited lower crown diameter and leaf dry mass in 2013 than plants grown in PE (T1). Among all treatments, the plants grown in PS25 gave the lowest seasonal yields during the 2013 growing season. Given that the number of fruits and the seasonal average fruit size were not significantly affected under T2 conditions, the lowest yields obtained in this study may be explained by smaller fruits produced during the early fruit production period. Consistent with these observations, strawberry plant growth limitations were previously reported for PS25 during plant

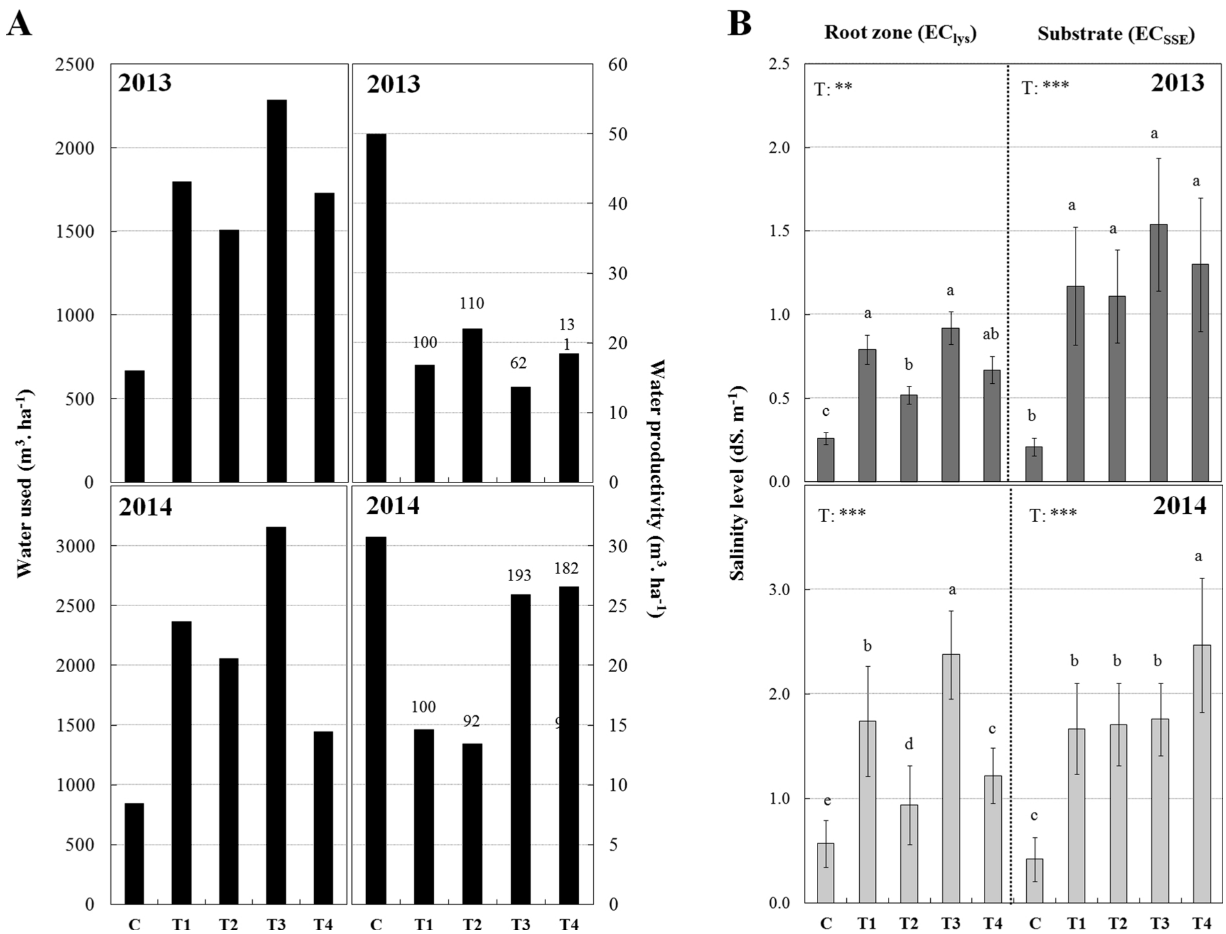

Fig. 3. Salinity control (A), water use and water productivity (B) measured during the two-year trial. (A) Means with SE are reported (EC_{lys}: n = 3; EC_{SSE}: n = 9). The P-values obtained from the generalized linear mixed model (GLMM) were used to fit the data and are reported for the test (T) effect as follows: ns: no significant; (*) = $P < 0.05$; (**) = $P < 0.01$; (***) = $P < 0.001$. (B): Precipitation was not taken into account to calculate the water use efficiency for the Control. Values of relative water productivity (in%, 100 being attributed to the T1 treatment) for strawberries grown under cover are reported on the top of bars.

establishment (Depardieu et al., 2016) and were attributed to nutrient immobilization by microorganisms in sawdust. Based on these observations, the initial fertilizer load was doubled for PS25 in 2014 and allowed to obtain similar seasonal total yield in T2 and T1, with no differences in terms of fruit quality between those treatments. These results demonstrate the high productivity potential of the peat-sawdust mixture for soilless strawberry production, once appropriate fertigation and irrigation management are defined. Further, the presence of the capillary mat underneath the PE substrate in T4 had no impact on plant growth, yields and fruit quality for the two cropping seasons, while generating considerable fertilizer savings. Compared to other treatments, greenhouse-grown strawberry plants gave two- to three-fold higher marketable yields in 2013 and 0.6–1.3 higher in 2014. Significantly higher production peaks were observed under T3 conditions compared to the other treatments (Fig. 4). In particular, one significant production peak occurred from July 16th to August 15th in 2013 while several and smaller peaks were obtained in 2014 during the two first weeks of August (Fig. 4A and B). Overall, forced plants gave higher yields in 2013, but to a lesser extent in 2014. As previously reported in several studies on strawberries, differences in plant performance between the two years may be explained by a different planting time (Hassell et al., 2007), plant size at time of transfer under rain shelters conditions (Menzel and Smith, 2012), and different cultural operations. In our study, the presence of several production peaks in 2014 may be attributed to the fact that the first flowers were not cut after 25 days of cultivation, unlike in 2013. Regarding fruit quality parameters, forced plants exhibited lower sugar content for the two trials as well as increased fruit firmness in 2013.

3.4. Mildew and gray mold infections

The use of rain shelters significantly reduced the severity of powdery mildew compared to unprotected treatment (Table 3). However in 2013, the infection by *Sphaerotheca macularis* in T3 was similar to that of the Control. While gray mold was not detected for plants transplanted under rain shelter conditions, a low proportion of infected plants were observed among forced plants. These results indicate that both diseases developed under greenhouse conditions in 2013. A significant increase in severity and occurrence of gray mold was observed in 2014, with a more pronounced infection for T1 and T3 conditions (Table 3).

3.5. Economic analysis

Table 4 presents an overview of the differential costs for the five treatments tested, C being the reference treatment. Given that different strategies were adopted for T2 and T3 between the two trials, the results are presented for each trial. Since significant differences in marketable yields were found among the treatments, differences in labor costs for harvesting, classifying and packing the strawberries were included in the analysis. Moreover, the substrate used in treatment T2 incurred a higher cost, with a difference of CAD $ 14.6 per cubic meter.

Compared to the reference open-air cultivation, our analysis revealed that the use of rain shelter structures was profitable under T3

Table 2
Effect of treatments on growth parameters, seasonal yields, percentage of unmarketable yields and seasonal fruit quality parameters during the two growing seasons. Means (n = 3) and SD are presented. Significant P-values are indicated in bold.

Year	Treatments (T)	Number of fruits	Crown diameter (mm)	Final leaf dry biomass (g plant^{-1})	Seasonal total yield (g plant^{-1})[a]	Seasonal marketable yield (g plant^{-1})[a]	Seasonal unmarketable yield (g plant^{-1})[a]	Percentage of unmarketable yield (%)[b]	Fruit size (g fruit^{-1})	Sugar content	Firmness
2013	C	6.03 (4.48) ab	14.69 (4.32) ab	11.97 (2.07) c	238.97 (14.70) c	209.92 (18.63) c	29.05 (13.10) bc	9.74 (2.73) b	22.82 (3.57)	8.74 (0.73) a	292.08 (29.96) ab
	T1	8.14 (8.14) ab	17.05 (7.38) a	22.15 (3.78) a	318.83 (29.74) b	282.68 (26.33) b	36.15 (9.24) b	10.67 (2.40) b	23.86 (4.71)	8.69 (0.86) a	250.31 (18.38) c
	T2	5.21 (5.1) b	13.29 (4.31) b	17.11 (3.08) b	255.50 (36.82) c	237.2 (32.66) c	18.30 (4.46) c	7.53 (2.19) b	24.46 (3.37)	8.61 (0.43) a	257.19 (24.54) bc
	T3	–	–	10.76 (0.36) c	755.22 (30.43) a	627.18 (32.37) a	128.03 (19.90) a	19.70 (3.12) a	19.56 (0.62)	7.03 (0.17) b	340.33 (27.54) a
	T4	9.19 (6.27) a	17.48 (6.34) ab	20.79 (1.75) ab	354.02 (21.80) b	306.42 (29.2) b	47.60 (26.00) b	11.52 (5.79) b	22.32 (4.35)	8.99 (0.29) a	243.54 (20.61) c
	P values										
	Treatment (T)	**0.0108**	**0.0002**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.012**	0.3118	**0.0023**	**0.0013**
	Date (D)	**< 0.0001**	**< 0.0001**	–	–	–	–	–	–	–	–
	T*D	0.1505	**0.0002**	–	–	–	–	–	–	–	–
	Contrasts										
	C vs T1	0.6481	0.096	**< 0.0001**	**0.0005**	**0.0006**	0.2232	0.6414	0.7681	0.8933	**0.0265**
	T1 vs T2	0.197	**0.0009**	**0.0147**	**0.0031**	**0.0213**	**0.0059**	0.0927	0.7297	0.8467	0.662
	T1 vs T3	–	–	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0015**	0.0236	0.1023	**0.0012**	**0.0006**
	T1 vs T4	**0.0459**	0.3437	0.4586	0.2007	0.3632	0.5049	0.9291	0.4842	0.4674	0.5741
2014	C	3.25 (2.49)	17.08 (4.99)	17.37 (2.61) a	378.58 (14.61) c	320.59 (18.48) c	57.98 (10.96) b	17.66 (15.64) b	17.22 (1.11)	8.16 (0.27) a	365.67 (18.00)
	T1	3.67 (3.81)	17.92 (5.59)	10.67 (1.96) b	444.98 (20.38) b	393.65 (11.01) b	51.33 (9.97) b	14.14 (11.33) bc	15.87 (0.71)	7.66 (0.44) a	355.65 (12.51)
	T2	3.62 (4.06)	17.94 (6.25)	10.39 (2.47) b	466.19 (30.24) b	408.68 (39.84) b	57.51 (10.89) b	14.30 (14.36) c	16.28 (1.94)	7.66 (0.36) a	338.21 (11.26)
	T3	–	–	13.64 (2.45) b	566.46 (15.74) a	459.39 (12.68) a	107.07 (9.34) a	18.93 (8.23) a	15.85 (0.97)	6.89 (0.43) b	358.39 (14.30)
	T4	4.48 (4.15)	19.30 (6.05)	11.75 (2.34) b	448.63 (17.87) b	398.22 (17.98) b	50.41 (10.96) b	15.50 (16.36) bc	15.78 (0.42)	7.96 (0.35) a	363.71 (25.18)
	P values										
	Treatment (T)	0.2142	0.0583	**0.0023**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.3691	**0.0048**	0.1677
	Date (D)	**< 0.0001**	**< 0.0001**	–	–	–	–	**< 0.0001**	–	–	–
	T*D	0.6043	0.3723	–	–	–	–	**< .0001**	–	–	–
	Contrasts										
	C vs T1	0.8183	0.3066	**0.0006**	**0.0005**	**0.0013**	0.3361	0.0522	0.1109	0.0864	0.3826
	T1 vs T2	0.7326	0.757	0.8504	0.1554	0.3448	0.3704	0.3633	0.6135	0.9991	0.1404
	T1 vs T3	–	–	0.0621	**< 0.0001**	**0.0012**	**< 0.0001**	< 0.0001	0.9842	**0.0133**	0.8089
	T1 vs T4	0.104	0.1021	0.4692	0.7990	0.7782	0.891	0.929	0.9129	0.2830	0.48

[a] The seasonal yields are the cumulative yields from (1) June 30th to October 13th in 2013 (28 harvests) and (2) from June 27th to October 13th in 2014 (26 harvests).
[b] Differences in the percentage of unmarketable yield among treatments were evaluated based on data from (1) July 12th to October 13th in 2013 and from (2) July 9th to August 30th in 2014.

and T4 conditions in 2013 and under T1, T2 and T4 conditions the following year. In 2013, plant growth restrictions under T2 conditions gave insufficient marketable yield to achieve additional net income compared to control conditions. Doubling the initial fertilizer load in 2014 significantly increased the marketable yield and positively affected the economic result during the second trial. Interestingly, T2 was the most profitable management practice in 2014 with a gain of CAD $ 9.1–10.3 per square meter, corresponding to a differential net income of CAD $ 1.3–1.8 compared to the reference. Plants grown in PE substrate (T1) gave significant additional gross revenues during the second growing season due to higher marketable yields and prices for fresh strawberries than in 2013. In particular, sensitivity analyses demonstrated the importance of berry price in affecting the magnitude of benefits (Table A.2, Appendix A in Supplementary material), and indicated that a minimum seasonal marketable yield of 506 kg per 0.1 ha combined with an average seasonal price of CAD $14 for 12 pints would have been necessary to ensure the profitability of such growing system. Available historical data for fresh strawberries in Quebec showed that annual prices were maintained above CAD $14 from 2005 to 2013 (Fig. A.3 ; Appendix A in Supplementary material), indicating that T1 is very likely to be more profitable than the control treatment whatever the year of production.

Among all treatments, T3 exhibited the highest levels of gross revenues (Table A.1, Appendix A in Supplementary material). Compared to open-air cultivation, T3 was more profitable in 2013 but generated significant losses of income the next year. Although strawberry prices were lower in 2013 (Fig. A.2, Appendix A in Supplementary material), the temporal variation of marketable yields obtained in 2014 resulted in lower gross revenues (CAD $ 25,492 in 2013 *vs.* CAD $17,211 in 2014; Table A.1, Appendix A in Supplementary material). These results show that a consistent production peak is needed during the period of high unit prices for fresh strawberries to compensate for the high initial investment for greenhouse and electricity costs during the forcing period. In both growing seasons, T4 gave systematically additional gross revenues with the highest ratio benefits/costs among protected treatments (ranging 1.36–1.80). Taking together, our data from the two trials suggest that this management practice corresponds to a technical-economic optimum. Overall, the economic analysis revealed that the implementation of rain shelter structures would be profitable due to its low initial investment and improved marketable yields compared to unprotected cultivation.

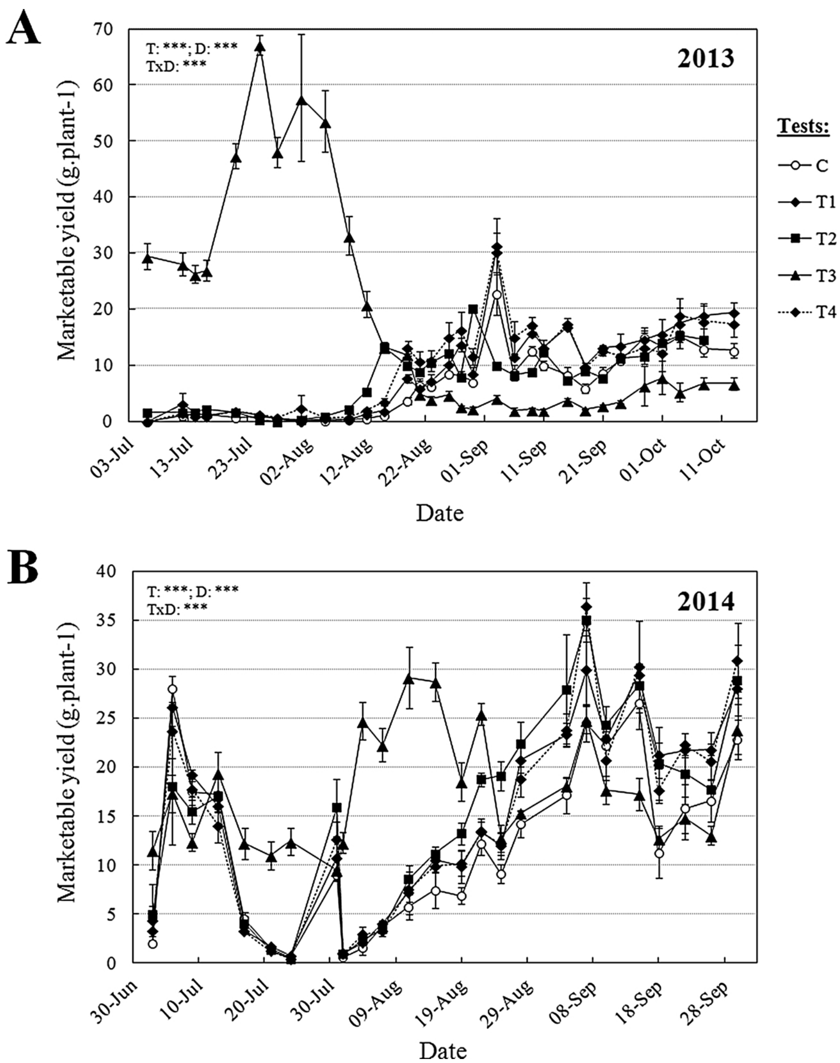

Fig. 4. Evolution of marketable yield for strawberry plants grown in open-field (Control) and under umbrella shelters (T1, T2, T3 and T4) during the 2013 (A) and 2014 (B) growing seasons. The P-values obtained from the generalized linear mixed model (GLMM) used to fit the data are reported for the test (T) and date (D) effects as follows: ns: no significant; (*) = $P < 0.05$; (**) = $P < 0.01$; (***) = $P < 0.001$. Each point represents the mean (n = 4) with SD.

4. Discussion

4.1. Using rain shelters to control diseases and improve seasonal yields

The difficulty to grow strawberries in cold-climate regions has been attributed to early frost events in spring and fall, in addition to heavy rain falls during the season production (Maughan et al., 2015). In North America, protected structures such as high (Rowley et al., 2011) and low tunnels (Petran et al., 2017; van Sterthem et al., 2017) can raise the temperature inside the structure and protect strawberries from winds and chilling injury, thus extending the harvesting period of day-neutral varieties. In northern Canadian climate, previous observations showed that rain shelters provide a substantial increase in air and root zone temperatures, in comparison to open-field conditions (Xu et al., 2013). Given that strawberry is one of the crop that respond well to increase in soil temperature under protected cultivation (Sonkar et al., 2012), the microclimate under shelters was likely to have a beneficial impact on plant growth and fruit production. In our specific experimental conditions, our results do not support this hypothesis. However, sheltering of strawberries efficiently slowed disease development of gray mold and mildew compared to open-field cultivation, in line with previous studies (Yu et al., 2017; Du et al., 2015; Chavarria et al., 2007). Although tunnels significantly reduced incidences of gray mold, short periods of leaf wetness in combination with high relative humidity levels led to higher incidences of powdery mildew when compared to open-air production (Xiao et al., 2001; Burlakoti et al., 2013). In contrast, rain shelters provide inadequate environmental conditions for powdery mildew primary infection by decreasing the relative humidity and the daily leaf wetness duration relative to open-field conditions (Blanco et al., 2004). Infected leaves generally serve as an inoculum source for fruit infections, and recent studies reported a positive correlation between the average aerial density of conidia and the average number of infected strawberries (Carisse and Bouchard, 2010; Blanco et al., 2004). Since airborne conidia are dispersed mainly by splashing rain and wind, shelters could effectively reduce the occurrence of secondary infection by limiting their germination and dispersion. Also, by reducing the rain impact on strawberry plants, rain shelters provide a decrease in the dependence on chemical pesticides. Hence, the reduced rain impact damage on fruits and decreased disease pressure provided by rain shelters likely resulted in increased total and marketable yields in our study, which is in contrast with previous observations made on drip-irrigated strawberries grown in beds (Rohloff et al., 2004). These apparent discrepancies may be explained by multiple factors such as growing systems, cultivars, rain shelter structure and environmental characteristics of the region under study.

4.2. Optimizing strawberry yields and water use under rain shelters

4.2.1. Early forcing: management difficulties and economical considerations

In this study, plants were forced under greenhouse conditions with the aim of (1) extending the strawberry production period and (2)

Table 3
Seasonal disease incidences for *Sphaerotheca macularis f.*sp. Fragariae and *Botrytis cinerea*. Means (n = 3) and SD are presented. nd: non detected. Significant P-values are indicated in bold.

Year	Disease	*Sphaerotheca macularis*		*Botrytis cinerea*	
	Treatments (T)	Number of plants	% of infected plants	Number of plants	% of infected plants
2013	C	8.00 (3.44) a	4.91 (6.28) a	nd	nd
	T1	3.94 (2.93) b	1.50 (1.65) b	nd	nd
	T2	3.19 (2.88) b	2.28 (4.47) b	nd	nd
	T3	7.75 (4.82) a	3.75 (2.83) a	1.38 (4.13)	2.88 (7.06)
	T4	3.44 (3.65) b	0.88 (1.63) b	nd	nd
	P values				
	Treatment (T)	**< 0.0001**	**0.0003**	–	–
	Date (D)	**< 0.0001**	**< 0.0001**	–	–
	T*D	**0.0079**	0.0573	–	–
	Contrasts				
	C vs T1	**0.0009**	**0.0358**	–	–
	T1 vs T2	0.417	0.8032	–	–
	T1 vs T3	**0.0029**	**0.0151**	–	–
	T1 vs T4	0.3586	0.0875	–	–
2014	C	7.5 (3.78) a	1.89 (1.55) a	0.13 (0.50) c	0.02 (0.06) b
	T1	1.69 (1.49) b	0.72 (0.97) b	0.75 (1.18) ab	0.41 (0.84) a
	T2	1.94 (1.57) b	0.67 (1.30) b	0.13 (0.50) c	0.02 (0.06) b
	T3	2.5 (3.1) b	1.22 (2.01) b	3.81 (4.26) a	1.67 (3.00) a
	T4	1.75 (1.53) b	0.36 (0.67) b	0.19 (0.54) bc	nd
	P values				
	Treatment (T)	**< 0.0001**	**0.0051**	**0.0023**	**< 0.0001**
	Date (D)	**0.0009**	0.1382	–	–
	T*D	0.7305	0.6085	–	–
	Contrasts				
	C vs T1	**< 0.0001**	**0.0112**		
	T1 vs T2	0.777	0.6067		
	T1 vs T3	0.9678	0.8273		
	T1 vs T4	0.9233	0.2725		

generating early and consistent marketable yields in order to capture local niche markets for farmers in Québec. In fall months, and more specifically during the two last weeks of July, the domestic strawberry supply is low while the demand remains high, and unit price for strawberries peaks for the fall production season in this province (Fig. A.1 ., Appendix A in Supplementary material). Forcing increased earliness of production by 13 and 6 days in 2013 and 2014, respectively (data not shown). Accordingly, the production peaks obtained (from July 15th to August 7th) coincided with a period of high demand for fresh day-neutral strawberries in Québec, thus providing the opportunity for farmers to generate significant increases in net income. The T3 treatment successfully captured the niche market during the first trial, leading to significant positive returns. However, the peak productions generated in 2014 were insufficient to increase the net income, relative to open-air production. Our economic analysis showed that the capital cost of the greenhouse structure and the high volatility of fresh strawberries market greatly affected what?. However in Canada, higher market prices have the potential to offset lower strawberry yields (Jirgena et al., 2013). In this context, local producers may consider using a low cost or low-tech greenhouse constructed with locally available materials to reduce the initial investment and further improve the financial effectiveness of forcing. The study also highlights technical difficulties such as the infestation of plants by mildew and gray mold, in spite of preventive measures to control them. Taken together, our results show that forcing plants requires a high degree of technical expertise on the part of the grower to ensure high productivity and product quality. Using strawberry plugs (Depardieu et al., 2017) or short-day cultivars (Guy Pouliot and Marine Marel, personal communication) could be interesting alternatives to obtain early fruit production and capture the niche market in Québec.

4.2.2. Promising practices for soilless strawberry production under rain shelters

Faced with rising awareness over the environmental impacts of soilless plant cultivation (Youbin et al., 2009), there is a critical need to develop sustainable management practices that are technically applicable, economically feasible and environmental friendly. Until recently, the main drivers for selecting a growing medium remain productivity and economical considerations (Barrett et al., 2016). However, the changing consumer preferences for local and sustainable crop production characteristics (Dukeshire et al., 2015; Khachatryan et al., 2014) urge scientists to develop environmental friendly substrates for soilless crop production. Because of its low cost and good moisture retention properties, sawdust is widely used in countries with intensive activities of the wood-processing industry (Bradley, 2007). Given the high availability and low cost of these by-products from traditional forestry processes, the development and commercialisation of new local horticultural mixes is likely to increase the competitiveness of strawberry cultivation. Mill residues are cheaper than *Sphagnum* peat and the prices of sawdust-peat horticultural mixtures are expected to be lower than those for pure peat material for large-scale sales. In our study, the peat-sawdust mixture (PS25) was especially prepared for the purpose of our experiments, thus resulting in higher price than for PE (Table 4). However, since PS25 is a cheap and locally-produced substrate while having a productivity potential similar to PE, this material can be used as alternative growing media to pure peat for soilless strawberry production.

The use of open fertigation systems causes serious environmental problems, with severe contamination of soil profiles with mineral nitrogen N-NO_3 (Breś, 2010). Previous studies showed that water barriers composed of polyethylene membranes (PM) can significantly reduce the leaching losses of fertilizers into groundwater for subsurface irrigation systems under open-air production (El-Nesr et al., 2014). Until now, information is scarce about the performance of PM under protected cultivation. In our study, we used a capillary mat underneath the peat substrate and generated substantial water and fertilizer savings while maintaining consistent marketable yields, thus identifying this practice as the most profitable during the two-year trial. Interestingly, the water retention technology improved the air-filled porosity and maintained the physico-chemical characteristics of the substrate during long-term cultivation periods. Furthermore, growers may use this cheap technology (Garrity et al., 1992) for 5–10 years of crop production. It is also expected to have a considerable positive environmental impact for large-scale production systems, in terms of water and nutrient recycling.

Interest in soilless culture of strawberry crops has increased worldwide in recent years (Urrestarazu, 2013). With this respect, strawberry soilless culture under rain shelters can be applied worldwide, especially in regions where rain shelters are already widely used (ex: Japan, China, Turkey, etc; see Inada et al., 2005; Huo et al., 2009; Ishikawa, 2013). Future research will be needed for the selection of day-neutral cultivars related to disease resistance to further increase the profitability of soilless strawberry production under rain shelters. Moreover, the extension of semi-closed systems, like capillary mat appears highly promising as it reduced the amount of nutrient and water use, while showing the highest profitability.

4.3. Conclusions

This study demonstrated the economic benefits of providing shelters

Table 4
Economical analysis (per 0.1 ha basis). The ratio benefits/costs (B-C ratio) represents the ratio of the gross revenues per the costs, with an B-C ratio higher than 1 indicating that the cultivation practice is profitable compared to the reference treatment (Control, C). Prices are reported in CAD $. PF: plastic film.

Costs (CAD $)	Year 1				Year 2			
	T1 vs C	T2 vs C	T3 vs C	T4 vs C	T1 vs C	T2 vs C	T3 vs C	T4 vs C
Fixed costs								
Rain shelters								
Depreciation								
Low price	115	115	115	115	115	115	115	115
High price	213	213	213	213	213	213	213	213
Interests								
Low price	34	34	34	34	34	34	34	34
High price	63	63	63	63	63	63	63	63
Greenhouse								
Depreciation								
Low price			1901				1901	
High price			2294				2294	
Interests								
Low price			561				561	
High price			677				677	
Irrigation system in the greenhouse								
Depreciation			300				300	
Interests			89				89	
Electricity in the greenhouse			2634				2049	
Variable costs								
Supplies								
Containers (Pints)	353	204	3143	605	557	828	1181	566
Pesticides			31				21	
Substrate material		312				312		
Capillary mat				32				32
Operation costs								
Plastic film (PF) for rain shelters								
Low price	40	40	40	40	40	40	40	40
High price	240	240	240	240	240	240	240	240
PF for the greenhouse			265				265	
Labor costs								
Fruit harvesting	325	188	2896	558	513	763	1088	521
Installation/uninstallation of the PF								
Low price	380	380	380	380	380	380	380	380
High price	500	500	500	500	500	500	500	500
Benefits (CAD $)								
Gross revenue	1640	1073	21,364	2998	3032	4295	6382	3046
Increase in net income								
Maximum (lowest costs)	392	−200	6005	1233	1393	1822	−4346	1356
Minimum (highest costs)	−117	−709	5496	724	884	1313	−4855	847
Ratio benefits/cost								
Maximum (lowest costs)	**1.31**	0.84	**1.39**	**1.70**	**1.85**	**1.74**	0.59	**1.80**
Minimum (highest costs)	0.97	0.62	**1.35**	**1.36**	**1.45**	**1.47**	0.57	**1.43**

to reduce disease incidence of powdery mildew and gray mold while improving yields of strawberry plants grown in organic substrates. Our findings suggest that rain-shelter is an environmental friendly agricultural practice for soilless production.

Interestingly, we found that combining the use of rain shelters with either a locally-produced growing media or a capillary mat technology were the most environmentally friendly and economical practices for soilless strawberry production. We strongly believe that these practices have the potential to be implemented at any scale to support eco-agriculture.

Acknowledgements

The authors wish to thank the Natural Sciences and Engineering Research Council of Canada and the project partners: Hortau Inc., Ferme Onésime Pouliot Inc. Authors also thank Guy Pouliot and Marine Marel for constructive comments that helped to improve the manuscript. We also thank Dr. J. Higgins for language editing of this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scienta.2017.12.056.

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