Using Pulsed Water Applications and Automation Technology to Improve Irrigation Practices in Strawberry Production

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SUMMARY. Quebec, Canada, is the third largest strawberry (*Fragaria × ananassa*) producer in North America, behind Florida and California. In view of increasing global water scarcity and the high water requirements of strawberry production, there is a critical need for growers to optimize irrigation practices to improve crop water productivity (CWP). In Quebec, pulsed irrigation has been shown to increase yields in strawberry crops while using the same volume of water as standard (nonpulsed) irrigation, thus improving CWP. However, more frequent and shorter-duration water applications (pulsed irrigation) might be more complex to manage manually; therefore, it could be of interest to automate the irrigation process at the farm scale. The first objective of our study was to assess the economic impact of pulsed irrigation compared with the standard irrigation procedure (nonpulsed irrigation) in a strawberry crop grown in a highly permeable clay loam soil in Quebec. The second aim was to determine whether pulsed irrigation would generate enough benefits to offset the cost of an automated irrigation system. We used data from three sites to determine the effect of pulsed irrigation on marketable yields and gross revenues compared with nonpulsed irrigation. We conducted a cost-benefit analysis to assess the cost-effectiveness of an automated irrigation system based on net gains associated with pulsed irrigation. Our results showed that pulsed irrigation was appropriate in strawberry crops grown in a highly permeable soil because it led to significant gross revenue increases relative to the standard irrigation procedure. Our results also revealed that pulsed irrigation generated enough additional benefits to cover the cost of an automated irrigation system, with a short payback period of about 1 year.

Despite its rigorous climate and relatively short growing season, Quebec, with 12,800 t of strawberries marketed in 2015, is the third largest strawberry producer in North America, behind the states of California and Florida (Statistics Canada, 2016; U.S. Department of Agriculture, 2016). The province accounts for more than 50% of strawberry

production in Canada (Statistics Canada, 2016). In a context of increasing water scarcity worldwide (Feres et al., 2011), one of the greatest challenges for Quebec's strawberry producers is to achieve more sustainable water use through the large-scale adoption of improved irrigation management practices.

Although Quebec has a relatively humid climate and a negative “potential

evapotranspiration (ETP)–precipitation (P)” balance (Agrométéo Québec, 2017), supplemental irrigation is a requirement for strawberry production in the province because the crop is often field-grown under a plastic mulch. Because strawberry plants have high water requirements and a shallow root system, they are particularly susceptible to water stress (Krüger et al., 1999; Liu et al., 2007; Manitoba Ministry of Agriculture, Food and Rural Development, 2015). These considerations point to the critical need for strawberry growers to adopt appropriate irrigation scheduling methods to optimize plant growth, yields, and crop water productivity. Irrigation management studies have been conducted on a wide range of crops, soil types and climatic conditions. In drip-irrigated strawberry crops, irrigation based on soil matric potential (ψ), with irrigation thresholds (IT) expressed in kilopascals (kPa), has been shown to positively affect crop yield and crop water productivity (CWP) at ITs ranging from –10 to –15 kPa compared with drier regimes (Bergeron, 2010; Evenhuis and Alblas, 2002; Guimera et al., 1995; Hoppula and Salo, 2007; Létourneau et al., 2015).

In silty clay loam to clay loam soils with a high proportion of shale fragments; however, Létourneau et al. (2015) reported that the advantages of the ψ -based irrigation management could be limited by the spatial variability of soil properties or by inadequate wetting patterns of the subsurface drip irrigation system. Indeed, observations and simulations in these soils clearly showed a dominant gravitational flow, with limited plant available water (Létourneau and Caron, 2017), a behavior usually found in sand and coarse sand soils

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
0.7457	horsepower	kW	1.3410
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg-ha ⁻¹	0.8922
28.3495	oz	g	0.0353
6.8948	psi	kPa	0.1450
0.4732	pt	L	2.1134

but not in fine textured soils like these. This unexpected behavior is attributed to the high proportion of shales found in these soils, which does not influence their texture (shales are sieved out for textural analysis) but affects their hydraulic conductivity and their water desorption curves. In Quebec, nearly 40% of the strawberry production area is characterized by these highly permeable soils (D. Bergeron, personal communication). The low soil water holding capacity of such soils leads to rapid water movement below the root zone, and irrigation may result in water and nutrient losses and groundwater pollution (Dukes et al., 2003; Skaggs et al., 2010). Nonetheless, more frequent and short-duration (pulsed) irrigation events have been shown to better match plant water uptake by improving soil water distribution (Assouline et al., 2006; Coolong et al., 2011; Eid et al., 2013), and irrigation can be managed on a time- or soil-measurement basis (Muñoz-Carpena et al., 2003). The positive effects of pulsed irrigation have been demonstrated for several crops grown in sandy soils (Dukes et al., 2003; Eid et al., 2013; Muñoz-Carpena et al., 2005) and in silt loam soils (Coolong et al., 2011), where yields were maintained despite reductions in the amount of water applied compared with non-pulsed irrigation. For strawberry plants grown in a highly permeable silt clay loam to clay loam soil, ψ -based pulsed irrigation significantly increased yields and CWP compared with non-pulsed irrigation based on ψ (Cormier, 2015; Létourneau and Caron, 2017).

Although manual ψ -based pulsed irrigation does not require production or irrigation system modifications relative to nonpulsed irrigation based on ψ , it may be more complex to manage, potentially leading to increased labor costs for watering. In this case, automatic-control pulsed irrigation based on preset ψ limits (Muñoz-Carpena et al., 2005) may be a more convenient way to manage irrigation (Dukes et al., 2003) for strawberry grown in highly permeable soils. Ançay et al. (2013) showed that an automated irrigation system could improve pulsed irrigation relative to manual pulsed management by lowering labor costs and water use in a strawberry crop in Switzerland. However, thus far, no economic

analyses have been done to determine whether ψ -based pulsed irrigation generates enough additional benefits compared with ψ -based nonpulsed irrigation to cover the cost of an automated irrigation system for strawberry production in North America.

Our study aimed to assess the economic impact of adopting pulsed irrigation instead of nonpulsed irrigation, considering that both methods are ψ -based with the same IT. It also aimed to assess the cost-effectiveness of investing in an automated irrigation system, given the potential gains associated with pulsed irrigation.

Materials and methods

SITE, EXPERIMENTAL DESIGN, AND CROP DESCRIPTION. We collected the data analyzed in this study over three growing seasons and on three sites in St-Jean-de-l'Île-d'Orléans, QC, Canada (lat. 46°54'N, long. 70°56'W) (Table 1). On all sites, we conducted field experiments from May to October in a typical humid continental climate, with strawberry plants planted in a highly permeable silt loam to clay loam soil with high proportion of shale fragments (Table 1). We grew bare-root strawberry plants (site 1: day-neutral cultivar Seascape; sites 2 and 3: short-day cultivar Monterey) in double rows, at a density of 54,800 to 56,000 plants/ha, on raised beds covered with black polyethylene mulch. The treatments were arranged in a randomized complete block design with three to four replicates (sites 1 and 2) or with six replicates (site 3). We used sprinkler irrigation during the early stages of plant growth. Subsequently, we drip-irrigated plants until the end of the season. The growing beds were irrigated by one drip line (1.5–2.5 L·h⁻¹·m⁻¹ with 10- to 20-cm emitter spacing) buried in the center of the bed, 3 to 5 cm under the soil surface. Field monitoring stations (TX3; Hortau, Levis, QC, Canada), measured and transmitted online ψ for real-time monitoring. The monitoring stations, consisting of two model HXM80 wireless tensiometers (Hortau) buried at two depths (15 and 30 cm) and connected to wireless transmitters, were installed in all replicates (site 1) or in three replicates (sites 2 and 3). On site 1, we triggered irrigation independently in each replicate once

the ψ measured by the 15-cm-deep probe reached the predetermined IT. On sites 2 and 3, we triggered irrigation simultaneously in all replicates once the average ψ measured by the shallow probes reached the target value. Except for irrigation management, all cultural operations were carried out by the grower following conventional farming practices, as described in more detail by Cormier (2015) and Létourneau and Caron (2017).

IRRIGATION TREATMENTS. On all sites, we tested two ψ -based irrigation treatments consisting of a control (nonpulsed) treatment and a pulsed treatment. Because the highly permeable soils under study had low soil water holding capacity leading to rapid water movements below the root zone (Bergeron, 2010), we expected pulsed irrigation events to better match plant water uptake by improving the soil water distribution (Assouline et al., 2006; Coolong et al., 2011; Eid et al., 2013).

For both treatments, we triggered irrigation once ψ reached a predetermined IT (site 1: -18 kPa; sites 2 and 3: -15 kPa), in accordance with previous studies conducted in a similar soil type (Bergeron, 2010; Létourneau et al., 2015). While irrigation events in control treatment lasted 45 to 60 min, consistent with common practice, irrigation in pulsed treatment, intended to improve water lateral distribution, was divided into two events lasting between 20 to 30 min each, separated by a period of 2 to 3 h (site 1) or 1 h (sites 2 and 3).

CROP YIELD AND GROSS REVENUES. Depending on the weather and the crop growth stage, fresh strawberries (also referred to as “marketable yields” in the present study) were harvested by the farm crew two or three times weekly from July to October, from either a fraction of the plot area (site 1) or the entire plot area (sites 2 and 3). We divided the quantity of fresh strawberries picked (grams) by the surface area harvested to obtain total marketable yield (kilograms per hectare). For the purposes of this study, we assumed that berries would be packed into 1-pt baskets (560 mL) and sold wholesale in Quebec. We obtained strawberry prices for high-quality strawberries from the Association des producteurs de fraises et de framboises du Québec (APFFQ).

Table 1. Characteristics of the sites where the experiments were held in St-Jean-de-l'Île-d'Orléans, QC, Canada (lat. 46.88°N, long. 71.00°W), in 2012, 2013, and 2014 and description of the experimental setup and the treatments tested at each site.

Site	Yr	Site area (ha) ^z	Individual plot area (ha)	Beds (no./plot)	Harvest measurement area	Experimental design ^y	Soil type ^x	Soil texture ^w	K _s (cm·h ⁻¹) ^y	Treatments (water application method) ^u
1	2012	2.67	0.11–0.15	9	Six full-length beds per plot	RCBD 3 reps	Silt loam to silty clay loam	47%–65% silt 8%–16% clay 21%–42% sand 2%–35% shale fragments	3–198	Nonpulsed (control treatment): –18 kPa Pulsed: –18 kPa
2	2013	2.29	0.05–0.06	2	Total plot area	RCBD 4 reps	Silty clay loam to clay loam	43%–48% silt 25%–29% clay 23%–31% sand 18%–24% of shale fragments	7–41	Nonpulsed (control treatment): –15 kPa Pulsed: –15 kPa
3	2014	1.34	≈0.03	2	Total plot area	RCBD 6 reps	Silty clay loam to clay loam	43%–48% of silt 25%–29% clay 23%–31% sand 18% to 24% of shale fragments	7–41	Nonpulsed (control treatment): –15 kPa Pulsed: –15 kPa

^z1 ha = 2.4711 acres.

^yRCBD = randomized complete block design, reps = replications.

^xAccording to the Canadian Soil Classification System (Soil Classification Working Group, 1998), soils in the area are silt loams to silty clay loams from the Orléans series.

^wA complete description of soil texture and hydraulic properties (saturated hydraulic conductivity and water desorption curve) of the three sites under study are available in Cormier (2015) and Létourneau and Caron (2017). Shale fragments are larger than 2 mm (0.08 inch).

^yK_s = saturated hydraulic conductivity in centimeter per hour; 1 cm = 0.3937 inch.

^uIrrigation events of nonpulsed irrigation lasted 45 to 60 min; with pulsed irrigation, irrigation was divided into two events lasting between 20 to 30 min each, separated by a period of 2 to 3 h (2012) or 1 h (2013 and 2014); 1 kPa = 0.1450 psi.

Prices were reported about every 2 d in dollars per 12 pt of fresh strawberries (see Supplemental Material for more details). On the basis of an estimated average pint weight of 375 g (Centre de référence en agriculture et agroalimentaire du Québec, 2014), we converted marketable yields into the number of 12-pt units harvested per hectare. Finally, we calculated weekly gross revenues by multiplying the average weekly strawberry price (Supplemental Fig. 1) by the number of pints harvested per week.

Other aspects of fruit quality such as fruit size (grams per fruit), sugar content (percent sucrose) and fruit firmness were studied on all sites but showed no significant differences and consequently are not discussed further here for clarity purposes. The results can be found in Létourneau et al. (2015) and Cormier (2015).

DATA ANALYSIS. We analyzed the data using SAS software (version 9.4; SAS Institute, Cary, NC). We conducted analyses of variance (ANOVA) with repeated measures using PROC MIXED to assess the impact of treatments (T), date (D) of harvest, and T × D interaction on both marketable yields and gross revenues. We used blocks as the random effect. We tested different covariance structures for the repeated statement to select the appropriate covariance model. In all analyses, we applied log transformations to the data sets to meet the assumption of homogeneity of variances. We compared least square means when the ANOVA model was significant at $P = 0.05$.

ECONOMIC ANALYSES. We performed economic analyses to assess whether pulsed irrigation generated enough benefits to cover the cost of an automated irrigation system to facilitate pulsed irrigation management at the farm scale. As a first step, we conducted a cost–benefit analysis to compare the positive and negative effects of adopting an automated irrigation system for pulsed irrigation instead of the nonpulsed, manual management system commonly used in the area (referred to as “standard procedure” in our study). Whereas we calculated positive effects, or benefits, based on yield gains, we calculated negative effects

based on additional operating costs associated with yield gains (variable costs) and the capital expenditure required to automate the irrigation system (fixed costs). Operating costs associated with the harvest of fresh strawberries were obtained from a commercial farm located in the area where the experiments were conducted. The labor costs were established at \$1.50/kg and included both fruit harvest and the disposal of fresh strawberries into common packages (C. Depardieu, unpublished data). Other operating costs, such as those related to the land preparation, plant establishment, fertilization, irrigation, pest management, equipment operating costs, and year-end cleanup, were not considered to be significantly different between treatments.

Fixed costs included the investment in an electronic diesel pump, an automated system and a control panel (see Supplemental Material for more details on equipment). We reported these costs on an annual basis through depreciation of the equipment, annual maintenance costs or service fees, and depreciated initial costs (Table 2). We estimated annual depreciation of the investment and of initial service fees using the straight-line method (Penson et al., 2002). We estimated a conservative 10-year life span for the pump and a 5-year life span for both the automated system and the control panel. Using a conservative approach, we assumed that one set of equipment, comprising one electronic diesel pump, one automated system, and one control panel, was installed for every 4 ha of production surface (Table 2). We also assumed that growers would require financing, and fixed the interest rate at 5%. Because the standard (non-pulsed) water application method relies on ψ measurements for managing irrigation, we assumed that the investment in field equipment, such as monitoring stations (tensiometers and web base) for irrigation management, was not necessary for the pulsed irrigation scenario. Indeed, the majority of the growers located in the area under study, which grow nearly 40% of Quebec strawberries, already use wireless tensiometers for managing irrigations. The total initial investment increased to about \$10,784/ha. When considered on

an annual basis, this investment and the annual service fees corresponds to annual costs of about \$1587/ha, before financial interests (Table 2).

We calculated net changes in revenues as the difference between positive and negative effects (Djidonou et al., 2013). Along with the cost-benefit analysis, we calculated the mean value of net change in revenues to estimate the long-run average economic result associated with the adoption of the ψ -based pulsed automatic irrigation management to replace the standard irrigation procedure. To assess the cost-effectiveness of automating the irrigation system for pulsed irrigation, we calculated payback periods;

i.e., the number of years required to generate sufficient revenue to reimburse the initial investment, for each year under study as well as for the mean value scenario (Zamalloa et al., 2011).

As a second step, we conducted a sensitivity analysis to evaluate the effect of changes in strawberry prices and marketable yield gains on net returns of automatic, ψ -based pulsed irrigation (see Supplemental Material for more details on the chosen price assumptions). Cost-effective investments were associated with positive net gains and with payback periods within the useful life of the equipment. Because different useful lives were under study, we calculated

Table 2. Equipment costs for irrigation automation (Province of Quebec, Canada) of a 4-ha (9.9 acres) production surface, considering that a set of one electronic diesel pump, one automated system and one control panel is required. For each component, the total cost is first reported, then the corresponding cost per hectare, and finally, the annual cost per hectare. The latter is obtained by dividing the cost per hectare by the useful life of the equipment. All prices are presented in Canadian dollars.

Component	Cost description	Value ^w
Electronic diesel pump ^z	Investment required for a 4-ha production surface	\$28,920
	Investment per hectare	\$7,230/ha
	Investment depreciation per hectare	\$723/ha
	Annual service fees	\$250
	Annual service fees per hectare	\$63/ha
	Initial costs	\$800
	Initial costs per hectare	\$200/ha
	Initial costs depreciation per hectare	\$20/ha
Automated system ^y	Investment required for a 4-ha production surface	\$6,000 ^v
	Investment per hectare	\$1,500/ha
	Investment depreciation per hectare	\$300/ha
	Annual service fees	\$475
	Annual service fees per hectare	\$119/ha
	Initial costs	\$300
	Initial costs per hectare	\$75/ha
	Initial costs depreciation per hectare	\$15/ha
Control panel ^x	Investment required for a 4-ha production surface	\$3,992
	Investment per hectare	\$998/ha
	Investment depreciation per hectare	\$200/ha
	Initial costs	\$2,945
	Initial costs per hectare	\$736/ha
	Initial costs depreciation per hectare	\$147/ha
Total investment		\$10,784/ha
Total annual costs, before financial interests		\$1,587/ha

^zThe electronic diesel pump was purchased at a 20% discount. The electronic diesel pump consisted of an engine (4LE2TABW01415C; Isuzu, Plymouth, MI) and a Berkeley pump (B3ZQM; Pentair, Delavan, WI). Characteristics and prices of each item are listed in Supplemental Table 1.

^yField monitoring stations (TX3; Hortau, Levis, QC, Canada) were interfaced to the electronic diesel pump for automating the irrigation system. The equipment needed for pump automation and prices are detailed in Supplemental Table 2.

^xA Lofa control panel (CP760G2R; Lofa, Roswell, GA) with wire and other components was required for remotely controlling the power unit (pump). Details are presented in Supplemental Table 3.

^w\$1/ha = \$0.4047/acre.

^vIn this study, each pump was assumed to rely on a different source of water. If several pumps were rather considered relying on a same source of water, which would be realistic on a farm, the investment cost in the automated system would have been of \$2500 per pump instead of \$6000. Therefore, the data used in this study were conservative.

a weighted life span depending on the useful life of each item based on the share of each piece of equipment in the total initial investment. We calculated break-even points, defined as the minimum marketable yield gain that would need to be obtained annually at a certain strawberry price to avoid a loss with the investment in an automated irrigation system.

Results

EFFECT OF PULSED IRRIGATION ON MARKETABLE YIELDS. The data analyses we performed to compare the effect of pulsed and nonpulsed irrigation on marketable yields in 2012, 2013, and 2014 revealed that pulsed water applications can improve strawberry production relative to the standard nonpulsed procedure (Fig. 1). On sites 1 and 2, pulsed irrigation increased marketable yields relative to the nonpulsed irrigation method, generating yield gains of 5221 and 2342 kg·ha⁻¹, respectively. On site 1, the analysis revealed that the positive effect of pulsed irrigation on marketable yields ($P = 0.001$) was the same regardless of the harvest date (Fig. 2A). However, on site 2, more frequent and short-duration water applications positively affected marketable yields at specific moments during the harvest period, as highlighted by the significant $T \times D$ interaction [$P < 0.0001$ (Fig. 2B)]. Indeed, significant yield increases associated with pulsed irrigation relative to the standard procedure corresponded to a period of high prices for fresh strawberries in early Aug. 2013. No significant differences between pulsed irrigation and nonpulsed irrigation were found for marketable yields on site 3, either cumulatively (seasonal marketable yields) (Fig. 1) or per harvest date (Fig. 2C).

EFFECT OF PULSED IRRIGATION ON GROSS REVENUES. The data analyses we performed to compare the effect of pulsed irrigation and nonpulsed irrigation on gross revenues revealed the same tendency as for marketable yields; i.e., pulsed irrigation generally increased gross revenues compared with nonpulsed irrigation (Fig. 1). On site 1, seasonal gross revenues associated with pulsed irrigation were significantly higher than those associated with the standard procedure ($P < 0.002$), with cumulative additional benefits of

Fig. 1. Comparison of the cumulative fresh strawberry yields (A) and gross revenues (B) by treatment in 2012 (site 1), 2013 (site 2), and 2014 (site 3). Treatments are nonpulsed and pulsed irrigation based on soil matric potential (ψ) with irrigation thresholds (ITs) of -18 kPa (-2.6 psi) in 2012 and -15 kPa (-2.2 psi) in 2013 and 2014. Irrigation events of nonpulsed irrigation lasted 45 to 60 min, whereas with pulsed irrigation, irrigation was divided into two events lasting between 20 to 30 min each, separated by a period of 2 to 3 h (2012) or 1 h (2013 and 2014). Gross revenues are calculated by multiplying weekly marketable yields by weekly strawberry prices in Quebec. The weekly gross revenues are then added together to obtain cumulative gross revenues. Means are presented [2012 ($n = 3$), 2013 ($n = 4$), 2014 ($n = 6$)], with SE. The probability values obtained from the generalized linear mixed model used to fit the data are reported for the treatment (T) effects as follows: NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; 1 kg·ha⁻¹ = 0.8922 lb/acre, \$1/ha = \$0.4047/acre.

\$24,036/ha. In this case, specific harvest dates did not significantly impact gross revenues (Fig. 2A). Similarly, data analyses for site 2 revealed that incomes were significantly increased by pulsed water applications relative to the standard procedure. However, on this site, differences in gross revenues also depended on the harvest date, as highlighted by the significant $T \times D$ interaction [$P <$

0.0001 (Fig. 2B)]. Additional gross revenues of \$14,762/ha were noted on site 2 for pulsed irrigation relative to nonpulsed irrigation, based on 2013 price data. No such increase was noted in 2014, either cumulatively (Fig. 1) or per harvest date (Fig. 2C).

ECONOMIC ANALYSES. We conducted a cost–benefit analysis to measure the additional costs (negative

Fig. 2. Time evolution of fresh strawberry yields by harvest date by treatment and average weekly fresh strawberry prices in Quebec in 2012 (A), 2013 (B), and 2014 (C). Gross revenues by harvest date by treatment in 2012 (D), 2013 (E), and 2014 (F). Treatments are nonpulsed and pulsed irrigation based on soil matric potential (ψ) with irrigation thresholds (ITs) of -18 kPa (-2.6 psi) in 2012 and of -15 kPa (-2.2 psi) in 2013 and 2014. Irrigation events of nonpulsed irrigation lasted 45 to 60 min, whereas with pulsed irrigation, irrigation was divided into two events lasting between 20 to 30 min each, separated by a period of 2 to 3 h (2012) or 1 h (2013 and 2014). Prices for high-quality strawberries in Quebec are obtained from Association des producteurs de fraises et de framboises du Québec (unpublished) and are expressed in Canadian dollars. Gross revenues are calculated by multiplying weekly marketable yields by weekly strawberry prices. Means are presented [2012 ($n = 3$), 2013 ($n = 4$), 2014 ($n = 6$)], with SE. Different letters indicate significant differences at $P = 0.05$. The probability values obtained from the generalized linear mixed model used to fit the data are reported as follows: NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; $1 \text{ kg} \cdot \text{ha}^{-1} = 0.8922 \text{ lb/acre}$, $\$1/\text{ha} = \$0.4047/\text{acre}$, $\$1/12 \text{ pt} = \$0.1761/\text{L}$.

effects) and benefits (positive effects) associated with the investment in an automated irrigation system based on the data collected on the three sites under study. In the first two scenarios, corresponding to sites 1 and 2, pulsed water applications generated enough additional benefits compared with nonpulsed irrigation to cover the cost of an automated irrigation system, with net gains of $\$14,295/\text{ha}$ on site 1 and $\$9356/\text{ha}$ on site 2. The payback period in these scenarios was less than 1 year (Table 3). However, in the third scenario (site 3), no significant gross revenue increases were noted with the adoption of pulsed irrigation relative to the standard procedure; instead, a net loss of $\$1880/\text{ha}$ was recorded. The mean value scenario, which considers that each of the three scenarios studied has an equal chance of occurring over the years, presented a net gain of $\$7257/\text{ha}$ and a payback period of 1.2 years, on account of an average yield gain of $2530 \text{ kg} \cdot \text{ha}^{-1}$ (at an average weighted price of $\$23$ for 12 pt of strawberries).

These are short payback periods considering that the weighted life span of the equipment is of ≈ 8 years (data not shown).

With sensitivity analyses, we measured the effects of strawberry price and marketable yield variations on net changes in revenues and payback periods. The results relative to payback periods are presented in Table 4. These results show that, at a conservative average yearly price of $\$20$ for 12 pt of fresh strawberries, a yield gain as small as $590 \text{ kg} \cdot \text{ha}^{-1}$, corresponding to additional gross revenues of $\$2622/\text{ha}$, would be enough to generate a net gain in revenue and a payback period (7.9 years) equivalent to the weighted useful life of the equipment (8.0 years). Likewise, if the average price for 12 pt of strawberries dropped to $\$15$, a conservative price considering historical strawberry prices in Quebec (Supplemental Fig. 2) and which also corresponds to the minimum strawberry price required to ensure the general profitability of a farm, the marketable

yield gain needed to generate a net gain and a payback period within the weighted useful life of the equipment was $950 \text{ kg} \cdot \text{ha}^{-1}$. These are low marketable yield gains, considering that the adoption of pulsed irrigation generated yield gains as high as 2342 and $5221 \text{ kg} \cdot \text{ha}^{-1}$ on two out of three sites studied and that the average marketable yield gain that can be expected over the years is $2530 \text{ kg} \cdot \text{ha}^{-1}$.

Discussion

PULSED IRRIGATION: A PROFITABLE WATER APPLICATION TECHNIQUE FOR FIELD-GROWN STRAWBERRY. Our results showed that pulsed irrigation has the potential to significantly increase marketable yield and thus greatly improve gross revenues in strawberry crops grown in a highly permeable soil relative to nonpulsed irrigation initiated at the same IT. The study demonstrated that marketable yield gains associated with the adoption of pulsed irrigation could coincide with high strawberry prices in Quebec (site 2), providing interesting opportunities

Table 3. Cost–benefit analysis associated with the adoption of an automated irrigation system for pulsed irrigation based on soil matric potential (ψ) instead of manually managed nonpulsed ψ -based irrigation (Province of Quebec, Canada). Cost–benefit analysis takes into account the additional benefits and costs associated with this change on an annual basis. Whereas additional gross revenues and operating costs vary with yield increases (when applicable), fixed costs are associated with the investment in equipment (pump, automated system and panel) and therefore represent annual depreciation of the equipment and its installation costs, as well as the opportunity cost of the invested capital (interest). The net change in revenue is used to calculate the payback period of the investment. All amounts are expressed in Canadian dollars.

Component	Scenario ^z			Mean value ^y
	1	2	3	
	Annual value ^x			
Gross revenue increases	\$24,036/ha	\$14,762/ha	–	\$12,933/ha
Expense increases				
Operating costs ^w	\$7,860/ha	\$3,526/ha	–	\$3,795/ha
Electronic diesel pump ^v				
Depreciation ^u		\$723/ha		
Interest ^t		\$217/ha		
Annual maintenance costs		\$63/ha		
Initial costs depreciation ^u		\$20/ha		
Automated system ^v				
Depreciation ^r		\$300/ha		
Interest ^t		\$47/ha		
Initial costs depreciation ^u		\$15/ha		
Annual service fees		\$119/ha		
Control panel ^v				
Depreciation ^{s,r}		\$200/ha		
Interest ^t		\$30/ha		
Initial costs depreciation ^r		\$147/ha		
Total expense increases	\$9,741/ha	\$5,406/ha	\$1,880/ha	\$5,676/ha
Net change in revenue	\$14,295/ha	\$9,356/ha	(\$1,880/ha)	\$7,257/ha
Payback period	0.6 years	0.9 years	NPB ^q	1.2 years

^zScenarios 1–3 refer to each site under study (sites 1–3). For scenario 1, the irrigation threshold for both nonpulsed and pulsed treatments was –18 kPa; for scenarios 2 and 3, it was –15 kPa. Irrigation events of nonpulsed irrigation lasted 45 to 60 min, whereas with pulsed irrigation, irrigation was divided into two events lasting between 20 to 30 min each, separated by a period of 2 to 3 h (2012) or 1 h (2013 and 2014); 1 kPa = 0.1450 psi.

^yThe mean value scenario considers that each of the three scenarios studied has an equal chance of occurring over the years.

^x\$1/ha = \$0.4047/acre.

^wVariable costs.

^vFixed costs.

^uThe useful life of the electronic diesel pump is 10 years. Therefore, irrigation pump and initial costs are amortized over a period of 10 years.

^tThe interest rate is fixed at 5%.

^rThe control panel depreciation includes equipment installation, programming and testing.

^sThe useful life of the automated system and of the control panel is 5 years. Therefore, their depreciation, as well as the initial costs depreciation, are calculated over a period of 5 years.

^qNPB = no payback on investment. Means that the benefits associated with the adoption of pulsed irrigation are not high enough to compensate for the costs associated with the adoption of an automated irrigation system.

for local growers. Moreover, for 2 out of the 3 years of experimentation, gross revenue gains of \$24,036 and \$14,762/ha were noted when pulsed irrigation replaced nonpulsed water applications with the same IT. Notably, the mean value scenario indicated that average long-run additional gross revenues of \$12,933/ha could be expected annually with pulsed irrigation relative to nonpulsed water applications. This represents a significant amount of money and yet is a conservative estimate considering

that the mean value scenario takes into account a year in which no significant differences between pulsed and nonpulsed irrigation were noted, most likely because of technical difficulties (Cormier, 2015). Indeed, in 2014, there was more rainfall (617 mm from May to October) than the average season (571 mm) and than in 2013 (518 mm for the same period); therefore, limiting the duration of the periods of stress for the plant relative to 2013. Also, due to increased rainfall, algae problems

created some plugging issues in the pumping system, requiring more maintenance than usual and sometimes delaying the second water application under the pulsed treatment. As a result, while the pulsed application maintained wetter conditions relative to control in the first 2 years, water potentials between nonpulsed and pulsed treatments were similar on the third year of experiment (data not shown), suggesting limited efficiency of the pulsed application that year. Site effect may also be involved in these differences, but this is unlikely because the texture, slope, orientation, and soil pH and EC were in the same range as those used in the previous 2 years. However, results of the third year were included in our study because they are part of technical limitations and weather conditions that a user may face and are likely to affect the possible benefits of the farm.

Although this study was conducted on highly permeable silty soils, we expect a similar behavior in coarse and medium sands and possibly on vertisols, high in clay content and developing preferential flow features (Coulombe et al., 1996), as pulsed irrigation is frequently performed on such soil textures. Therefore, given the promising results obtained, further studies should be extended to these other soil types and weather conditions for validation, particularly in California, North America's largest strawberry-producing area (87%) where the potential profitability of ψ -based irrigation management has been demonstrated (Gendron et al., 2018) and where some cracking soils of high permeability are found in the Salinas and Watsonville areas.

TOWARD MORE CONVENIENT PULSED IRRIGATION WITH AUTOMATION.

In addition to increasing gross incomes relative to the standard irrigation procedure, pulsed irrigation generated enough additional benefits relative to the nonpulsed procedure to cover the cost of an automated tensiometer-controlled irrigation system. Interestingly, the study shows that the profitability of the investment was not greatly affected by strawberry prices but rather was tied to marketable yield gains and the corresponding increases in gross revenues. To determine how the profitability of the investment in automation would vary

Table 4. Impact of marketable yield gain and price variation on the payback period of an investment in an automated irrigation system for pulsed irrigation based on soil matric potential (ψ) instead of manually managed nonpulsed ψ -based irrigation. Prices for 12 pt (5.7 L) of strawberries are expressed in Canadian dollars.

Marketable yield gain (kg·ha ⁻¹) ^z	Payback periods (years)					
	Average price for 12 pt of strawberries (\$) ^y					
	15	20	22	25	30	35
0	NPB ^w	NPB	NPB	NPB	NPB	NPB
590 ^x	NPB	7.9	6.5	5.2	3.8	3.0
950 ^v	7.9	4.3	3.6	2.9	2.2	1.8
2,530	2.4	1.4	1.2	1.0	0.8	0.6
3,600	1.6	1.0	0.8	0.7	0.5	0.4

^z1 kg·ha⁻¹ = 0.8922 lb/acre.

^yPrices for high-quality strawberries in Quebec are obtained from Association des producteurs de fraises et de framboises du Québec (unpublished) and are reported in dollars per 12 pt (5.7 L) of fresh strawberries; \$1/12 pt = \$0.1761/L.

^xBreak-even point defined as the minimum marketable yield gain necessary to generate a payback period within the useful life of the equipment at a strawberry price of \$20 for 12 pt of strawberries.

^wNPB = no payback on investment. Means that the benefits associated with the adoption of pulsed irrigation are not high enough to compensate for the costs associated with the adoption of an automated irrigation system.

^vBreak-even point defined as the minimum yield gain necessary to generate a payback period within the useful life of the equipment at the lowest strawberry price acceptable of \$15 for 12 pt of strawberries.

depending on the pint weight used for the calculations, we also conducted the economic analyses considering pint weights of 227 and 454 g, respectively (Agence canadienne d'inspection des aliments, 2013; APFFQ, unpublished). Whereas gross revenues increased with a pint weight of 227 g, generating shorter payback periods (7 months for the mean value scenario; data not shown), gross revenue gains decreased when a pint weight of 454 g was used as a reference, leading to longer payback periods (1.6 years on average; data not shown). However, in all cases, conclusions remained unchanged: pulsed irrigation generated enough additional benefits compared with nonpulsed irrigation to cover the cost of an automated irrigation system, with payback periods within the useful life of the equipment. Such cost-effectiveness makes automation both interesting and accessible to local growers.

Considering its convenience relative to manual management, automatic irrigation is certainly a practice that growers can adopt for pulsed water applications (Dukes et al., 2003; Muñoz-Carpena et al., 2005). For strawberry grown in highly permeable soils, previous studies revealed that pulsed irrigation improved CWP compared with nonpulsed irrigation initiated at the same IT by increasing marketable yields without increasing the amount of water used (Cormier, 2015; Létourneau and Caron, 2017), in

keeping with the objective of sustainable water use (Lin et al., 2013). If pulsed irrigation can generate higher yields than the standard procedure using a same amount of water, it follows that each drop of water is not being used to its full potential with nonpulsed water applications in this type of soil. Finally, it must be emphasized that additional gains could be expected after adopting an automated irrigation system for pulsed irrigation given that Ançay et al. (2013) found that automatic pulsed irrigation based on ψ led to water savings relative to manual ψ -based pulsed water applications without negatively affecting strawberry yields. Further research is needed to assess the profitability of this practice in highly permeable soils in Quebec.

Finally, despite showing the relevance, due to gains in productivity, of moving to pulsed irrigation in soils presenting preferential flow features (e.g., soils with a high proportion of shale fragments, coarse soils) in drip-irrigated strawberry production, these results point out to the potential challenges of training existing irrigators to implement such technology. Although the economic aspect makes the decision simple, the implementation at farm scale of such irrigation system for pulsed irrigation may require technical support because proper installation and continuous maintenance remain an issue with real-time technology. It is our experience that unsupported technology rapidly outperforms,

and real-time field controller systems are no exception.

Conclusion

This study reveals that pulsed irrigation based on ψ constitutes a sustainable and economic practice that strawberry growers operating in highly permeable soils can adopt, possibly in combination with an automated system, as this study also highlighted the high profitability of automation technology for pulsed irrigation in these conditions. In fact, a short payback period of the investment in automation technology was obtained with the mean value scenario (1.2 years) and, remarkably, an increase in gross revenues as little as \$2622/ha (corresponding to a yield gain of 590 kg·ha⁻¹) was enough to ensure a payback period within the weighted useful life of the equipment. These conclusions are particularly relevant considering that they potentially apply to more than 20% of Canada's strawberry production.

In conclusion, our results provide a useful tool for growers who are considering the adoption of a pulsed water application technique, possibly combined with an automation technology, for greater convenience in managing pulsed irrigation at the farm scale and profitability.

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Supplemental Material

WEEKLY VARIATIONS OF FRESH STRAWBERRY PRICES IN THE PROVINCE OF QUEBEC, CANADA.

Fresh strawberry prices were extracted from daily reports provided by the Association des producteurs de fraises et framboises du Québec (APFFQ, unpublished). We calculated weekly average prices that corresponded to the harvest time in our study. Two sources of strawberry prices were analyzed: 1) prices at the Central Market in Montreal, QC, Canada and 2) recommended prices by the provincial committee. Average prices obtained from both sources are presented in Canadian dollars in Supplemental Fig. 1.

While the Montreal Central Market prices corresponded to the prices received by the producer for day neutral strawberries sold at the market place in Montreal, the recommended prices referred to suggested prices for high quality strawberries delivered to the retailer's platforms and warehouses in Montreal and Quebec City, QC, Canada. Because the quality of the berries sold at the Central Market was sometimes lower than that of the berries sold to the retailers, the Montreal market prices

exhibited a lower tendency compared with the recommended prices. In the present study, we assumed that high-quality strawberries were packed into pints of 560 mL (18.94 fl oz) weighing about 375 g (13.23 oz) and sold wholesale through the Province of Quebec. Thus, the recommended prices were considered the most representative and were used for further analyses.

Supplemental Fig. 1 shows marked temporal variations in strawberry prices throughout the season. At all years, the highest prices were recorded from about mid-July to early August, which corresponds to a historical short period of low strawberry production in Quebec province.

The weekly price data were used to calculate gross revenues, multiplying the average weekly recommended prices by the corresponding weekly fresh strawberry yields measured in both treatments. It has to be noticed that no recommended price was available for the week of 16 Sept. 2014. To calculate weekly gross revenues, we estimated the missing data based on the price evolution (see the gray dot in Supplemental Fig. 1C).

AVERAGE SEASONAL STRAWBERRY PRICES IN THE PROVINCE OF QUEBEC.

The average seasonal strawberry prices, calculated as the mean of weekly prices over the season, indicated that average seasonal price for 12 pt (5.7 L) of strawberries increased from 2012 to 2014 (see red dotted lines in Supplemental Fig. 1), with minimum and maximum prices ranging from \$16 to \$32 for 12 pt of strawberries ($\$1/12 \text{ pt} = \$0.1761/\text{L}$). These average seasonal prices were used to define price ranges for the sensitivity analysis.

HISTORICAL FRESH STRAWBERRY PRICES IN THE PROVINCE OF QUEBEC.

Prices for day-neutral fresh strawberries sold at the Central Market in Montreal exhibited consistent variations from year to year (Supplemental Fig. 2). It is assumed that recommended prices experienced a similar time evolution. Considering the data provided by the APFFQ from 2005 to 2013, annual prices fall in the range of \$14.05 and \$20.74 per 12 pt of strawberries.

Because fresh strawberry prices at the Central Market in Montreal sometimes refer to lower-quality berries, these historical data were used to define conservative price ranges for the sensitivity analysis.

Supplemental Fig. 1. Weekly recommended prices for 12 pt (5.7 L) of fresh day-neutral strawberries in Quebec in (A) 2012, (B) 2013, and (C) 2014. Means are presented, with SE representing the variation between the minimum and maximum prices. As opposed to 2014, in 2012 and 2013 the recommended prices for the first weeks of October were not available (Association des producteurs de fraises et de framboises du Québec, unpublished); In C, we estimated the missing data based on the price evolution (gray dot). \$1/12 pt = \$0.1761/L.

Supplemental Fig. 2. Historical prices data for 12 pt (5.7 L) of day-neutral fresh strawberries sold at the Montreal, QC, Canada, central market (Association des producteurs de fraises et de framboises du Québec, unpublished); \$1/12 pt = \$0.1761/L.

Supplemental Table 1. Engine and electronic diesel pump characteristics for irrigation automation of a 4-ha (9.9-acre) production surface.

Engine (4LE2TABW01415C; Isuzu, Plymouth, MI)

- 35 horsepower (46.9 kW) at 2000 rpm
- Engine mounted on two wheels with a frame and a galvanized cabinet
- Three stabilizers
- Security guard
- Muffler
- Primer exhaust
- Electronic control panel
- Electric cables
- 12-V battery

Berkeley pump (B3ZQM; Pentair, Delavan, WI)^z

- Maximum capacity of 500 gal/min (1892.7 L·min⁻¹) at 50 psi (344.7 kPa)
- 5-inch vertically positioned foot valve (Klompox Alu; Sure-Flo, Ann Arbor, MI)
- 5 × 30-inch suction port (Marani, Modena, Italy)
- 5-inch male input (Marani)
- 4-inch output female pipe threads

^z1 inch = 2.54 cm.

Supplemental Table 2. List of the items needed for automating the irrigation system composed of an electronic diesel pump interfaced to field monitoring stations on a 4-ha (9.9-acre) production surface.

Automated system features (Hortau, Levis, QC, Canada)

- Pump auto start equipment
- A 30-ft (9.1 m) tower for data transmission with the devices installed in the field (control units)
- Pressure sensor for maintaining the pressure at the right level
- Solar panel and 12-V battery for feeding the pump auto start equipment
- Electric cable for connecting the pump auto start equipment to the control panel

Supplemental Table 3. Characteristics of the control panel and other components needed for remote control of irrigation on a 4-ha (9.9-acre) production surface.

Control panel features (Lofa, Roswell, GA)

- Panel CP760G2R
- Glow Plug 12 V
- Starter 12 V
- Temperature sensor and engine oil pressure