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Potato Varieties Response to Soil Matric Potential Based Irrigation

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Abstract: Potato is one of the most cropped plants worldwide. Hundreds of different varieties are cultivated only in North America. Potato growers usually crop multiple varieties on their farms to answer the market demands for potato's specific physical properties. However, few pieces of information are available regarding the optimal management of irrigation across potato varieties. Knowing that modern potatoes share genetics similarities, the optimal irrigation comfort zone for the potato crop might be the same for different groups of varieties. This study evaluates the effect of precision irrigation thresholds on the potato yields of three varieties (Envol: very early, Kalmia: early, and Red Maria: mid-late) with different maturity classes. In a greenhouse, a soil matric potential sensor network used in combination with a precise irrigation system allows the identification of a common optimal precision irrigation threshold, allowing optimal yields for the three varieties. This paper presents the first identification of an optimal irrigation threshold, −15 kPa, shared by different potato varieties. The optimal irrigation threshold identified in this study is not dependent on the maturity class, plant height or tuber potential production. The determination of an optimal precision irrigation threshold will allow potato growers to adapt their farm management processes to integrate more sustainable water management practices as they will be able to irrigate a field with multiple varieties with the same threshold.

Keywords: precision irrigation; crop production; water use efficiency; potato variety; drought tolerance; water stress; drip irrigation; tensiometer; soil matric potential

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1. Introduction

With an annual production of 322 million tons, potato is ranked fourth among the most cultivated food crops, behind wheat, maize and rice [1]. It is expected that the world population will reach 8.5 billion by 2030 and 9.7 billion by 2050 [2], increasing the demand for both food and agricultural production. Potato is currently cultivated on an estimated 18 million hectares worldwide, with 763,000 hectares only in North America [1]. There are more than 4000 varieties of native potatoes, creating an important genetic pool for potato breeding [3]. Despite this vast genetic pool, modern cultivated potatoes are similar at the genome level [4]. More than 100 varieties are grown for the tablestock market in North America only, excluding the processed potato market [5]. In Canada, 50 varieties cover 83% of the registered seed potato areas [6]. The variability between potato varieties is represented in several physical aspects such as size, shape, flavor, texture and color [3,5].

Several physiological variations have been observed between potato varieties, such as stomatal conductance [7], water use efficiency [7,8] and drought tolerance [8–10]. Besides this, potato growers usually crop multiple varieties with different maturity classes to answer the market demand for colors and sizes and to stagger production and processing across the growing season. Cropping multiple varieties also helps to share risks, as the drought and disease tolerance of potato varieties is variable. Due to the sensitivity of potato to drought [8,11–13], irrigated areas for potato growing have increased over the last decade, and this trend is likely to be maintained due to climate changes and increasing food demand [14–16]. The research into hydric comfort zones between potato varieties is very scarce [10,17]. Thus, water management methods are required to establish precision irrigation management guidelines across potato varieties, increasing crop productivity and improving water use.

Among the existing methods, the soil matric potential (SMP) has proven to be a reliable criterion to characterize soil water availability [11]. Water management based on SMP is known to increase water use efficiency, especially in lettuce [18], cotton [19], corn [20,21] and potato [22]. Crop-specific optimal SMP thresholds, avoiding excessive water input or water shortage, have been determined for numerous crops, including celery, onion [23], tomato [24,25], lettuce [26], strawberry [27] and cranberry [28,29]. The objective of an irrigation management based on SMP is to keep the plants in a comfort zone, making their physiological process efficient. Knowing that modern potatoes share genetics similarities [4], the optimal irrigation comfort zone for the potato crop might be the same for different groups of varieties. Therefore, to ensure an optimal potato yield and efficient water productivity, developing a precise water management method across various potato varieties is necessary.

Here, we aimed to evaluate the effect of precision irrigation thresholds on the potato yields of three varieties (Envol: very early, Kalmia: early, and Red Maria: mid-late) with different maturity classes. According to local potato growers' insights, the three varieties also have different drought resistances. In a greenhouse, a soil matric potential sensor network used in combination with a precise irrigation system allowed the identification of a common optimal irrigation threshold, allowing the highest tuber yields for the three varieties.

2. Materials and Methods

2.1. Experimental Design

We conducted eight irrigation experiments using three potato varieties in the high-performance greenhouse complex of Laval University (Québec, QC, Canada) from 2017 to 2019. The experiments were arranged as a split-plot design of four repetitions of three soil matric potential thresholds repeated three times for two varieties (Envol and Red Maria) and two times for Kalmia across four greenhouse growing seasons. The three soil matric potential thresholds tested were −15, −30, and −45 kPa. They were selected based on the distribution of the soil matric potential on the soil water retention curve to cover a wide range of field-realistic water contents, as shown in Figure 1. The van Genuchten parameters [30] used to generate the water retention curve were fitted based on the SMP and soil water volumetric data measured throughout one growing season using the L-BFGS-B method [31].

The soil was extracted at Dolbeau-Mistassini city (48°51′31″ N and 72°11′50″ W) from a potato field. It was collected from the first 20 cm, homogenized and placed into each experimental unit. The soil was a Podzolic sandy soil (0% clay, 8.2% silt, 91.8% sand, 3.1% organic C, 0.48% porosity and a pH of 5.01) according to the Canadian soil classification [32]. It was saturated with water before planting and was replaced between experiments to avoid soil-borne diseases. The sedimentation method was used to assess the particle size distribution [33].

The potatoes were grown in plastic experimental units of 0.14 m^3 (60 × 40 × 40 cm). We planted two tubers at a depth of 7.5 cm and installed one tensiometer at a 10 cm depth in each experimental unit (Figure 2). The spacing between tubers in the experimental units and between experimental units was equivalent to a field potato spacing. Data from the tensiometer were collected at two-minute intervals. These measurements were used to calculate the mean SMP for each precision irrigation threshold to trigger irrigation automatically.

Individual irrigation lines were used to control irrigation independently for each precision irrigation threshold, allowing accurate irrigation management. The duration of irrigation was adjusted throughout the growing seasons to reach an SMP of between −1 and −5 kPa after irrigation. Irrigation water was applied using drip irrigation emitters placed on the soil surface. From potato seeding to emergence, irrigation was the same for all thresholds to ensure uniform emergence. The irrigation experiment began with the potato emergence, around 20 days after planting, and continued until around 90 days after planting for the Envol (advance maturity stage) and Kalmia (early maturity stage) varieties and 100 days after planting for Red Maria (to engage senescence).

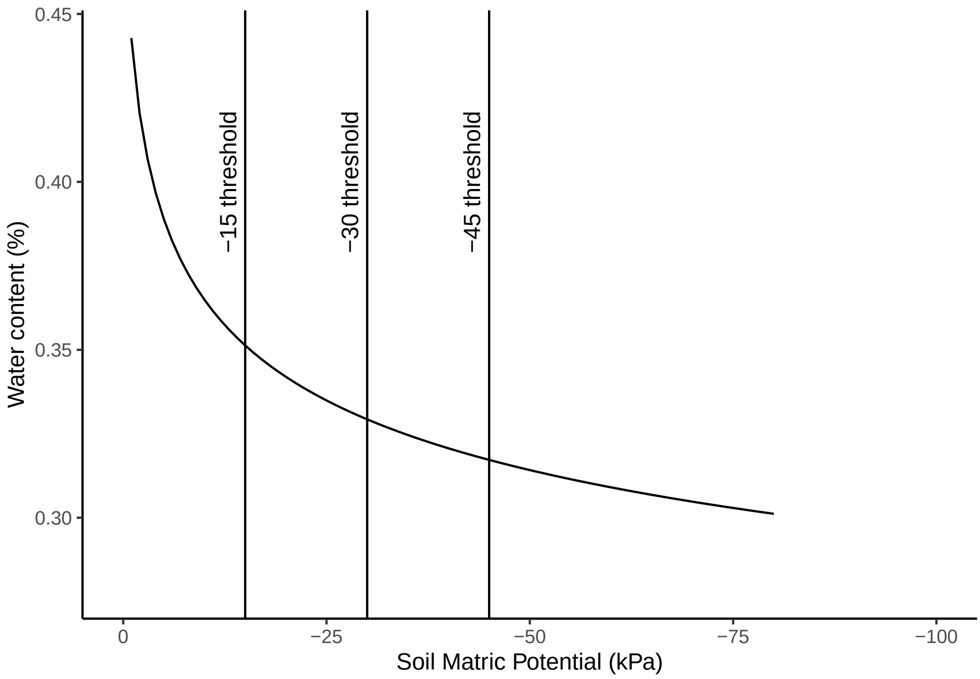

Figure 1. Distribution of the irrigation thresholds (vertical lines) used in this study related to the soil water retention curve (exponentially decreasing line).

We evaluated the cumulative irrigation water volume for each precision irrigation threshold by recording the opening time of the automatic valves used in the irrigation system and the manufacturer's flow rate for the in-line emitters (1.09 L/h). The total tuber weight divided by the amount of water applied in the specific precision irrigation threshold was used to calculate the WUE.

The water content was measured in 12 experimental units (three units in the SMP threshold −15, −30 and −45 kPa, randomly selected) in 2018 at a 10 cm depth using GS3 probes (Decagon Devices, Inc., Pullman, WA, USA) at 15 min intervals to create the in situ water retention curve.

2.2. *Agronomic Practices*

The three potato varieties used in this study were Envol, Red Maria and Kalmia. Due to considerations of the greenhouse space and seed availability, all varieties were not always cultivated simultaneously. The first experiment used Envol and Red Maria following growers' insights on their contrasting drought tolerances. In accordance with preliminary results suggesting a uniform precision irrigation threshold, the variety Kalmia was added in the experiment.

The Envol variety was bred and selected in Quebec, QC, Canada in 1987 and has been officially certified and registered in Canada since 1999. It is the third most important variety in terms of potato seed production area in Quebec [6]. This variety is characterized by very early maturity, a medium height and smooth white skin, with round to oval tubers. The Envol is considered a very good early yielding variety with a high percentage of large tubers for the early and fresh market.

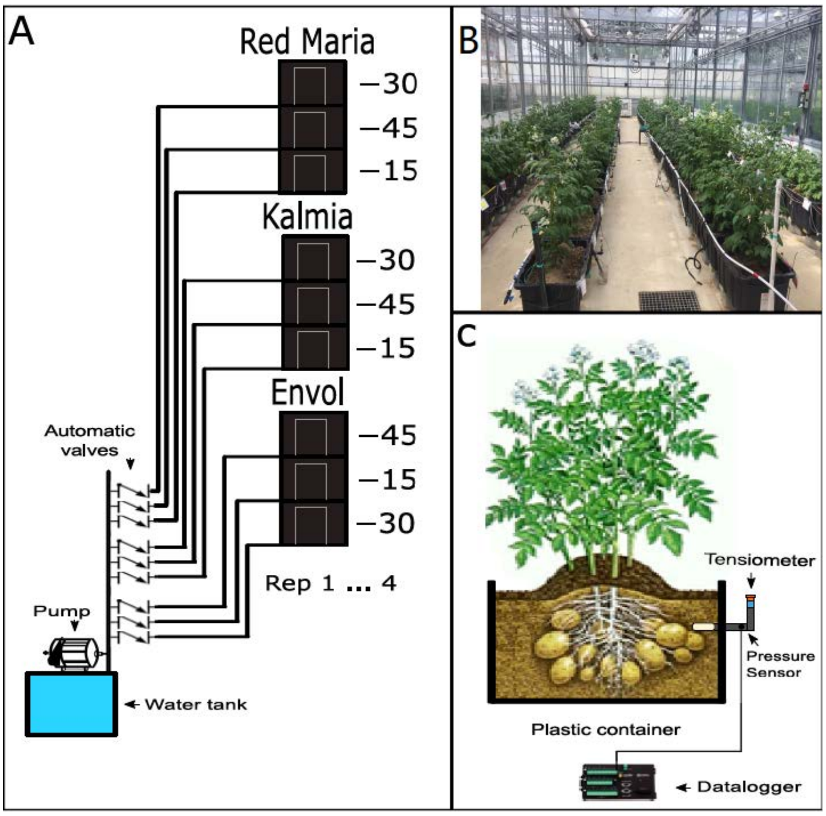

Figure 2. (**A**) Scheme of the experimental design in winter 2019 in the greenhouse, including three precision irrigation thresholds (−15, −30, and −45 kPa) and three potato varieties. (**B**) Picture of the greenhouse experiment. (**C**) Scheme of the short side of an experimental unit.

The Red Maria variety was bred and selected in New York, NY, USA and was officially released in 2010. This variety is characterized by late maturity, a medium to high height and round red-skinned tubers. The Red Maria is considered a good variety for the tablestock market with excellent yields.

The Kalmia variety was bred and selected in Quebec, Canada in 1995 and has been officially certified and registered in Canada since 2008. This variety is characterized by an early maturity, a high height and round, white-skinned tubers. The Kalmia is considered a high yield variety.

Fertilization was carried out uniformly for the varieties following the local crop recommendation for potato [34]. The available nutrient concentration (P, K, Ca, Mg and Al) was extracted using the Mehlich III extraction method [35] and determined at the Institut de Recherche et de Développement en Agroenvironnement (IRDA, Sainte-Foy, QC, Canada) using inductively coupled plasma optical emission spectrometry (ICP–OES) (Model ICAP; PerkinElmer, Boston, MA, USA). The fungicides APROVIA (benzovindiflupyr) and Senator PSPT (thiophanate-methyl) were used at planting following the manufacturer's rates to eliminate soil-borne diseases.

Tubers were collected, washed and weighed to measure the total yield after enough maturation to avoid skin damage while harvesting. The tuber density was measured using three medium tubers (between 112 and 224 g) of each experimental unit by immersion in water.

2.3. Greenhouse Environmental Conditions

The environmental conditions in the greenhouse were measured with a complete weather station set inside the greenhouse. The mean temperature and relative humidity were 20.13 °C ± 3.34 °C and 45.05% ± 17.80%, respectively. The temperature and relative humidity for each experiment are shown in Table 1.

Table 1. Mean temperatures (°C) and relative humidity (RH, %) over the different growing seasons for the three experiments.

Exp	Temperature	RH
Envol		
1	18.67 ± 2.24	39.67 ± 14.12
2	20.40 ± 4.29	62.10 ± 16.16
3	21.58 ± 2.88	38.80 ± 14.41
Kalmia		
2	20.40 ± 4.29	62.10 ± 16.16
3	21.58 ± 2.88	38.80 ± 14.41
Red Maria		
1	23.34 ± 2.35	59.56 ± 8.39
2	18.67 ± 2.24	39.67 ± 14.12
3	21.58 ± 2.88	38.80 ± 14.41

2.4. Statistical Analysis

All data were analyzed using R software [36]. The variance homogeneity was acknowledged using the Levene test from the Car packages [37]. The data normality was determined using the Shapiro–Wilk test [37]. Significant differences of potato yields between thresholds were acknowledged for each variety by the ANOVA test, followed by the least significant difference (LSD) test from the Agricolae package [38]. The differences were considered significant when p-values were under 0.05 (LSD test, $p < 0.05$).

3. Results

3.1. Precision Irrigation Thresholds and Yield

Precision irrigation thresholds affected potato yield significantly, as a −15 kPa threshold showed the highest yield for all the varieties tested. As shown in Figure 3, the potato yield varied between the experiments. The second experiment for Envol and Kalmia varieties showed lower total yields than the other experiments. This was due to the impact of *Verticillium* and *Fusarium*, which caused damages to the potato in this experiment. Nonetheless, a general trend emerged in which the yield of the −15 kPa threshold was systematically higher than the others for each variety and experiment. For Envol and Red Maria, the descending trend between −15 kPa to −45 kPa was linear, whereas Kalmia yields for the −45 kPa threshold were maintained to a similar level as at the −30 kPa threshold.

Table 2 shows the total potato yield and the significant difference (p-value < 0.05) according to the LSD test. For the Envol variety, the −45 kPa threshold led to significantly lower yields than −15 kPa with a reduction of 31%. The −30 kPa threshold was neither different from −15 nor −45 kPa. For the Kalmia variety, the yield under the −15 kPa threshold was significantly higher than both dryer thresholds: 34% and 33% for −30 and −45 kPa, respectively. For the Red Maria variety, the yields under the three thresholds were significantly different from one another. The yield of Red Maria under the −15 kPa threshold was the highest, followed by the −30 and −45 kPa thresholds, with a reduction of 22% and 54%, respectively. The precision irrigation thresholds did not significantly affect the tuber density, as shown in Table 2.

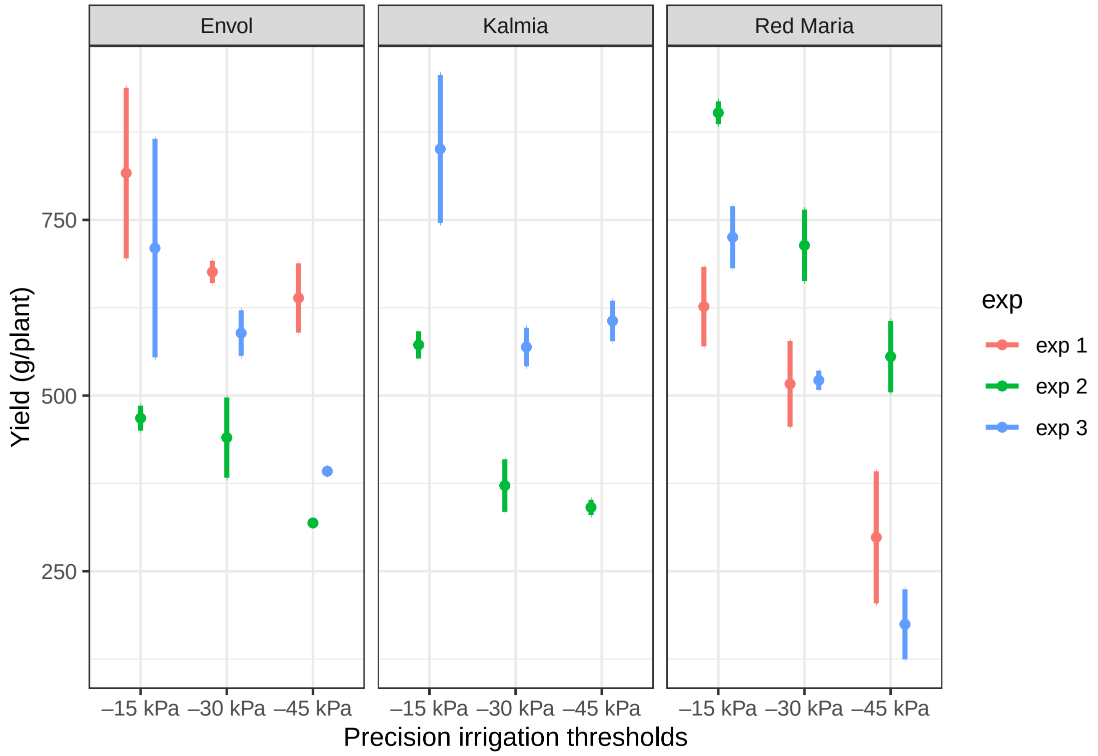

Figure 3. Distribution of the total tuber yield of each variety, experiment and precision irrigation thresholds. Error bars show the standard error of the total yields. The colors show the experiments for each variety.

Table 2. Precision irrigation thresholds and variety effects on total tuber yield, tuber density and water use efficiency with the standard error for three potato varieties. The values from the same variety in a column with different letters are significantly different according to the least significant difference (LSD) test. SMP: soil matric potential; WUE: water use efficiency.

SMP	Total Yield (g/Plant)	Tuber Density (g/mL)	WUE (g/L)
Envol			
–15 kPa	664.79 ± 74.17 a	1.09 ± 0.01	7.35 ± 0.83 c
–30 kPa	579.99 ± 34.50 ab	1.08 ± 0.02	10.85 ± 1.18 b
–45 kPa	461.88 ± 46.31 b	1.08 ± 0.01	15.88 ± 1.21 a
Kalmia			
–15 kPa	711.52 ± 72.32 a	1.09 ± 0.00	13.38 ± 0.79 c
–30 kPa	470.51 ± 43.01 b	1.07 ± 0.01	15.98 ± 0.98 b
–45 kPa	473.58 ± 52.15 b	1.06 ± 0.01	21.89 ± 0.73 a
Red Maria			
–15 kPa	751.49 ± 40.94 a	1.08 ± 0.01	12.59 ± 0.91
–30 kPa	584.05 ± 36.84 b	1.14 ± 0.05	10.58 ± 0.76
–45 kPa	342.71 ± 59.60 c	1.14 ± 0.03	9.00 ± 1.71

3.2. Irrigation Volume

The irrigation volume used for each variety by experiment is shown in Figure 4. The first experiment of the Red Maria variety showed a plateau at the end of the seasons. In this case, irrigation was stopped to induce the maturation process earlier for experimental purposes. The second experiment for the Envol and Kalmia varieties showed an irregular irrigation distribution at 70 days after planting. This is probably due to the symptoms of *Verticillium* and *Fusarium* that occurred in these varieties in this experiment. Otherwise, the water distribution along the growing season was comparable between the experiments and the precision irrigation thresholds. On average, for the −15, −30, and −45 kPa thresholds, Envol received 192.1, 124.7 and 57.5 liters, respectively, Kalmia received 209.1, 105.7 and 62.5 liters, respectively, and Red Maria received 123.9, 112.5, and 83.7 liters, respectively. Throughout all the experiments, no leaching was observed for any experimental units.

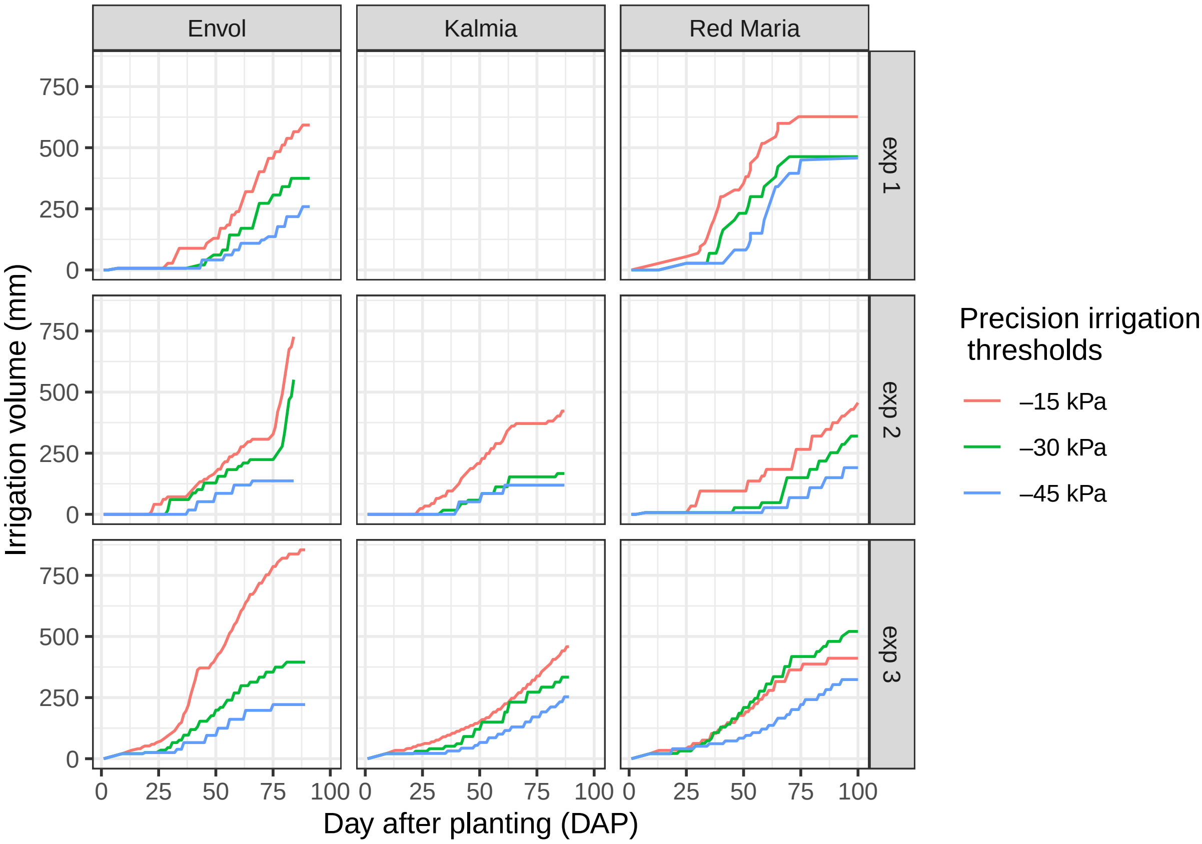

Figure 4. Cumulative irrigation volume for each variety, experiment and precision irrigation threshold.

3.3. Water Use Efficiency

The water use efficiency (WUE) values for the different precision irrigation thresholds are shown in Table 2. For Envol and Kalmia, the −15 kPa threshold led to the lowest water use efficiency, followed by the −30 kPa and −45 kPa thresholds. For the Red Maria, the trend was reversed, and the −15 kPa threshold led to the highest WUE, followed by the −30 kPa and −45 kPa thresholds. As shown in Table 2, the difference between the WUE was significant for Envol and Kalmia and not significant for Red Maria.

4. Discussion

In recent years, numerous examples of different detrimental effects of drought on potato varieties have been documented, highlighting a difference in drought tolerance among potato varieties [8,9]. However, the existence of soil matric potential thresholds allowing the optimal production of groups of potato varieties under precision irrigation is still an open question. The results of the present study demonstrate that three potato varieties with different physiological properties achieved their highest yield under the same precision irrigation threshold, −15 kPa. The three varieties, Envol, Kalmia, and Red Maria, belong to different maturity classes; respectively, very early, early, and mid-late. They also have different yield potential and plant heights. Therefore, the precision irrigation threshold preference of the potato varieties used in this study does not depend on the previous characteristics. Optimal soil matric potentials between −15 kPa and −25 kPa have already been suggested for other varieties such as Favorita [39], Katahdin and Russet Burbank [40]. In [10], the authors also stated that potato yields for seven varieties (Umatilla Russet, Russet Legend, Russet Burbank, Shepody, Frontier Russet and Ranger Russet) increased when irrigation replenished evapotranspiration completely.

In our study, the three varieties needed different water volumes to maintain similar soil matric potential. This indicates that evapotranspiration is different among the varieties and that soil matric potential-based irrigation is suitable to allow the precise irrigation of potato varieties. The effect of deficient irrigation across the season created with the −45 kPa threshold differed across the varieties, in accordance with previous findings [8,10]. Nonetheless, a clear general trend appears, as all the varieties tested showed their lowest yield at the −45 kPa threshold. A similar negative general trend across numerous potato varieties caused by deficit irrigation was also observed in [9].

Under water scarcity conditions, our study shows that using a precision irrigation threshold of −30 kPa allows intermediate yields and intermediate water use efficiency. Irrigation based on the −30 kPa threshold reduces irrigation water by almost 30% on average across the three varieties. For Envol and Kalmia, the highest WUE was achieved with the −45 kPa threshold. The dryer threshold exhibited the lowest WUE for the Red Maria variety. Genetic differences among potato varieties were reported to explain the photosynthetic characteristic differences leading to WUE variation [7]. However, the potatoes cultivated in North America originate from a narrow genetic base [4]. The shared genetic components could explain that numerous potato varieties could share the same soil matric potential comfort zone irrespective of evapotranspiration and WUE variations.

5. Conclusions

Evidence is provided in this study that the management of the irrigation of different potato varieties could use the same precision irrigation threshold. The identification of an optimal precision irrigation threshold that is usable for different potato varieties could allow potato growers to manage fields with varieties with different maturity classes using a single irrigation threshold. Future works should test more varieties, soils and climates to provide a broader variability and acknowledge the potato comfort zone. Future research should also focus on the precision of the potato comfort zone, identifying its limits and the SMP range and allowing optimal yields. It is also necessary to test the effect of an SMP higher than −15 kPa and acknowledge if it causes an increase or a decrease in potato yield. Furthermore, a genuinely integrated irrigation approach is required to assess the different environmental effects of irrigation. Therefore, future works should also focus on identifying the potential impacts of optimizing irrigation on the soil, environment and yield in potato production.

Author Contributions: J.-P.M., S.J.G., T.G. and P.C. conceived the presented idea. J.-P.M., G.L. and S.J.G. conceived and designed the experiments. J.-P.M. and G.L. performed the experiments. J.-P.M. analyzed the data. All authors have read and agreed to the published version of the manuscript.

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