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Irrigation, potatoes and unintended consequences of optimizing water management

CAPI Doctoral Fellow 2017-2019 Paper

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October 2019

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Research Paper
October 2019

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Executive summary

The human use of freshwater has expanded at a rate twice that of the population increase. Nowadays, 70 percent of the 3 830 cubic km of water withdrawals are by the agricultural sector (FAO, 2008). Among the major crops, the potato ranks high for caloric production per liter of water. Ironically, potato yields are particularly sensitive to soil water deficit. Therefore, to ensure an optimized potato yield and high-water efficiency, an intelligent water management method must be developed. Irrigation management based on soil matric potential (SMP) increases water efficiency. However, SMP thresholds need to be clearly defined. Thus an integrated water management approach in potato crops needs to be determined, and the consequences of optimizing water management need to be assessed.

This experiment was performed in a greenhouse using a highly monitored experimental setup, including two tensiometers for two potato plants, eight soil moisture probes and meteorological sensors controlling the greenhouse climate. In this study, four different irrigation thresholds (-15 kPa, -30 kPa, -45 kPa and drought imitation) were tested to determine the optimal SMP range for optimizing potato yields and water efficiency.

It was found that the water management treatment that included more water and more frequent irrigation (-15 kPa SMP), yielded the highest number of potato tubers. The greatest decrease in total yield was observed at an SMP of -45 kPa, and the drought treatments. Our results indicate that drought sensitivity or resistance seems to be independent of the yield potential and the variety growth duration. However, the ratio of tuber production per liter of water used is optimized at an SMP of -45 kPa and drought treatment, where the water used decreases proportionally with tuber production.

Besides the effect of water management on potato yields, optimizing water use creates unintended impacts on the potato crop. The architecture of the roots and, therefore potato tuber distribution is modified by water management.

Potato tuber distribution plays an important role in the share of potatoes harvested ("potato lifting percentage") and on the amount of soil loss during harvesting. However, due to the opaque characteristic of the soil or other growing media and the fragility of some of the root system structure, being able to observe tuber distribution remains difficult. Furthermore, the 3D model construction of plants and root system is also a challenge. Computed Tomography (CT) technology to identify the correct representation of potato tuber distribution is promising and could allow a more accurate phenotypic description and greater information gathering using a non-destructive method. Moreover, little is known about the effect of irrigation management on tuber 3D distribution.

The results showed that for the -15 kPa water management treatments, tubers are distributed closer to the seed potato. For the -30 kPa water management treatments, tubers are further from the seed potato and were even found at the very bottom of the container.

Another side effect of optimizing water management is on soil organic matter dynamics. Soil organic matter has an important impact on the global carbon cycle and is influenced by water management. Our results suggest that a constantly dryer soil tends to create more stable organic matter.

The irrigation thresholds identified in this study will benefit potato growers and may serve as guidelines for more efficient water management, reducing water use and the unintended consequences of irrigation on potato production

Setting out the research problem and disciplinary orientation

In future years, droughts are expected to increase and worsen, especially in the already arid regions of the world (Center for Climate and Energy Solutions, 2019). At the same time, the world population is expected to reach 8.6 billion by 2030 and 9.8 billion by 2050 (United Nations, 2017), increasing the demand for both food and agriculture production. Optimizing agricultural production with productive crops in terms of water use and caloric production is one answer to these challenges.

In the past few years, human use of freshwater has expanded at a rate twice that of the population increase (FAO, 2008). Nowadays, 70% of the 3 830 cubic km of freshwater withdrawals each year are by the agricultural sector (FAO, 2008). The potato is the most efficient crop in terms of calories produced per liter of water used among the major crops (FAO, 2008). However, potato yields are especially sensitive to drought conditions and need a regular water supply. Their sensitivity can be attributed to shallow and inefficient root systems, whose development is interrupted by tuber growth (Joshi et al., 2016)

With an annual production of 322 million tons, the potato is the fourth most important crop in the world, after wheat, maize and rice (FAO, 2014). Canada is the 12th largest potato producer in the world. The potato is the most important vegetable crop in Canada, representing 29% of all vegetable revenues and 15% of farm income (Statistique Canada, 2015). As a consequence of climate change, irrigated potato crop area has grown in recent years (Haverkort and Verhagen, 2008; Richter et al., 2006).

Therefore, to ensure water use efficiency and optimal potato yield, the development of integrated water management in potato crops is needed. Agricultural water management based on soil matric potential (SMP) (the strength with which the water is held to the soil particles) enhances water use efficiency (Phene and Howell, 1984) and is well adapted to potato production (Shock et al., 2007). However, irrigation criteria based on SMP need to be defined for each crop and can vary by crop, depending on the variety (Shock et al., 2003; Stark et al., 2013).

Developing an integrated agricultural water management approach addresses multiple goals. Crop productivity needs to be optimized, while unintended negative impacts need to be assessed so that negative impacts are minimized and positive ones are maximized. Little is known about the spatio-temporal aspects of potato irrigation, nor the impacts on potato yields of optimizing water use and potato yield.

This paper will investigate the positive and negative effects of irrigation from the agronomic point of view by comparing irrigation effects on tuber yield, tuber distribution and soil organic matter and some of their environmental impacts using empirical data gathered in a greenhouse experiment and literature review.

Literature review and methodology

Literature review

Water is present in the soil in three forms, liquid, gaseous and adsorbed on soil particles. Water content in soil can be measured using numerous methods and technology, from direct to indirect measurements (Topp 1980; Gardner et al., 2000; Gaskin and Miller, 1996). However, a measurement based on soil water content gives few inputs on the soil-water-plant continuum. Soil water content measurements do not provide an evaluation of water availability for plants (Mullins, 2000). The soil matric potential (SMP), which is part of the total water potential, refers to the strength with which water is retained by the soil matrix (Marshall, 1959), which is the inverse of the energy a plant needs to deploy to use the same water molecule. The tensiometer is one of the instruments that measures the SMP. It consists of a water-filled probe with a porous ceramics inserted in the soil. Once the porous ceramic is in contact with the soil, a hydraulic connection between the soil's moisture and the water inside the tensiometer is formed. Movement between the water in the soil and the water in the tensiometer will create negative pressure (tension) that can be measured in kilopascals (kPa). Movement in the tensiometer water volume will be associated with soil drying (higher negative pressure) or rewatering (pressure closer to zero), and provide information on the water available for plants.

The potato crop needs a regular water supply and is sensitive to drought stress (FAO, 2008; Shock et al., 2007). Both long or short duration drought can have a significant impact on potato yields, even when the drought stress is moderate (Bradley and Pratt, 1954; Dalla Costa et al., 1997; Darwish et al., 2006; Stark et al., 2013). Drought stress also has a significant impact on the potato's physiological process and photosynthesis (Dalla Costa et al., 1997; Epstein and Grant, 2010; Quiroz et al., 2013), on potato tuber quality (Shock et al., 1993; Wang et al., 2007) and on tuber size (Landry et al., 2014; Miller and Martin, 1987).

Numerous potato varieties have been bred, resulting in different features, such as the days until maturation, potential yield, disease sensitivity or resistance and drought sensitivity or resistance (Agence Canadienne d'inspection des aliments, 2019). Variation of yield under different degrees of drought stress has been observed for different potato varieties (Miller and Martin, 1987; Schapendonk et al., 1989; Shock et al., 2003). Establishing an optimum SMP threshold, taking into account drought stress sensitivity of the potato, is part of an integrated water management approach.

In order to optimize water management, different SMP thresholds around tuber root zones have been tested in field experiments (-15 to -60 kPa) (Aksic et al., 2014; Epstein and Grant, 1973; Shock et al., 1998; Wang et al., 2007). Despite the diversity in tuber varieties and soil diversity, some trends are emerging in the literature. SMP over -80 kPa causes decreases in potato yield. Depending on the studies, drought stress symptoms on plants begin between -25 kPa (Epstein and Grant, 1973) and -35 to -55 kPa (Wang et al., 2007). However, too much soil humidity can lead to a decrease in tuber yields (Aksic et al., 2014; Wang et al., 2007). Therefore, the optimum SMP for potato yields can range between -20 kPa and -30 kPa for the majority of potato varieties.

The SMP can have other effects, causing unintended consequences (i.e. externalities) when optimizing yield. The root system of the potato is influenced by water management. A potato crop under irrigation possesses a higher proportion of their roots on the surface soil layer (Stalham and Allen, 2001). Therefore, as tuber growth inhibits root growth (Joshi et al., 2016), the tuber distribution should also be dependent on water management. The harvesting of potatoes can result in significant soil erosion (Parlak and Blanco-Canqui, 2015; Ruysschaert et al., 2006). The mean mass of soil loss could vary between 1.81 Mg/ha to 3.2 Mg/ha (Parlak and Blanco-Canqui, 2015; Ruysschaert et al., 2006), and the soil moisture at harvest has been identified as the main factor influencing soil loss (Ruysschaert et al., 2006). The depth of the crop also plays a role in harvesting efficiency, as a reduced crop depth causes a significant decrease in the percentage of potatoes harvested (Kheiry et al., 2018). The soil water management system can have a double impact by optimizing the depth of the tubers allowing an efficient harvest at a shallow depth and by reducing soil moisture at harvest time.

The depth of tillage has a negative impact on soil structural stability and on surface soil organic carbon, which is critical in controlling the water dynamics in soil (Carter, 1992; Franzluebbers, 2002; Hernanz et al., 2002). Soil organic carbon, a part of soil organic matter, has a significant impact on the carbon cycle, acting as a carbon sink or source (Lal, 2004). Soil organic matter contains more than three times more carbon than the atmosphere or the terrestrial vegetation (Lehmann et al., 2011). Water management can have a significant impact on soil organic matter stabilization and, therefore, on sequestration of carbon in soils (Rahman et al., 2018). The use of the standardized Tea Bag Index (TBI) method has shown great potential for studying soil organic matter transformation and dynamics (Keuskamp et al., 2013; Rahman et al., 2018). The TBI method consists of using two types of tea, which have significantly different decomposition properties, acting as recalcitrant organic matter and labile organic matter. The decomposition rate difference of the standardized TBI for the two teas allows for the construction of a decomposition curve using a single measurement in time (Keuskamp et al., 2013). The TBI is composed of two parameters, describing the decomposition rate (k) and the litter stabilization factor (S). Optimizing soil water management could allow for the optimization of the TBI parameter and therefore optimize soil carbon sequestration properties. In this way, soil water management could contribute to decreasing atmospheric CO^2 and the greenhouse effect.

Methodology

Experimental design

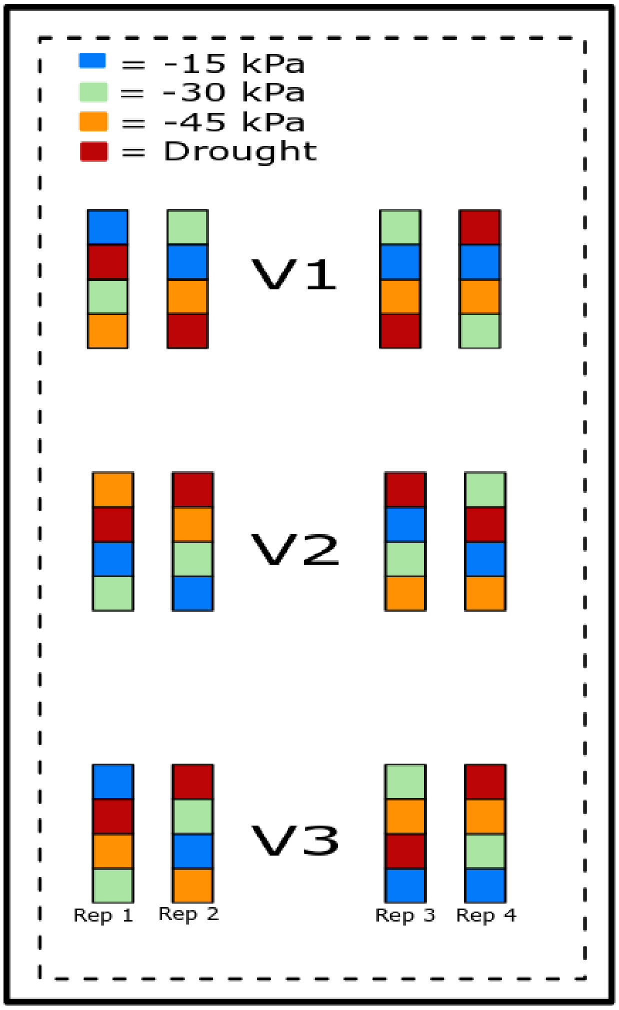
The experiment was conducted in a high-performance greenhouse of Laval University campus (Québec, QC, Canada) from 2018 January 15 until 2018 May 10 (potato harvest). Potatoes were cultivated in 48 experimental units of 0.14 m^3 (60 X 40 X 60 cm) using four replicates of four SMPs repeated with three potato varieties (Fig. 1). Two tubers were planted in each experimental unit at a depth of 7.5 cm. One tensiometer was installed at 10 cm depth for each experimental unit. Results from the tensiometer were collected at a two-minute time step. The tensiometer data was also used to calculate the mean SMP required to trigger irrigation.

The soil used in the experiment was sourced from samples from a potato field at Dolbeau-Mistassini, QC, Canada ($48° \, 51' \, 31''$ N and $72° \, 11' \, 50''$ W). The soil was collected from the topsoil (0-20 cm), homogenized and placed into the plastic container. The soil was classified as sandy soil (0% clay, 8.2% silt, 91.8% sand, 3.1% C_{org}, and pH 5.01), according to the Canadian soil texture classification. Particle size distribution was determined by the sedimentation method (Bouyoucos, 1962). Fertilization was carried out following local best practices for potatoes (Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ), 2010). Available nutrient concentrations (Phosphorous (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Aluminum

(Al)) were determined using Mehlich III extraction method (Mehlich, 1984)**.** The soil was saturated with water before planting.

There were four water management treatments applied based on different levels of mean SMPs (15kPa, -30kPa, -45kPa, and drought[1]). The levels of SMPs were selected based on a previous study focusing on irrigation levels in potato production (Wang et al., 2007).

Figure 1: Greenhouse experimental design included four water management treatments (-15, -30, -45 kPA and drought) and three potato cultivars (V1, V2, V3) aggregated in 48 experimental units.



Twelve irrigation lines were used to control irrigation independently for each water management treatment and variety, allowing for the accurate management of irrigation. Irrigation was triggered

[1] The drought water management treatment was irrigated only once each month except when the SMP reached -60 kPa which triggered an irrigation to ensure potato survival

automatically when the SMP thresholds were reached. Irrigation duration throughout the growing season was adjusted to achieve a SMP between -1 and -5 kPa after irrigation. Irrigation was applied using drip irrigation placed on the soil surface.

The three potato cultivars used were Red Maria (mid-late to late variety, V1), Envol (early variety, V2) and Goldrush (mid-season variety, V3). From seeding to emergence, irrigation was the same for all treatments to ensure uniform emergence. The irrigation experiment began with the potato plant's emergence and went on until the maturity and senescence of each variety.

Tubers were harvested from each experimental unit at maturity and refrigerated. Tubers were counted and weighed to evaluate the total yield per plant.

Tuber distribution was analyzed using a computed tomography (CT) scan. The CT is an imaging procedure using special x-ray equipment to create a detailed scan of areas inside a solid object, such as soil. Four plants under two irrigation thresholds (-15 and -30 kPa) were tested and scanned at the end of the growing season. The images were taken using a Siemens SOMATOM Definition AS+ 128 CT-scan at maturity of the potato, between the end of wilting and the harvest. The resolution of the images was 0.93 X 0.93 X 1.17 mm^3. Analyses were made using the ImageJ software (Schindelin et al., 2012).

The decomposition of organic matter was tested using the Tea Bag Index (TBI) methodology and indices defined in Keuskamp et al. (2013). The calculation of the TBI indices was done using the five steps described in Keuskamp et al. (2013). The method consists of using two types of tea, Rooibos and Green tea, which are known to have significantly different decomposition properties. The Rooibos tea is characterized by a slow decomposition rate, acting as recalcitrant organic matter, while the Green tea is characterized by a fast decomposition rate, acting as labile organic matter. The decomposition rate difference between the two standardized teas allows for the construction of a decomposition curve using a single measurement in time (Keuskamp et al., 2013). The TBI is composed of two parameters, describing the decomposition rate (k) and the litter stabilization factor (S).

All statistical analysis was done using R software (R Development Core Team, 2005). The data were analyzed as a split-plot design. The differences in TBI indices and potato yields under the different water management treatments were compared using ANOVA-test with the Agricolae package (Mendiburu, 2019). The differences were considered significant when p-values were under 0.05. An LSD post-hoc test was done to identify significantly different treatments.

Analysis of the problem

The effects of irrigation on potato yield

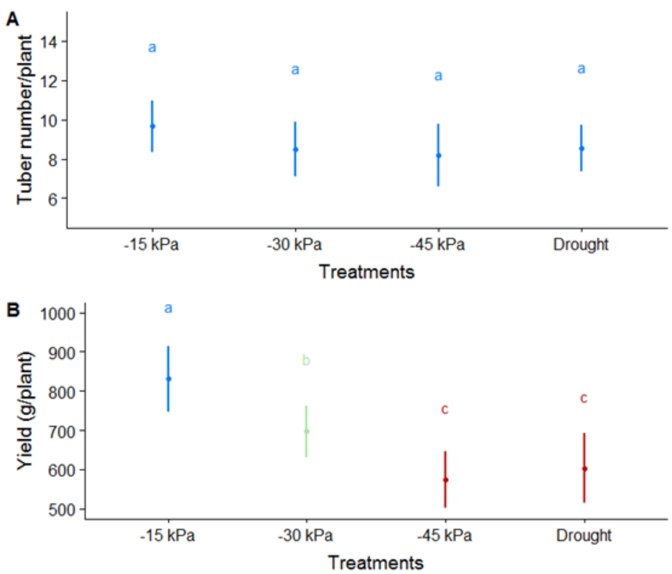
Table 1 lists the results of the experiment for tuber number and potato yield (g/plant) based on different water management treatments, including the volume of water applied through irrigation and the mean irrigation time or direction. The highest water volume was applied for the -15kPa treatment.

Table 1: Yield, tuber number, actual water applied, mean irrigation time and their respective standard errors for the four water management treatments in the greenhouse experiment. The values with different letters in parenthesis are statistically different according to the LSD test.

Treatments (kPa)	Yield (g/plant)	Tuber number/plant	Total water applied (L)	Mean irrigation time (min)
-15	1661.6 ± 83.7 (a)	19.3 ± 1.3 (a)	137.34 ± 7.73	145.4 ± 3.3
-30	1394.2 ± 65.3 (b)	17 ± 1.4 (a)	101.92 ± 2.38	155.8 ± 3.6
-45	1147.7 ± 71.5 (c)	16.4 ± 1.6 (a)	65.4 ± 1.89	130 ± 10.6
Drought	1206.6 ± 89 (c)	17.1 ± 1.2 (a)	60.97 ± 9.23	222.7 ± 20.2

The -45 kPa and the drought water management treatments were comparable in terms of irrigation water volume. The notable difference between the drought treatment and the three others is the duration of the irrigation. The duration of irrigation for the drought treatment was 47% longer than the -45kPa treatment. Another notable difference between the drought treatment and the -30 and -45 kPa treatments is that irrigation began two weeks earlier because scheduling of irrigation was not based on soil tensiometer readings, but rather treatments received one irrigation after planting and one irrigation before emerging. The effect of the treatment on the varieties was not significant (ANOVA, p-value > 0.05), indicating that the yields and the effects of water management are independent of the variety in this study. None of the varieties used have a known resistance or sensitivity to water stress. This may explain why water management treatments have no effect on the varieties.

Figure 2: Measured tuber numbers per plant (A) and yield in grams per plant (B) for the four water management treatments (-15 kPa, -30 kPa, -45 kPa and drought). The points represent the mean and the error bars, using the standard error. The values with different letters and colors are statistically different by LSD test.



It was found that the total number of potato tubers was higher with the water management treatment that included more water and more frequent irrigation, -15 kPa (see Figure 2-B). The most extreme decrease in total yield was observed in the -45 kPa and the drought treatments. The differences in tuber numbers between treatments were not significant. However, the results show a tendency to follow the same decreasing trend as the total yields. The decrease in potato yield, due to different levels of drought stress, has also been found in the literature in cases where water restrictions and SMP under -40 kPa causes potato yields decrease (Abbas and Ranjan, 2015; Quiroz et al., 2013; Wang et al., 2007).

The experimental results indicate that in order to maximize total potato yield, the optimal threshold to initiate irrigation is -15 kPa. This result is in accordance with Dash et al. (2018), who found that frequent irrigation leads to the highest yields, using potato varieties with a low yield potential and varieties with early maturation. The results are also in accordance with Shock et al. (2003, 1998), who found a linear relationship between irrigation and total yield using mid-season varieties with medium yield potential and known moisture stress sensitivity. However, the results are different from Aksic et al. (2014) and Wang et al. (2007), who found an optimal SMP of -30 kPa and -25 kPa respectively. Both studies found a decrease in potato yield at higher levels of soil humidity. This difference may be due to the fact that these studies both used early maturing varieties of potatoes with known resistance to drought stress.

These results indicate that optimal SMPs for potatoes could be different for each variety, considering their drought sensitivity or resistance. Our results indicate that drought sensitivity or resistance seems to be independent of the yield potential and the variety time to maturity. This is in accordance with the results of Stark et al. (2013). The optimal range of SMP for optimizing potato yields is between -15 and -30 kPa, depending on the variety's drought sensitivity. From a water consumption perspective, the total water applied in the -15 kPa treatment is more than twice the volume of the -45 kPa and the drought treatment. Yet, the total yield is not reduced by the same proportion. The ratio of tuber production per liter of water used is in favor of the -45 kPa and the drought treatments (12.09 g of tubers per liter of water for the -15 kPa treatment and 17.55 and 19.79 g of tubers per liter of water for the -45 kPa and the drought treatments, respectively).

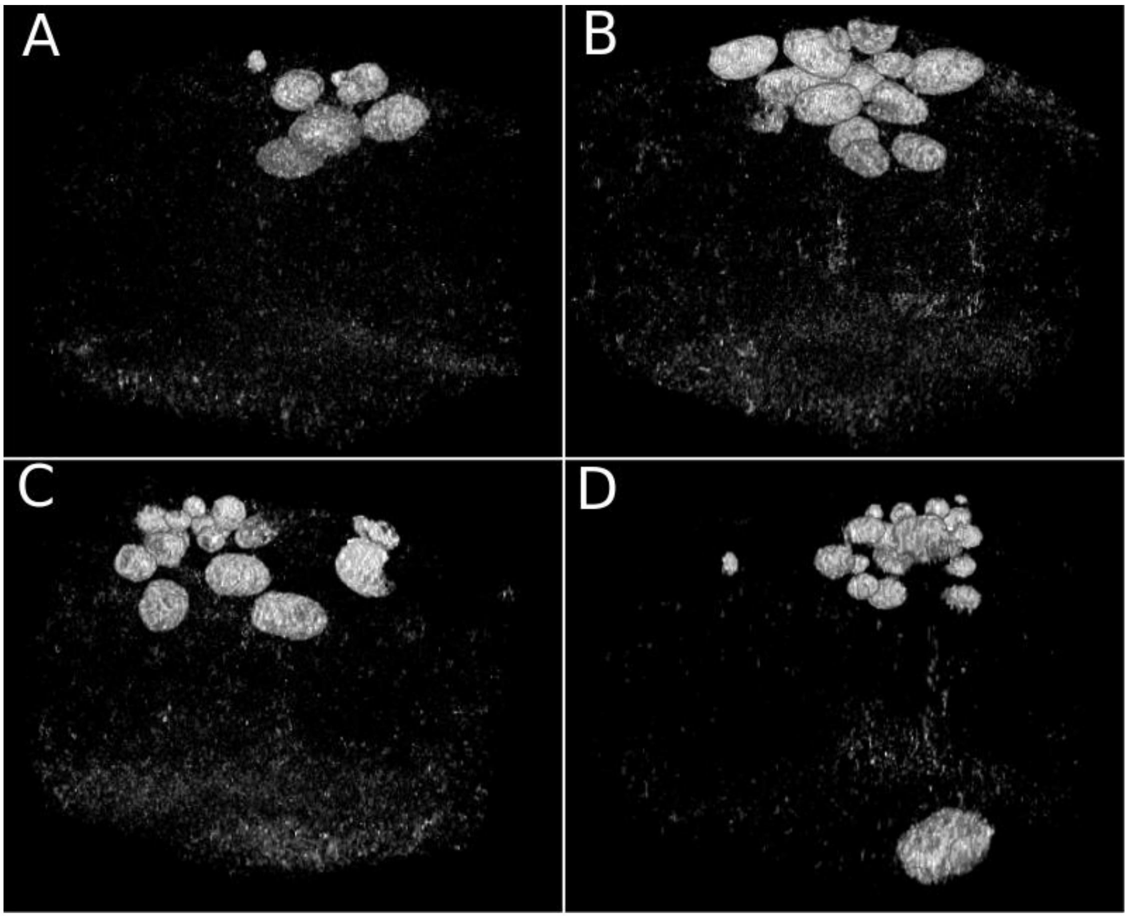
The effects of irrigation on tuber distribution and environmental impact

The images taken with the CT-scan show different trends than the potato yields measured by tuber numbers. As shown in Figure 3, for the -15 kPa water management treatments (see A-B), production ranges from 7 to 12 tubers and the tubers are clustered close to the seed potato. For the -30 kPa water management treatments (see C-D), production ranges from 14 to 15 tubers, but the tubers are more dispersed around the seed potato, with one tuber at the very bottom of the container.

One of the indicators of potato harvest performance indicators is the "potato lifting percentage", which refers to the percentage of potatoes harvested as a share of the total number of potatoes in the field. It has been shown that this share decreased from 93% to 87% when harvest depth decreased from 21 cm to 18 cm (Kheiry et al., 2018). Keeping a higher SMP and keeping the tuber close to the seed potato also helps increase the share of potatoes harvested and a shallower harvest depth.

Harvesting potatoes has also been identified as a significant contributor to soil loss and erosion with a mean annual net soil loss per harvest ranging between 1.81 Mg/ha to 3.2 Mg/ha (Parlak and Blanco-Canqui, 2015; Ruysschaert et al., 2006). The soil loss due to potato harvesting could decrease by reducing the harvest depth. By planting the potato in the upper layer of the soil, with an optimal control of the SMP, this could be done without any loss of economic profitability. More statistical study and image scanning should be done to confirm this hypothesis.

Figure 3: Tuber position and distribution extracted from CT-scan images. A-B are the tuber images of the two replicates for the -15 kPa threshold and C-D are the tuber images of the two replicates for the -30 kPa threshold water treatment.



However, the results indicate that a SMP irrigation threshold of -15 kPa would allow a concentration of the tubers in the upper soil layer and therefore, increase the share of potatoes harvested and decrease annual soil loss due to harvesting. The reduction in harvest depth would also decrease the negative tillage impact on soil structure stability and surface soil organic carbon.

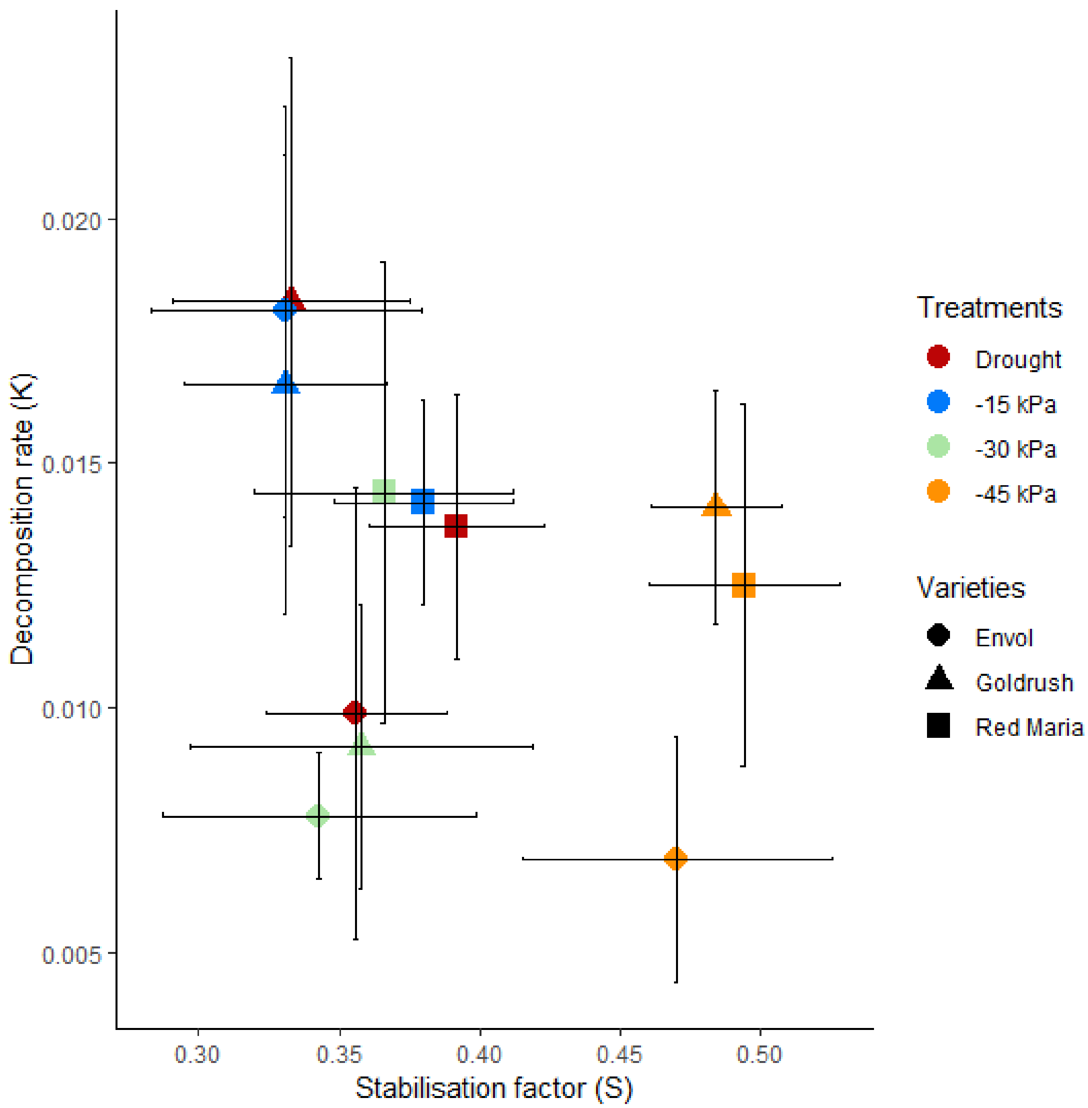
The effects of irrigation on organic matter dynamics and the environment

The average loss in organic matter from the Green tea ranged from 43.6% ± 1.7% (SE) to 54.9% ± 2.4% for the various water management treatments. The Rooibos tea experienced a lower average organic matter loss, which ranged from 28.6% ± 1.1% (SE) to 36% ± 1.6%. The -45 kPa treatment showed the lowest average mass loss for both Green and Rooibos tea.

The average decomposition rate (k) by water management treatments ranged from 0.0105 $\pm$ 0.0018 (SE) to 0.0163 $g\ g^{-1}\ d^{-1}$ $\pm$ 0.0024. The average stabilization factor (S) by water management treatment ranged from 0.348 $\pm$ 0.020 to 0.483 $\pm$ 0.029 (Fig. 4).

The average decomposition rate did not show any significant difference between water management treatments (ANOVA, p-value > 0.05). The stabilization factor was significantly higher (ANOVA, p-value < 0.05) for the -45 kPa water management treatment with an average S of 0.483 $\pm$ 0.021. The average stabilization factor for the drought, -15 kPa and -30 kPa water management treatments were respectively 0.360 $\pm$ 0.020, 0.348 $\pm$ 0.022 and 0.356 $\pm$ 0.029.

Figure 4: The mean decomposition rate k and stabilization factor S of the Tea Bag Index (TBI) for each water management treatment (colors) and variety (shapes). Each point contains four replicates. Error bars are standard errors.



Soil organic matter contains up to three times more carbon than the atmosphere or terrestrial vegetation (Lehmann et al., 2011). Some of this soil organic matter decomposes rapidly, while other matter persists for millennia. The impact of soil on the global carbon cycle is significant and understanding how water management interacts with it is essential for developing an integrated global agricultural management system. The factor S of the Tea Bag Index (TBI) measures the stabilization of soil organic matter, and therefore allows an evaluation of the long term C sequestration potential (Keuskamp et al., 2013). The S values gathered in this study are in the upper range of other studies using the TBI (Keuskamp et al., 2013; Macdonald et al., 2018; Rahman et al., 2018), indicating high stabilization in the greenhouse environment. The factor S is expected to be higher under dry conditions. As expected, in this study the -45 kPa water management treatment showed a significantly higher S factor. Surprisingly, the drought treatment did not show the same trend, as the drought treatment was not significantly lower than the -15 and -30 kPa treatment. Longer irrigation times and an earlier start for an irrigation treatment most likely compensate for the drier conditions. The dynamics of soil organic matter, and therefore its sequestration, is more influenced by the biotic and abiotic environment than the molecular structure of plant inputs (Lehmann et al., 2011). This study showed that a higher SMP (-45 kPa) increases soil organic matter stabilization, which could enhance the sequestration of carbon in soil.

Suggestions for policy options and further research

Policy options

Future Canadian water management and irrigation policies need to take into account the many research results for each crop, taking into consideration empirical results as well as fundamental knowledge.

- Precision water management and precision irrigation should be the preferred approaches, as they allow for better control over the agricultural impacts on both production and the environment.
- Water management policies should consider the water supply, but not exclusively, as demonstrated in this study. Water management can have a global impact on potential yield, carbon cycle, and on soil erosion, even at field scale.
- A global water management policy, adapted for each crop, could assist the producer in achieving an optimal potential yield while supporting environmental conservation as well as helping fighting climate change altogether.

Research suggestions

Further study should focus on identifying one or more critical time periods where the SMP influences potato yield, tuber distribution, and soil organic carbon sequestration. Identifying key milestones in the growing season, when potential yields are optimized and when the potential unintended consequences of irrigation are minimized, would point to better water management choices.

Future studies should provide a better understanding and a global evaluation of other side-effects or unintended consequences of optimizing water management in agriculture.

The effects of higher SMP on nutrient availability and leaching should be assessed for the potato crop. In this study, using drip irrigation, no leaching was observed for any of the water management treatments. This observation should be investigated to confirm if a higher SMP causes nutrient availability to decrease or nutrient leaching to occur.

The observations of tuber distribution should be repeated in a statistically viable experimental design and their statistical differences should be analyzed.

Finally, further study should be conducted to determine the real cause of the differences in potato yield by variety in terms of their drought sensitivity, since it is not the variety's time to maturation or the potential yield that drive the drought sensitivity of the potato.

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