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Yield responses of four common potato cultivars to an industry standard and alternative rotation in Atlantic Canada

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Abstract

This study was conducted to evaluate yield responses of four potato (*Solanum tuberosum* L.) cultivars ('Russet Burbank', 'Shepody', 'Gold Rush', and 'Russet Prospect') and soil N dynamic changes to two 3-year rotations in Prince Edward Island, Canada. The two rotations were the local industry standard potato–barley (*Hordeum vulgare L.*)–red clover (*Trifolium pratense* L.) rotation (PBC) and an alternative potato–soybean (*Glycine max* L.)–barley rotation (PSB). All potato cultivars received 170 kg N ha^{-1} input at planting without irrigation. Soil mineral N content before potato planting was significantly higher under the PBC rotation. However, the PBC rotation produced significantly lower yields, suggesting the possibility of excessive N supply from the plowed-down red clover. While cultivar and the interaction between cultivar and rotation did not show a significant difference in yield, yields of all cultivars were positively affected by the PSB rotation. The Gold Rush cultivar was affected the most (36%), followed by Russet Burbank (17%) and Prospect (14%) cultivars, with Shepody being the least affected (3%) by the alternative PSB rotation. Russet Burbank was the highest yielding cultivar under both rotations. With the three russet cultivars combined as a single russet cultivar, the PSB rotation significantly increased tuber yields, while the Shepody cultivar did not significantly benefit from the PSB rotation, suggesting that the russet cultivars responded more sensitively to the alternative rotation. Results demonstrate that adequately accounting for N supply from a preceding green manure crop is required for sustainable potato production in this humid temperate region.

Keywords Crop Rotation · Red Clover · Soybean · Soil Nitrogen

Resumen

Se desarrolló este estudio para evaluar las respuestas de rendimiento de cuatro variedades de papa (Solanum tuberosum L.) ('Russet Burbank', 'Shepody', 'Gold Rush' y 'Russet Prospect') y los cambios dinámicos de N del suelo a dos rotaciones de 3 años en la Isla del Príncipe Eduardo, Canadá. Las dos rotaciones fueron papa-cebada estándar de la industria local (*Hordeum vulgare* L.)–trébol rojo (*Trifolium pratense* L.), rotación (PBC), y una alternativa de papa–soya (*Glycine max* L.)–cebada, rotación (PSB). Todas las variedades de papa recibieron 170 kg N ha –1 en la siembra sin riego. El contenido de N mineral del suelo antes de la siembra fue significativamente mayor bajo la rotación de PBC. Sin embargo, la rotación de PBC produjo rendimientos significativamente más bajos, lo que sugiere la posibilidad de un suministro excesivo de N del trébol rojo incorporado. Si bien la variedad y la interacción entre la variedad y la rotación no mostraron una diferencia significativa en el rendimiento, los rendimientos de todas las variedades se vieron afectados positivamente por la rotación de PSB. La variedad Gold Rush fue la más afectada (36%), seguida por las variedades Russet Burbank (17%) y Prospect (14%), siendo Shepody la menos afectada (3%) por la rotación alternativa de PSB. Russet Burbank fue la variedad de mayor rendimiento en ambas rotaciones. Con las tres variedades de russet combinadas como una sola variedad de russet, la rotación de PSB aumentó significativamente los rendimientos de tubérculos, mientras que la variedad Shepody no se benefició significativamente de la rotación de PSB, lo que sugiere que las variedades de russet respondieron de manera más sensible a la rotación alternativa. Los resultados demuestran que se requiere una contabilidad adecuada del suministro de N de un cultivo de abono verde previo para la producción sostenible de papa en esta región templada húmeda.

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Introduction

Potatoes are the third most important food crop in the world, after rice and wheat, and the predominant vegetable crop in Canada, representing 27% of all vegetable receipts (Agriculture and Agri-Food Canada 2020). Potatoes are the primary cash crop in Prince Edward Island (PEI), where 23% of Canada's potatoes are produced (Statistics Canada 2021). An average area of 34,500 ha is under potato cultivation in PEI each year, responsible for an annual average potato production of 36.2 t ha^{-1} (Statistics Canada 2021). In PEI, a province with a relatively short growing season (Jiang et al. 2012; Nyiraneza et al. 2021), Russet Burbank, Eva, HO2000, Gold Rush, Prospect, and Shepody are the top seven registered seed potato cultivars (Agriculture and Agri-Food Canada 2020).

Intensive potato production can result in undesirable environmental and economic consequences. Some of these negative consequences, especially in Atlantic Canada, include increased soil erosion (Edwards et al. 1998; Tiessen et al. 2009; Abolgasem 2014) and excessive nitrogen leaching into receiving waters (Jégo et al. 2008; Jiang et al. 2012). Liang et al. (2020) reported that 84.5% of the nitrate load in an agricultural watershed in PEI was sourced from lands under potato cultivation. Based on data from 27 watersheds in PEI, Jiang et al. (2015) estimated that potato field contributed 75–98% of the nitrate load in estuaries. In addition, high frequency and intensive potato cropping can reduce potato yield and quality due to increased soil-borne pathogenic organisms (Vos and Van Loon 1989), increased weed risk (Pawlonka et al. 2015), and incidences of harmful fungi (Grandy et al. 2002).

Crop rotation has been demonstrated to be an efficient Best Management Practice (BMP) for reducing the environmental impacts of intensive potato production while maintaining soil quality and improving productivity. Wei et al. (2014) reported that coupling crop rotations with land closure treatments significantly reduced soil erosion on gentle slopes. Similarly, Freebairn et al. (1993) observed a potential yield increase and reduction in soil erosion after reducing tillage in combination with crop rotation. Moreover, crop rotation has been reported to influence soil quality and productivity, possibly by regulating soil microbial communities and reducing soil-borne diseases (Larkin and Honeycutt 2006; Qin et al. 2017; Gao et al. 2019). It has also been suggested that increased cropping frequency of potatoes in a crop rotation could increase incidences of diseases such as stem canker and black surf (Scholte 1992). Previous research has indicated that crop rotation directly or indirectly affects potato tuber yield through mediation of soil-borne diseases, microbial communities, fertility, and soil quality.

The effect of crop rotation on potato yield depends on rotation crop selection (Scholte 1990). In a study of 3-year rotations, soybean–canola–potato and soybean–barley/clover–potato rotations led to a 9–12% increase in total yield compared to continuous potato (Larkin and Honeycutt 2006). Nyiraneza et al. (2015) assessed the yield of potato rotated with barley–red clover (PBR), barley–sorghum Sudan grass/winter rape (PBSW), and barley–canola/winter rape (PBCW) in PEI from 2006 to 2013. They reported that PBSW and PBCW had higher yields than PBR due to noticeable residual effects of rotation.

The influence of rotation and cover crops on potato yield depends on potato cultivars as well as cover crop cultivars. Sturz et al. (2003) studied the influence of potato and red clover cultivar combinations in a potato–barley–red clover rotation in PEI. The study found that the yield of Shepody potato following AC Kingston red clover significantly increased compared to other red clover cultivars, while Russet Burbank and Kennebec yields were not differently influenced by any preceding red clover cultivar. Sturz and Christie (1998) reported that root zone bacteria associated with red clover cultivar Marino led to the best performance of potato cultivar Russet Burbank while Shepody benefited from bacteria from 'Altaswede' root zones. These results indicate that there are potential interactions between cultivar and rotation cycles.

In PEI, potato growers commonly adopt the minimum length of 3-year rotation as mandated by the Province and follow local industry-standard management practices (Bernard et al. 1993). Traditionally, growers mainly planted barley and forages (e.g., red clover or a mix of red clover and one or two perennial grass species) as the rotation crops. In recent years, many potato growers have included soybean as a second cash crop in the rotation to increase farm profit (Government of Prince Edward Island 2019). Liang et al. (2019) compared the effects of an alternative potato–soybean–barley rotation (PSB) and conventional potato–barley–clover rotation on soil mineral N, N concentrations in soil leachate and potato yield in PEI. They demonstrated that replacing red clover with soybean in the rotation improved N utilization efficiency by as much as 1.6 times while increasing potato yield by 13.4% and farm income from soybean as a second cash crop. The alternative rotation provides a promising opportunity for farmers to increase farm income while reducing their environmental footprint. However, their results were derived from only the Russet Burbank cultivar. Whether the results are applicable to other common potato cultivars remains unknown. The objective of this study was to investigate the impacts of the PSB and PBC rotations on the yield of four common cultivars of potatoes and soil N dynamics.

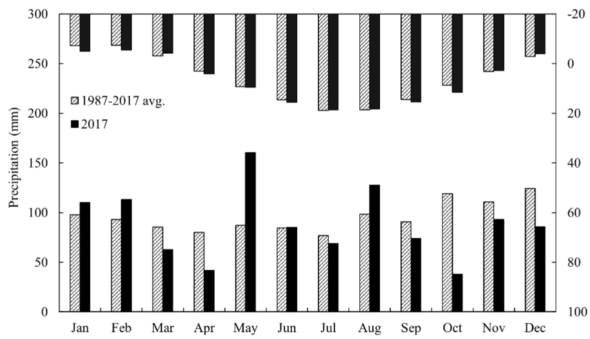

Fig. 1 Monthly precipitation and temperature at the Environment and Climate Change Canada weather station at Charlottetown Airport

Materials and methods

Study Site

The experiment was conducted at the Harrington Research Farm of Agriculture and Agri-Food Canada from 2014 to 2017. The farm is located 12 km northwest of Charlottetown, PEI, Canada (46°20'31.045" N, 63°10'19.8" W, elevation of 57 m above sea level). The experimental field had a slope of about 1.5%. The soil was classified as Orthic humo-Ferric Podzols and Gleyed Eluviated Drystic Brunisols in the Canadian soil classification system (MacDougall et al. 1988). The sand, silt, and clay contents of the soil were 51%, 38%, and 11% (fine sandy loam) respectively based on tests using the hydrometer method presented by Gee and Bauder (1979). The total soil organic carbon content was 28 g kg^{-1}. The soil in the top 20 cm of the profile was well-drained with a bulk density ranging from 1.33 to 1.39 g cm^{-3}. The average soil pH was estimated to be 6.5 from measurements using 10 g soil/10 mL water. Tests conducted in this field showed low variability of soil organic carbon, soil fertility, C:N ratio, and bulk density in the top 45 cm ($p < 0.05$), indicating relatively uniform soil conditions (see Supplemental Table 1 for more details).

Weather

The mean annual precipitation was 1174 mm (25% as snow) based on historical data from 1988 to 2017 at the Charlottetown Airport (46°17'21.000" N, 63°07'09.000" W). The frost-free period ranged from 100 to 160 days. The site was characterized by a humid climate and cool to mild temperatures, with the growing season precipitation and mean air temperature being 437 mm and 14 °C, respectively. Precipitation during the growing season of the 2017 potato year (May–September) was 515 mm, which was 17% more than the long-term average from 1988 to 2017 (Fig. 1). The monthly precipitation during May and August of 2017 was much higher than the long-term average (46% and 23% respectively). Precipitation in July and September of 2017 was lower than the long-term average (11% and 19%, respectively; Fig. 1). Air temperatures during the 2017 growing season were similar to the long-term averages (Fig. 1).

Field Experiment

Russet Burbank, Shepody, Gold Rush, and Prospect cultivars were chosen for this study. These cultivars are widely grown in North America. Russet Burbank is a late-maturing cultivar with large tubers. Shepody is an early to mid-maturing cultivar with medium tubers mainly grown as an early french fry or baking potato. The Prospect is a mid-season cross-bred (Russet Burbank/Shepody) cultivar that produces large tubers and matures earlier than Russet Burbank. Gold Rush is a mid-season russet cultivar with average-sized tubers. Whole seeds with an average weight of 70 g were used for Shepody and Gold Rush cultivars. For Prospect and Russet Burbank, whole seeds could not be found and therefore hand-cut average 70 g seed pieces were used. The seeds were obtained from the PEI Potato Board (Charlottetown, PEI). The experimental factors included two rotations and four cultivars. The two rotations were randomly assigned on 12 plots (six replications). Each plot was subdivided into two sub-plots in the final year (2017) to accommodate the four cultivars. Originally, the experiment was designed to include three replicates for each combination of cultivar and rotation levels. However, due to events beyond our control, the experiment was implemented by having two replications of Prospect and Shepody under PSB rotation and four replications under PBC rotation while having four replications of Russet Burbank and Gold Rush under PSB rotation and two replications under PBC rotation. The 12 main plots were distributed across four rows and three columns, with a row spacing of 6 m and a column spacing of 14 m acting as buffer zones. Each sub-plot accommodated six longitudinal rows (14 m long) of potatoes with row and plant spacing of 91 cm and 38 cm, respectively. Final field plan is presented in Fig. 2.

In the reference year of 2014, all plots were planted with the Russet Burbank cultivar and managed identically in order to create uniform fertility conditions before 2015. The PBC and PSB rotations were initiated in 2015 with barley and soybean, respectively. Red clover was the second crop in PBC and barley for PSB in 2016. The rotations were completed with potato cultivation in 2017. All plots were planted and harvested following standard production practices for potatoes at the commercial scale according to the Atlantic Canada Potato Guide (Bernard et al. 1993). The standard rate of N fertilizer application proposed for potatoes was

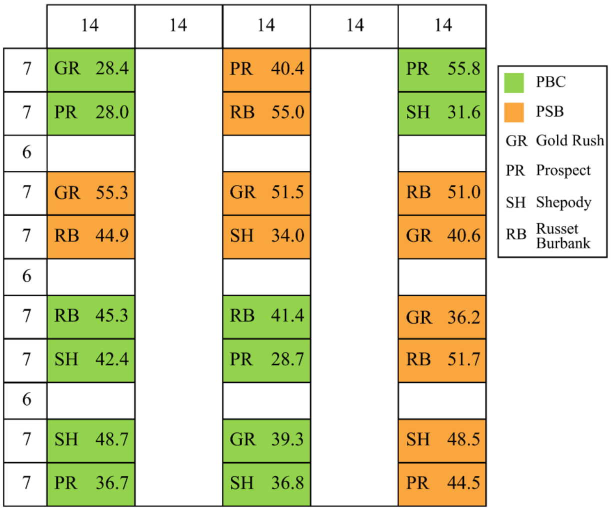

Fig. 2 Field treatments layout and tuber yield (t ha^{-1}) of each plot. Row and column spacing is in meters

155 kg N ha^{-1} in PEI (PEI Analytical Laboratories, Department of Agriculture and Fisheries, PEI). The recommended rate of N fertilizer for different potato cultivars varies from 130 to 185 kg N ha^{-1}. In this study, the N application rate of 170 kg N ha^{-1} was banded to all treatments as Nitrogen–Phosphorus–Potassium (17–17–17) compound fertilizer at planting time. Crop sequence and other rotation management operations are summarized in Table 1.

Soil Sampling and Analysis

Soil samples were collected from all experimental plots at 15 cm increments from depths of 0–15, 15–30, and 30–45 cm with a handheld Dutch auger (5 cm diameter). Soil samples were collected in three random locations before planting in the spring and immediately following harvest in the fall. The collected soil samples were mixed to create a pooled soil sample for each plot and soil depth. Soil samples were stored at < 4 °C prior to analysis (usually within two weeks after collection). Potassium chloride (KCl) extraction was carried out for each sample using 2 mol L^{-1} KCl. Concentrations of NO_3-N and NH_4-N in the extracts were determined using flow injection analysis on a Lachat QuikChem 8500 system (Lachat Instruments, USA). The concentrations of N in the extract were converted to kg N ha^{-1} based on a pre-determined bulk density, dry matter factor, as well as the specific depth of each layer.

Plant Sampling and Analysis

Four side-by-side specimens of potato plants in one row were obtained from each sub-plot before top kill application in mid-September. Potato tubers were cleaned, weighed,

Table 1 Summary of field management practices

Season / year	Cultural practices
Spring 2014	Planted Russet Burbank on May 31; applied 170 kg N ha^{-1} (banded) Nitrogen–Phosphorus–Potassium (17–17–17) compound fertilizer at planting time.
Summer 2014	Followed standard local cultural practices to manage potato diseases; applied Admire[1] in furrow at a rate of 198 mL ha^{-1} to control insects; applied Sencor or Lorox 927 g ha^{-1} before potato emergence to control weeds; applied Manzate (1.98 kg ha^{-1}) or Bravo (2.47 L ha^{-1}) to control blight.
Fall 2014	Vine desiccation was facilitated using Reglone (1.98 L ha^{-1}) in September 15–16; Potatoes were harvested on October 12.
Spring 2015	PBC: Planted barley on May 29; applied 50 kg N ha^{-1} (banded) 17–17–17 compound fertilizer (ammonium nitrate) at planting time. PSB: Planted soybean on May 29 without fertilization.
Fall 2015	PBC: Harvested barley on August 8 and left straw in field. PSB: Harvested soybean with shoots left in the field on November 10.
Spring 2016	PBC: Planted red clover without fertilization on May 23. PSB: Planted barley on May 23; applied 50 kg N ha^{-1} (banded) 17–17–17 compound fertilizer (ammonium nitrate) at planting time.
Summer 2016	Red clover was clipped by flailing on June 15 with residues left in field; red clover regrew and was clipped by flailing on July 28 with residues left in field.
Fall 2016	PBC: Red clover regrew and was clipped by flailing on September 3 with residues left in field; killed red clover using Roundup on September 13; moldboard plowing was done on October 15. PSB: Harvested barley with straw returned to the field on September 17.
Spring 2017	Planted potato on May 31; applied 170 kg N ha^{-1} by banding Nitrogen–Phosphorus–Potassium (17–17–17) compound fertilizer at planting time.
Summer 2017	Followed standard local cultural practices to manage potato diseases; applied Admire in furrow at a rate of 198 mL ha^{-1} to control insects; applied Sencor or Lorox 927 g ha^{-1} before potato emergence to control weeds; applied Manzate (1.98 kg ha^{-1}) or Bravo (2.47 L ha^{-1}) as a means of late blight control.
Fall 2017	Reglone was used as Vine desiccation (i.e., topkill) at rate of 1.98 L ha^{-1} September 15–16; the potato crops were harvested on October 12.

and converted into total potato yield in t ha^{-1} by multiplying a density factor based on the potato row and plant spacings. Six tubers from these four plants were subsampled, sliced and oven-dried at 60 °C for 48 h to measure the dry matter content of tubers. Representative tubers were used to calculate specific gravity by recording the weight in air and weight in water using the following Eq. 1 (Gould 1995). Calculation of starch content was carried out according to Eq. 2 (Kawano et al. 1987).

$$\text{Specific gravity (g cm}^{-3}\text{)} = \frac{Weightinair}{Weightinair - Weightinwater} \quad (1)$$

Starch (%) = $(112.1 \times SpecificGravity) - 106.4$ (2)

Statistical Analysis

Normality and homogeneity of the dataset were confirmed using Shapiro-Wilk's and Levene's tests, respectively. All statistical analyses were performed using R 3.2.3. The significance level was set at a probability of $< 5\%$. The differences in tuber yields among cultivars and rotations factors were tested with two-way Analysis of Variance (ANOVA). In addition, a Student's t-test was used to examine if the differences between yield and soil mineral N content under PBC and PSB rotations were statistically significant among the potato cultivars.

Results

Soil Mineral N Contents Before Planting in 2014

The variation of the historical mineral N content (Nm) of the soil in the top 45 cm before planting is plotted in Fig. 3. Nm prior to the beginning of the experiment in the spring of 2014 in the PBC (= 16.4 kg N ha^{-1}) and PSB (= 16.8 kg N ha^{-1}) rotation plots did not have a significant difference ($p > 0.05$). This suggests relatively uniform fertility conditions due to similar field management before the experiment started. In the fall of 2014, after potato harvest, soil mineral N in the upper 45 cm soil layer increased to 149.0 and 125.3 kg N ha^{-1} in the PBC and PSB plots, which were significantly higher than spring N contents ($p < 0.001$). In the spring of 2015, however, soil mineral N in the upper 45 cm soil layer dropped by 72.6% for the PBC rotation and dropped by 62.4% for the PSB rotation. No significant difference in soil mineral N content was found between the PBC and PSB plots ($p > 0.05$).

Despite fertilization, only a slight decrease in Nm (3.3 kg N ha^{-1}) was observed in barley plots in the second year of the rotations in the fall of 2015. Similarly, the Nm in the soybean plots decreased slightly to 39.2 kg N ha^{-1}, and the difference between the two rotations was not significant ($p > 0.05$). Soil mineral N had a substantially lower reduction rate in the non-growing season between 2015 and 2016 compared to the previous non-growing season. The barely plots showed a 2.5% decline in soil Nm in the spring of 2016, and the soil Nm of the soybean plots decreased by 22%.

Soil Nm in PBC plots increased to 45.3 kg N ha^{-1} in the fall of 2016, following red clover, while soil Nm in PSB plots exhibited a further decline to 15.7 kg N ha^{-1} after barley in the fall of 2016. The difference in soil Nm between PBC and PSB rotations in the fall of 2016 was significant ($p < 0.05$).

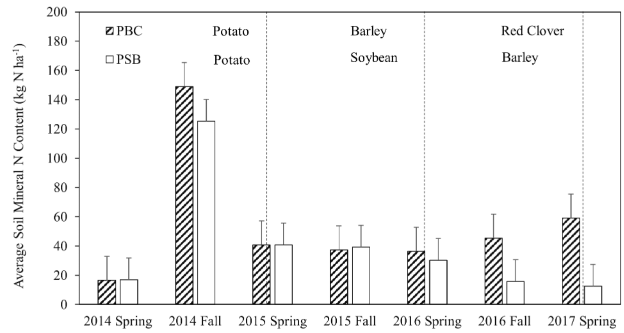

Fig. 3 The variation of the historical mineral N content (Nm) of the soil in the top 45 cm before the planting. Error bar demonstrates standard error of mean

Soil mineral N content before planting in the spring of 2017

The PBC plots had a significantly higher soil mineral N content ($p < 0.001$; Table 2) in the spring of 2017 before planting. As demonstrated in Fig. 3, the preceding red clover crop in the PBC plots led to significantly higher soil mineral N content after the completion of one rotation cycle from 2015 to 2017. On average, the PBC plots contained 59 kg N ha^{-1}, representing 4.7 times more soil Nm than the PSB plots with 12.5 kg N ha^{-1}. Variations in N content of different treatments are shown in Fig. 4. The standard deviation of soil mineral N content in the PBC plots was 25.2 kg N ha^{-1}, compared to 6.5 kg N ha^{-1} in the PSB plots. This indicates that the PBC plots demonstrated a considerably large spatial variation in soil mineral N content while the soil Nm in the PSB plots was relatively uniform. The PBC plots planted with Gold Rush and Shepody cultivars contained the lowest (37.3 kg N ha^{-1}), and highest (71 kg N ha^{-1}) mean soil Nm, respectively (Table 2). In order to assess the difference between cultivars within each rotation system, an analysis of variance was carried out separately for each group of the rotations. Results indicate that soil mineral N content was not significantly different between cultivars within the same rotation system for both PBC and PSB treatments (Table 3).

Total Tuber Yield

Potato yields were significantly different between the PBC and PSB rotations ($p < 0.05$), while cultivar and the interaction between cultivar and rotation did not show significant differences (Table 4). Analysis of variance performed on each rotation separately also indicated no significant differences ($p > 0.05$) between cultivars within the same rotation system (Table 5). Potato yields of different cultivars under

Table 2 Average tuber yields and soil mineral N content under different rotations and cultivars along with the results of Student's t-test

Source of variation			Tuber yield				Pre-plant soil NO3			
Cultivar	Rotation	N	Mean ($t\ ha^{-1}$)	Std. deviation	% Increase	Significance	Mean (Kg N ha^{-1})	Std. deviation	% Decrease	Significance
Gold Rush	PBC	2	33.9	7.7	35.6	0.18	37.3	15	75.8	0.01**
	PSB	4	45.9	9			9	3.3		
Prospect	PBC	4	37.3	12.9	13.8	0.62	54.3	15.7	71	0.03*
	PSB	2	42.5	2.9			15.7	8.7		
Russet Burbank	PBC	2	43.4	2.8	16.7	0.09	66.1	31.5	83.1	0.01**
	PSB	4	50.7	4.2			11.1	7		
Shepody	PBC	4	39.9	7.4	3.3	0.86	71	33	73.5	0.1
	PSB	2	41.3	10.2			18.8	6.7		
Rotation average	PBC	12	38.6	8.7	19.5	0.03*	59	25.2	78.8	< 0.001
	PSB	12	46.2	7.2			12.5	6.5		
Russet cultivars	PBC	8	38	9.7	24.2	0.03*	53.0	20.1	78.9	< 0.001
	PSB	10	47.2	6.7			11.2	5.9		

the two different rotation systems are shown in Table 2. We found that the PSB rotation resulted in higher potato yields for all cultivars (Fig. 5). On average, potato yields were 46.2 t ha^{-1} in the PSB plots, compared to 38.6 t ha^{-1} in the PBC plots (Table 2), representing a 19.5% difference.

Under the PSB rotation, Russet Burbank, Gold Rush, Prospect, and Shepody yielded 50.7, 45.9, 42.5 and, 41.3 t ha^{-1}, respectively. In contrast, 43.4 t ha^{-1} of tuber yield was produced by Russet Burbank, 33.9 t ha^{-1} by Gold Rush, 37.3 t ha^{-1} by Prospect and, 39.9 t ha^{-1} by Shepody under the PBC rotation. In comparison with the PBC rotation, the largest increase in yield under the PSB rotation was observed for the Gold Rush cultivar (35.6%), followed by Russet Burbank (16.7%), then Prospect (13.8%). The yield of Shepody under the PSB rotation was only 3.3% higher than its yield under the PBC rotation. The differences in yield between cultivars under the two rotations were not statistically significant ($p > 0.05$), likely due to the relatively small sample size (two to four replicates for each treatment). However, increasing the sample size by combining the three russet cultivars (Russet Burbank, Gold Rush, and Prospect) into a single Russet group revealed that the PSB rotation significantly increased the yield ($p < 0.05$) (by 24% on average).

Tuber Specific Gravity, Dry Matter and Starch Content

The PSB rotation resulted in higher specific gravity, starch, and dry matter for all cultivars combined (1.0898, 15.770%, and 10.7 t ha^{-1}, respectively). In comparison, the specific gravity and dry matter for the PBC rotation were 1.0868 and 8.9 t ha^{-1}, respectively. The estimated starch content of PBC plots averaged 15.425%. The PSB rotation increased the starch content and specific gravity in three cultivars only. However, under PSB, the Prospect cultivar demonstrated a decrease in specific gravity from 1.0865 to 1.0857 and in starch from 15.392 to 15.307%, compared with the values under PBC.

The highest specific gravity and starch content were 1.0923 and 16.05, respectively, both achieved by Russet Burbank under the PSB rotation. Gold Rush under the PSB rotation had the second highest specific gravity (1.0901) and starch content (15.805%). Prospect had a specific gravity of 1.0857 and a starch content of 15.805% under the PSB rotation. The lowest measured specific gravity (1.0846) and estimated starch content (15.193%) in the experiment were produced by Russet Burbank under the PBC rotation. The highest specific gravity and starch content under the PBC rotation were 1.0884 and 15.614%, by the Gold Rush. The Shepody cultivar produced 15.481% and 1.0872 starch content and specific gravity respectively, under the PBC rotation and 15.601% and 1.0883, respectively, under the PSB rotation.

Dry matter content of all cultivars was positively affected by the PSB rotation. A higher tuber dry matter was produced by the PSB rotation with an average of 10.7 t ha^{-1} compared to that of PBC with 8.9 t ha^{-1}. Tuber dry matter of Gold Rush was affected the most, with a 42.4% increase from 7.3 to 10.4 t ha^{-1}, followed by Russet Burbank, which

Table 3 Separated analysis of variance of pre-plant soil mineral N content for cultivars within each rotation

		df	Sum sq.	Mean sq.	F-value	P-value
PBC	**Cultivar**	3	1708	569.3	0.865	0.498
	Residuals	8	5266	658.2		
PSB	**Cultivar**	3	158	52.8	1.402	0.311
	Residuals	8	301	37.6		

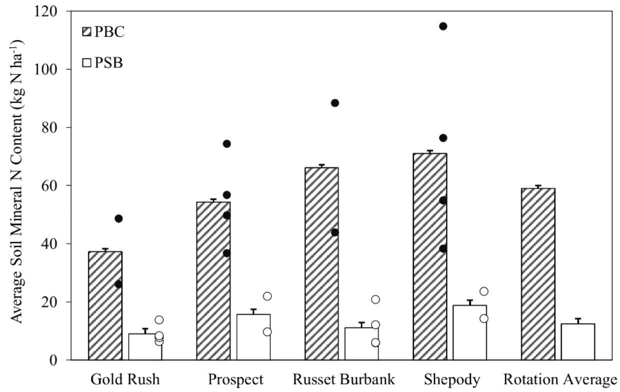

Fig. 4 The variation of the soil mineral N content in the spring of 2017 before planting. Error bar represents standard error of mean

Table 4 Analysis of variance of tuber yield with consideration of rotation and cultivar as sources of variation

	df	Sum sq.	Mean sq.	F-value	P-value
Rotation	1	339.7	339.7	4.76	0.044*
Cultivar	3	181.7	60.6	0.848	0.487
Rotation:Cultivar	3	80.3	26.8	0.375	0.772
Residuals	16	1142	71.4		

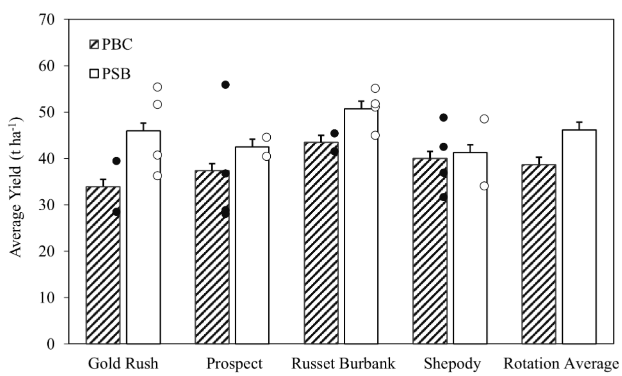

Fig. 5 Average yield variation of all treatments. The yield of each plot is represented with a dot on the relative bar. Error bar represents standard error of mean

experienced a 17% increase in tuber dry matter under PSB compared to PBC. The Prospect was affected the least, with a 9.3% increase in dry matter. Statistically, the rotation factor had a significant increasing effect on specific gravity, starch and dry matter ($p < 0.05$), while cultivar and interaction effect did not lead to a significant difference (Table 6).

Discussion

N Contribution to Potato Crops from Red Clover

We found that the PBC plots had significantly higher potato pre-plant soil N content than the PSB plots. Nitrogen from the plowed-down red clover probably contributed to the elevated soil N content in the PBC plots. On average, pre-plant soil mineral N content in the red clover plots was 4.7 times (46.5 kg N ha^{-1}) higher than the barley plots. In addition, in-season mineralization of the red clover can release more N into the soil. However, the additional soil N in the PBC rotation did not translate into higher potato yields compared to those of the PSB rotation (Fig. 4; Table 2). On the contrary, the PBC rotation consistently produced lower yields for all cultivars. This suppressed yield was likely the result of an oversupply of N in soil from the red clover residue given the relatively short growing period.

Jiang et al. (2019) reported that higher levels of soil N from mineralization of plowed-down red clover and soil organic matter can lead to over-fertilization and yield suppression of the late-maturing Russet Burbank cultivar when accompanied with the shorter than ideal growing season of PEI. Similarly, in another study conducted in PEI, Nyiraneza et al. (2015) compared cultivating an early to mid-maturing cultivar (Shepody) in the PBC rotation with two alternative rotations in which red clover was substituted with cover crops from the grass and vegetable oil family. They observed that the PBC rotation produced a lower yield and suggested that the extra N supply from red clover didn't necessarily translate to higher yields. A number of studies have indicated that the soil N supply in cool, humid Atlantic conditions is primarily dominated by N mineralization during the growing season (Ojala et al. 1990; Zebarth et al. 2004b; Sharifi et al. 2007; Zebarth and Rosen 2007), and is subject to great uncertainty in terms of timing and amount (Sharifi et al. 2007; Nyiraneza et al. 2012). The uncertain level of soil N supply from growing season mineralization of the preceding legume can result in a poor correlation of tuber yield and pre-planting N measurements (Belanger et al. 2000; 2001). Other researchers have also documented that excessive N fertilization leads to tuber yield reduction (Ojala et al. 1990; Griffin and Hesterman 1991). Many previous studies documented that the over-application of nitrogen in the form of mineral fertilizer or organic manure not only causes potato yield reduction, but also leads to the

Table 5 Analysis of variance of tuber yields for cultivars within each rotation

		df	Sum sq.	Mean sq.	F-value	P-value
PBC	**Cultivar**	3	104.4	34.8	0.379	0.771
	Residuals	8	733.5	91.7		
PSB	**Cultivar**	3	157.6	52.5	1.029	0.43
	Residuals	8	408.4	51		

Table 6 Average dry matter, specific gravity, and starch content of tubers under various cultivars and rotations

Rotation	Cultivar	Dry matter (t ha^{-1})	Specific gravity (g cm^{-3})	Starch (%)
PBC	Gold Rush	7.3	1.0884	15.614
	Prospect	8.6	1.0865	15.392
	Russet Burbank	10.0	1.0847	15.193
	Shepody	9.4	1.0872	15.481
	Average	8.9	1.0868	15.425
PSB	Gold Rush	10.4	1.0901	15.805
	Prospect	9.4	1.0857	15.307
	Russet Burbank	11.7	1.0923	16.050
	Shepody	10.8	1.0883	15.601
	Average	10.7	1.0898	15.770
Significant effects ($P<0.05$)		Rotation	Rotation	Rotation

degradation of potato quality (Li et al. 1999; Zebarth et al. 2004a; Sincik et al. 2008).

In addition, excessive N supply early in growing season can also suppress yield as a result of delaying tuber initiation and bulking (Lynch and Tai, 1989; Sarkar and Naik, 1998; Thornton 2020; Jones et al. 2021) as well as reducing tuber dry matter and specific gravity (Millard and Marshall, 1986; Laboski and Kelling, 2007; Maltas et al., 2018). Our observations were consistent with these results. The tuber dry matter and specific gravity were significantly lower under the PBC rotation.

Potato producers should adequately account for N supply from preceding rotation crops, especially legumes like red clover. However, the relatively large spatial and temporal variation of soil N from the preceding red clover creates a practical challenge for growers to accurately account for soil N supply where spatiotemporally consistent N supply is the management goal. Applying the same amount of fertilizer N to potato crops under the PBC and PSB rotations would not only increase costs, but could also cause yield losses in the PBC fields and lead to water quality contamination as a result of excessive N leaching (Zebarth et al. 2012; Jiang et al. 2019; Liang et al. 2019).

N Supply from Soybean Residues

In this experiment it was evident that the leguminous soybean did not provide considerable N supply to the subsequent crop. In fact, the spring soil N content experienced a greater decrease from fall to spring after soybean compared to barley. This can be explained by two main factors. Firstly, about 66% of total soybean nitrogen was harvested in seeds. The remaining roots and shoots contained about 76 kg N ha^{-1}, while barley residues contained about 36.5 kg N ha^{-1} (data reported elsewhere, Liang et al. 2019). Secondly, soybean residues have low C:N ratios and tend to mineralize quicker after being incorporated into soil (Baggs et al. 2000; Dessureault-Rompré et al. 2013). Several studies have reported the high leaching potential of these mineralized residues over winter in the climatic conditions of Atlantic Canada (Sanderson et al. 1999; Seneviratne, G. 2000; Zebarth et al. 2005). Therefore, the decline of soil N in PSB plots was likely a result of the quick mineralization of soybean residues and later loss through leaching during winter. In addition, the average non-growing season nitrate leaching of soybean plots was significantly higher than that of barley plots in 2016 (data reported elsewhere, Liang et al. 2019), which further supports this explanation.

Effects of Rotation and Cultivar on Tuber Yield, Dry Matter, Specific Gravity, and Starch Content

With all cultivars combined, the PSB rotation resulted in a significant increase (19.5%) in total tuber yield. In a study carried out in Maine, US, using the Russet Burbank cultivar, 224 kg N ha^{-1} fertilization and similar management conditions, it was reported that the soybean-barley/clover-potato rotation produced 9.7% higher yields than that the standard three-year barley/clover-clover-potato rotation, with yields of 28.7 t ha^{-1} and 31.5 ta ha^{-1}, respectively. However, the difference was not statistically significant (Larking and Honeycutt 2006). We found that PSB and PBC rotations considerably influenced potato yields for different cultivars. We observed that the PSB rotation led to higher yields for the Russet Burbank, Gold Rush, and Prospect (except for one sample of Prospect) cultivars. The Gold Rush cultivar was affected the most (36%), followed by Russet Burbank (17%) and Prospect (14%) cultivars, whereas Shepody was not affected as much (3%) under different rotations.

We found that Russet Burbank maintained a relatively high yield under both rotations with an average yield of 50.7 t ha^{-1} and 43.4 t ha^{-1} for PSB and PBC respectively. Zaeen et al. (2020) reported that an increase of N fertilization from 168 kg N ha^{-1} to 228 kg N ha^{-1} resulted in a slight decrease in Shepody's tuber yield without influencing Russet Burbank yield. They reported an N fertilization rate of 168 kg N ha^{-1} as an optimal rate for both Shepody and Russet Burbank to maximize tuber yield and quality. These results indicated that Russet Burbank is able to maintain a relatively high yield within a wider range of N supply, although excessive N supply can still suppress the yield.

The PSB rotation led to a significant increase in specific gravity, starch content, and tuber dry matter with averages of 1.0898, 15.770%, and 10.7 t ha^{-1}, respectively, compared to the PBC averages of 1.0868, 15.425%, and 8.9 t ha^{-1}. While the cultivar effect didn't show statistical significance for these dependent variables, the studied cultivars responded differently to the alternate rotation. The highest and lowest specific gravity and starch content were observed in Russet Burbank under PSB and PBC rotation, respectively, making it the most affected cultivar. Shepody was the least positively affected cultivar and Prospect was the only cultivar that experienced a decrease in specific gravity and starch content under the PSB rotation. Tuber dry matter increased in all cultivars under the PSB rotation. Similar to tuber yield, Gold Rush benefited the most from the alternative rotation in dry matter with a 42.4% increase, followed by Russet Burbank (17%), Shepody (14.8%), and Prospect (9.3%).

Economic Implications of PSB Rotation

In the conventional rotation, the potato crop creates about 93.5% of the total gross income of a PBC rotation cycle, which approximated to be \$7496 ha^{-1} (Supplemental Table 2). Therefore, an increase in the potato yield along with the addition of a secondary cash crop to the rotation can translate into a significant economic benefit for potato farmers. It is estimated that replacing red clover with soybean in potato rotation can increase the gross income of a rotation cycle by 30%. This increase is composed of about \$792 ha^{-1} from 2.2 t ha^{-1} soybean yield (yield results reported elsewhere, Liang et al. 2019) and \$1472 ha^{-1} from the 7.6 t ha^{-1} increase in average potato yield of the PSB rotation. Incomes are estimated based on the 2011–2019 average unit price of \$344.6 ton^{-1} and \$193.8 ton^{-1} for soybean and potato, respectively (Government of Prince Edward Island 2019; 2020). Note that these results are based on data from one cycle of a three-year rotation and more work is required to assess the long-term economic and environmental implications of the PSB rotation.

Conclusions

The PSB rotation had significantly higher yields than PBC rotation and positively influenced the yield of all cultivars. The russet cultivars were more sensitive to the alternative PSB rotation, with the Gold Rush (36%) being the most affected, followed by Russet Burbank (17%) and Prospect (14%) cultivars, whereas Shepody was not affected as much (3%) under the two different rotations. Russet Burbank had the highest yield under both PBC and PSB rotations. Although the differences in yields were numerically clear, an analysis of variance did not detect statistically significant differences between cultivars nor between rotations within each cultivar. This is likely because the sample sizes (two to four replications) were relatively small compared to the high variation in the dependent variables. However, increasing the sample size by treating the three russet cultivars as a single russet group, the PSB rotation significantly increased tuber yield. In addition, a preliminary economic analysis revealed that the average increase in potato yield along with the additional income from soybeans in the PSB rotation can increase gross income by as much as 30%. Soil analyses showed that the PBC rotation had significantly higher pre-planting soil mineral N content than the PSB rotation. The elevated mineral N content in PBC plots was probably sourced from the decomposition of the plowed-down red clover biomass. The lower yield of the PBC rotation despite higher mineral N available at planting was likely caused by an oversupply of nitrogen from red clover residue decomposition. Results indicate that potato growers should adjust the N application rate based on pre-plant soil N concentration by taking into account extra N supply from residues of nitrogen-fixing cover crop such as red clover. This will produce higher yields and improve tuber quality while at the same time reducing nitrate leaching. It is important to stress that these are preliminary results concluded from a short-term field study. More comprehensive and longer term studies with increased replications are needed to further verify the results.

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Declarations

Conflict of interest The authors have no conflict of interest.

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