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Trends in the variability of potato tuber yield under selected land and soil characteristics

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Abstract: The objective of this study was to evaluate variations in potato tuber yield with the selected land and soil characteristics including (i) topography (elevation and slope); (ii) geometry (horizontal coplanar geometry (HCP) and perpendicular coplanar geometry (PRP)); (iii) hydrology (volumetric moisture content; θv), and (iv) chemistry (phosphate, potash, organic carbon; organic carbon and pH). Analyses of the data collected across four potato fields, two each in Prince Edward Island and New Brunswick (NB), showed that the tuber yield negatively correlated with the field slope and positively correlated with most of the soil characteristics studied. Field elevation affected yield only under certain conditions such as higher range of elevation (≥ 7 m) (Field 2 in NB). Among soil characteristics, only HCP and PRP correlated with field elevation. The slope and elevation explained 22% to 36% variability of yield. Investigations of yield and topography by zonal analysis showed that yield was lower in zones of higher slope or elevation and lower θv, as the mean θv decreased in zones with a higher slope.

Keywords: Atlantic Canada; *Solanum tuberosum* L.; land surface; site-specific crop management; precision agriculture

Potato is the most important root and tuber crop worldwide, and Canada is the world leader in potato production. In Atlantic Canada, Prince Edward Island (PEI) and New Brunswick (NB) share 24.5% and 13.6% of the potato industry needs, respectively (AAFC 2017). The biggest challenge, as communicated by farmers of this region, is uncertainty and variations in estimating tuber yield.

Topography measurements are highly related to variations in crop yield and are easy to obtain compared to time-consuming and costly as well as destructive measurements of soil characteristics (Kravchenko and Bullock 2000). Elevation and slope are the most important topographical factors affecting the yield of a crop (Kitchen et al. 2003). Higher corn yields were reported at lower slope positions by Spomer and Piest (1982) compared to mid or high positions. Afyuni et al. (1993) observed lower silage corn yield at a higher elevation. Kravchenko and Bullock (2000) calculated yield-topography-soil relationships using dense corn and soybean data collected from 1994 to 1997 in central Illinois and eastern Indiana and found that slope and elevation had the highest impact on yield. Kumhálová et al. (2008) studied the impact of field topography on nitrogen content in soil and yield of winter wheat and rapeseed. They concluded that the relation between yield and topography was more important in dry years. Contrarily, Kumhálová et al. (2011) reported no significant impact of topography on soil characteristics and thus on yield. Wang et

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al. (2016) found that the effects of the soil factors on vegetation restoration were higher than those of the topographic factors. Grzebisz et al. (2018) reported that the pattern of nitrogen net change in potato tops depended on the change of phosphorus and potassium contents.

As reviewed above, the relationships among yield of various crops, field topography, and various soil characteristics have been reported in the literature; however, little attention has been paid to the relationships of potato yield with characteristics of lands and soils of Atlantic Canada. Therefore, the objective of this study was to evaluate the trends of variations in potato tuber yield with selected land and soil characteristics including (i) topography (elevation and slope); (ii) geometry (horizontal coplanar geometry (HCP) and perpendicular coplanar geometry (PRP)); (iii) hydrology (volumetric moisture content (θv)), and (iv) chemistry (phosphate, potash, organic carbon and pH).

MATERIAL AND METHODS

Study sites and the establishment of grids for data collection. The fieldwork was conducted on four potato fields of different size (Table 1) in NB (Field 1: Grand Falls 47.100965°N, 67.777873°W and Field 2: Riverveiw 46.384169°N, 67.7226°W) and PEI (Field 3: Souris 46.3550°N, 62.2518°W and Field 4: O'Leary 46.7071°N, 64.2269°W). The potato cultivar used in the selected fields was Russet Burbank (a common cultivar in Atlantic Canada). The cut-seed was used for potato plantation in selected sites. The seed size ranged from 55–85 g. The data for field elevation, field slope, HCP, PRP, θv and soil samples were collected during mid-May 2017. All the fields had sandy loam soil (Orthic Humo-Ferric Podzol) and were under conventional management practices for potato production over the past decade.

Ground conductivity surveys, using the DualEM-II sensor (DUALEM Inc., Milton, Canada), were conducted to establish grids for data collection. The geo-statistical analysis of the DualEM-II sensor data was utilized to generate semivariograms using GS+ (Mail Gamma Design Software LLC, Plainwell, USA). Various models of semivariogram including Gaussian, exponential, linear, and spherical were used to best fit the collected data. The highest coefficients of determination (R^2) and minimum residual sum of squares (RSS) were the criteria to select the best-fitted model. The coordinates for each sampling point and field boundary in each field were recorded using a real-time kinematics global positioning (RTK-GPS) system. The field layouts are presented in Figure 1 showing the grids (n = 40; 25 m × 25 m for each field) for soil sampling purposes.

Topographical characteristics. Elevation was obtained from RTK-GPS (Topcon Positioning System Inc., Livermore, USA) and the slope was measured using the handheld slope meter (Sears Holding Corporation, Hoffman Estate, USA).

Soil hydrology. A pre-calibrated TDR-300 (time domain reflectometry) sensor (Spectrum Technologies, Inc, Plainfield, USA) (R^2 = 0.98; RMSE (root mean square error) 0.6%) was used to record soil volumetric moisture content by inserting TDR probes 15 cm below the soil surface. Five measurements of θ_v were recorded within the radius of 1 m of each grid point at each of the four fields to minimize error and maximize the accuracy of the collected data.

Soil geometry data. The HCP and PRP readings were recorded using the DualEM-II at each sampling location within the selected sites. Five readings of DualEM-II sensor were recorded at each sampling point to ensure precision and accuracy. Location of sampling points was recorded using an RTK-GPS for geo-referencing purposes.

Table 1. Values of minimum, maximum, and range of field elevations and corresponding slopes across four selected fields in the provinces of New Brunswick (Field 1 and 2) and Prince Edward Island (Field 3 and 4)

Field	Area (m^2)	CEC ($mmol_+/kg$)	pH	Ca	P	K	Organic carbon (g/kg)	Elevation (m a.s.l.)		Slope (deg.)	
					(mg/kg)			min	max	min	max
1	31 970	9.72	6.00	1122	549	152	20.0	232	237	0.10	4.88
2	33 754	9.95	5.81	801	392	144	21.9	136	143	0.10	4.86
3	18 661	6.80	5.73	779	394	160	21.9	1.34	5.04	0.40	5.80
4	30 652	4.10	5.99	590	460	146	9.70	31.5	35.5	0.60	5.02

CEC – cation exchange capacity

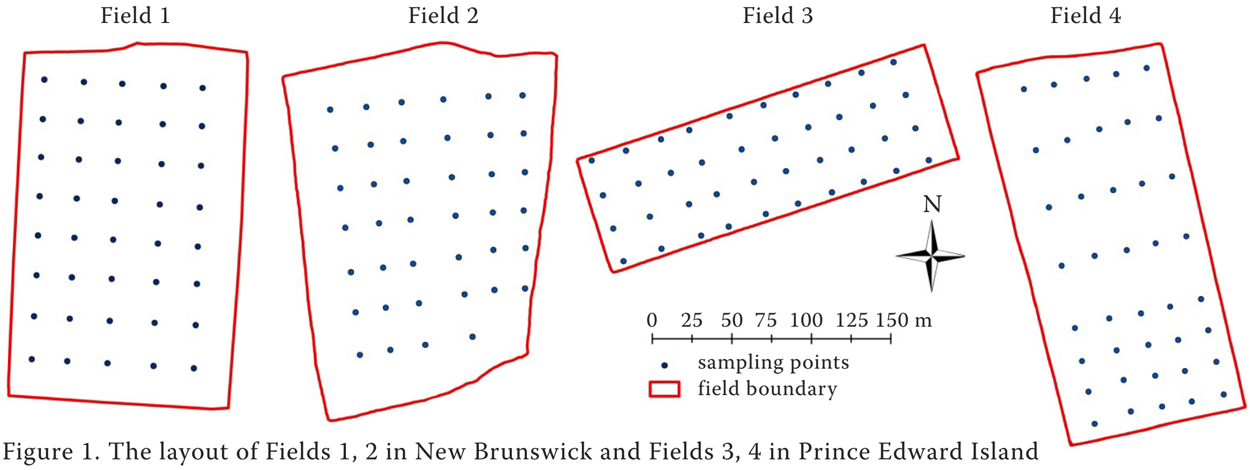

Figure 1. The layout of Fields 1, 2 in New Brunswick and Fields 3, 4 in Prince Edward Island

Soil sampling for chemical characteristics. Five soil samples within the radius of 1 m from each grid were collected using a soil augur at the root zone depth of potato, mixed, pooled to for a homogeneous sample, labelled and secured in a refrigerator before further processing. The samples were air dried, ground using a soil grinding machine and passed through a 2-mm sieve to quantify levels of potash and phosphate, organic carbon and pH.

Yield data. For the yield sampling, the plot size was 1 m^2 as the yield samples were collected by digging the plots manually. The potatoes from each plot were cleaned and weighed using a balance.

Statistical analysis. Statistical analyses were performed using Minitab 17 (Minitab Inc., State College, USA). Data measurements or log 10 of them were tested for normal distribution using the Kolmogorov-Smirnov (K-S) test. Parameters that did not pass the normal test were excluded from further analysis. Pearson's correlation coefficients (r) were calculated between yield and the selected land and soil characteristics. Forward stepwise regression was performed to analyse the cumulative effect of land and soil characteristics on yield, and only significant parameters were introduced into the regression equation. All differences between the mean values were declared significant at 0.05 level unless stated otherwise.

RESULTS AND DISCUSSION

Table 1 shows the minimum and maximum values of elevation and slope of the four experimental fields. Field 1 in Grand Falls was among the most elevated positions in NB as it lies on the highlands of NB, where the elevation varies from 150 to 610 m a.s.l. Ranges of slopes of Fields 1 and 2 were 4.76 to 4.78 degrees. Field 2 in Riverview was on the lowlands of NB, in the central and eastern parts of NB. This low-lying area is mostly less than 100 m a.s.l., and its altitudes rarely exceed 180 m a.s.l. The land surface of PEI ranges from nearly levelled in the west to hilly in the central region, the highest elevation is 142 m a.s.l. in central Queens County. Field 3 in Souris (PEI) had the lowest elevation (1.34 m a.s.l.) being on the island and Field 4 in O'Leary was also on lowlands of the island. Fields of PEI had comparatively higher slope ranges, i.e., 4.42 to 5.40 degrees.

Relationships among land and soil characteristics. Correlation coefficients between land and soil characteristics are shown in Table 2. No significant correlations were found between elevation and most of the soil characteristics across the sites. However, a negative significant correlation was observed between HCP/PRP and elevation in Field 2. This may suggest that higher range of elevation (≥ 7 m) in Field 2 influenced the ground conductivity. Soil characteristics were reported to vary with topographic settings (Kumhálová et al. 2008). One reason is the orientation of hill slopes on which soils develop; this affects the microclimate, such as north vs. south-facing slopes, and hence the soils (Iqbal et al. 2004).

Slope better correlated with soil characteristics. Lower ground conductivity, θv, organic carbon, and phosphate were detected at higher slopes across most of the sites. These are recognized by a negative correlation for slope-soil characteristics. An increase in potash concentration at lower slope positions was found in Field 1, but for the remaining fields, no significant correlation of potash with slope was observed. Similarly, pH did not show a significant correlation with slope as well.

Table 2. Correlation coefficient (with *P* values in parentheses) between land characteristics (including slope, elevation) and soil geometry (horizontal coplanar geometry (HCP), and perpendicular coplanar geometry (PRP)), hydrology (volumetric moisture content; θv), and chemistry (organic carbon (OC), phosphate, and potash) across the four fields selected in New Brunswick (NB) and Prince Edward Island (PEI)

	Field	Slope	Elevation	Slope	Elevation
		HCP		**PRP**	
NB	Field 1	−0.592 (0)	ns	−0.701 (0)	ns
	Field 2	−0.444 (0.004)	−0.561 (0)	−0.313 (0)	−0.695 (0.049)
PEI	Field 3	−0.345 (0.029)	ns	−0.337 (0.034)	ns
	Field 4	−0.370 (0.023)	ns	ns	ns
		θv		**OC**	
NB	Field 1	−0.631 (0)	ns	ns	ns
	Field 2	nn	nn	−0.484 (0.002)	−0.484 (0.002)
PEI	Field 3	ns	ns	ns	ns
	Field 4	−0.505 (0.001)	ns	−0.377 (0.017)	−0.377 (0.017)
		Phosphate		**Potash**	
NB	Field 1	ns	ns	−0.417 (0.007)	ns
	Field 2	−0.336 (0.034)	ns	ns	ns
PEI	Field 3	−0.414 (0.008)	ns	nn	nn
	Field 4	ns	ns	ns	ns

**P* = 0.05; *P* = 95%; nn – not normal data available for analysis; ns – not significant data were not used in regression analysis

The negative correlations between organic carbon, phosphate, and potash are mentioned in the findings of Kravchenko and Bullock (2000). The correlation coefficient of θ_v with slope was negative and significant in Field 1. Insignificant or inconsistent correlations between soil characteristics and landscape position were also reported by Day et al. (1987). They detected lower organic carbon content at lower landscape positions. They also observed an inconsistent correlation of P and K and suggested that it might be due to past management practices. Comparison of the results suggests that correlation analysis is site-specific, and management practices such as the application of fertilizers and pesticides can alter the results.

Potato yield versus land and soil characteristics. Average yield exceeded 50 000 kg/ha in Field 1 and 2 in NB; however, lower yield values were recorded in Field 3 (37 384 kg/ha) and 4 (47 518 kg/ha) in PEI. The yield was moderately variable (*CV* (coefficient of variation) between 15% and 35%) across the sites, with the lowest variability in Field 2 in NB and the highest variability in Field 4 in PEI. The size of the tuber yield varied from 100 g to 285 g in weight and 50 mm to 125 mm in diameter.

Correlation of yield with elevation was not significant except in Field 2 which had the highest elevation difference (≥ 7) among the sites (Table 3). Non-significant correlation of yield with elevation contradicted the findings of Jaynes et al. (2003) who observed that both significant positive and negative correlation of crop yield with elevation might be due to low range of elevation across the fields of this study. Field slope was negatively correlated with yield; correlations of yield with slope were stronger in Field 1, 3, and 4. Slope was more variable in these sites (*CV* > 51%) compared to Field 2 with *CV* = 45%. These results

Table 3. Correlation between yield, land characteristics (slope and elevation) and soil characteristics; (i) geometry (horizontal coplanar geometry (HCP) and perpendicular coplanar geometry (PRP)); (ii) hydrology (volumetric moisture content; θv), and (iii) chemistry (organic matter (OC), phosphate, and potash). The coefficient of determination between yield and land characteristics (R_1^2), yield and soil characteristics (R_2^2), and between yield and land/soil characteristics (R_3^2) (forward stepwise)

Field	Slope	Elevation	HCP	PRP	θv	OC	Phosphate	Potash	R_1^2	R_2^2	R_3^2
1	−0.59	ns	0.81	0.80	0.66	0.48	nn	0.60	35.13	58.78	59.12
2	−0.35	−0.44	0.69	0.58	nn	0.45	0.61	0.47	26.21	71.50	71.50
3	−0.49	ns	0.74	0.72	0.67	0.66	0.58	nn	24.29	71.32	73.92
4	−0.50	ns	0.82	0.59	0.71	0.52	0.54	0.45	24.81	86.27	86.27

nn – not normal data available for analysis; ns – not significant data were not used in regression analysis were in agreement with the findings of Kravchenko and Bullock (2000) and Kitchen et al. (2003).

Table 3 also shows the coefficient of determination between yield-land characteristics (R_1^2), yield-soil characteristics (R_2^2), yield and combined land-soil characteristics (R_3^2). For regression analysis, only significant factors were introduced into the forward stepwise regression. Topography (slope and/or elevation) explained 20–35% of yield variability across the sites. The highest R^2 between yield and slope was observed in Field 1, which is in agreement with the higher correlation coefficient in this site. Topography data well explained yield variability. These findings confer the reports in the literature. For example, field elevation (Bakhsh et al. 2000) and slope (Kravchenko and Bullock 2002) were reported significant topographical characteristics in conventional crop production systems. Kravchenko et al. (2000) found a strong effect of field slope on the yield of soybean and corn during some cropping seasons they monitored, possibly due to consistently larger yields at sites with lower elevations and gentle slopes.

All of the significant correlations between yield and soil characteristics were positive suggesting

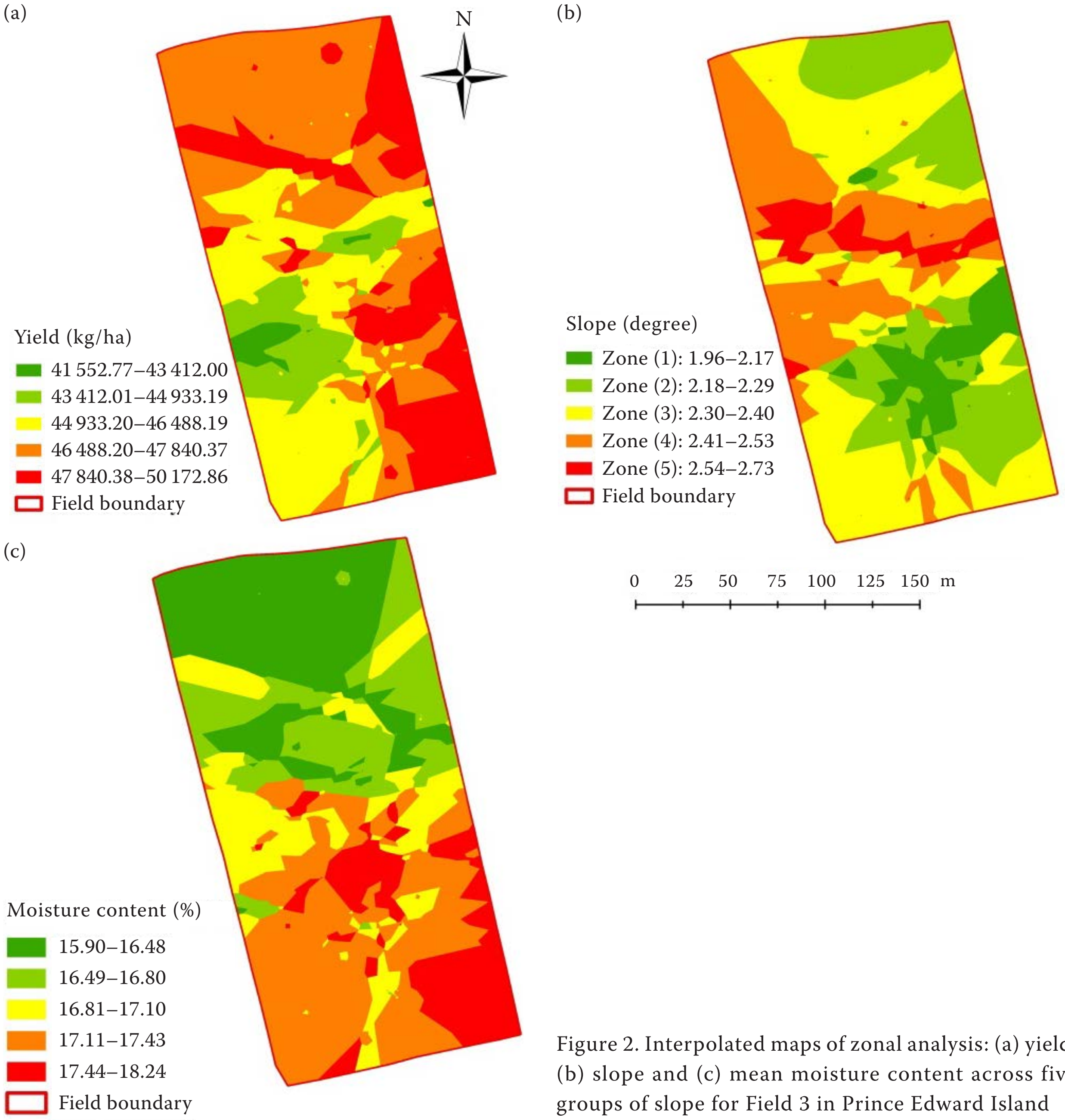

Figure 2. Interpolated maps of zonal analysis: (a) yield; (b) slope and (c) mean moisture content across five groups of slope for Field 3 in Prince Edward Island

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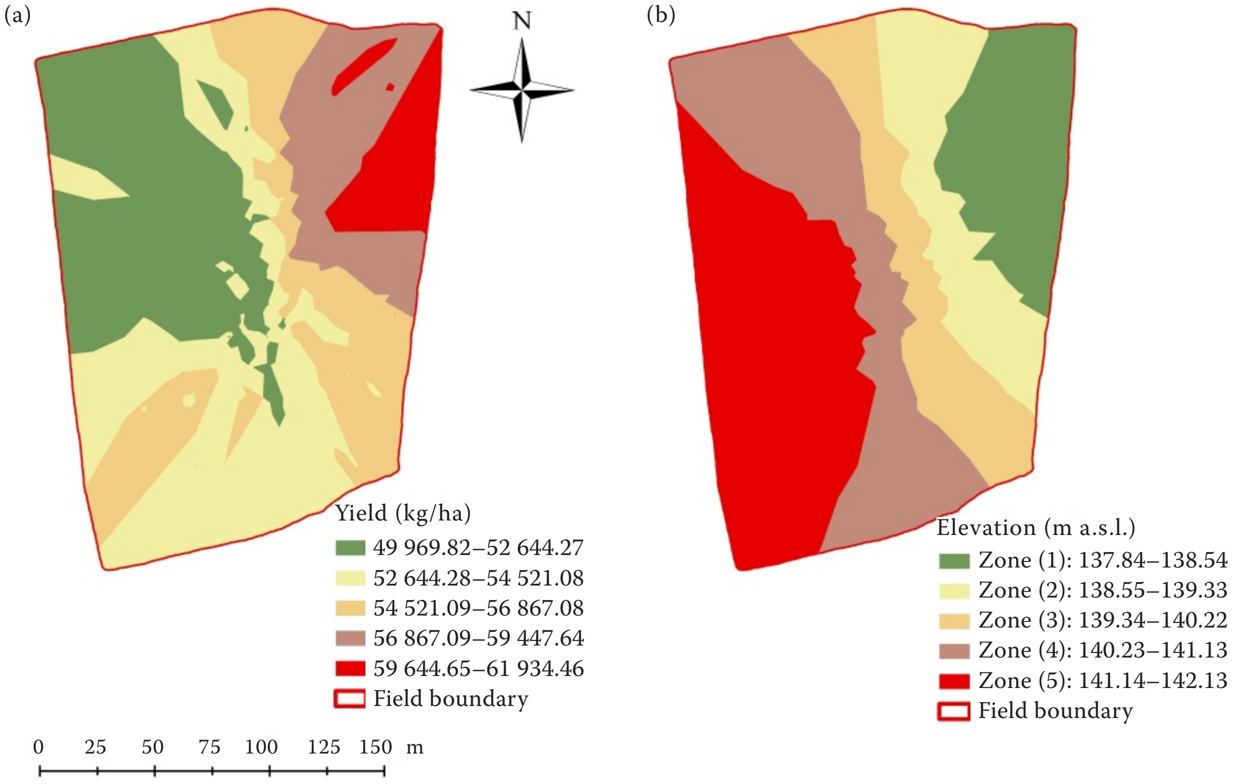

Figure 3. Interpolated maps of zonal analysis: (a) elevation and (b) yield in Field 2 in New Brunswick

higher values of soil characteristics resulted in greater potato yield (Table 3). Among all soil characteristics, ground conductivity measurements showed the highest correlation with yield. The coefficient of determination for soil characteristics was higher than those for topography across all sites, signifying that topography by itself was not as informative as soil characteristics (Kravchenko and Bullock 2000). Soil characteristics in combination with topography did not cause a major increase in R^2 compared to soil characteristics in most of the campaigns. HCP or PRP were the major contributors among soil characteristics to the regression equation. The R^2 obtained from the current study were in agreement with the findings of Kravchenko and Bullock (2000). They observed that the cumulative effect of topographical features from forwarding stepwise regression explained 6% to 50% of yield variability in a four-year study of corn and soybean in the USA. Kitchen et al. (2003) also reported R^2 of (2–28%) for the regression between topography and yield in a three-year study using multiple linear regressions.

Results of the zonal analysis. The potato yield, field slope and θ_v data were plotted using the ArcGIS to visualize how yield varied across zones with the selective land characteristics that vary every time the field is ploughed (i.e., slope) and with soil characteristics that vary most with changing the environment and/or growing season (i.e., θv). Results of the zonal analysis revealed that mean values of yield were higher in zones with lower slope and decreased with increasing slope (Figure 2), which supports the outcome of correlation and regression analysis shown in Table 3. For example, while the mean yield in zone 1 of Field 4 was 47 594 kg/ha that decreased significantly to 45 481 kg/ha in zone 5 with values of 47 433, 46 816, and 45 741 in zones 2, 3, and 4, respectively. The mean θv in the top 15 cm soil layer of the above 5 zones were 17.39, 17.04, 16.90, 16.90 and 16.61%, respectively. The corresponding relationship between yield and θv, when plotted the former versus later, was Yield (kg/ha) = 2885 × θv (%) – 2338 (R^2 = 0.71) for Field 4 (O'Leary, PEI).

Zonal analysis of soil characteristics, such as θv in Field 3 was also in agreement with the results of the correlation coefficient and showed that mean θv decreased in zones with higher slope (Figure 2). Comparison of interpolated maps of yield (Figure 2a) and slope (Figure 2b) for Field 3 showed high tuber yield in North East and South East of the map (lower slope). On the other hand, on the western centre of the map where the slope is higher, a lower yield was observed.

Similar to slope, the potato tuber yield varied with elevation, too. For instance, the zonal analysis of elevation and yield in Field 2 in NB showed that yield was higher in zones with lower elevation (Figure 3) and confirmed the results of negative correlation between yield and elevation in this field (Table 3). In zone 1 with the lowest elevation (137–138 m a.s.l.), maximum mean yield (59 443 kg/ha) was observed; however, in zone 5 (141–142 m a.s.l.), the mean value of yield significantly decreased to 53 088 kg/ha. Comparison of interpolated maps of yield (Figure 3a) and elevation (Figure 3b) in this field also showed that yield was higher on the eastern side of the map (lower elevation); whereas, on the western side of the map having the highest elevation, the potato tuber yield was lower. These results suggest that maps of yield and topography can be used to implement the site-specific management zones as part of precision agriculture practices for improving potato tuber yield and decreasing the expenses as well as damage to the environment associated with extensive soil sampling. Given the importance of this crop to the economy of the Atlantic Canada and Canada as a whole, assessment of topographic features on yield variability is necessary and that would provide farmers and producers with information for proper decision making and site-specific crop management.

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