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Use of remotely measured potato canopy characteristics as indirect yield estimators

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Abstract

Prediction of potato (Solanum tuberosum L.) yield before harvest is important for making agronomic and marketing decisions. Indirect yield estimators are sought to replace time- and labor-consuming crop yield measurement during the growing season. The aim of the research was to i) determine the relationship between manually and remotely measured potato crop characteristics throughout the growing season and yield determined at the termination of the crop, and ii) calculate the yield prediction errors of the crop characteristics that most accurately estimate potato yield in two commercial potato fields. The crop characteristic determined manually was crop height (m), whereas remotely measured were: NDVI – Normalized Difference Vegetation Index using an active light optical sensor (AOS) – GreenSeeker (Trimble Inc., Sunnyvale, CA, USA), LAI – Leaf Area Index determined by the SunScan system (Delta-T Device, Ltd. Cambridge, UK), and percent of canopy coverage derived from images obtained with a digital camera Sony DSC-HX400V and analyzed using Image J software. Canopy coverage showed the strongest relationship with yield. The mean absolute error of yield prediction was from 3.78 to 3.97 $t \cdot ha^{-1}$, and the relative error was from 14.1 to 20.7%. Overestimation of yields could have been caused by stress that did not allow translocation of the sugars produced in the leaf down to the developing tubers. Underestimation of yields could result from potato vines bending on the neighboring rows or between them in furrows, thus decreasing the canopy coverage.

Keywords
potato, canopy coverage, crop height, LAI, active optical sensors, NDVI, yield prediction

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Introduction

Prediction of potato yield before harvest is important for making agronomic and marketing decisions. Indirect yield estimators are sought to replace time- and labor-consuming measurement of crop biophysical characteristics: leaf area index – LAI, crop height, or canopy coverage. Asghari-Zakaria et al. (2007) showed that tuber yield positively correlated with crop height measured 30 days after planting (DAP). Canopy coverage is an indirect measurement of intercepted solar radiation. It represents a physical expression of a series of underlying processes and interactions that affect the growth and development of a crop (Bojacá et al. 2011). Rapid establishment of full soil coverage by the potato canopy and maintenance of that coverage for a long time is required to obtain high yields (Tiemens-Hulscher et al. 2014). Detailed crop biophysical characteristics (LAI, percent cover, crop height, etc.) and canopy reflectance data were collected in Idaho by Jayanthi et al. (2007) in multiple potato fields to develop and validate canopy reflectance-based crop coefficients. Bowen et al. (2005), found that optically sensed NDVI (Rouse et al. 1973) readings effectively delineated “greenness” attributed to nitrogen rate and thus can be used to variably apply N to potatoes prior to row closure. However, active optical sensors (AOS) are rarely used together with other hand-held instruments for monitoring potato growth, including yield prediction (Jasim et al. 2020; Zaeen et al. 2020). Jasim et al. (2020) found that vegetative indices (VIs) derived from AOSs showed weak correlations with potato yield. Recently, Cai et al. (2020), derived potato canopy coverage from images taken with a mobile phone’s built-in camera and obtained a strong relationship (R^2=0.94) between this crop trait and LAI. In a study established in two commercial fields, Po et al. (2010) investigated how specific soil and plant variables, including spectral reflectance, affect yield across a landscape. However, there is limited literature on the variability of potato crop biophysical characteristics (crop height, LAI, NDVI, and canopy coverage) registered throughout the growing season within commercial potato fields and their relationship with yield.

The aim of this research was to determine the relationship between manually (crop height) and remotely (LAI, NDVI, canopy coverage) measured potato crop characteristics throughout the growing season and yield determined at the termination of the crop in two commercial potato fields. A second objective was calculating the yield prediction errors of the crop characteristic that most accurately estimates potato yield.

Materials and Methods

Location and cultural practices

The research was conducted in 2018 and 2019 in northern (54°31'13"N, 17°18'33"E) and central (52°4'54"N, 21°8'32"E) Poland respectively, on two (21.9 and 10.5 ha) commercial fields (A and C) cropped with potato (*Solanum tuberosum* L.). Field A was planted with a medium early, French fry variety *Ivory Russet* on April 14th following winter wheat (*Triticum aestivum* L.). On field C, a medium early, chips variety *Hermes* was planted on April 27th after winter rape (*Brassica napus* L.). All field operations were conducted under best management practices developed by the cooperating farms over the years.

Climatic and soil conditions

The soil texture (ST) of the northern, irrigated field was sandy loam, and the ST of the central, rainfed field was loamy sand. Predominant soil type (WRB 1998*) of field A was Dystric Cambisols, and of field, C was Dystric Arenosols, Phaeozems. Detailed information on ST derived from the agricultural soil maps and soil sampling within fields A and C was presented in Stępień et al. (2016). Altitude (a.s.l.) for fields A and C was 48-61 m and 89-91 m, respectively.

The average air temperature from May to the end of August in 2018 and 2019 was 16.6°C and 18.3°C, respectively (Figure 1). The total precipitation during the respective periods in those two years was 266 and 354 mm. According to Chmura et al. (2013), this amount of rainfall on medium soil (field A) and light soil (field C) in Polish conditions was suboptimal and optimal, respectively, for growing potatoes. On field A, the rainfall distribution was 56 mm during May and June and 155 mm in July and August. Additionally, the crop was irrigated five times through reel and lateral systems with a total amount of 58 mm, of which 28 mm was applied in June and 30 mm from July 1st to August 7th. However, to achieve the maximal yield on field C, the distribution of rainfall should be as follows, about 143 mm during May and June and 220 mm in July and August. However, the crops on field C received these amounts of rainfalls in these two periods: 179 mm and 112 mm. Thus, the experiment was carried out in a year with insufficient rainfall in the second part of the season.

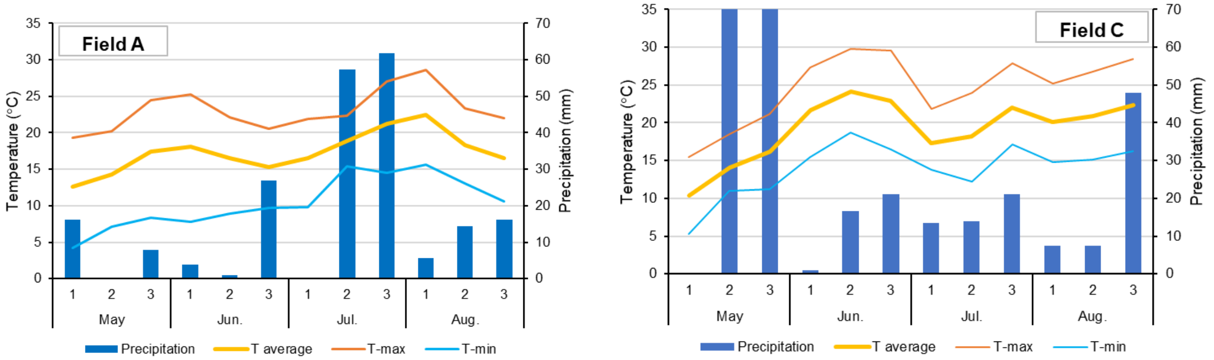

Fig. 1 Monthly averages of maximum, minimum, and mean air temperatures, and precipitation with dates of crop measurements from May to August of 2018 (field A) and 2019 (field C)

Plant measurements

The crop measurement points consisted of two 1 m long ridges (beds) marked with labels located in areas of different yield potential established using soil maps at a scale of 1:5000, ST information, and historical aerial images. Seventeen and 21 sampling sites were established on the northern and central fields, respectively (Figure 2). Weed infestation was successfully limited by pre-emergent herbicides to eliminate its negative effect on plant measurements.

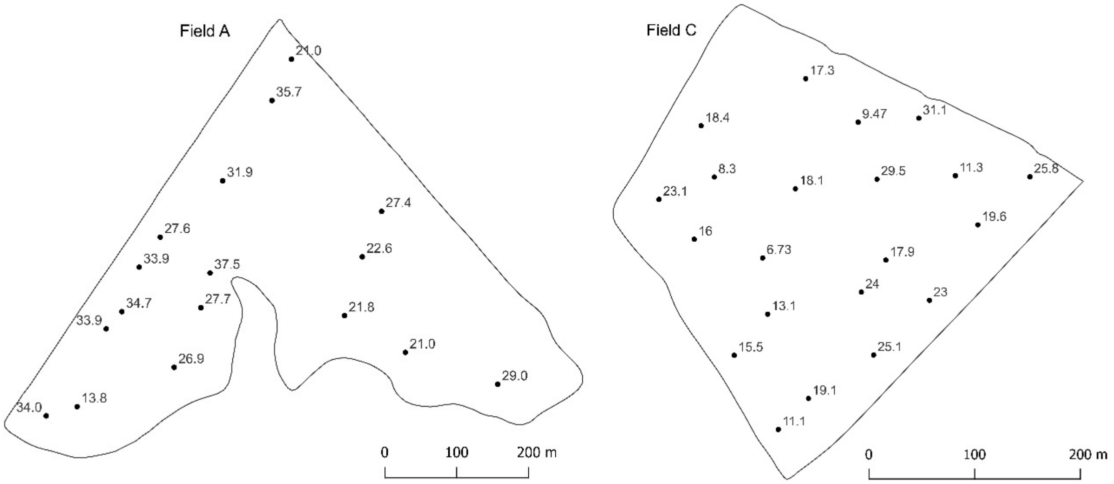

Fig. 2 Location of plant measurements and harvest sampling sites and yield (t·ha^{-1}) variability within fields A and C

The only manually determined crop characteristic was crop height (m), averaged out of three measurements done along the 1 m bed. The NDVI was measured with three replications using a GreenSeeker (Trimble Inc., Sunnyvale, CA, USA) handheld about 1 m above the canopy. The LAI was measured in 3 replications using the SunScan measurement system (Delta-T Device, Ltd. Cambridge, UK). The system includes two independent sensors: a beam fraction sensor that measures direct and diffuse incident radiation above the canopy and a 1 m linear probe with 64 equidistant calibrated photodiodes which measure the Photosynthetically Active Radiation below the plant canopy. The linear probe was placed in the middle of the potato ridge and at the left and right sides of the ridge. The LAI was calculated using the inverted Beer's law equation based on both simultaneously measured radiation fractions.

The percent of soil cover (canopy coverage) was derived from images obtained with a digital camera Sony DSC-HX400V oriented in a nadir position over the two 1 m long ridges. Images were analyzed using Image J software (Schneider et al. 2012). A macro was developed which imported each image, cropped it to the area of interest, converted the image from Red Green Blue (RGB) color space to Hue Saturation Brightness (HSB) color space, and performed an HSB color threshold, which split the image into the three individual channels (hue, saturation, and brightness components) and applied a predefined threshold to each channel separately, and enabled the export of the results to a spreadsheet file where the percentages were calculated using Microsoft Excel (version 2016). The threshold values for the hue 8-bit single-channel image used were: 20:45 and 50:95 for the dead and green components, respectively. All values, 0:255, were accepted for both the saturation and brightness channels when identifying both dead and green pixels.

All four (height, NDVI, LAI, and percent of soil cover) crop measurements on potato field A were done four times at growth stages (BBCH 52, 75/79, 79/80, and 87), and on potato field C were performed six times at growth stages (BBCH 31, 51, 69, 75, 79, and 81). The measurement dates in tables 1-4 are given as DAP. The measurements of LAI were not performed on field A at 117 DAP due to very intensive plant senescence and on field C at 94 DAP due to the unavailability of the measurement tool. The potatoes were manually harvested at each sampling point at the termination of the crop over an area of 3 m^2 by collecting tubers along 3.33 m and 4 m distances from a row of 0.90 m and 0.75 m width, respectively, on fields A and C.

Statistical Analysis

Relationships between crop characteristics and potato yield were analyzed using correlations and linear regression in Excel software. The yield was predicted for each sampling point based on regression functions, and the residuals as a difference between observed and predicted yield were calculated. The Mean Absolute Error (MAE) and Relative Error (RE) of the potato predicted yield were calculated based on crop characteristics showing the strongest relationship with yield in both locations.

Results and discussion

Variability of potato yield

The average yield on field A was 28.3 t ha^{-1}, and it ranged from 13.8 to 37.5 t ha^{-1} (figure 2) with a coefficient of variance (CV) of 23.1%. On a rainfed field C with lighter soil, the average yield was low at 18.3 t ha^{-1}, and its variability was higher (CV of 37.2%) than on field A, ranging from 6.73 to 31.1 t ha^{-1}. This potato yield variability was mainly associated with ST and topography variability. On field A the lowest yield was obtained in sandy areas prone to water erosion, while on field C, the lowest yields were achieved in areas covered with light soil. The distribution of precipitation in 2019 was not well synchronized with potato growth stages and did not provide a consistent moisture supply during the critical tuber bulking period. Whereas, in 2018, the experiment was located on soil less prone to drought and with supplemental irrigation.

Variability of potato crop characteristics

The crop characteristics measured on fields A and C from the most to the least labor-intensive are crop height, LAI, NDVI, and percent canopy cover. However, regarding the last measurement, additional time had to be dedicated to digital image processing.

Table 1. Variability of potato crop characteristics: NDVI, percent of soil cover, LAI, and crop height (m) within field A during 2018.

DAP	Growth stage (BBCH scale)	NDVI			Percent of soil cover			LAI			Crop height (m)		
		average	range	CV (%)	average	range	CV (%)	average	range	CV (%)	average	range	CV (%)

52	52	0.77	0.69-0.82	5.30	42.8	29.4-56.8	16.4	4.11	2.50-5.40	23.4	0.303	0.243-0.377	12.5
73	75/79	0.79	0.65-0.86	6.74	73.1	44.6-91.4	20.2	5.32	3.37-7.23	22.9	0.417	0.287-0.550	18.7
87	79/80	0.70	0.52-0.79	8.98	70.2	36.0-83.2	17.6	3.80	2.30-5.90	21.4	0.368	0.267-0.457	14.9
117	87	0.20	0.11-0.31	27.2	6.00	0.20-18.8	80.6	NA	NA	NA	0.225	0.125-0.350	35.1

Among the crop characteristics measured on both potato fields, the percent of soil cover and NDVI showed the highest and lowest variability, respectively (tables 1 and 2). The increasing variability of all four crop traits across measurement dates on both fields was related to plant senescence. A direct comparison of the average values of the crop characteristics for fields A and C is challenging because of the different potato varieties grown and a slight shift in measurement growth stages. However, if not considering the former limitation, higher values of the crop characteristics were observed in field A than in C for the two measurements done at almost the same growth stages, namely BBCH 51/52 and 79/80. This was probably because biomass production was water-limited in field C.

Table 2. Variability of potato crop characteristics: NDVI, percent of soil cover, LAI, and crop height (m) within field C during 2019.

DAP	Growth stage (BBCH scale)	NDVI			Percent of soil cover			LAI			Crop height (m)		
		average	range	CV (%)	average	range	CV (%)	average	range	CV (%)	average	range	CV (%)
38	31	0.45	0.29-0.65	18.1	21.0	7.34-34.2	34.6	1.41	0.80-2.08	23.7	0.177	0.130-0.240	15.1
52	51	0.65	0.54-0.73	9.50	62.8	37.5-89.8	23.5	3.16	1.45-4.57	23.0	0.386	0.313-0.467	11.8
66	69	0.58	0.44-0.72	10.1	54.3	26.4-90.4	30.5	2.73	1.83-4.08	23.3	0.397	0.303-0.490	11.9
80	75	0.57	0.44-0.69	13.4	58.5	17.9-88.3	37.0	2.20	1.28-3.18	28.9	0.343	0.200-0.467	16.8
94	79	0.56	0.36-0.73	16.1	39.4	14.5-87.3	56.9	NA	NA	NA	0.291	0.180-0.430	21.0
108	81	0.45	0.34-0.60	16.5	29.8	4.95-70.2	64.3	1.31	0.62-2.13	31.7	0.250	0.177-0.353	22.5

Relationship between potato crop characteristics and yield

Among the different crop characteristics evaluated on field A, crop height had the strongest relationship with potato yield at 2 out of 4 measurement dates (table 3). Most potato plants were dead during the last measurement time, so height measurements were impossible in some cases. However, percent soil cover showed only a slightly lower correlation with yield than crop height. Measurements of any of the four crop characteristics seemed unjustified to be performed as late as BBCH 79 if the percent soil cover is so low (6%) as in field A. On field C) the opposite trend was noted: crop height showed a significant correlation (r=60-0.61) with potato yield but only on 2 out of 5 measurement dates. However, percent soil cover was more strongly correlated with yield (r=0.64-0.81) than LAI (r=0.57-0.79) or NDVI (r=0.51-0.63) (table 4).

Table 3. Correlation coefficient (r) between yield and NDVI, percent of soil cover, LAI, crop height (m), crop height x percent of soil cover, and NDVI x percent of soil cover for field A during 2018.

DAP	Growth stage (BBCH scale)	NDVI	Percent of soil cover	LAI	Crop height (m)	Crop height x percent of soil cover	NDVI x percent of soil cover
52	52	0.27	0.45	0.46	0.44	0.50*	0.41
73	75/79	0.36	0.62*	0.60*	0.73*	0.69*	0.60*
87	79/80	0.58*	0.69*	0.59*	0.74*	0.85*	0.69*
117	87	0.27	0.12	NA	-0.21	0.11	0.12

* – *a critical value of r=0.482 at α=0.05*

Table 4. Correlation coefficient (r) between yield and NDVI, percent of soil cover, LAI, crop height (m), crop height x percent of soil cover, and NDVI x percent of soil cover for field C during 2019.

DAP	Growth stage (BBCH scale)	NDVI	Percent of soil cover	LAI	Crop height (m)	Crop height x percent of soil cover	NDVI x percent of soil cover
38	31	0.40	-0.04	0.19	0.09	0.02	0.11

52	51	0.19	0.40	0.22	0.60*	0.49*	0.41
66	69	0.43	0.71*	0.79*	0.61*	0.75*	0.72*
80	75	0.63*	0.81*	0.76*	0.24	0.74*	0.83*
94	79	0.51*	0.78*	NA	0.01	0.65*	0.79*
108	81	0.42	0.64*	0.57*	-0.05	0.60*	0.66*

** – a critical value of r=0.433 at α=0.05*

Relationship between combined potato crop characteristics and yield

Measuring two or more crop characteristics simultaneously to predict yield makes the procedure more complicated but may increase the yield prediction accuracy. In our case, considering the percent of soil cover along with crop height slightly improved yield prediction accuracy on 3 out of 4 and 2 out of 6 measurement dates on fields A and C, respectively. The fusion of the measurements of NDVI and the percent soil cover has slightly increased the yield prediction accuracy on field C only in comparison to each measurement considered separately. Likewise, the incorporation of spring wheat crop height together with NDVI into a yield prediction algorithm increased the accuracy from R^2 of 0.68 (NDVI vs. yield) to R^2 of 0.73 (NDVI * crop height vs. yield), (personal communication, Walsh (2022). Recently, Li et al. (2020) suggested that crop heights derived from a digital surface model should be incorporated into yield prediction models because they are likely to be more accurate than those manually estimated crop heights from limited sampling. Franceschini et al. (2017) compared ground-based and UAV-mounted spectrometers in organic potato cultivation. The UAV-based estimates of canopy structure, leaf chlorophyll, LAI, and percent soil cover were relatively more accurate than those derived from ground-based measurements.

Estimation of potato yield with the use of percent soil cover

A digital camera for potato canopy cover estimation has been rarely used (Bojacá et al. 2011; Cai et al. 2020). Due to the color characteristics of soils and plants, only the brightness component of the color map is necessary to identify the pixels that corresponded to the crop. The relationship between potato yield and percent soil cover is presented for both potato fields in figure 3. The MAE was very similar for fields A (3.97 t ha^{-1}) and C (3.78 t ha^{-1}). The relative error was higher for field C (20.7%) than for field A (14.1%), as a result of a much lower average yield on field C (18.3 t ha^{-1}) versus field A (28.3 t ha^{-1}).

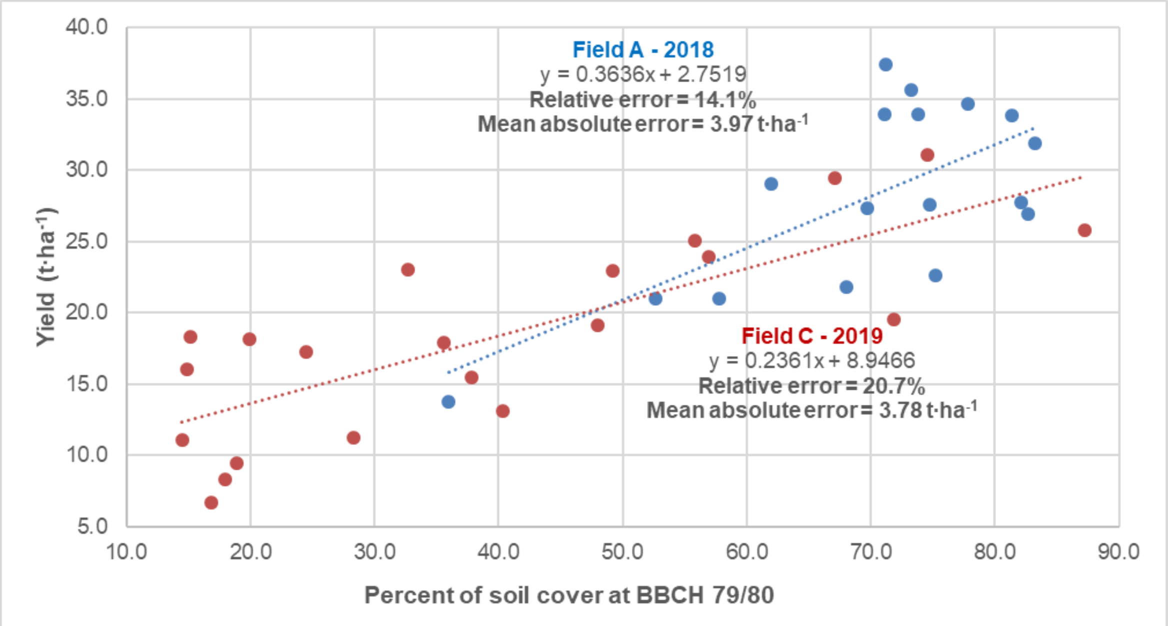

Fig. 3 The relationship between potato yield (t ha^{-1}) and percent of soil cover derived from RGB images taken by a digital Sony DSC-HX400V camera at growth stage BBCH 79/80 within fields A and C

A closer look at RGB images where yield was estimated with the highest error (figures 4 and 5) using the percent of soil cover revealed that overestimation of yields could be caused by stress that did not allow translocation of the sugars produced in the leaf down to the developing tubers.

Fig. 4 Images of a crop measurement area within field A, left) plot no 15 (75.2% of soil coverage), yield overestimated by 7.48 t ha^{-1}, right) plot no 10 (71.1% of soil coverage), yield underestimated by 5.38 t ha^{-1}

On the other hand, underestimation of the yield can result from potato vines bending on the neighboring rows or between them in furrows, thus decreasing the percentage of soil covered by crops.

Fig. 5 Images of a crop measurement area within field C, left) plot no 10 (71.8% of soil coverage), yield overestimated by 6.34 t·ha^{-1}, right) plot no 21 (32.7% of soil coverage), yield underestimated by 6.40 t·ha^{-1}

Summary

Among the manually and remotely measured potato crop characteristics, the percent of soil cover showed the strongest relationship with yield in two commercial potato fields. The mean absolute errors for fields A and C were 3.97 and 3.78 (t ha^{-1}). The relative error was higher for field C (20.7%) than for field A (14.1%), as a result of a much lower average yield on field C versus field A. Overestimation of yields could have been caused by stress. Underestimation of the yield can result from potato vines bending on the neighboring rows or between them in furrows, thus decreasing the canopy coverage.

Acknowledgments

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