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GETTING DOWN TO THE PLANT LEVEL: POTATO TRIALS ANALYSIS USING A UAV EQUIPPED WITH UN-MODIFIED AND MODIFIED COMMERCIAL OFF-THE-SHELF DIGITAL CAMERAS

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Summary: In recent years unmanned aerial vehicles (UAV) have become much easier to obtain and operate, and due to the aerial viewpoint they provide can be useful tools to enhance agricultural research. This paper investigates the use of UAVs equipped with commercial off the shelf (COTS) digital cameras, to determine if aerial imagery can give detailed information at the plot and plant level that is comparable to traditional ground based methods. A potato (*Solanum tuberosum L.*) trial was monitored over the 2016 growing season, with the performance of the trial being recorded using traditional ground based methods, and from the air using automatic analysis methods. The results indicate that very early emergence cannot be detected from the air, but that later counts of individual plants show correlation between methods. In contrast, ground cover estimates between methods correlate strongly and may prove to be a more robust monitoring method.

INTRODUCTION

Unmanned aerial vehicles are increasingly being used to monitor a large variety of crops (Zhang & Kovacs, 2012) including potatoes, where they have been used to assess damage (Zhou *et al.* 2016) and disease (Suigiura *et al.* 2016). Recently some studies have targeted emergence and establishment of both field crops (Gnädinger & Schmidhalter, 2017) and row crops (Sankaran *et al.*, 2017), indicating that it may be possible to monitor at the plant rather than plot level. For commercial growers of potato seed and ware crops, being able to accurately identify when plants have emerged and track their individual growth throughout their lifecycle could lead to more informed yield prediction, as well allowing identification of the source and spread of disease (Gibson-Poole *et al.*, 2017). For potato trials, being able to add more detail to existing recording methods will likely enhance the quality and efficiency of monitoring and may reveal new measures that could be used to make predictions. The aim of this paper is to investigate methods of collecting and analysing aerial data to enable the condition of individual plants to be monitored throughout their growing cycle, and compare these results with existing ground based methods.

MATERIALS AND METHODS

The trial plots used for this experiment were located to the east of Dundee, Scotland and were part of a series of trials investigating the effects of different treatments in a field system containing a high egg load of potato cyst nematodes. As this paper is investigating the differences between ground based and aerial based observations, the actual treatments and differences in their effectiveness are not directly reported on. The trial was composed of 48 plots, containing two beds (four rows in total, the outside two being guard rows) with 21 tubers per row. All of the plots were planted on the 11/05/2016 and split into two varieties, 24 of Harmony and 24 of Maris Piper. Tubers were planted using a customised planter with an expected spacing of 25 cm and a drill width of 0.865 m.

Manual methodology

Two sets of manual data were acquired by an experienced observer to record potato development. Emergence counts were conducted at 19, 23, 30, 33 and 37 days after planting (DAP), with emerged plants being estimated by grouping closely located emerged shoots. Only the central two rows of each plot were counted (guard rows were ignored), added together and if equalling 21 or higher, then the 50% emergence DAP would be set for that plot. Ground cover assessments were conducted at 54, 61 and 89 DAP with percentage of potato leaf ground cover being estimated using a hand-held grid of 100 equal sized squares to view the central two rows (aligned to the trough-centres on outside of the rows), whilst ignoring the row-end plants.

Aerial methodology

Aerial data was acquired using two different aircraft and two different sets of sensors, with data acquired at 16, 22, 27, 33, 41, 46, 54, 61, 69 and 79 DAP. Nine sets of data were collected using a custom multi multi-rotor UAV (UAV1) equipped with a dual camera system capturing raw imagery, with one un-modified camera acquiring true colour imagery (RGB) and one modified to detect near infra-red (NIR) wavelengths (Gibson-Poole *et al.* 2017). The data acquired at 54 DAP was collected using a 3D Robotics Solo (3D Robotics, Berkeley, CA, USA) quadcopter UAV (UAV2) equipped with a single Canon ELPH 115 IS (Canon, Tokyo, Japan) capturing RGB imagery in JPEG (joint photographic experts group) format. Both UAVs used pre-programmed automatic flights at 35 m above ground level to capture imagery at ~1 cm per pixel ground sample distance, with an expected image overlap of 60% and side overlap of 87% for UAV1 but only ~60% total overlap for UAV2 as its camera was set to take a picture every 2 seconds. All datasets were captured with a photographic grey card placed within the scene surveyed to aid in image normalisation and 11 ground control points (GCP) to aid in georectification. The GCPs were surveyed using a Piksi (Swift Navigation, San Francisco, USA) real-time kinematic global navigation satellite system (GNSS), with an expected accuracy of ±13 cm.

Image Processing

The raw images from UAV1 were geotagged and processed into 16 bit linear TIFFs (tagged image file format) using the same method as Gibson-Poole *et al.* (2017), whereas the images from UAV2 were simply geotagged with no extra processing. All of the datasets were then processed using Agisoft Photoscan (v1.2.5; Agisoft LLC, St. Petersburg, Russia), using high settings with mild depth filtering to produce a georeferenced orthomosaic for each dataset (RGB and NIR) plus a digital surface model (DSM). The method indicated by Troscianko & Stevens (2015) was used to normalise the RGB and NIR orthomsaics, by using the average pixel values of the photographic grey cards placed within the scene of each survey.

Emergence analysis

Two automatic methods were employed, with the first (AUTO1) following that of Gibson-Poole *et al.* (2017), and the second (AUTO2) being a modification to make it more robust with regards to the spacing of tubers within each row and the high level of weeds present. Both methods required manual thresholding of the data in order to separate soil from vegetation for each survey date.

This was achieved by using the normalised difference vegetation index (NDVI; Rouse *et al.* 1974), however as UAV2 was not equipped to capture NIR data the vegetation threshold was manually set by using the excess green minus excess red index in a similar manner to Meyer & Neto (2008). Five plots from each variety were also randomly selected for direct visual analysis (VIS) of the aerial imagery, with the same field observer stepping through each survey date counting what they believed were emerged plants per date (they could look backwards but not forwards in time from the date they were currently assessing).

Ground cover analysis

The processed data for each survey date was classified using the object based image analysis (OBIA) software eCognition Developer (v9.2.1, Trimble, Munich, Germany) into five classes, potato, potato flowers, weeds, soil and shadow following a similar method to Gibson-Poole *et al.* (2017) but with modifications using fuzzy logic to separate vegetation into weeds or potatoes.

RESULTS

Statistical analysis was carried out using Microsoft Excel (Microsoft, Redmond, WA, USA) to calculate the Pearson correlation coefficients (*r*) and probability values (*p*).

Emergence

The manual data revealed that all Maris Piper plots had reached 50% emergence by 23 DAP and all Harmony plots by 30 DAP. AUTO1 and AUTO2 reached the same level by 27 DAP and 41 DAP respectively, indicating that the automatic methods may not be as sensitive as the manual method in detecting emergence. In general, the manual method detects more emerged plants earlier than any of the other methods. Both ground and aerial surveys were conducted at 33 DAP so direct comparisons could be made (Table 1). For the Maris Piper plots, the AUTO1 and AUTO2 methods showed a significant moderate correlation whilst the VIS method showed a significant strong correlation with the manually acquired data. However, for all methods, no significant correlation was achieved for the later emerging Harmony plots. The automatic and visual methods indicated that all plants had emerged by 54 DAP, however final plant counts were not recorded manually so this could not be directly compared.

Table 1. Correlation analysis between manual emerged plant counts and the three analysis methods at 33 DAP (*r* correlation coefficient, *i* intercept, *s* slope, *p* probability, *n* number of pairs, *Not significant at α = 0.05).

Method	Variety	*r*	*s*	*i*	*n*	*p*
AUTO1	Maris Piper	0.43	0.18 ± 0.08	34.86 ± 3.02	24	0.0373
	Harmony	0.29*	0.09 ± 0.07	37.67 ± 1.56	24	0.1673
	Combined	0.52	0.11 ± 0.02	37.31 ± 0.85	48	0.0002
AUTO2	Maris Piper	0.47	0.27 ± 0.11	30.72 ± 4.38	24	0.0215
	Harmony	0.29*	0.09 ± 0.06	37.70 ± 1.53	24	0.1621
	Combined	0.52	0.10 ± 0.02	37.41 ± 0.83	48	0.0002
VIS	Maris Piper	0.94	0.63 ± 0.13	16.11 ± 5.16	5	0.0156
	Harmony	0.07*	-0.04 ± 0.33	39.31 ± 11.37	5	0.9147
	Combined	0.50*	0.29 ± 0.18	28.95 ± 6.80	10	0.1436

Ground cover

Direct comparison of potato leaf ground cover could be made for 54 and 61 DAP, with the manual method reporting a larger percentage of potato leaf ground cover in general however both dates showed a strong positive correlation for both varieties (Table 2) that were also highly significant.

Table 2. Correlation analysis results between the manual and automatic analysis of potato leaf ground cover (*r* correlation coefficient, *i* intercept, *s* slope, *p* probability, *n* number of pairs.

DAP	Variety	*r*	*i*	*s*	*n*	*p*
54	Maris Piper	0.81	12.64 ± 7.09	0.99 ± 0.15	24	< 0.0001
	Harmony	0.75	12.59 ± 7.39	1.32 ± 0.24	24	< 0.0001
	Combined	0.73	23.71 ± 4.44	0.82 ± 0.11	48	< 0.0001
61	Maris Piper	0.82	14.09 ± 9.12	0.90 ± 0.14	24	< 0.0001
	Harmony	0.66	27.15 ± 7.60	0.69 ± 0.16	24	0.0004
	Combined	0.80	22.60 ± 4.90	0.78 ± 0.09	48	< 0.0001

DISCUSSION

From the emergence results it is clear that the resolution of the aerial imagery is not sufficient to be able to detect emerging shoots until they had started to develop some leaves (i.e. a leaf area > 1 cm^2), hence why the Maris Piper plots showed significant correlation compared to the Harmony plots, as the Maris Piper emerged earlier and were therefore large enough to be detected by the automatic methods. As the 50% emergence measure can be used to allow prediction of tuber initiation (O'Brien *et al.*, 1998), being able to detect this from the air would be advantageous, so increasing resolution by flying lower or using a different sensor could help solve this, although this could lead to increased flight times and the time taken to post process the imagery produced.

The resolution should have been sufficient to get accurate plant counts but was hampered by irregular tuber spacing due to tubers rolling during the planting operation, resulting in a reduction of plants counted due to the closer proximity of emerging shoots and early merging of canopies, which in turn lead to irregular sized plant growth spaces (Figure 1d). AUTO1 consistently produced lower plant counts as it was not robust enough to handle the irregularity and although this improved with AUTO2 the final plant counts per plot was still generally lower than the expected amount. Including plant sizing as another parameter in the automatic method as Sankaran *et al.* (2017) have shown, or making more use of height data could improve this, as would ensuring that the planting itself was more regular in the first place as tuber spacing (and weed control) are factors important to the development of the crop (Bussan *et al.*, 2007). The emergence of weeds (Figure 1a) to a very high level by the end of the trial (100% weed coverage for some plots towards the end of the growing season), resulted in an increase in false positive results (mainly for the later emerging Harmony plots), an issue that Gnädinger & Schmidhalter (2017) also commented on when trying to count maize plants. Even the direct visual analysis of some plots resulted in weeds being misinterpreted as emerged plants.

Aerial ground cover analysis initially looked poor when the raw numbers were compared as the manual method reported much higher ground cover in general. However, the two methods correlated well and further investigation into the manual method revealed why the raw numbers may have differed so much. Due to the perspective that the observer has when looking at a plot on the ground using a grid, a considerably smaller area of the plot is in fact viewed. This resulted in only ~1.65 m wide and ~1.2 m long area of the plot being measured for ground cover with more of it being obscured if some of the plants are tall. The manual method is a fast and efficient measure however the aerial approach could give a more representative measure as it is observing the entire plot and the spaces between the rows. The very high level of weeds within the rows and canopy of the potato plants made classification more difficult (Figure 1c), likely resulting in error being introduced. However, the accuracy of the classification was not directly verified in this paper, it was only compared to the ground truth results.

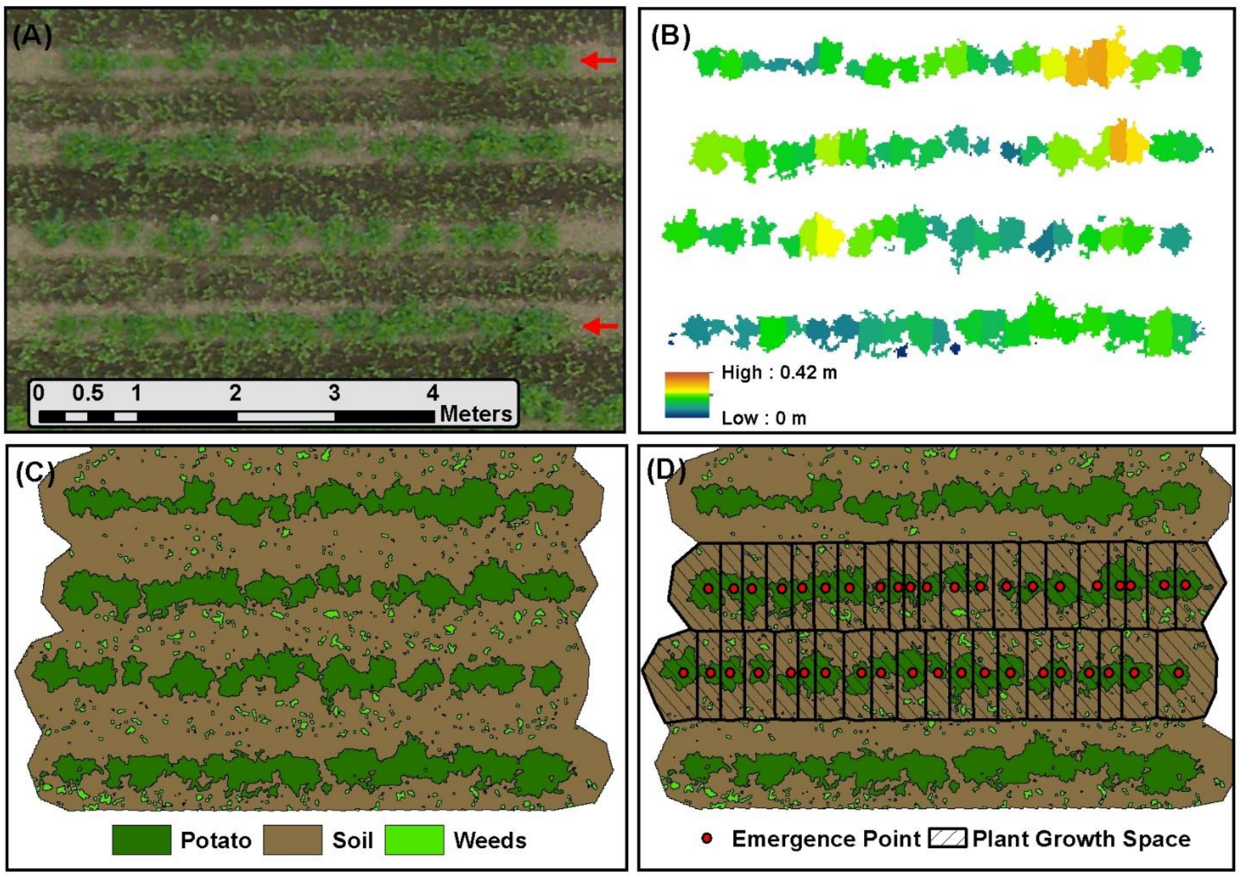

Figure 1. Example plot results at 41 DAP; (A) RGB where weeds can already be seen between rows, showing guard rows (red arrows); (B) Mean height of individual plants; (C) Classification of plot; (D) Detected emerged plant points and growth spaces allocated to each plant.

Using aerial data allows measurements of all aspects of the trial from the same survey effort. Being able to view and analyse the trial as individual plants rather than just plots or rows could allow more detailed analysis of trial development and issues. As the photogrammetry process produces high resolution DSM as well as orthomosiac data, the ability to measure the height of the plants surveyed is also possible (Figure 1b) and would further add to trial analysis as plant height has input in predicting yield (Arslan, 2007). Producing accurate height data can be an issue once the crop reaches a stage of complete canopy closure as the ground level cannot be seen. The use of highly accurate GNSS systems onboard the UAV could help with this respect, would negate the need to use GCPs and likely help with other issues encountered in this trial with regards to slight shifts in the georeferenced position of orthomosaic data between survey dates and possibly reduce misalignment when co-registering the RGB and NIR layers.

To conclude, as small UAVs can only really be used in good weather conditions (i.e. not raining and wind speeds < 8 m/s to ensure safe operation), they are unlikely to replace traditional ground based methods completely, but the results of this study indicate that aerial data would complement existing methods and give a wider coverage of measures that would benefit trials monitoring and analysis in the future.

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