Final Scientific Report

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Project Title:

Fusion of Hyperspectral and Thermal Images for Evaluating Nitrogen and Water Status in Potato Fields for Variable Rate Application

Investigators	**Institutions**
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with substantial assistance of: Ronit Rud (ARO) and Tyler Nigon (UOM)

Keywords Crop water stress index, Stomatal conductance, spectral indices, Normalized difference index 2, nitrogen sufficiency index, partial least square, N concentrations

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Abbreviations <u>commonly</u> used in the report, in alphabetical order**:**

AR – Alpine Russet

AWRS - Artificial Wet Reference Surface

CWSI - Crop water stress index

- CWSIe – Empirical CWSI
- CWSIs – Statistical CWSI
- CWSIt – Theoretical CWSI

DAE – Days after Emergence

DAP - Days after Planting

HS - Hyperspectral

M – Maturity

N - Nitrogen

NDI2 - Normalized Difference Index 2

NSI - Nitrogen Sufficiency Index

PLS – Partial Least Square

RB- Russet Burbank

SC - Stomatal Conductance

TB – Tuber bulking

Tl – Canopy temperature

Twet, Tdry - the referenced minimum and maximum baseline temperatures, respectively

VIS-(N)NIR - visible and (near) near infrared

WI – Water Index

Budget: IS: $ 162,000 US: $ 163,000 Total: $ 325,000

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Signature
Principal Investigator

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Abstract

Potato yield and quality are highly dependent on an adequate supply of nitrogen and water. Opportunities exist to use airborne hyperspectral (HS) remote sensing for the detection of spatial variation in N status of the crop to allow more targeted N applications. Thermal remote sensing has the potential to identify spatial variations in crop water status to allow better irrigation management and eventually precision irrigation.

The overall objective of this study was to examine the ability of HS imagery in the visible and near infrared spectrum (VIS-NIR) and thermal imagery to distinguish between water and N status in potato fields.

To lay the basis for achieving the research objectives, experiments in the US and in Israel were conducted in potato with different irrigation and N-application amounts. Thermal indices based merely on thermal images were found sensitive to water status in both Israel and the US in three potato varieties. Spectral indices based on HS images were found suitable to detect N stress accurately and reliably while partial least squares (PLS) analysis of spectral data was more sensitive to N levels. Initial fusion of HS and thermal images showed the potential of detecting both N stress and water stress and even to differentiate between them. This study is one of the first attempts at fusing HS and thermal imagery to detect N and water stress and to estimate N and water levels. Future research is needed to refine these techniques for use in precision agriculture applications.

Main Achievements

Thermal indices (CWSI, canopy temperature) based on thermal images were found sensitive to water status in both Israel and the US in the three potato varieties. Spectral indices based on HS images were found suitable to accurately and reliably detect N stress while PLS analysis of spectral data was more sensitive to N levels. Initial fusion of HS and thermal images showed the potential of detecting both N stress and water stress. This study is one of the first attempts at fusing HS and thermal imagery to detect N and water stress and to estimate N and water levels.

General description of the research activity and achievements[1]

The overall objective of this study was to examine the ability of HS imagery in the visible and near infrared spectrum (VIS-NIR) and thermal imagery to distinguish between water and N status in potato fields. Three specific objectives were defined: 1) Develop improved methodology to combine high-resolution images in the visible range with thermal imagery to evaluate water status of potato plants; 2) Investigate and characterize the ability of spectral data and imagery to evaluate N level and water status of potato plants under combined stress; 3) Develop a method to optimally fuse HS aerial images in the VIS-NIR with thermal imagery to evaluate and map water and N status in potato fields. To lay the basis for achieving the research objectives, experiments in the 1st and 2nd years in the US and in the 2nd and 3rd years in Israel were conducted in potato with different irrigation and N-application amounts (Table 1-2). The description of the achievements is divided into three parts according to the specific objectives.

Table 1 N application and irrigation rates in two-factor experiments[1] - Minnesota, USA, 2010-11

N Fertilizer Management Strategy and rates						
		Timing of Application				
	Label	Planting† (kg ha^{-1})	Emergence†	Post-Emergence†	Total N†
1	Starter Only (control)	34	0	0	34
2	180 N split	34	78	17	180
3	270 N split	34	124	28 (*4)	270
4	270 N split (+ surfactant)	34	124	28 (*4)	270
5	270 N early	34	124	112	270
Irrigation rates (sprinklers)					
1	Non-stressed	100%			
2	stressed	80% (89% and 81% in 2010 and in 2011 respectively taking into account irrigation + rainfall)			

[1] Each combination of irrigation and N application rates had four replications in two potato varieties; † kg ha^{-1}

Table 2 N application and irrigation rates in two-factor experiments[2] - Israel, 2011-12

N rates (slow release) (kg ha^{-1})	
1	280 + 3 pre-season
2	200 + 3 pre-season
3	140 + 3 pre-season
4	0 (1 replication only in 2012) + 3 pre-season
Irrigation rates in the main irrigation period (drip irrigation)	
1	100%
2	70%
3	50%

[2] Each combination of irrigation and N application rates had 3 replications.

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[1] A detailed report can be found at http://www.agri.gov.il/download/files/ThirdYearReport_TIR_HS_Potato_v4_3.pdf

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Part 1: Develop improved methodology to analyze thermal imagery to evaluate water status of potato plants (Israel).

Highlights In this part of the research we showed that instead of using a complex procedure that fuse images in the thermal and the visible ranges, the thermal image can be used alone for reliable extraction of CWSI. For this we proposed the theoretical and the statistical (virtual) wet references. Together with their accuracy and reliability, these methodologies are much simpler than the initially proposed method (as presented in the proposal). The results indicate for the possibility to manage irrigation using aerial based CWSI mapping.

A 3-year field experiment was conducted in spring growing seasons (February to June) in commercial potato fields (*Solanum tuberosum* L. cv. Desiree) in a semi-arid zone, Israel. Field campaigns were conducted 4-5 times throughout the season every 7-10 days, between 1130 to 1430 h. Two scenarios of water deficit were tested: a short-term water deficit, and a long-term cumulative water deficit. Plant and soil water status were determined by measuring leaf water potential (LWP), leaf osmotic potential (LOP), stomatal conductance (SC), and gravimetric water content (GWC), calculated as water percentage in a bulk of soil sampled at depths of 0–0.2, 0.2–0.4 and 0.4–0.6 m. Among the biophysical measure-ments, SC and GWC were the best at distinguishing between irrigation treatments. Images were acquired in the thermal and VIS ranges from ground and air. For ground images pure canopy pixels were selected using images in the VIS range (vegetation index). For aerial images extraction of canopy pixels was conducted based merely on thermal images following the methodology suggested by Meron et al. (2010). For calculating crop water stress index (CWSI), *Tdry* was used in its empirical form, *Tair* + 7ºC while 3 forms of *Twet* were examined: empirical (CWSIe), theoretical (CWSIt) and statistical (CWSIs). High correlation values obtained between CWSI values and SC in all three seasons. The analysis of the different types of CWSI indicated that the *Twet* can be estimated based either on theoretical and statistical calculations. CWSI values were quite stable, suggesting the feasibility of implementing this method for irrigation management even along a transition season in which changing meteorological conditions exist. As a spatial plant-based water status measure the CWSI may improve irrigation management, detect irrigation malfunctions and reduce irrigation amounts. Nevertheless, the usefulness of CWSI as a water status indicator in potato crops should be examined in relation to tuber yields. This is an essential stage in the use of the CWSI for irrigation management in commercial fields.

Part 2: Investigate and characterize the ability of spectral data and imagery to evaluate N level and water status of potato plants under combined stress (US).

Highlights The results from this research suggest that canopy-level spectral reflectance data obtained from aerial or ground imagery provides reliably estimation of N concentration in potato. The best results were obtained using the PLS and the best index was found to be NDI2. No significant effect was found between spectral data (in the VIS-NNIR) range and water levels.

Field experiments were conducted over two years (2010-2011) at the University of Minnesota Sand Plain Research Farm near Becker. The study included two potato varieties (Russet Burbank and Alpine Russet), two irrigation regimes (unstressed (100%) and stressed (~80%)), and five N treatments (Table 1). In-season field ground based measurements were collected on 4-5 dates along the season, and included: tissue samples; chlorophyll meter readings; and multispectral reflectance. Two aerial HS and thermal images were captured in 2010 and two in 2011. In 2011, aerial multispectral imagery was also acquired above the treatment plots and a commercial potato field. Reflectance data in various modes were used in a preliminary analysis to determine the wavelengths and/or indices that had the best overall ability to detect N stress. Partial least squares regression (PLS) models were constructed across image dates. The best predictor of N stress was determined to be the PLS regression model using derivative reflectance as input for its independent variables (r^2 of 0.77-0.79). Normalized different Index 2 (NDI2) performed best among the narrowband indices over all dates, and Normalized green index (NG) performed best among the broadband indices over all dates. While imagery correlated well with conventional N measurements, the use of a nitrogen sufficiency index (NSI) was used to normalize the data collected. Based on the NSI approach, the best technique for determining N stress level for variable rate application of N fertilizer was determined to be MTCI (MERIS Terrestrial Chlorophyll Index) because the combination of its good relationship with leaf N concentration and high accuracy. Because of differences in sensors, potato variety, growth stage, or other local conditions, reference areas with an adequate amount of N are needed in order to make accurate recommendations about N status of the crop. Selection of a reference N rate for the potato crop, however, is challenging because too much N applied can reduce yield. The N rate selected for an N sufficiency reference should be based on local N response data based on previous research.

Part 3: Develop a method to optimally fuse HS aerial images in the VIS-NIR with thermal imagery to evaluate and map water and N status in potato fields.

Highlights Spectral data based on HS images were significantly affected by N levels but unexpectedly insignificantly affected by irrigation treatments. Canopy temperature was more affected by irrigation treatments and in one case also by N levels. A two-step threshold-based classification procedure was conducted using fused data from HS and thermal images. The fused data detected N stress and differentiated between N stress with water stress and without water stress. N sufficient and excess levels were not differentiated.

In general, this objective was partially addressed in this study since the two-factor experiments did not obtained the expected ranges in water status and in N levels in all cases and because of technical problems that did not enable all measurements that were needed for such analysis.

In the proposal we proposed a methodology which was based on the assumption that spectral data in the VIS and near NIR range (400-900 nm) are affected by both N levels and water status and that canopy temperature is not affected by N levels. The effect of water status on spectral data from the HS images was examined through NDI2 and water band index (WI). The effect of N level on canopy temperature was examined using the canopy temperature extracted from the thermal images following soil pixels extraction. The results rejected the assumption and an alternative methodology was used for fusing HS and thermal images. The leaf nitrogen concentration was divided into three levels 1) Low N level (stress) - below 3.5% (35 g kg^{-1}); 2) Sufficient N - between 3.5 to 4.5%; 3) High N level (excess) – above 4.5%. Each replicate was classified according to its N concentration mean. The replicates were further divided merely by the irrigation treatment. According to a visual analysis of NDI2 histograms thresholds were set to differentiate between N levels. Similarly, canopy temperature threshold was set to differentiate between the two water statuses. The NDI2 and the thermal images were divided using the threshold and a fused image was created in which each pixel was classified into 6 classes (3 N levels X 2 irrigation treatments). In 2010, NDI2 and WI from both dates and varieties was affected by N treatments but was not affected by water status. In comparison, canopy temperature was more affected by irrigation treatments than by N treatments. Overall classification accuracies obtained were 83% and 65% for AR and RB, respectively. N stress with water stress was clearly differentiated from N stress with no water stress. This result could not be obtained without the fusion of HS and thermal images.

Future Research

- Because canopy-level spectral indices/models acquired with aerial or ground based imagery were able to distinguish between the N treatments better than traditional measurements of N status (such as petiole NO_3-N and leaf N concentration) future studies should evaluate in more detail the comparison of spectral data with biomass measurements such as the Nitrogen Nutrition Index (NNI).

- One of the limitations of the present study was the cost of acquiring aerial images. Identifying a more economical means of acquiring spectral imagery should be considered. This might include the use of lightweight cameras and GPS instruments in unmanned aerial vehicles (UAVs). The capabilities of UAVs have improved substantially over the past 2-3 years. With these improvements, the ability to obtain spectral data at frequent intervals through the growing season and at a reasonable cost may now be feasible for applications in precision agriculture

- Canopy-level CWSI acquired with aerial or ground based imagery were good predictors of tuber yield and sometimes better than traditional plant measurements of water status (such as stomatal conductance). Future studies should concentrate on CWSI threshold determination for irrigation management. In addition, CWSI-based irrigation management should be compared with conventional approaches.

- The best indices identified in this study should be verified over a wider range of N rates. In addition, a treatment in which in-season N applications are based on real-time thresholds using an NSI should be evaluated.

Description of Cooperation

The collaboration between the two groups was accomplished in several ways:

Date transfer: A combined multi-year database of data from the experiments of the two groups was characterized and built during the visit of Ronit Rud in the UOM and the visit of the US group in Israel. In this way each group used the combined data for manipulations and analysis. This database can be used for further analysis. E.g. the thermal and HS images from the UOM experiments were transferred to- and analyzed by the Israeli group (Objective 3). The analysis was enabled only due to the structured database.

Methodology transfer:

- In her visit Ronit Rud introduced the use of ENVI software to Tyler Nigon for HS image analysis. Also, the PLS analysis was introduced by the Israeli group and conducted by the UOM group.
- The Decagon porometer was purchased by the UOM group to collect water status data for thermal images analysis. It was encouraged by the Israeli group. Unfortunately the tool was found unstable and the data could not be used.
- The NDI2 and the NSI was introduced by the UOM group and was used by the Israeli group to analyze HS images for N levels estimation. Unfortunately no differences were obtained between N levels in the Israeli experiments. Yet, this methodology was used to analyze Israeli archive HS images form a previous study (data not shown).

The two groups published four papers together, 2 in Precision agriculture journal and 2 in peer reviewed proceedings. Two additional papers of the two groups together are going to be submitted to the PA journal.

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	1	1		2
Longer Visits (Sabbaticals)				

List of Publications

1. Nigon, T., C. Rosen, D. Mulla, Y. Cohen, V. Alchanatis and R. Rud. 2012. Hyperspectral imagery for the detection of nitrogen stress in potato for in-season management. In: (R. Khosla, ed.) Proc. 11th Int'l Conf. Precision Ag. Ft. Collins, CO.
2. Rud, R., Y. Cohen, V. Alchanatis, Z. Dar, A. Levi, R. Brikman, C. Shenderey, B. Heuer, H. Lemcoff, T. Markovits, D. Mulla, C. Rosen. 2012. Evaluating water status in potato fields using combined information from RGB and thermal aerial images. In: (R. Khosla, ed.) Proc. 11th Int'l Conf. Precision Ag. Ft. Collins, CO.
3. Mulla, D. J. 2013. Twenty Five Years of Remote Sensing in Precision Agriculture: Key Advances and Remaining Knowledge Gaps. Biosystems Engineering. 114 (4): 358–371. (invited)
4. Rud, R., Y. Cohen, V. Alchanatis, Z. Dar, A. Levi, R. Brikman, C. Shenderey, B. Heuer, T. Markovits, D. Mulla, C. Rosen. 2013. The potential of CWSI based on thermal imagery for in-season irrigation management in potato fields. In: (J. Stafford, ed.) Proc. 9th Euro. Precision Ag. Conf. Leide, Spain.
5. Nigon, T. J., D. J. Mulla, C. J. Rosen, Y. Cohen, V. Alchanatis, and R. Rud. Evaluation of the nitrogen sufficiency index for use with high resolution, broadband aerial imagery in a commercial potato field. Prec. Ag. Online 10.1007/s11119-013-9333-6
6. R. Rud, Cohen, Y., V. Alchanatis, M. Sprintsin, A. Levi and R. Brikman, B. Heuer, H. Lemcoff and T. Markovits, Z. Dar, 2012. Evaluating water status in potato fields using thermal images. Sade Ve'Yarak, 247: 38-42 (invited) *(Hebrew)*
7. Rud, R., Y. Cohen, V. Alchanatis, Z. Dar, A. Levi, R. Brikman, C. Shenderey, B. Heuer, H. Lemcoff, T. Markovits, D. Mulla, C. Rosen, T. Nigon. Crop water stress index based on ground and aerial thermal images as an indicator of potato water status: a three year study. Submitted to Prec. Ag. (re-submitted after major revision)
8. Nigon, T., D. Mulla, C. Rosen, J. Knight, Y. Cohen, V. Alchanatis, and R. Rud. Hyperspectral imagery for detecting nitrogen stress in two potato varieties. Rejected Remote Sensing Environ. – will resubmit to Precision Agriculture.
9. Nigon, T., C. Rosen and D. Mulla. Plant-based approaches for tracking the N status of two potato varieties throughout the season. In preparation.
10. Nigon, T., C. Rosen and D. Mulla. Irrigation and nitrogen management effects on potato nitrogen use indices and tuber yield and quality. In preparation.
11. Rud, R., Y. Cohen, V. Alchanatis, Z. Dar, D. Mulla, C. Rosen. The potential of CWSI based on thermal imagery for in-season irrigation management in potato fields. In preparation

Thesis

Nigon, T.J. (2012). Aerial imagery and other non-invasive approaches to detect nitrogen and water stress in a potato crop. Master's thesis. University of Minnesota Digital Conservancy, http://purl.umn.edu/143695.

Additional Presentations (abstracts)

Nigon, T., C. Rosen, D. Mulla, Y. Cohen, and V. Alchanatis. Fusion of hyperspectral and thermal imagery for evaluating nitrogen and water status in potato (Solanum tuberosum, L.) for variable rate application. Annual Meeting of Soil Science Society of America. San Antonio, TX. Oct. 18, 2011.

Nigon, T., C. Rosen and D. Mulla. Plant-based approaches for in-season detection of nitrogen stress in potato. Annual Meeting of Soil Science Society of America. Cincinnati, OH. Oct. 24, 2012.

The Israeli group was invited to present the results of the experiments presented in Israel in the annual report day of potato research in 2011 and 2012.

Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted) BARD support acknowledged	1			1
Submitted, in review, in preparation	3	2		5
Invited review papers		1		1
Book chapters				
Books				
Master theses	1			1
Ph.D. theses				
Abstracts	1	1	3	4
Refereed proceedings	1			1
Not refereed (proceedings, reports, etc.)	2		1	3

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