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

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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

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

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.

Introduction

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.

Objectives

The overall objective of this study was to examine the ability of HS imagery in the visible and NIR 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.

Main experiments

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 summarize N application and irrigation rates in two factor-experiments conducted in the US and in Israel, respectively.

The report was divided into three parts according to the 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 (kg ha^{-1})	Post-Emergence (kg ha^{-1})	Total N (kg ha^{-1})
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.

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.

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 research proposal).

Materials and methods

Study site and experimental setup

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 at Kibbutz Ruhama, Israel (31.38º N, 34.59º E). The site is characterized by a soil classified as Loessial arid brown and annual average precipitation of 300 mm. Field campaigns were conducted four or five times throughout the season every 7 to 10 days, between 1130 to 1430 h. Table 3 summarizes the plant and soil measurements conducted during the research period.

Two scenarios of water deficit were tested: a short-term water deficit, and a long-term cumulative water deficit. In 2010, short-term water deficit was induced by suppressing irrigation for 0 (non-stressed), 2, 4, 6 and 8 days before the field campaign. Each treatment was replicated four times. Each replicate was 6 m wide (six rows) by 20 m long. In 2011 and 2012, cumulative water deficit was induced by applying 50%, 70% and 100% of the nominal water application used for conventional irrigation in adjacent commercial fields. Conventional irrigation was determined according to pan-evaporation rates measured during the growing season. Each irrigation treatment was replicated three times, and replicates were 18 m wide (18 rows) by 60 and 34 m long in 2011 and 2012, respectively. Each replicate was divided into three nitrogen treatments as described in Table 2. According to the objective, however, this section focuses on evaluating water status using thermal imaging regardless of the nitrogen treatments. Ignoring nitrogen treatments was done because no significant differences were found between nitrogen treatments in both seasons (data not shown; refer to part 3 of the report for more details).

Drip irrigation was used from planting to approximately 120 days after planting (DAP). Thereafter, overhead irrigation was used to keep the soil temperature low and to enable adequate tuber skin formation. Irrigation treatments (long term and short term water deficit) were applied starting two weeks before the first measurement campaign. Before that, all experimental plots were treated identically.

Table 3 Data collection for plant and soil water status

	2010				2011					2012				
Date	Mar. 25	Apr. 11	Apr. 21	May 5	Apr. 10	Apr. 17	Apr. 28	May 5	May 19	Apr. 4	Apr. 16	Apr. 24	May 3	May 10
Days after planting	49	66	76	90	52	59	70	77	91	55	66	75	84	91
Phenological stage[a]	V	TI	TB	M	V	TI	TB	TB	M	V	TI	TB	TB	M
Soil water content	✓	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
Leaf osmotic potential	✓	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
Leaf water potential	✓	✓	×	✓	✓	✓	×	✓	✓	×	×	×	×	×
Stomatal conductance	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓
Ground thermal imaging	✓	✓	×	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓
Aerial thermal imaging	×	×	×	×	×	×	×	✓	✓	×	✓[b]	✓[b]	✓[b]	×
Meteorological conditions	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[a] V- vegetative stage, TI-tuber initialization, TB-Tuber bulking, M-maturity; [b]2012 aerial data were not analyzed. Ground imaging included RGB images as well.

Water status evaluation

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. Soil samples were weighed before and after drying in an oven at 105 °C. In 2010. In 2010, SC was measured with a Decagon SC-1 leaf porometer (Decagon Devices, Pullman, WA , USA), and in 2011 and 2012 with a LI-COR® 1600 leaf porometer (LI-COR Biosciences, Lincoln, NE, USA). LWP was measured with a pressure chamber (model ARIMAD 1, Mevo Hama Instruments, Mevo Hama, Israel), as described by Meron et al. (1987). LOP was measured in the laboratory, as described by Heuer and Nadler (1995). SC, LWP and LOP measurements were taken at the terminal leaflet of the fourth leaf from the apex of the shoot. Four to six leaves were measured from each replicate. SC was measured from sunlit leaflets.

Thermal image acquisition

Images were acquired in two spectral ranges—TIR and VIS, and from two platforms—ground and aerial. Ground images were acquired simultaneously from 10 m above the canopy at 30-s time intervals, and then co-registered. TIR and RGB cameras were mounted on top of a platform pointing in the same direction and their fields of view (FOVs) overlapped considerably. Aerial images were acquired and rectified (georeference and atmospheric correction) by Icaros Geosystems Ltd. (Herzliya Pituach, Israel). Images were taken from about 400 m above the field. Table 4 provides details of the cameras that were used for image acquisition, and of the acquired image properties.

Table 4 Camera and image details

Image type	Platform	Year	Camera model	Sensor (pixels)	Sensitivity (°K)	Accuracy (°K)	Spectral range (µm)	Resolution (cm/pixel)
TIR	Ground	2010-2011	SC2000, FLIR systems	320×240 [a]	0.1°	±2°	7.5-13	1.5
TIR	Ground	2012	SC655, FLIR systems	640×480 [a]	0.05°	±2°	7.5-13	0.75
RGB	Ground	2010-2012	Power Shot A640, Canon	3648×2736	--	--	0.46-0.70	0.1
TIR	Aerial	2011-2012	IDM200, JeanOptics	640×480 [a]	0.1	±1.5	7.5-13	35

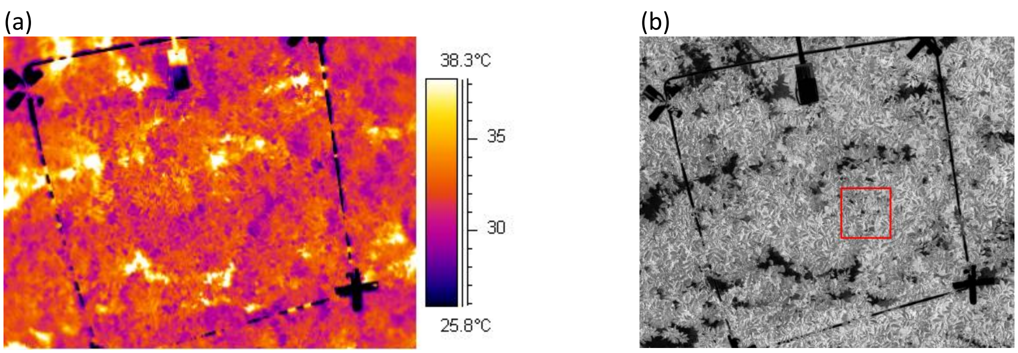
[a] microbolo-meter sensor

Thermal image analysis

Pure canopy pixels were selected in two ways: (i) Using complementary RGB data for ground images: vegetation indices in the VIS spectral range were used to distinguish between vegetation and soil, to extract pure sunlit vegetation pixels in the RGB images and mask the synchronized and spatially-registered TIR images. The vegetation index was based on the RGB image bands (raw data) and calculated as follows:

Eq. 1 $$VI_{RGB} = \frac{\text{green}-\text{red}}{\text{green}+\text{blue}}$$

where green, red and blue are intensity values in the corresponding color image bands. The result of this stage is a VIRGB image that was used to create a binary mask of the vegetation. Sunlit leaves were extracted from the RGB image by applying a threshold value on a local spatial statistic which characterizes the illumination levels (Rud et al. 2013). This final mask was applied on the co-registered TIR image, to produce a TIR image with pixels belonging only to sunlit leaves (Fig. 1). Canopy temperature was calculated as the mode value of the sunlit leaves temperature distribution. (ii) Using only TIR images for aerial images: separation between vegetation and background was based on differences between canopy and air temperatures measured at the time of TIR image acquisition. Extraction of pixels relating to canopy was determined using the rule of Tair - 10 °C < Tcanopy < Tair + 7 °C following Meron et al. (2010, 2013). Then the mean of the lowest 33% of the canopy temperature of each replicate was used as Tl (Fig. 2).



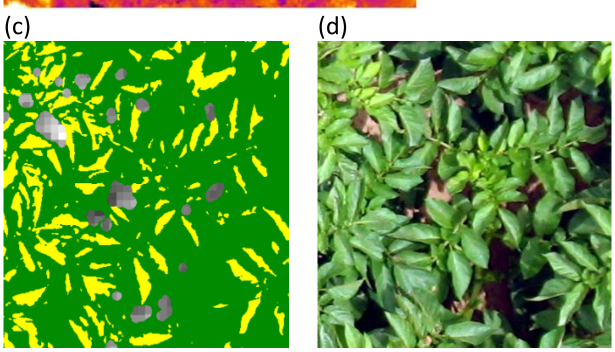


Figure 1: Ground imagery sample: **a** thermal image May 5 2011displayed with pseudo colors, **b** VI_{RGB} image (the area marked with the rectangle is zoomed-in in **c** and **d**) **c** shadowed and sunlit leaflets overlaid a gray scale thermal image (green and yellow respectively), and **d** the corresponding RGB image.

<u>Crop water stress index (CWSI)</u>: The CWSI is based on the difference between leaf and air temperatures normalized to the variation in environmental meteorological conditions (Idso et al. 1981). The CWSI is defined as follows (Jones 1992):

Eq. 2 $$CWSI = \frac{Tl - Twet}{Tdry - Twet}$$

where *Tl* is the temperature of the sampled leaf or canopy, and *Twet* and *Tdry* are the lower and upper baseline temperature, respectively under similar meteorological conditions. The upper baseline represents the temperature of a non-transpiring leaf with completely closed stomata, and the lower baseline represents the leaf temperature when stomata are fully open (undisturbed transpiring leaf). CWSI values are in the range of 0–1 with larger values indicating higher water deficit stress. The lower and upper baseline temperatures, *Twet* and *Tdry*, can be derived empirically, theoretically, or statistically.

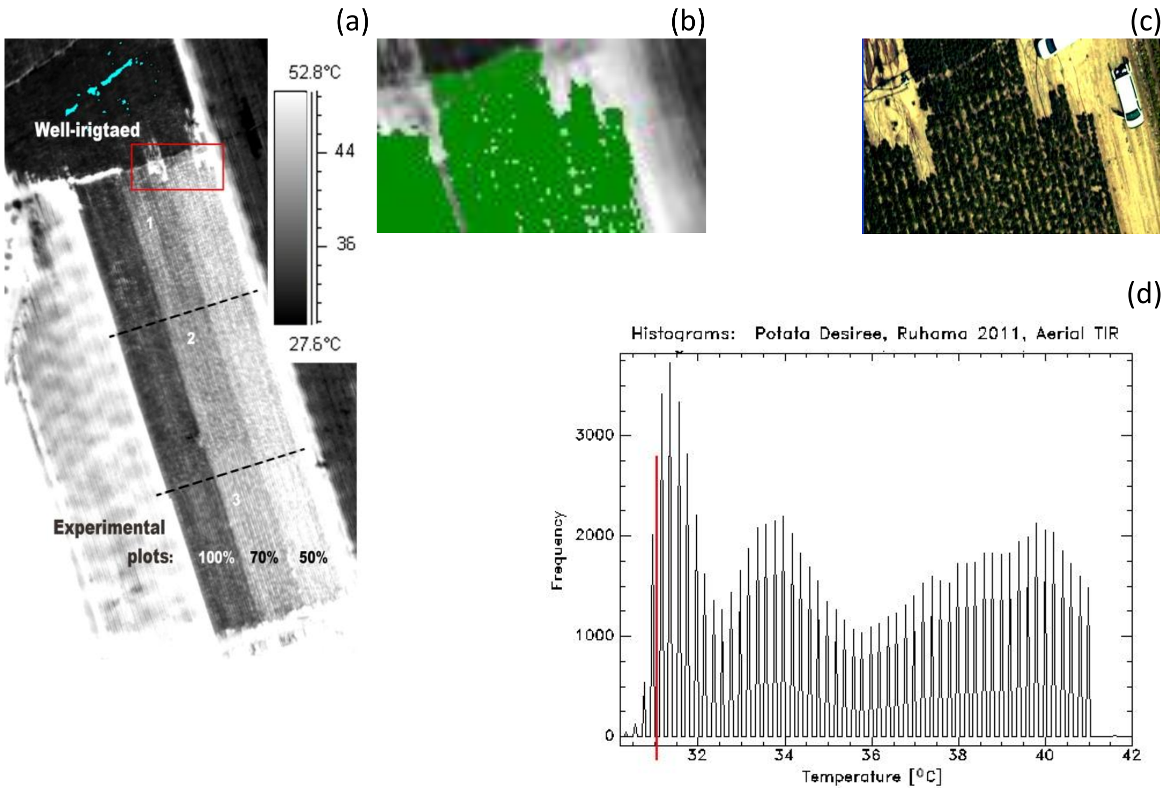


Figure 2 Aerial imagery sample: **a** Thermal image of potato fields May 5 2011, well irrigated (dark upper part) and experimental plots (three gray shade stripes). The area marked with the rectangle is zoomed-in in b and c. The colored pixels in the well irrigated plot were used as reference (the lower baseline) **b** Pixels relating foliage (in green). **c** Corresponding sample of RGB image, and **d** histogram of surface temperature relating foliage of potato (well irrigated and experimental plots). Lowest 5% that used for threshold temperature in selecting pixels for lower baseline marked in red and corresponding pixels are colored (cyan) in **a**.

In this study, *Tdry* was used in its empirical form, *Tair* + 7ºC (Möller et al. 2007; Gonzalez-Dugo et al., 2013). Three forms of *Twet* were examined: (i) empirical *Twet* which was determined based on measurements of an artificial wet reference surface (AWRS) (Meron et al. 2003; Cohen et al., 2005) (Fig. 1(a)); (ii) theoretical *Twet* which was calculated based on radiative energy balance (O'Shaughnessy et al. 2011); (iii) statistical *Twet* which was determined as the mean of the lowest 5% of the whole field canopy temperature (Fig. 2(d)) (Alchanatis et al., 2010; Gonzalez-Dugo et al. 2013). Under the statistical approach, it is assumed that certain areas in the field are well- or over-irrigated. Table 5 describes the different approaches used for calculating empirical (CWSIe), theoretical (CWSIt), and statistical (CWSIs) CWSI.

Table 5 CWSI forms and their corresponding parameters–*Tl* (canopy temperature) and *Twet* and *Tdry* (the referenced minimum and maximum baseline temperatures, respectively)

Image platform	CWSI type	*Tl* source	*Twet* source
Ground	CWSIe	TIR[b]+RGB	Empirical (AWRS)
	CWSIt	TIR[b]+RGB	Meteorological conditions
Aerial	CWSIt	TIR[c] (stat.)	Meteorological conditions
	CWSIs	TIR[c] (stat.)	TIR (stat.)

[b]Canopy temperature is the mode value for segments of pixels relating to sunlit vegetation, based on fused information from co-registered TIR and RGB images; [c]Canopy temperature is the mean of the lowest 33% of the histogram of canopy temperature in the region of interest, based only on TIR image.

Results

<u>Tuber yield and quality</u>

Figures 3a-d present yield parameters for the growing seasons 2011 and 2012 for each irrigation treatments.

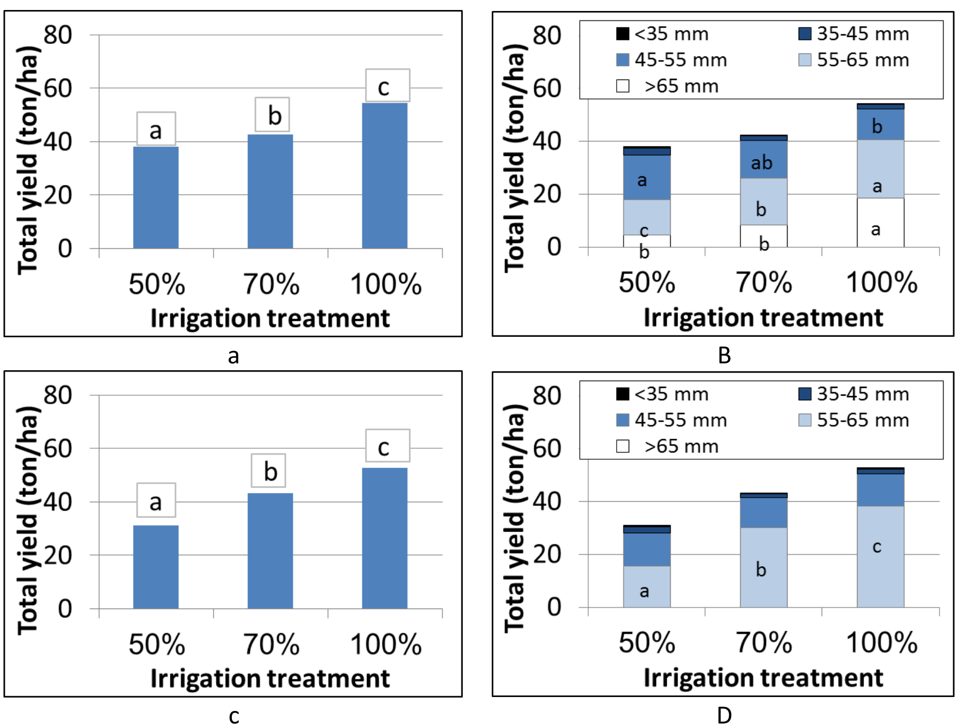


Figure 3 Yield parameter for irrigation treatments: **a,c** total yield in the growing seasons 2011 and 2012 respectively **b,d** Tuber size in the growing seasons 2011 and 2012 respectively

Irrigation treatments significantly affected potato yield and quality, providing relevance to the imagery measurements obtained during the growing season. In general, ground-based CWSI predicted tuber yield better than direct measurements of SC. Their coefficient of determination (r^2) values ranged from 0.6-0.9 on all measurement dates throughout the 2011.

Plant and soil response to irrigation treatments via biophysical measures

The response of potato plants and soil to irrigation treatments throughout the growing seasons of 2010–2012 is presented in Table 6. Among the four biophysical measurements, SC and GWC were the best at indicating trends and distinguishing between irrigation treatments under the different meteorological conditions and under both short and long term water deficit stress.

No differences between irrigation treatments were observed in the first measurement date of the campaigns (approximately 50 DAP). At this time, the plants are still small, the weather is temperate, and the soil may still be wet from the winter rainfall. From the second measurement date to the end of the campaigns, SC and GWC were higher in the irrigation treatments that supplied more water. The significant differences between treatments, as indicated by SC and GWC, were similar in all 3 years (at $\alpha = 0.05$). At 70–75 DAP in 2011 and 2012, both SC and GWC indicated significant separation into three levels of irrigation.

Relationships between CWSI and stomatal conductance

Since SC was found the best plant water status measure it was used for the further evaluation of the different types of CWSI as water status indicator in potato plants. Figures 3 and 4 display the relationship between the empirical and theoretical CWSI values and SC based on ground thermal images. Correlation results of CWSIt with SC for all seasons of the experiment were similar to those with CWSIe. The coefficient of determination using CWSIt was high (Fig. 4, $0.72 \le R^2 \le 0.97$), and seasonal variation occurred at the same growth stage. An additional test for the relationship of CWSIt and SC was performed based on airborne TIR data (Fig. 5a). In contrast to the ground image data, pure canopy pixels were delineated using only the TIR image, based on the difference between canopy and air temperatures (Meron et al. 2013). Although ground TIR images have higher spatial resolution than aerial ones, aerial CWSIt values on both flyover dates were highly correlated with SC (R^2 was 0.9 and 0.8 for 77 and 91 DAP, respectively). Furthermore, when the theoretical *Twet* was replaced with the statistical *Twet* (lowest 5%), the coefficient of determination remained the same (Fig. 5b). Nevertheless, CWSIs values were lower than CWSIt values.

Table 6 Plant and soil response to irrigation treatments throughout the growing seasons of 2010–2012.

		2010				
		Days with no water				
	DAP	8	6	4	2	0
-LWP (Atm)	49	7.0 ab	8.7 a	6.5 ab	7.2 ab	5.3 b
	66	11.7 a	11.8 a	11.5 a	11.8 a	11.2 a
	76	10.3 a	10.0 a	10.3 a	9.2 a	10.4 a
	90	8.3b	11.4a	9.5 ab	10.1 ab	8.5 b
LOP (MPa)	49	0.7 a	0.7 a	0.7 a	0.7 a	0.6 a
	66	--	--	--	--	--
	76	1.0 a	1 ab	0.9 ab	0.9 b	0.95 ab
	90	1 a	1.1 a	1.0 a	1.0a	0.97 a
SC (mm ol/m^{2}s)	49	726 a	941 a	881 a	921a	997 a
	66	194 c	222 bc	308 ab	321 a	366 a
	76	321 b	682 ab	822 a	788 a	710 ab
	90	374 a	245 a	380 a	352 a	442 a
GWC (%) in 40 cm depth	49	11.7 a	12.4 a	18.5 a	16.3 a	17.1 a
	66	--	--	--	--	--
	76	11.8 a	13.3a	14.4 a	22.6 a	18.2 a
	90	15.4c	14.1 d	17.2 b	19.3 a	19.6 a

	2011				2012			
	Cumulative irrigation deficit				Cumulative irrigation deficit			
	DAP	50%	70%	100%	DAP	50%	70%	100%
-LWP (Atm)	52	3.3 a	2.6 a	--	55	--	--	--
	59	5.3 b	7.1 a	7.2 a	66	--	--	--
	70	--	--	--	75	--	--	--
	77	11.3 a	11 a	8.6 b	84	--	--	--
	91	9.9 a	9.4 a	7.9 b	91	--	--	--
LOP (MPa)	52	--	--	--	55	0.7 b	0.7 b	0.7 a
	59	1.3 a	1.2 a	1.3 a	66	1.0 a	0.9 a	0.9 a
	70	1.0 a	1.0 a	1.0 a	75	1.2 a	1.1 b	1.1 b
	77	1.0 a	1.0 a	1.0 a	84	1.1 a	1.0 ab	1.0 b
	91	1.0 a	1.0 a	1.1 a	91	1.2a	1.0 ab	1.1 b
SC (mm ol/m^{2}s)	52	278 ab	268 b	301 a	55	512 a	537 a	542 a
	59	62c	90 b	145 a	66	307 b	507 a	545 a
	70	--	--	--	75	152 c	302 b	374 a
	77	80 c	99 b	132 a	84	103 b	130 b	230 a
	91	97 b	104 ab	122 a	91	57.3 c	93 b	124 a
GWC (%) @ 0.4 m	52	--	--	--	55	12.5 b	12.6 ab	13.7 a
	59	7.7 b	8.1 b	10.1 a	66	9.5 a	9.5 a	11.3 a
	70	8.3 b	9.4 b	11.0 a	75	7.9 b	9.6 a	10.6 a
	77	7.9 c	9.1 b	10.9 a	84	7.3 c	9.1 b	11.2 a
	91	10.7 a	9.0 b	11.5a	91	8.6 b	9.4 ab	10.2 a

Different letters indicate significantly different values at α = 0.05.

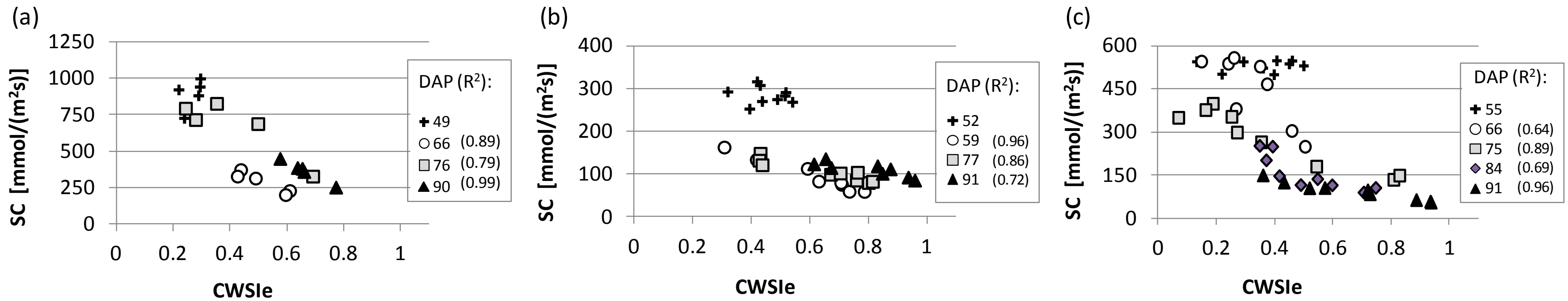


Figure 3 Plant status and thermal image measure: the relationship between SC and empirical CWSI (CWSIe) based on ground imaging for **a** 2010, **b** 2011 and **c** 2012. In 2010, values are averages per treatment.

In 2011 and 2012 values are averages of replicates (there were only three water levels). Canopy temperature for calculation of CWSIe was extracted using additional information from co-registered RGB image.

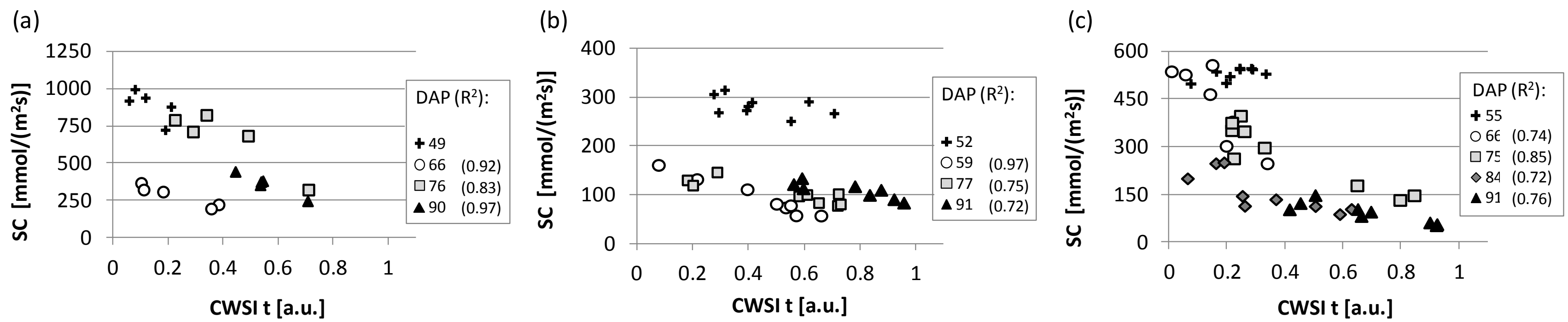


Figure 4 Theoretical CWSI (CWSIt) based on ground imaging for **a** 2010, **b** 2011 and **c** 2012. In 2010, values are averages per treatment.

In 2011 and 2012, values are averages of replicates (there were only three water levels). Canopy temperature for calculation of CWSIt was extracted using additional information from co-registered RGB image.

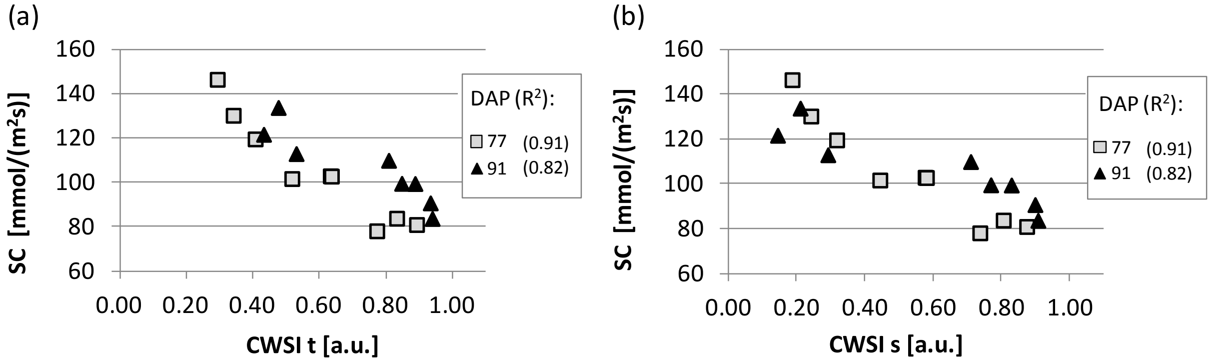


Figure 5 a Theoretical CWSI (CWSIt) and **b** statistical CWSI (CWSIs) based on aerial imaging for 2011 flyover missions (77 and 91 DAP).

Values are averages of replicates. Canopy temperature for calculation of CWSIt and CWSIs was extracted using only TIR image.

Conclusions

This study showed that thermal imaging is an effective tool for monitoring potato plant water status, as indicated by the high correlation values obtained in three growing seasons between remotely sensed image-based CWSI values and SC. The analysis of the different types of CWSI indicated that the reference minimum temperature (*Twet*) can be estimated based on meteorological conditions, and there is no need for an AWRS. This outcome enables efficient usage of aerial thermal images to monitor plant water status using the CWSIt. The use of CWSIs further simplifies the data processing and extraction of the measured CWSI. *Twet* determination is based merely on the thermal image data, eliminating the need for complex meteorological parameters aside from air temperature. 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. 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 (mainly US). This will be done both using specific indices and using chemometric methods (specifically Partial Least Squares Regression) which have not used before in HS imagery analysis.

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 (data shown in part 3).

Materials and Methods

<u>Study site and experimental setup</u>

Field experiments were conducted over two years (2010-2011) at the University of Minnesota Sand Plain Research Farm (45°23'N, 95°53'W) near Becker, MN. The soil at this location is classified as excessively drained Hubbard loamy sand (sandy, mixed, frigid Typic Hapludoll) comprised of 82% sand, 10% silt, and 8% clay and is typical of the soil used for potato production in the area. The study included two potato varieties (Russet Burbank and Alpine Russet), two irrigation regimes (unstressed and stressed), and five N treatments categorized by three N rates (34 kg N ha^{-1}, 180 kg N ha^{-1}, and 270 kg N ha^{-1}) in which the 270 kg N ha^{-1} rate had post-emergence N either split applied or applied early in the season (Table 1; Figure 6). In addition, one of the 270 kg N ha^{-1} rates with post-emergence N split applied included a soil surfactant application (Table 1; Figure 6).

The whole plot treatment was irrigation rate, (i.e., unstressed and stressed treatments). Irrigation was applied with an overhead sprinkler system. A water balance method was used to schedule irrigation applications for the unstressed treatment. The stressed plots were irrigated at a rate in which cumulative water (rainfall + irrigation) equaled approximately 89% and 81% of the unstressed plots in 2010 and 2011, respectively, and was calculated from total water applied between emergence and vine kill. Timing of irrigation was variable between years and depended on weather conditions.

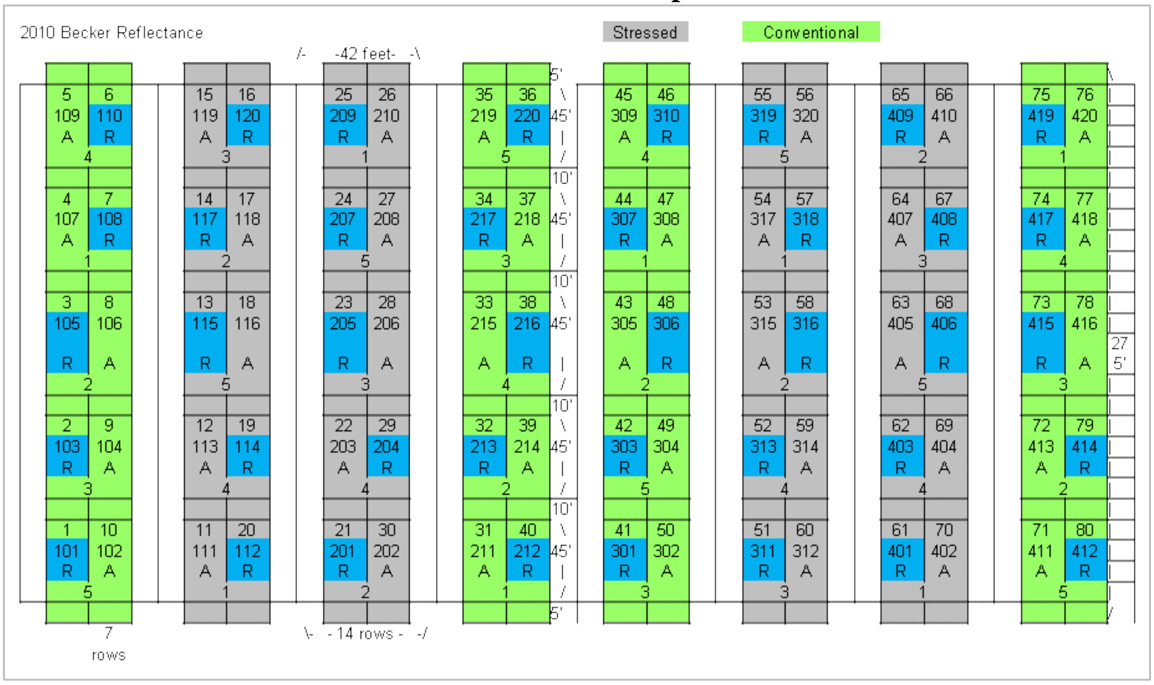


Figure 6 Experimental design at the Sand Plain Research Farm, Becker, MN.
R denotes Russet (blue), A denotes Alpine varieties of potato; Gray and green are stress and non-stressed irrigation treatments; the numbers 1-5 appear in each block (for every couple of Russet and Alpine plots) assign for N treatments described in Table 1.

Vines were mechanically killed and tubers were mechanically harvested from the third and fourth rows from the alley in each treatment plot approximately 1-2 weeks after the vines were killed. Tubers were sorted into weight classes for total and graded yield. Grade A yield was determined by subtracting undersized tuber yields (85 g) from the total yield.

In addition to the experimental plots at Becker in 2011, image data and plant samples were also acquired for a 59 ha center-pivot irrigated commercial field which was located 3.2 km southeast of the experimental plots. The northern section of the field (~60%) was planted into the Alpine Russet variety, and the southern section (~40%) was planted into the Russet Burbank variety. Selected indices using imagery from the experimental plots were used to evaluate nitrogen status of the commercial field.

In-season field ground based measurements were collected on four dates in 2010 and five dates in 2011, and included: tissue samples (petioles and leaflets); chlorophyll meter readings (Minolta SPAD-502, Spectrum Technologies, Plainfield, IL); and multispectral reflectance (MSR16R Cropscan, Cropscan, Inc., Rochester, MN, Serial no. 249).

Nitrogen stress evaluation

For conventional N testing, the 4th leaf from the apex of the shoot was sampled from 20 plants in each replicate. Relative chlorophyll was immediately measured at a central point on the terminal leaflet between the midrib and leaf margin. The 20 measurements from each plot were averaged to represent a single value for each treatment plot. Immediately following relative chlorophyll measurements on each leaf, leaflets were stripped from the petiole and both the leaflets and the petioles were separately saved for analysis.

Leaflet and petiole samples were oven-dried at 60^{o}C, each tissue part was weighed for dry matter yield, and then each was ground separately. Total N concentration in ground tissue samples was determined with a combustion analyzer and NO_3-N concentration was determined using a Wescan analyzer. To obtain total N and NO_3-N concentrations for the whole leaf, petiole and leaflet concentrations were first used to calculate N and NO_3-N content on a dry weight basis by multiplying dry matter by N or NO_3-N concentration; next, the leaf was reconstructed by combining the N or NO_3-N content of the petioles and leaflets. Finally, leaf N or NO_3-N content was calculated back to a concentration by dividing content by total dry weight of the leaf (leaflets plus petioles).

Spectral data and image collection

Ground-based reflectance with the Cropscan was measured on the same days as the tissue samples. Scans were taken 2 m above the canopy to give an approximate field-of-view diameter of 1 m. Percent reflectance was recorded at 16 narrowband wavelengths (10-14 nm bandwidth) through the visible and near-infrared regions; narrowbands were centered at 460, 510, 560, 610, 660, 710, 760, 810, 870, 900, 950, 1000, 1320, 1480, 1500, and 1720 nm.

Aerial hyperspectral images were acquired with an Airborne Imaging Spectrometer for Applications (AISA Eagle) visible/near-infrared hyperspectral imaging sensor (SPECIM, Spectral Imaging, Ltd., Oulu, Finland) by the Center for Advanced Land Management Information Technologies (CALMIT) from the University of Nebraska-Lincoln, USA. The AISA Eagle is a complete pushbroom system, consisting of a hyperspectral sensor head, a miniature GPS/INS sensor, and a data acquisition unit in a rugged PC with a display unit and power supply. It has a 1,000 pixel swath width and was configured to capture imagery in 63 narrowbands (2.3 nm spectral resolution) covering the visible and near-infrared portions of the solar spectrum from 401 to 982 nm; bandwidths ranged from 8.8 - 9.6 nm. Images were captured with 1.0 m spatial resolution on 1 July [47 days after emergence (DAE)] and 6 August (83 DAE) in 2010 and on 6 July (43 DAE) and 29 July (66 DAE) in 2011.

In 2011, aerial multispectral imagery was acquired with a Redlake MS4100 3-Charge Coupled Device (CCD) digital multispectral camera by the Upper Midwest Aerospace Consortium (UMAC) from the University of North Dakota, Grand Forks, ND. The Redlake MS4100 uses three CCD imaging sensors to capture energy at wavelengths corresponding to broadbands centered in the near-infrared (NIR), red, and green regions of the electromagnetic spectrum, respectively. The Redlake MS4100 was used to capture images of the treatment plots and a commercial potato field about 5 km from the experimental site. Images of the treatment plots and commercial field at a 0.25 m spatial resolution were captured from approximately 235 m above the ground on 23 June, 19 July, and 11 August 2011; in the experimental year, these dates corresponded to 30, 56, and 79 DAE, respectively

Thermal data and image collection

Two non-invasive remote sensing techniques that measure canopy temperature were broadly evaluated in this study. The first was to use ground-based infrared radiometers to obtain canopy temperature over the course of the growing season. The second technique was to use aerial-based thermal imagery to obtain instantaneous temperature measurements of the entire research field. The infrared radiometers continuously record the apparent canopy temperature at desired time intervals, but they do not account for spatial variability. Thermal imagery can account for spatial variability, but it is not practical to obtain measurements at frequent time intervals.

Hyperspectral image analysis

Reflectance data for all broadband and narrowband wavelengths, first derivative reflectance data for all narrowband wavelengths, and a comprehensive list of 17 broadband and 82 narrowband previously published spectral indices were used in a preliminary analysis to determine the wavelengths and/or indices that had the best overall ability to detect N stress. The correlation coefficient (*r*) was calculated for each of these wavelengths/indices using the CORR procedure of SAS in order to determine the wavelengths/indices that had the best relationships with leaf N concentration on each image date. To determine which wavelengths and indices performed best overall, r^2 was averaged for each wavelength/index among the four image dates. The indices that had the best average r^2 from this preliminary analysis were used for comparison in all subsequent analysis techniques for detecting N stress. There were no broadband/narrowband wavelengths or first derivative wavelengths that performed particularly well across all image dates. Narrowband NDVI did not perform particularly well, but it is included for comparison with other indices and previously published research. ENVI software (Version 4.8, Exelis, Inc., USA) was used for image analysis.

Three partial least squares regression (PLS) models were constructed across image dates, and three PLS models were constructed for each potato variety by image date combination, each using different sets of independent spectra. Independent spectra for the three models included: (i) hyperspectral reflectance only; (ii) first derivative reflectance only; and (iii) both hyperspectral and first derivative reflectance. The independent spectra were used to predict leaf N concentration in the models. There were 20 samples used as input for each of the models constructed within image dates, and 80 samples used as input for each of the models constructed across image dates. The PLS models were calibrated and cross-validated by a full one-at-a-time cross-validation using the PLS procedure of SAS Using the *CVTEST (STAT = PRESS)* option of the PLS procedure of SAS (SAS Institute, 2008), model predictions were made for the least number of latent variables in which the predicted residual sum of squares (PRESS) were not significantly greater than those of the model with the minimum PRESS. The PRESS is used as an indication of the predictive power of a model.

Spectral data were kept in image format until it was necessary to perform statistical procedures outside of ENVI. Several analysis techniques were performed and were used as metrics to evaluate the spectral indices/wavelengths that were best able to determine N stress. These analysis techniques included: (i) linear regression analysis; (ii) normalized nitrogen sufficiency; (iii) calculation of the coefficient of variation across N treatments, and (iv) accuracy assessment.

A nitrogen sufficiency index (NSI) was applied to the plant measurements and spectral indices/models in order to normalize them for comparative purposes. By applying an NSI to the spectral data, values were normalized to a non-limiting N reference area.

<u>Multispectral data analysis</u>

Formulas for three narrowband spectral indices (Normalized difference index 2 - NDI2; Normalized difference vegetation index - NDVI; and Simple ratio 8 - SR8) were applied to the Cropscan data. Narrowband NDI2 and SR8 were chosen because they performed very well in predicting leaf N using canopy-level HS data from the same field plots. Other narrowband indices performed well, but they could not be used in this study because not all wavelengths needed for their calculation were obtained by the Cropscan sensor. Narrowband NDVI did not perform particularly well in that analysis, but it was included in this study for comparison with the other indices and previously published research. Linear regression models were used to determine the relationships comparing leaf N concentration and Grade A yield to that of chlorophyll meter readings and each of the spectral indices at different growth stages.

Results

Tuber yield and quality

Both water and nitrogen treatments significantly affected yield and quality of both potato varieties, providing relevance to the imagery measurements obtained during the growing season (Tables 7 and 8). Insufficient supplemental water during critical growth stages was found to decrease tuber yield and quality. Tuber yield generally increased with increasing N rate.

Table 7 Analysis of variance for potato tuber yields and fresh quality

Effect	Total yield	Grade A yield	Tubers >170g
Year [Y]	***†	***	***
Irrigation [I]	**	*	**
N treatment [N]	***	***	***
Variety [V]	-	***	***
I × N	-	-	-
I × N × V	-	-	-
I × N × Y	-	-	-

†***, **, and * are significant 0.001, 0.01, and 0.05, respectively; - is not significant.

Table 8 Main effects of year, irrigation, N treatment, and variety on potato tuber yields

Sources of Variation	Total Yield	Grade A yield†	Tubers >170 g†
Year			
2010	58.5 a‡	52.1 a	55.4 a
2011	49.5 b	40.3 b	37.1 b
Irrigation			
Unstressed	57.1 a	49.8 a	50.8 a
Stressed	50.9 b	42.7 b	41.7 b
N treatment§			
34 N early	43.9 c	33.6 c	27.3 c
180 N split	56.2 ab	48.6 ab	47.5 b
270 N split	57.4 a	50.4 a	52.5 a
270 N split + s	57.7 a	50.5 a	51.6 a
270 N early	54.8 b	48.1 b	52.4 a
Variety			
Russet Burbank	53.6a	43.2 b	34.9 b
Alpine Russet	54.4a	49.3 a	57.5 a

†Response variables that had at least one significant interaction, refer to Table 7 and text for explanation; ‡Means followed by the same letter are not significantly different (α=0.05); §N rates are expressed in kg N ha^{-1}, refer to Table 1 for detailed rates and timing.

In general, ground-based spectral data predicted tuber yield better than N-based tissue sampling procedures. Their coefficient of determination (r^2) values ranged from 0.40-0.85 on all measurement dates throughout the 2010 and 2011 seasons.

Conventional measurements of N status

Tissue samples analyzed for NO_3-N were very responsive to N fertilizer applications that occurred within about 7 days of the sampling date, and are therefore a good indicator of current plant N uptake (Figure 7). Alternatively, tissue samples analyzed for total N were more stable over sample dates, and appear to be a better indicator of overall plant N uptake at the time of sampling (Figure 8).

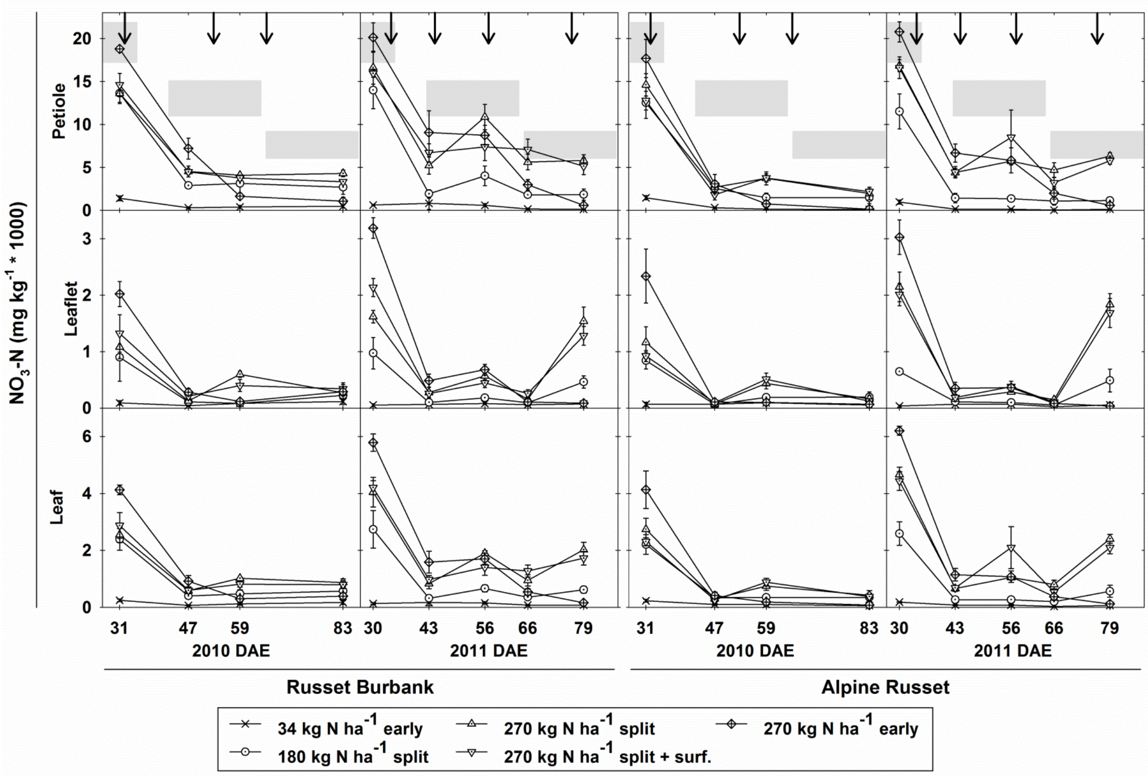


Figure 7 Petiole, leaflet, and whole leaf nitrate-nitrogen (NO_3-N) concentrations under various N treatments for Russet Burbank and Alpine Russet potato varieties at different days after emergence (DAE) in 2010 and 2011.

Means are presented with standard error bars, and gray shaded areas represent petiole NO_3-N sufficiency levels according to Rosen & Eliason (2005). Arrows signify when split applications of post-emergence N fertilizer were applied.

Relationships between hyperspectral imagery data and N Status

The best predictor of N stress of the potato crop was determined to be the PLS regression model using derivative reflectance as input for its independent variables (r^2 of 0.79 for RB and 0.77 for AR). 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 (Table 9). The NDI2 formula is as follows (Datt, 1999): $(R_{847} - R_{713})/(R_{847} - R_{676})$. The NG formula is as follows (Sripada et al., 2006): $R_G/(R_{NIR} + R_R + R_G)$. An example of the NDI2 layer created based on HS image for Russet Burbank taken 66 days after emergence in 2011 is shown in Figure 9. This layer is just one of many created over the course of the study, but clearly shows differences in reflectance due to N stress.

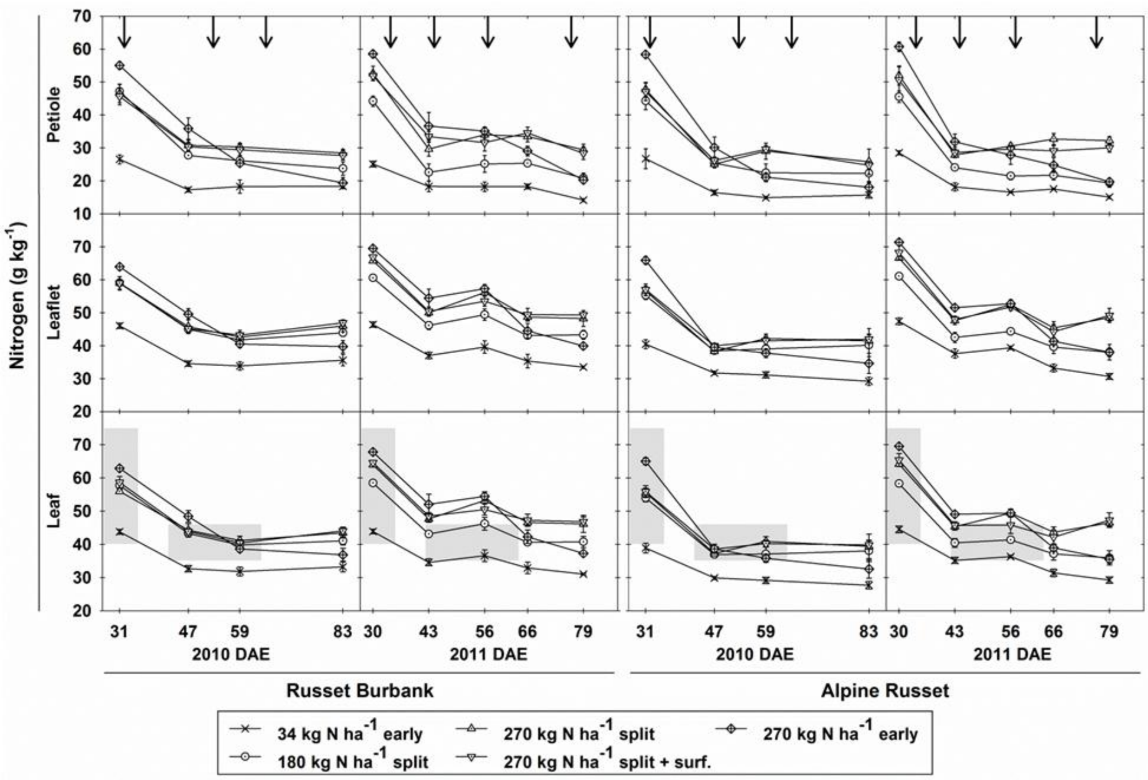


Figure 8 Petiole, leaflet, and whole leaf N concentrations under various N treatments for RB and AR potato varieties on different days after emergence (DAE) in 2010 and 2011. Means are presented with standard error bars, and gray shaded areas represent leaf N sufficiency levels according to Rosen & Eliason (2005) and Westermann (1993). Arrows signify when split applications of post-emergence N fertilizer were applied.

Table 9 Linear regression analysis across all dates to predict leaf N concentration.

Wavelength/Index	Russet Burbank	Alpine Russet
R_{572}	0.56	0.33
Chlorophyll meter	0.74	0.59
NG	0.69	0.49
MTCI	0.72	0.51
NDI2	0.74	0.57
NDVI	0.31	0.27
PLS RD	0.79	0.77

While imagery correlated well with conventional N measurements, the use of a nitrogen sufficiency index (NSI) was used to normalize the data collected. The NSI is defined as:

Eq. 3 $$NSI = \frac{N_i}{N_{ref}} \times 100$$

where NSI is the nitrogen sufficiency index; N_i is the measured pixel value of the spectral indices; and N_{ref} is the reference value and for this study was the higher average replicate value of either 270 split or 270 split + s from the research plots.

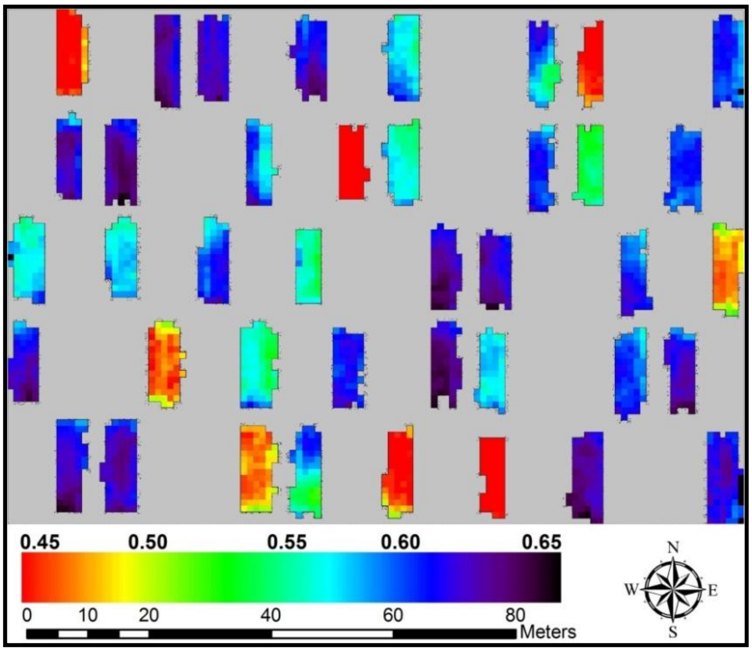


Figure 9 NDI2 image of Russet Burbank Plots, 66 days after emergence in 2011.
Red indicates N stressed plots and blue indicates N sufficient plots

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. The MTCI formula is as follows (Dash and Curran, 2004): $(R_{751} - R_{713})/(R_{713} - R_{676})$. The inherent variability of a spectral index should be considered before determining the N sufficiency threshold for determining the rate and timing of post-emergence N fertilizer applications. Applying the NSI to plant measurements and spectral indices/models made them mostly insensitive to the effects of variety; this was found to be an effective way to normalize data based on local growing conditions and cultural practices.

In a study using broadband imagery from a commercial field, the GRVI (Green Ratio Vegetation Index) normalized by an NSI detected areas of the commercial field that were most unsuitable for supplemental N fertilizer applications on different measurement dates.

The GRVI formula is as follows (Sripada et al., 2006): R_{NIR}/R_G . On 56 and 79 DAE in 2011 (Figure 10), most of the commercial field was above the GRVI NSI over-sufficiency threshold level of 120% (the mean pixel values were greater than 127% for both varieties). Using GRVI normalized by NSI values could help reduce over-fertilization of commercial potato fields without affecting tuber yield or quality.

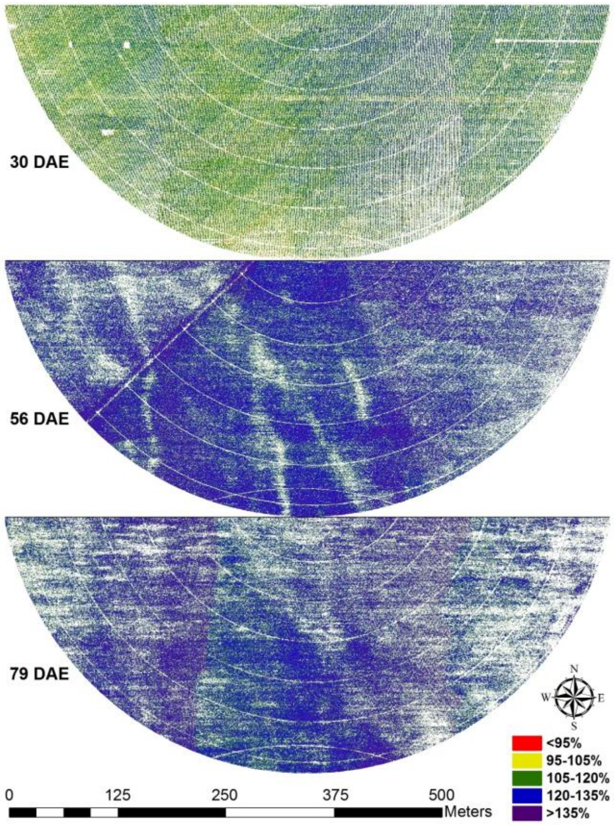


Figure 10 Broadband GRVI index for the RB variety on 30, 56, and 79 DAE
Images are shown after they were normalized by a nitrogen sufficiency index using the recommended rate from the research plots as a reference.

Conclusions

Overall, the results from this research suggest that diagnostic criteria based on biomass and nutrient concentration (e.g., canopy-level spectral reflectance data obtained from aerial or ground imagery) were best suited to determine overall potato crop N status for determination of in-season N fertilizer recommendations. 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. This will be done also using VENµS images (simulated or real images from 2010-11).

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.

Material and Methods

In general, this objective was partially addressed in this study for the following reasons:

1. We succeeded to obtain the expected ranges in both measures only in the US in 2010. In Israel a sufficient range was obtained in water status in all seasons but not in N levels. No differences were found in N concentrations and the yield was not affected by the N treatments. N amounts for this research was determined based on a previous 3-years study (2006-2008) on the effect of N levels on spectral data in which we used slow release N (SRN) (Cohen et al., 2010). In the previous study in the same farm significant differences were found between N treatments every year. The only difference between the two experiments (that we can observe) is the irrigation method. While in the previous study irrigation was applied by sprinklers, in this study drippers were used. The effect of the combination of SRN and drip irrigation might be of an interest for further research.
2. While in Israel we succeeded to obtain reliable and accurate measurement of water status in plants (mainly stomatal conductance using Licor-1800 porometer) in the US the Decagon promoter which was purchased specially for this research failed to provide reliably measurements[1]. Measurements of soil metric were made in few replicates only and indicated that differences were obtained between the two irrigation treatments (Appendix 1) but they cannot be used to validate the canopy sensitivity to water status. Moreover, canopy thermal indices are less correlated with soil water status compared with plant water status (e.g. Möller et al., 2007).

[1] Recently Campbell declared that the Decagon porometers was limited by RH range. In the last few months after fixing the problem they started replacing the heads of the porometers free of charge.

This means that despite the success in the US experiment to obtain sufficient differences no plant water measures were available to adequately test the results.

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. Hyperspectral images acquired above the two-factor experiment in the US in two dates along the 2010 growing season were used firstly to examine this assumption. The effect of water status on spectral data from the HS images was examined through NDI2 and water band index (WI) which was suggested for plant water status estimation and mapping (Penuelas et al., 1997). WI formula is: R_{900}/R_{970}. 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 according to the N sufficiency levels presented in Figure 8: 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. Following the division into N levels the replicates were further divided by their water status. Since no plant measures were available for water status the replicates were divided merely by the irrigation treatment (despite the variance that can be found between the replicates under the same treatment).

According to a visual analysis of NDI2 histograms of the pixels of the three N levels 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: N1W1 – Low N and water levels; N2W1 – Sufficient N level and low water level; N3W1 – High N level and low water level; N1W2 – Low N level and sufficient water level; N2W2 – Sufficient N and water levels; N3W2 – High N level and sufficient water level. In this stage all data were used for the division with no validation sets.

A confusion matrix was formed to calculate the overall accuracy of the classification and the accuracy and reliability of each class.

Results

In 2010, NDI2 from both dates and varieties was significantly affected by N treatments but was not affected by water status (Table 10, Figure 11a,d). Additionally and unexpectedly, WI was not affected by irrigation treatments (Figure 11b,e; visual interpretation, no statistical test was done yet). Moreover, it seems that it was more affected by N treatments (34N treatments had relatively lower values). In comparison, canopy temperature was more affected by irrigation treatments than by N treatments (Table 11, Figure 11c,f). Significant differences were found between irrigation treatments at 83 and 47 DAE in AR and RB respectively. In 83 DAE significant differences in canopy temperature was found only between 34N and 270 N split + s.

Table 10 Effects of irrigation and N treatment on NDI2 in 2010 (Aerial HS images)

Effect		Alpine Russet		Russet Burbank	
		TB (47 DAE)	M (83 DAE)	TB (47 DAE)	M (83 DAE)
Irrigation					
	Unstressed	0.64 a†	0.58 a	0.61 a	0.56 a
	Stressed	0.65 a	0.57 a	0.63 a	0.57 a
*N treatment**					
	34 N early	0.55 c	0.46 c	0.51 d	0.47 c
	180 N split	0.66 b	0.58 b	0.63 c	0.58 b
	270 N split	0.67 ab	0.63 a	0.65 b	0.62 a
	270 N split + s	0.67 ab	0.63 a	0.64 bc	0.62 a
	270 N early	0.68 a	0.57 b	0.66 a	0.56 b

† Means followed by the same letter are not significantly different (α=0.05); Differences were tested using Tukey-Kramer method within JMP6 software package.

Table 11 Effects of irrigation and N treatment on canopy temperature in 2010 (Aerial thermal images)

Effect		Alpine Russet		Russet Burbank	
		TB (47 DAE)	M (83 DAE)	TB (47 DAE)	M (83 DAE)
Irrigation					
	Unstressed	27.2 a†	29.9 a	27.6 b	31.4 a
	Stressed	29.2 a	32.4 b	29.2 a	34 a
*N treatment**					
	34 N early	28.9 a	32 a	29.2 a	35.4 a
	180 N split	27.5 a	30.9 a	28.2 a	32.3 ab
	270 N split	28.2 a	30.9 a	28.6 a	32.2 ab
	270 N split + s	27.8 a	30.7 a	27.9 a	31.7 b
	270 N early	28 a	31.3 a	28.1 a	32 ab

† Means followed by the same letter are not significantly different (α=0.05); Differences were tested using Tukey-Kramer method within JMP6 software package.

A B c

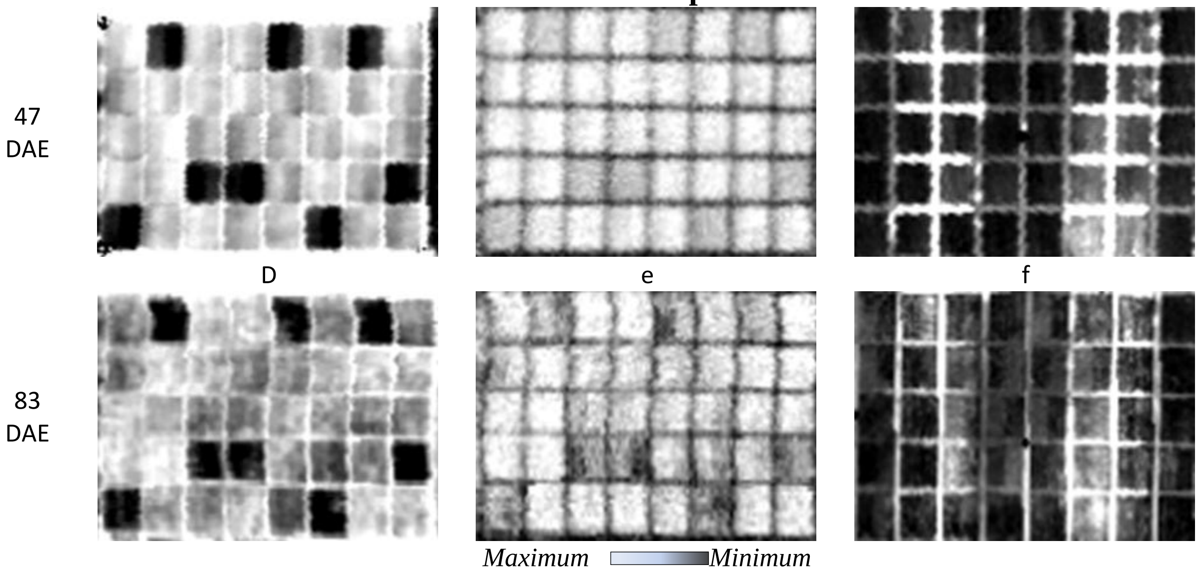


Figure 11 Images of NDI2 (a,d), WI (b,e), and canopy temperature (c,f) of the experimental site from 47 and 83 DAE in 2010

According to these results classification into 6 combinations of water status and N concentration levels were conducted by two steps: first, thermal images was grouped into two classes according to irrigation treatments. Secondly, each irrigation class was further grouped according to its N concentration level. Classification and reference images are presented in Figure 12.

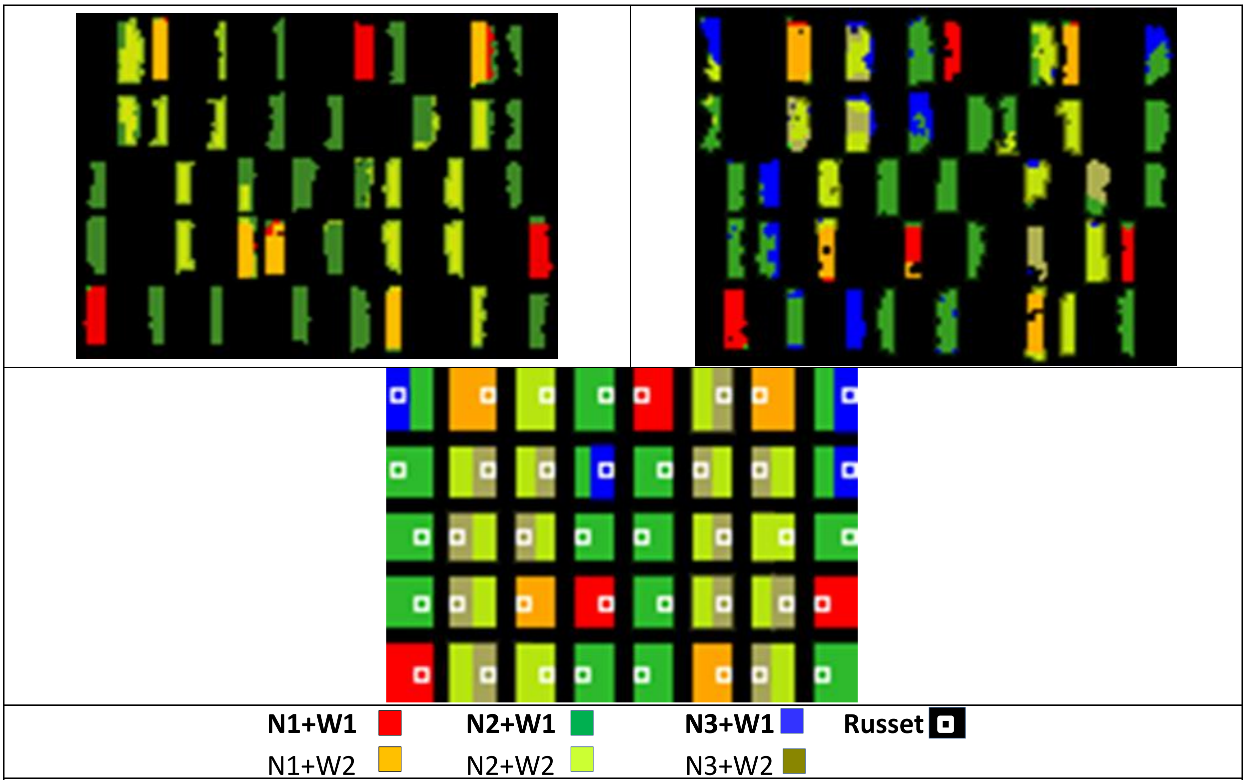


Figure 12 Classification images based on fused HS and thermal images of AR (left) and RB (right) and the reference image (bottom)

Overall classification accuracies obtained were 83% and 65% for AR and RB, respectively. Most of the N stress plots of the two varieties (N concentration lower than 3.5%) were classified correctly (15 out of 16). Moreover, N stress with water stress was differentiated from N stress with no water stress. This result was obtained from the fusion of HS and thermal images. In AR, where no N excess was established, most of the confusion was found between water levels. In RB confusion was found also between N sufficient and N excess levels.

Table 12 Confusion matrices of the classifications into combined effect of N levels and water status based on HS and thermal images, 43 DAE, 2010, USA (upper – AR, lower- RB)

AR	Image classification							
Reference	N1W1	N2W1	N3W1	N1W2	N2W2	N3W2	# of plots	**Accuracy**
N1W1	3			1			4	**75%**
N2W1		14			2		16	**88%**
N3W1								
N1W2				4			4	**100%**
N2W2		4			12		16	**75%**
N3W2								
# of Plots	3	18		5	14			
Reliability	**100%**	**78%**		**80%**	**86%**		**Overall Accuracy**	**83%**

RB	Image classification							
Reference	N1W1	N2W1	N3W1	N1W2	N2W2	N3W2	# of plots	**Accuracy**
N1W1	4						4	**100%**
N2W1		12					12	**100%**
N3W1		2	2				4	**50%**
N1W2				4			4	**100%**
N2W2			1		1	1	3	**33%**
N3W2		2	1		7	3	13	**23%**
# of plots	4	16	4	4	8	4		
Reliability	**100%**	**75%**	**50%**	**100%**	**13%**	**75%**	**Overall Accuracy**	**65%**

Histograms of canopy temperature of the different irrigation treatments show that there is no clear difference between them and they suffer from high heterogeneity at least in terms of canopy temperature (Figure 13). In this case, plant water status measurements could assist with more adequate division between water statuses. Histograms of NDI2 show that NDI2 is sensitive to N stress but not to N excess (Figure 14). If only N stress is to be differentiated from other N levels higher overall accuracy would be obtained for RB (90%) with confusion only between irrigation treatments. The fused data should further be analyzed by dividing the data into calibration and validation sets to validate the classification results.

Alpine Russet Russet Burbank

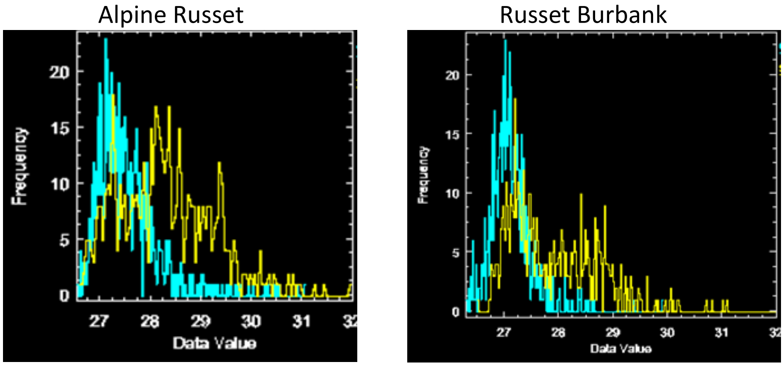


Figure 13 Histograms of canopy temperature of stress (yellow) and unstress (blue) irrigation treatments in 47 DAE in 2010

Alpine Russet Russet Burbank

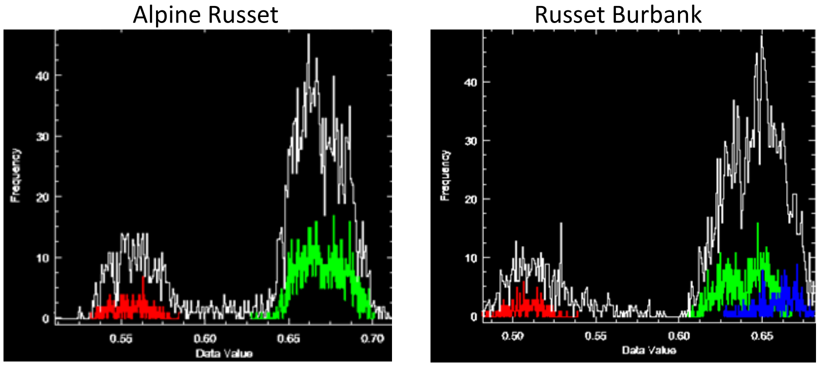


Figure 14 Histograms of NDI2 of N stress (red), sufficient N (green) and N excess (blue) in 47 DAE in 2010.

Summary and Conclusions

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.

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.

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.

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List of Publications (output of BARD cooperation)

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.

Final Scientific Report

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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