2010 BARD Progress Report

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

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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. The overall objective of this study is to examine the ability of HS imagery in the in the visible and NIR spectrum (VIS-NIR) and thermal imagery to distinguish between water and N status in potato fields. This general objective will be accomplished by pursuing three specific objectives:

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.

In the first year, experiments in Israel evaluated the fusion of thermal and RGB images to estimate water status in potato plants (Proposal Objective 1), while experiments in the USA investigated and characterized the ability of spectral data and imagery to evaluate N level and water status of potato plants under combined stress (Objective 2). Since each group was focused on different objectives the first year, cooperation between groups will be enhanced during the next year.

ISRAEL

Following the approach outlined in the initial proposal, experiments in Israel during the first year evaluated the fusion of thermal and RGB images to estimate water status in potato plants (Objective 1).

STUDY SITE & EXPERIMENTAL DESIGN:

Field experiments were conducted in the spring growing season of 2010 on a commercial potato field (*Solanum tuberosum L*. cv. Desiree) at Kibbutz Ruhama, Israel (31.38º N, 34.59º E). The soil at the site is classified as Loessial arid brown soil. The commercial plot was irrigated with sprinklers, while the experimental plot was irrigated with drippers. The experimental plot was divided into 20 sub-plots (Figure 1). Five water levels were induced by suppressing irrigation for 0 (not-stressed), 2, 4, 6 and 8 days before measurement days (designated as Tr-0, Tr-2, Tr-4, Tr-6 and Tr-8). Each treatment was replicated four times, and each replicate was 6 m wide (6 rows) by 20 m long). Only the third and the fourth rows were considered for measurements. For each measurement day, different treatments were induced within a sub-plot in order to minimize the variability in phenological stage between sub-plots. Between measurement days, sub-plots were irrigated in accordance with the commercial plot, thus all sub-plots were irrigated with similar overall irrigation amounts (with some differences). An additional treatment denoted by F in Figure 1 was irrigated with drippers at 80% irrigation rates and Commercial sub-plots irrigated with sprinklers with 100% irrigation rates. These two treatments will not be further described in this report.

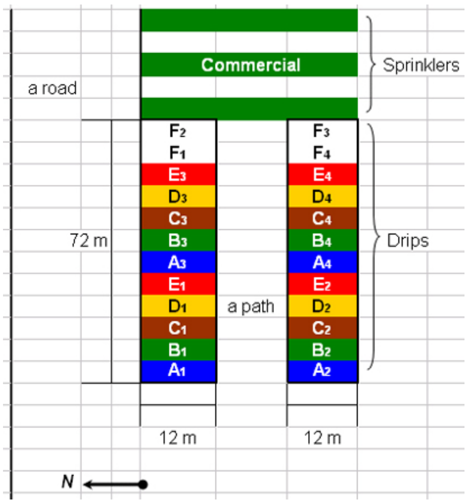


Figure 1: Experimental set-up.

A-E: irrigation treatments;

F: 80% irrigation rate with drippers; and

Commercial: 100% irrigation rate with sprinklers

FIELD DATA COLLECTION:

Field data were collected 5 times throughout the growing season at around the time of solar zenith (1130-1430 local time – GMT + 2 h) (Table 1).

Table 1: Data collection for plant and soil water status measurements in spring season 2010

Measure	Date					
	Mar. 25	Apr. 11	Apr. 21	May 5	May 20	Jun. 7
Soil water content (SWC)	✓		✓	✓	✓	
Leaf osmotic potential (LOP)	✓		✓	✓		
Leaf water potential (LWP)	✓	✓	✓	✓		
Stomatal conductance (SC)	✓	✓	✓	✓		
Thermal and RGB image acquisition	✓	✓	✓	✓	✓	
Yield sampling						✓

Plant and soil water status readings were taken 3-4 times throughout the growing season. Stomatal conductance (SC), leaf water potential (LWP) and leaf osmotic potential (LOP) were measured in 4-6 leaves from each replicate in each date. SC was measured using the Decagon leaf porometer (Decagon Devices, Inc., Pullman, WA, USA); LWP was measured using a pressure chamber (model ARIMAD 1, Mevo Hama Instruments, Israel), as described by Meron et al. (1987); and LOP was measured in the laboratory, as described by Heuer and Nadler (1995). The measurements were taken at the terminal leaflet of the fourth leaf from the apex of the shoot. Soil water content (SWC) was measured gravimetrically from samples taken from each treatment at depths of 20, 40 and 60 cm.

Thermal images of the plots were taken with an uncooled infrared thermal camera. The camera (ThermaCAM model SC2000, FLIR systems) had a 320×240 pixel microbolometer sensor, sensitive in the spectral range of 7.5-13 nm, and a lens with an angular field of view of 24°. The camera was mounted at a height of 10 m above the ground, pointing downwards. The canopy height was about 1 m, so the images had a spatial resolution of 2 cm/pixel. RGB images were also acquired to enable the distinction between soil and plants and to detect sunlit leaves for further analysis.

A weather station was located adjacent to the experimental plot, and measured and stored air temperature, relative humidity and wind speed. Meteorological data were acquired every 10 s and average values over 1-min intervals were stored.

DATA ANALYSIS:

Thermal images were processed with digital image processing tools using ENVI 4.3 software (ITT Visual Information Solutions, Boulder, CO, USA). TIR and RGB images were aligned and registered. Then, the co-registered images were used for segmentation of sunlit leaves using vegetation indices and local geo-statistical measures. Canopy temperature was extracted and statistical regression models were built with the plant and soil water status measurements.

RESULTS AND DISCUSSION:

Figure 2a presents thermal images of treatment Tr-8 and Tr-0 from the second date. Figure 2b presents the process of selecting pixels representing sunlit leaves in the thermal image using the RGB image.

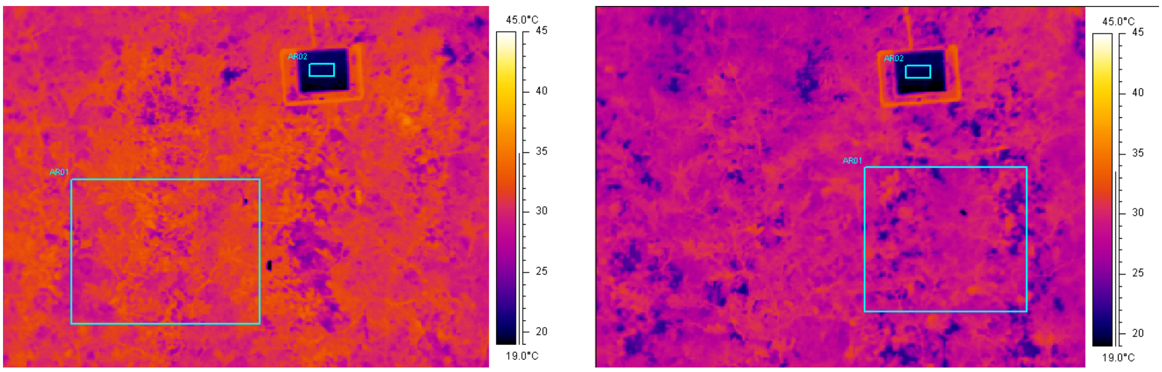


Figure 2a: False colors of thermal images of potato experimental plots. On the left an image above Tr-8 and on the right an image above Tr-0. Potato plants inTr-8 have higher temperature than those in Tr-0. The dark square is the wet reference for CWSI calculation. The displayed temperature range is 19-45^{0}C.

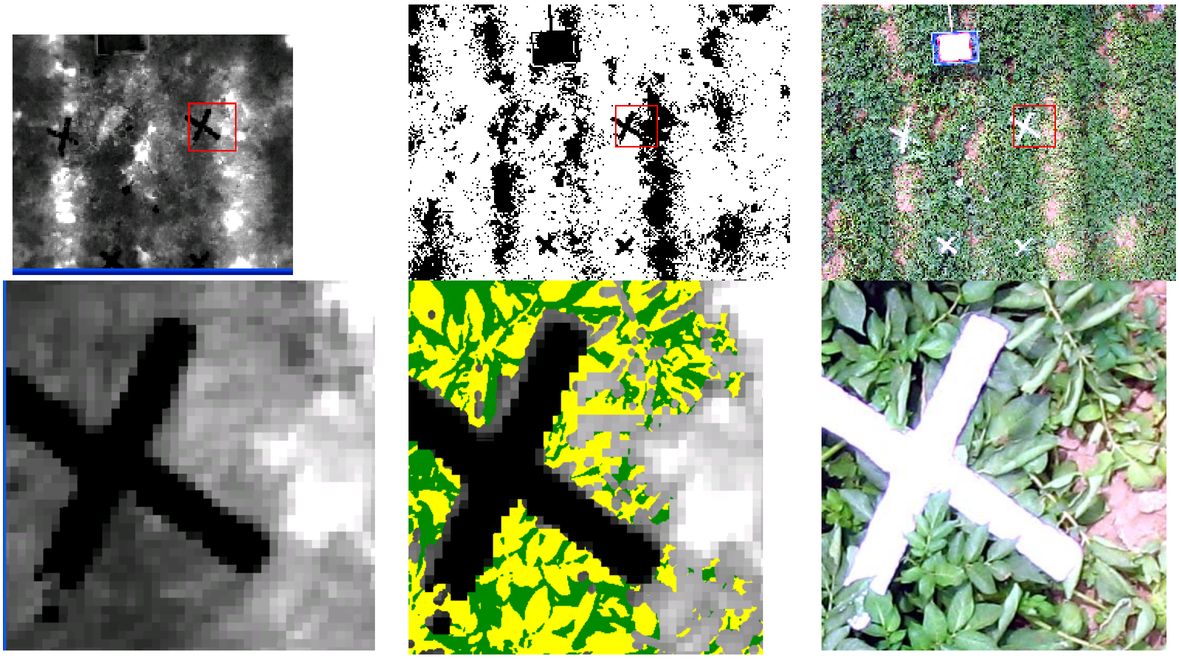
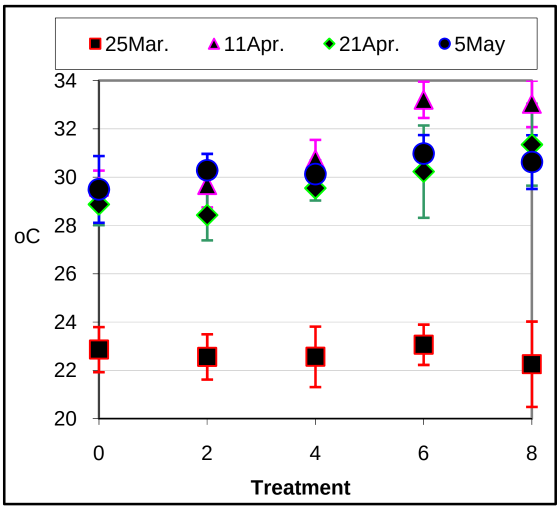


Figure 2b: Delineation of sunlit leaves. *Top: co-registered images, thermal gray scale (left), vegetation mask (middle) and RGB (right). Bottom: Zoom-in to the marked area in the top. In the middle, the colored pixels over the thermal image represent leaves: shadowed in green and sunlit in yellow.*

Following the detection of sunlit leaves, the modal temperature of the image was extracted. The extracted temperatures and SWC averaged by treatment in each date are presented in Figures 3 and 4, respectively. As expected, SWC and canopy temperature exhibited opposite trends. While SWC decreased with deficit irrigation throughout the season, canopy temperature increased over the last three dates of measurement.



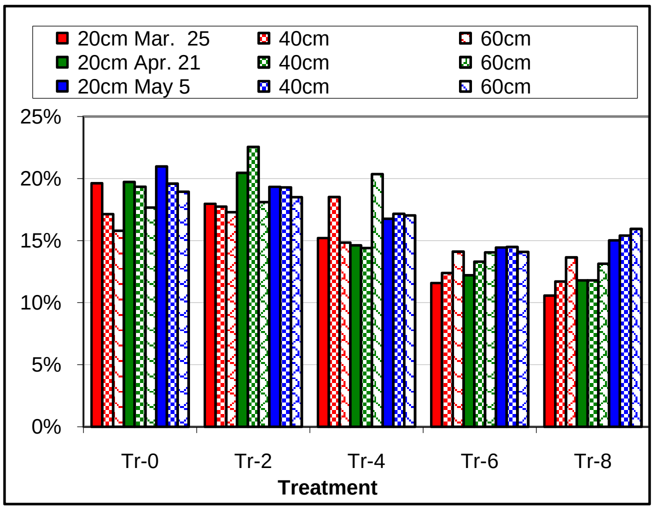


Figure 3: Canopy temperature by treatment and measurement day.
Error bars are confidence interval at p=0.05.

Figure 4: Soil moisture related to treatment, measurement date and depth.

In the first day of the measurements, the plant measures including canopy temperature showed low values of water stress (relatively low canopy temperatures, low negative LWP and LOP and high SC) and there were no differences between treatments (Figure 5). The difference between the first and the later dates might be explained in two ways: 1. despite the differences in SWC between the treatments, the plants did not express any water stress; or 2. the plants were still in their vegetative stage and all selected plant measurements did not represent the water status well. The second explanation is supported by a similar phenomenon found in cotton (Sela et al., 2007).

The canopy temperatures from all dates showed good correlations with plant water status measures. The good correlations were partly achieved because of the significantly different values measured on the first day. Poor correlation was found between canopy temperature and SWC (0.2).

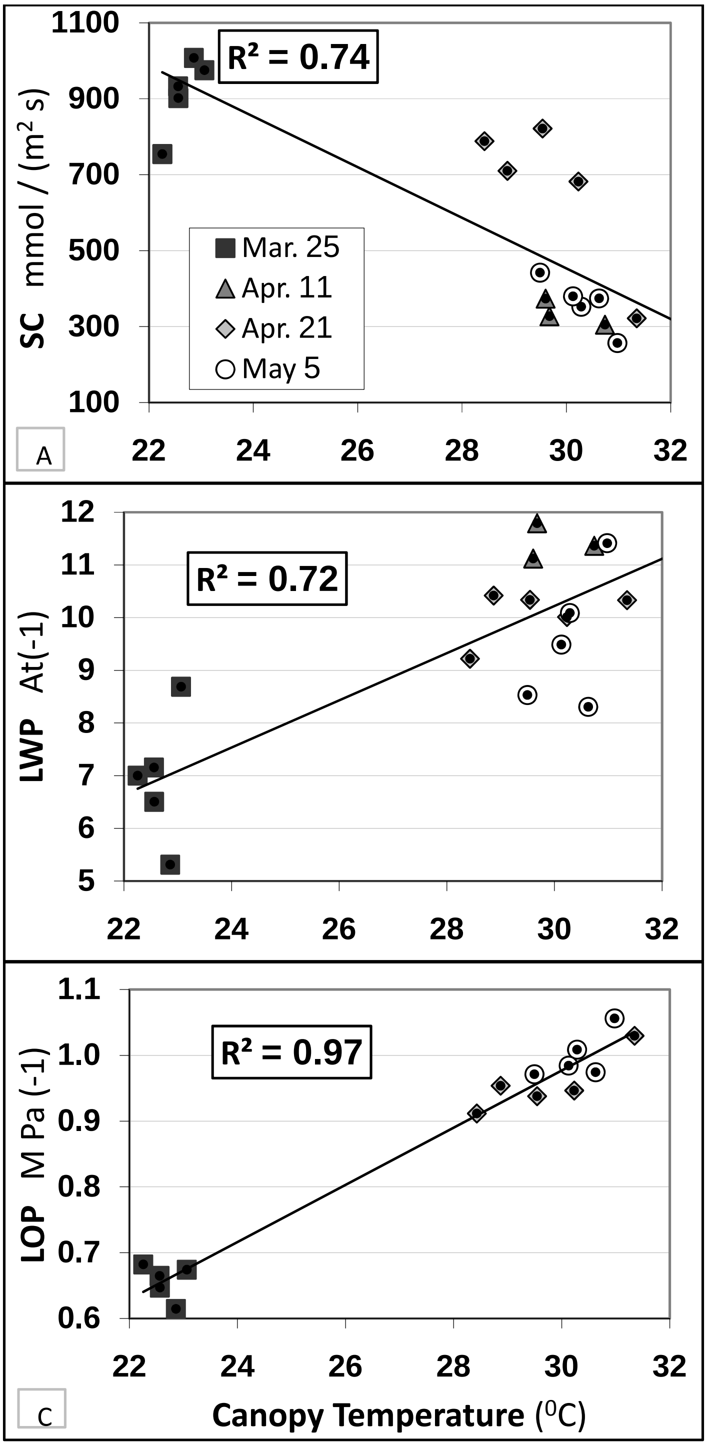


Figure 5: Canopy temperature plotted against SC (A), LWP (B), and LOP (C)

When the values from the first day are excluded, medium correlations are found between canopy temperature and all measures except LWP (Table 2). Along with that, the ranges in all plant measures are significantly reduced in size but to a lesser extent with the SC measure. For the next season we may try to increase the plant water status range in the productive stage by increasing the days with no irrigation before measurement days.

Table 2: Range of water status measures and correlation level with canopy temperature in all measurement dates and when the first date is excluded

		All dates		First date excluded	
Measure		R^2	**Range**	R^2	**Range**
Stomatal conductance (SC) (mmol/m^2 sec)		0.74	824	0.25	638
Leaf water potential (LWP) (Atm -1)		0.72	6.5	0.56	3.5
Temperature (^{0}C)			10.9	0.13	4.8
Leaf osmotic potential (LOP) (MPa -1)		0.97	0.44	0.68	0.14
Soil water content (SWC) (%)	20 cm	---	10.4	0.54	9.7
	40 cm	---	10.8	0.63	10.7
	60 cm	---	7.2	0.50	7.2

The stronger correlation achieved between LOP and canopy temperature may be due to the low variability in the measurement of the two parameters. Table 3 presents the coefficient of variation for plant and soil water status measurements. The canopy temperature, LOP and SWC have low variations (with some exceptions in SWC). In comparison, the SC and the LWP suffer from medium and very high variations, respectively. The SC was measured with Decagon porometer which appears to be unstable. In the next season we will use also the Licor-6400 which is much more complicated to use, but may provide greater accuracy.

<u>NEXT STEPS:</u>

Fusion of thermal and RGB images to extract canopy temperature will be enhanced by: 1. Using an automatic co-registration methodology developed in a parallel study funded by BARD; 2. using an unmixing methodology described in the proposal. CWSI will be calculated empirically by the artificial wet surface (Figure 1) and theoretically using the energy balance. The use of CWSI instead of canopy temperature might improve the correlation between canopy temperature and water status measurement by calibrating the effect of meteorological conditions.

Table 3: Coefficient of variation in water status measurements

Date	Measurement		Treatments					All Treatments
			Tr-0	Tr-2	Tr-4	Tr-6	Tr-8	
Mar. 25	SC		0.15	0.17	0.16	0.17	0.21	0.37
	LWP		0.28	0.10	0.16	0.26	0.18	0.28
	LOP		0.09	0.10	0.08	0.21	0.13	0.13
	Canopy temp.		0.04	0.04	0.06	0.04	0.08	0.05
	SWC	20 cm	0.01	0.06	0.09	0.11	0.15	0.21
		40 cm	0.04	0.08	0.39	0.07	0.08	
		60 cm	0.05	0.22	0.05	0.07	0.05	
Apr. 11	SC		0.33	0.35	0.44	0.70	0.45	0.50
	LWP		0.13	0.13	0.08	0.08	0.10	0.13
	Canopy temp.		0.03	0.04	0.03	0.03	0.04	0.06
Apr. 21	SC		0.37	0.50	0.82	0.60	0.65	0.63
	LWP		0.21	0.32	0.21	0.21	0.28	0.23
	LOP		0.07	0.07	0.11	0.09	0.07	0.09
	Canopy temp.		0.03	0.04	0.02	0.06	0.06	0.06
	SWC	20 cm	0.03	0.19	0.05	0.06	0.06	0.33
		40 cm	0.06	0.51	0.04	0.06	0.08	
		60 cm	0.06	0.20	0.60	0.04	0.08	
May 5	SC		0.68	0.76	0.33	0.64	0.52	0.57
	LWP		0.23	0.17	0.21	0.14	0.22	0.20
	LOP		0.11	0.04	0.09	0.05	0.07	0.08
	Canopy temp.		0.05	0.02	0.02	0.03	0.04	0.03
	SWC	20 cm	0.02	0.02	0.03	0.04	0.06	0.13
		40 cm	0.04	0.04	0.02	0.04	0.05	
		60 cm	0.01	0.03	0.02	0.05	0.03	
Average for all days and all treatments	SC							0.69
	LWP							0.28
	LOP							0.20
	Canopy temp.							0.13
	SWC							0.24

USA

Following approaches outlined in the proposal, experiments in the USA during the first year investigated and characterized the ability of spectral data and imagery to evaluate N level and water status of potato plants under combined stress (Objective 2).

STUDY SITE & EXPERIMENTAL DESIGN:

Field experiments were conducted in the summer of 2010 at the University of Minnesota Sand Plain Research Farm near Becker, MN. The soil at the site is classified as a Hubbard loamy sand. Experiments were conducted on two potato varieties (Russet Burbank & Alpine Russet), with two irrigation rates (conventional irrigation and water stressed – by the checkbook method), and with five different N treatments (Table 4). Note that N treatments 3 and 4 had similar rates and timing, however, N treatment 4 was treated with a soil surfactant (IrrigAid Gold®) at a rate of 2.5 L/ha. Each treatment was replicated four times. The planting N source was diammonium phosphate, and the emergence N source was urea. Post-hill N was applied as a 1:1 mixture of urea and ammonium nitrate by hand on crop canopies, and was watered in immediately by overhead irrigation.

Table 4: N application rates and timing.

N Fertilizer Application Rates (kg/ha)					
		Timing of Application			
Treatment		Planting[1]	Emergence[2]	Post Hill UAN	Total N
1	Starter Only	34	0	0	34
2	180 N Conv.	34	78	17 (*4)[3]	180
3	270 N Conv.	34	124	28 (*4)[3]	270
4	270 N + Surf.[5]	34	124	28 (*4)[3]	270
5	270 N early	34	124	112[4]	270

[1]16 April; [2]17 May; [3]Applied 3 June, 16 June, 7 July, & 19 July; [4]Applied 3 June;
[5]Surfactant was applied 24 May.

A randomized split-split plot design was used for the experiment (Figure 6).

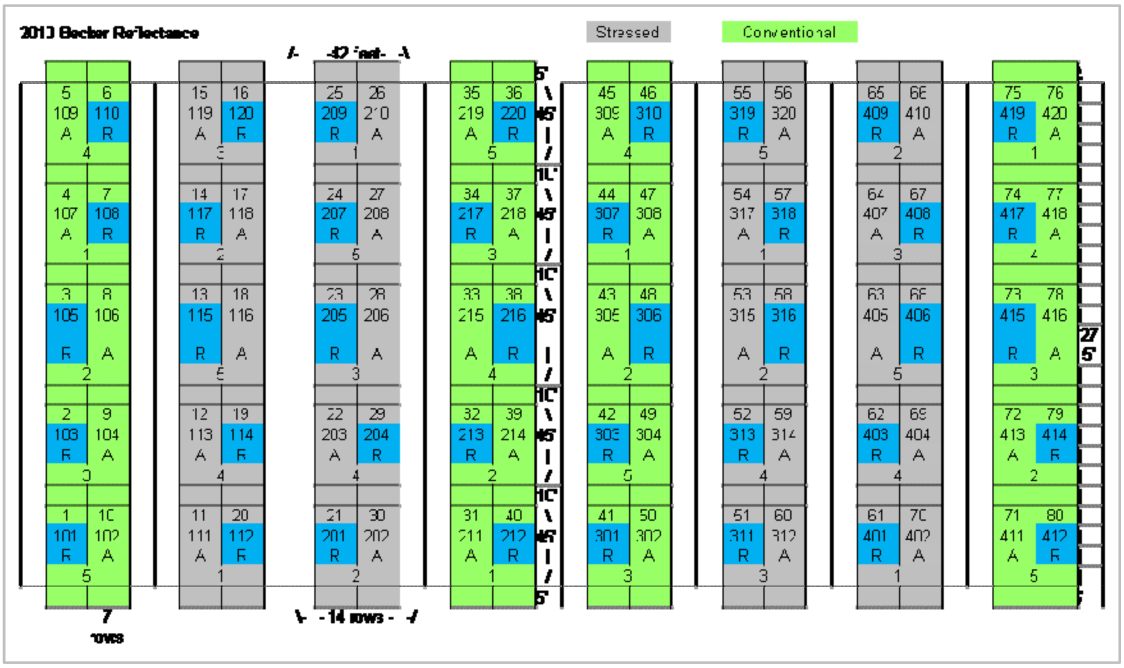


Figure 6: Experimental design at the Sand Plain Research Farm, Becker, MN. *R denotes Russet, A denotes Alpine varieties of potato.*

Irrigation was the main plot, fertilizer treatment was the subplot and variety was the sub-subplot. Row spacing was 91 cm between rows, 30 cm within rows, and seed pieces were individually placed by hand 30 cm apart. Each plot consisted of seven 13.7 m rows, and only the third and fourth rows from the alleys were considered for yield. Rows were mechanically hilled at plant emergence. Chemicals were applied as needed during the season for the control of pests, disease, and weeds according to standard practices. Overhead supplementary irrigation was applied according to the checkbook method. Water was limited on the water stressed plots by reducing the amount of irrigation applied on each irrigation date. There was no precipitation at least three days before each fly-over date, and irrigation was completely withheld on the water stressed plots during this time. Weather stations located throughout the plots measured and stored rainfall, soil matric tension, air temperature, and leaf canopy temperature data hourly.

<u>FIELD DATA COLLECTION:</u>

Petiole and leaflet samples and chlorophyll meter readings were taken five times throughout the growing season. Chlorophyll readings were taken with a Minolta SPAD-502 chlorophyll meter to measure relative chlorophyll content on 20 plants per plot. The measurements were taken on randomly selected plants at the terminal leaflet of the fourth leaf from the apex of the shoot. Measurements were made at a central point on the leaflet between the midrib and the leaf margin. The 20 measurements from each plot were averaged to represent a single SPAD value for each treatment plot. The petioles of these leaflets were collected at the time the measurement took place, and all leaflets were stripped from the petiole and both the petioles and leaflets were separately saved for analysis. Petioles and leaflets were dried, weighed, and ground; analysis for NO_3^-, NH_4^+, and total N has just begun.

Leaf area index (LAI) was measured with a LAI-2000 plant canopy analyzer on five dates throughout the growing season. On each date, there were two replications made for each treatment plot. Each replication included one above-canopy reading and four below-canopy readings for a total of eight below canopy readings per plot. The four below canopy readings for each replication followed diagonal transects spaced 0%, 25%, 50%, and 75% of the distance across the row to improve the spatial coverage. An opaque mask with a 45° opening was used to restrict the view of the fish-eye lens, so direct sunlight hitting the lens was limited. Readings of LAI were taken in the late morning or early afternoon. The shadow of the operator was used to shade the lens if necessary.

Ground measurements for reflectance were taken on six dates with an MSR16R Cropscan on the same day or within two days of the SPAD readings. Field-of-view diameter of Cropscan measurements are about ½ the height of the sensor above the plant canopy. Scans were taken one meter above the canopy on 4 June in 2010 (before full cover), to minimize the effect soil had on the readings. For the remainder of the measurements when little or no soil was exposed, scans were taken 2 meters above the canopy to give an approximate field-of-view diameter of one meter.

On the days of the flyovers (1 July and 6 August), thirteen subsamples were taken per treatment plot so Cropscan subsamples could be matched and compared to individual pixels from the aerial hyperspectral imagery. On these days, subsamples were taken over the third row from the alley along the side of each treatment plot at 1.52m, 3.35m, 5.18m, 7.01m, 8.84m, 10.67m, and 12.50m, as well as over the fourth, fifth, and sixth rows at both ends of each treatment plot (Figure 7). On the end rows, the operator was careful not to include the marker plants in the measurements. When readings were taken on non-flyover days, three subsamples were taken over the third row from the alley along the side of each treatment plot at 3.35m, 7.01m, and 10.67m.

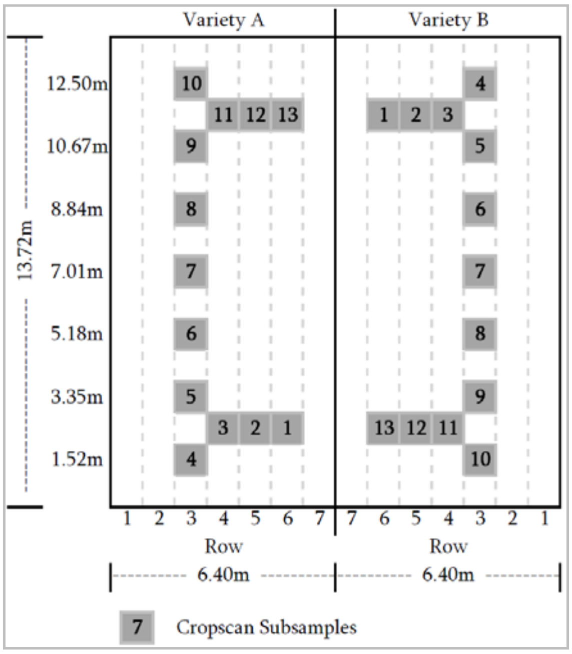


Figure 7: Approximate locations of Cropscan readings on 1 July and 6 August 2010.

Soil matric tension was measured with granular matrix soil moisture sensors (Watermark Model 200) in and below the root zone. Data loggers were located in four locations and each recorded matric potential (kPa) in one of four plots. Soil matric tension was measured for both irrigation treatments, both varieties, and N treatments 3 and 4.

Leaf canopy temperature was measured with infrared radiometers (Apogee Model SI-111). Probes were installed approximately 2 meters high and were aimed at a 45° angle and measured the temperature of the target leaves that represented the top portion of the plant canopy. Measurements of leaf canopy temperature from each radiometer were taken every second and were averaged and recorded every half hour. The infrared radiometers were not installed until 13 July.

For measurement of soil water NO_3 concentration, lysimeters were installed 120 cm vertically below the third hill of each Russet Burbank plot. Soil water samples were collected weekly or following any significant rain event in which drainage was suspected to occur. Samples will also be collected after ground thaw in the spring of 2011.

Aerial hyperspectral and thermal remotely sensed images were acquired with an AISA Eagle VNIR hyperspectral imaging sensor and a FLIR Systems ThermaCam SC640, respectively, by the Center for Advanced Land Management Information Technologies (CALMIT) at the University of Nebraska-Lincoln, USA. AISA Eagle is a complete, pushbroom system, consisting of a hyperspectral sensor head, miniature GPS/INS sensor, and data acquisition unit in a rugged PC with display unit and power supply. It has a 1,000 pixel swath width and was configured to capture imagery in 63 bands covering a spectral range from 392 to 982 nm, with band widths ranging from 8.76 to 9.63 nm. The spatial resolution is 1.0 m and 0.75 m for the 1 July imagery and the 6 August imagery, respectfully (cloud cover on 6 August forced the pilot to fly at a lower elevation than was intended). Thermal imagery was collected with an infrared camera in the spectral range from 7.5 to 13 µm with a spatial resolution of 0.75 m.

A post processing software package, CaliGeo, was used for radiometric correction (using NIST traceable calibrations) and rectification (using a C-Migits III GPS/INS unit manufactured by Systron Donner Inertial Division, Walnut Creek, CA, USA). To be able to better match Cropscan subsamples to the individual pixels from the hyperspectral aerial imagery, locations of plot corners were acquired by using a 0.3 m accuracy GPS unit, and in-house geo-referencing will be done. Plot corners will be used to geo-reference the corrected images to the Universal Transverse Mercator (UTM) World Geodetic Survey 1984 (WGS-84), Zone 15 coordinate system using ERDAS Imagine. The data from the aerial hyperspectral and thermal imagery will be extracted and the effects on irrigation, variety, and N treatment will be analyzed. Additionally, the hyperspectral imagery will be compared to the Cropscan measurements and the thermal imagery will be compared to the leaf canopy temperatures that were measured with the infrared radiometers.

Vines were manually harvested from the middle three meters of the two harvest rows (rows 4 and 5) and weighed on 10 September. On 28 September, tubers were mechanically harvested from the fourth and fifth rows. Vine and tuber samples from each plot were collected to determine dry matter content and N uptake. Marketable tuber yield, tuber quality, specific gravity, and zero and six month sugar content was/will also be measured from tuber samples. Following harvest, four soil cores to a depth of 61 cm from each plot were collected to determine the residual soil inorganic N.

<u>RESULTS AND DISCUSSION:</u>

Average daily air temperature and cumulative water totals from the reflectance plots are shown in Figures 8 - 9, respectively. Cumulative water totals for the conventional plots were approximately 100 mm greater than for the stressed plots throughout the growing season.

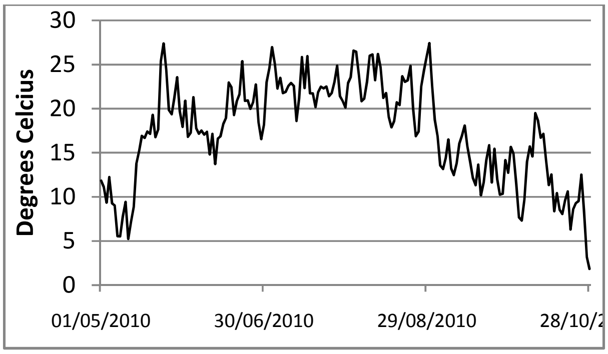


Figure 8: Average daily air temperature in the reflectance plots at the Sand Plain Research Farm, Becker, MN.

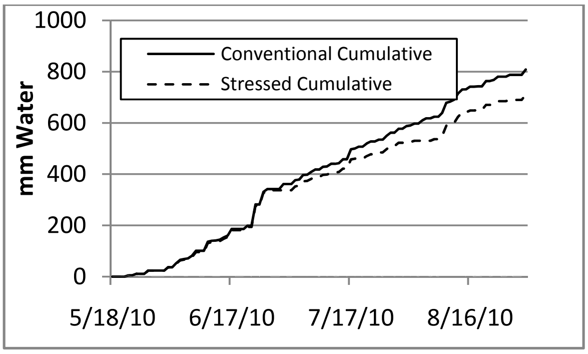


Figure 9: Cumulative rainfall + irrigation totals by irrigation treatment in the reflectance plots at the Sand Plain Research Farm, Becker, MN.

Figure 10 shows matric tension in the root zone throughout the growing season by irrigation treatment for both varieties for N treatment 3. Water stress was limited to short periods in June and July.

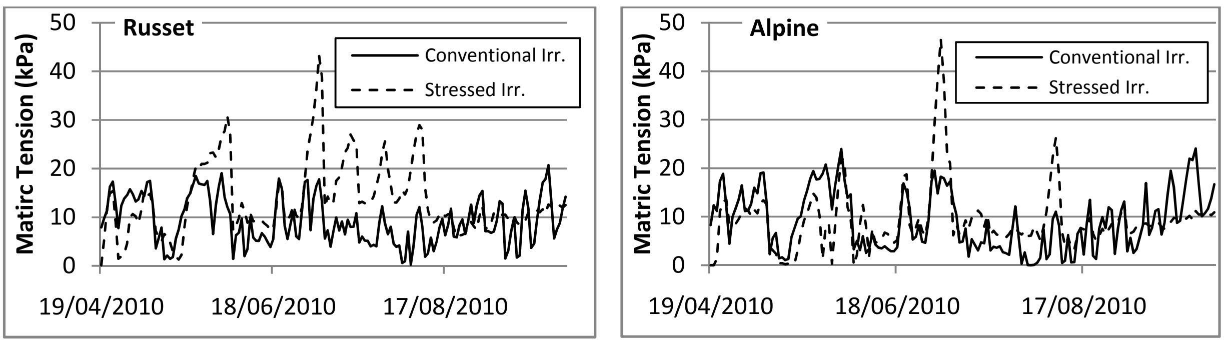


Figure 10: Effect of irrigation treatment on soil matric tension in the root zone throughout the 2010 growing season for Russet & Alpine varieties and N treatment 3.

Figure 11 shows differences in canopy temperature between the conventional and stressed irrigation treatments throughout the day on 6 August for both varieties for N treatment 3. On these two dates, leaf canopy temperature differences between the conventional and stressed plots were greatest during early to mid-afternoon. Differences were negligible in the morning and evening.

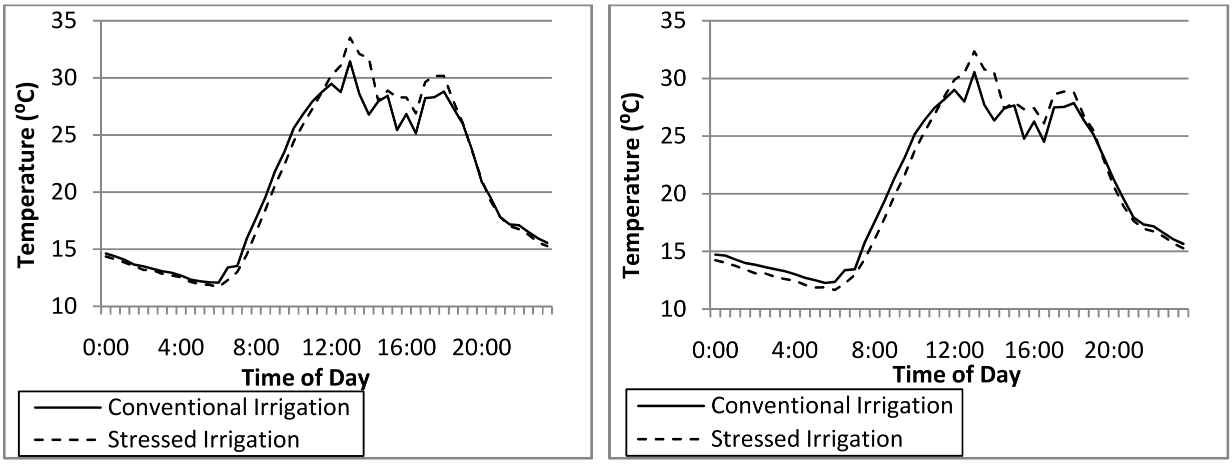


Figure 11: Effect of irrigation treatment on leaf canopy temperature throughout the day of 6 August, 2010 for Russet & Alpine variety and N treatment 3.

Figure 12 shows the effect of irrigation treatment on leaf canopy temperature from the aerial thermal remote sensing imagery from the 6 August flyover. The blue and red dots represent a specific pixel in the Russet Burbank plots and the numbers represent the temperature of that pixel. The blue outline identifies conventionally irrigated plots, and the red outline represents the stressed plots. In all four of the conventionally irrigated plots the temperature is lower than the four stressed plots for the pixels used in the example.

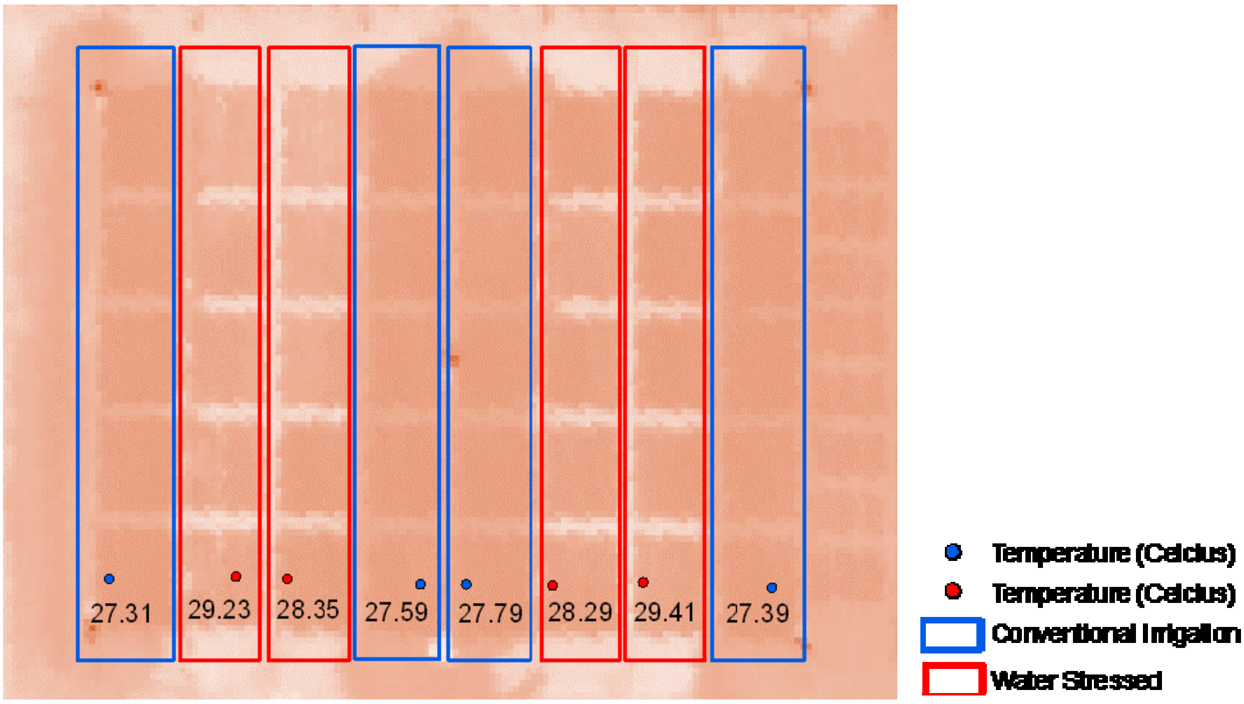
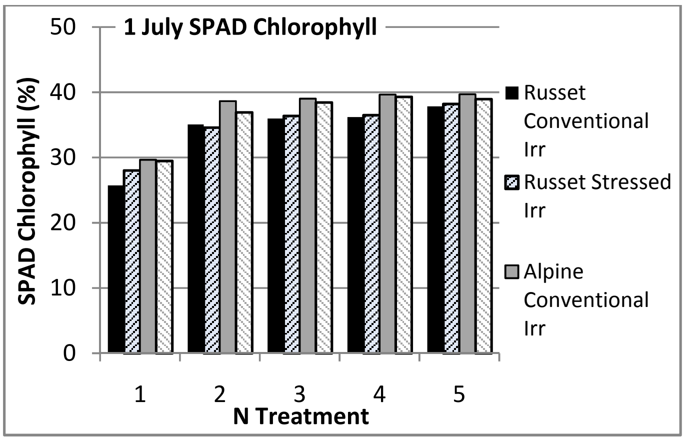


Figure 12: Effect of irrigation treatment on leaf canopy temperature from aerial remote sensing on 6 August, 2010 across the experimental site at Becker, MN.

Figure 13 shows SPAD chlorophyll contents on 1 July and 5 August by N treatment for both varieties and both irrigation schemes. N treatment and timing seemed to affect chlorophyll content. The statistical analysis is in progress.



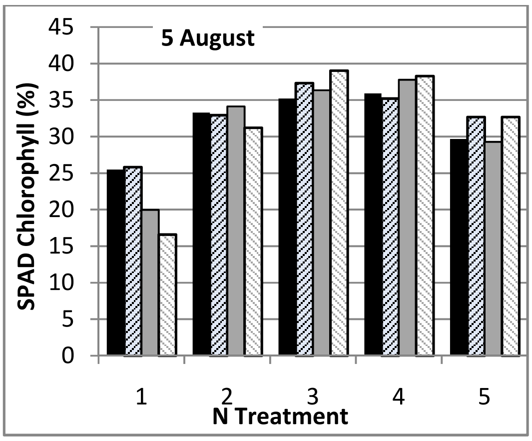


Figure 13: Effect of N treatment, irrigation, and variety on SPAD chlorophyll measurements on 1 July and 5 August 2010

Figure 14 illustrates differences on 1 July and 6 August for measurements of % reflectance (as a function of wavelength) by N treatment for conventionally irrigated Russet Burbank plots. N treatment seemed to affect reflectance, although N treatment 1 is the only one that is distinctly different from the others in the near infrared wavelengths for both dates. The other N treatments had more similar reflectance patterns. Statistical comparisons are in progress.

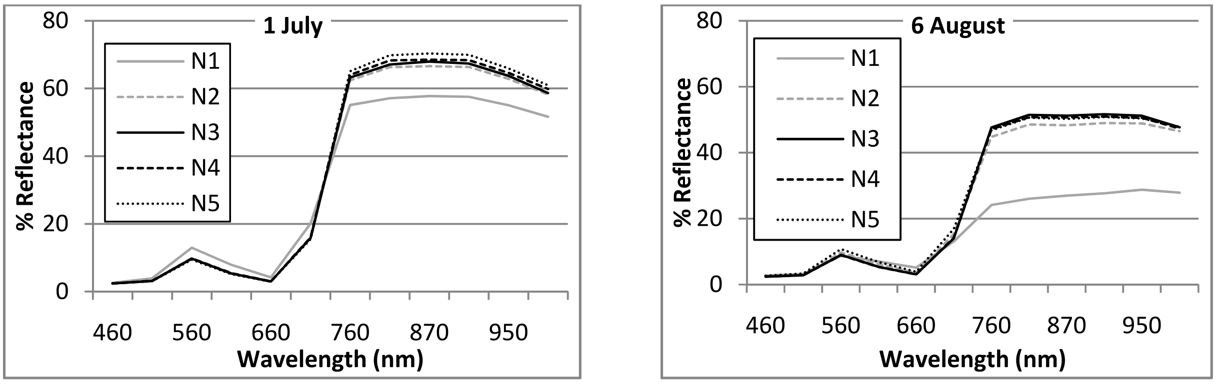


Figure 14: Effect of N treatment on Cropscan readings for Russet Burbank variety and conventional irrigation on 1 July and 6 August, 2010.

Figure 15 shows the effect of N treatment on leaf canopy reflectance using aerial hyperspectral remote sensing imagery from the 1 July flyover. N treatment and variety appeared to have the greatest effect on canopy reflectance in this imagery. Distinct pixel values have not yet been extracted to make statistical comparisons between treatments.

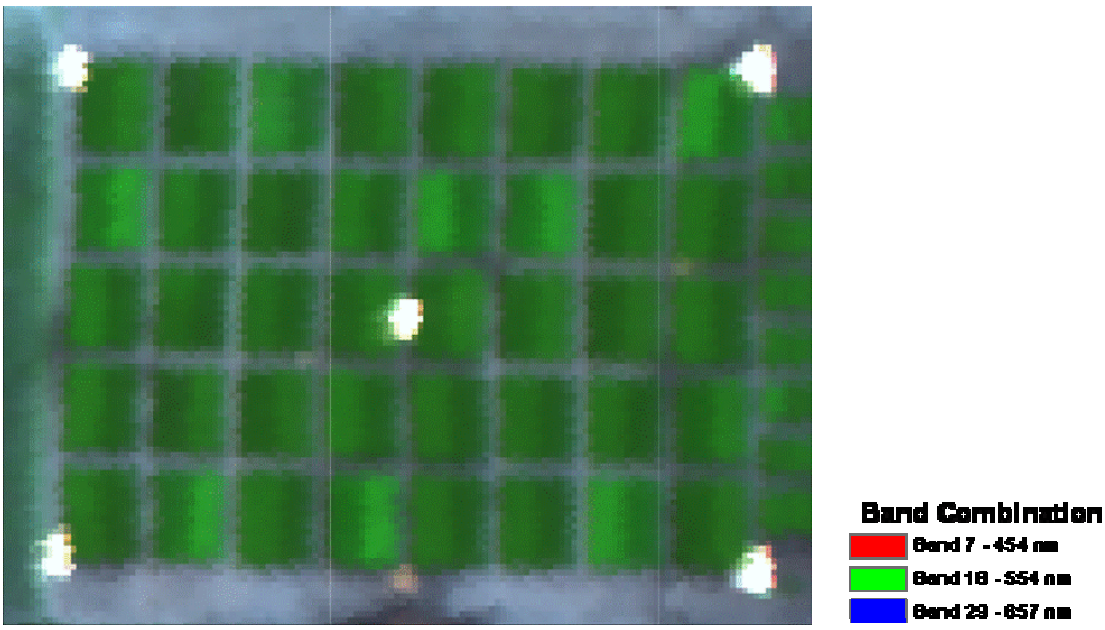


Figure 15: Effect of N treatment and variety on leaf canopy reflectance from aerial remote sensing on 1 July, 2010 across the experimental site at Becker, MN.

Figure 16 shows LAI on 30 June and 4 August by N treatment for both varieties and both irrigation schemes. N treatment seemed to have an effect on LAI; however, the effects of variety and irrigation treatment are inconsistent. This is potentially because of flaws in the methodology used to measure LAI.

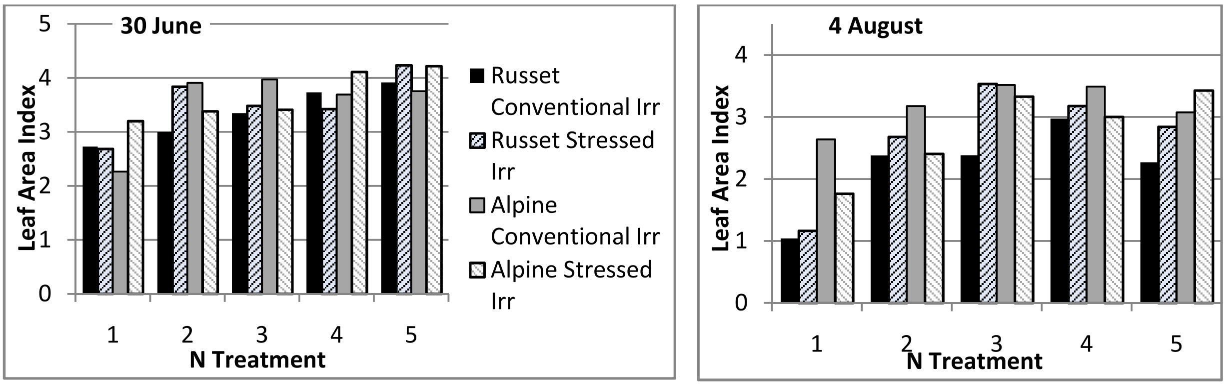


Figure 16: Effect of N treatment, irrigation, and variety on leaf area index measurements on 30 June and 4 August 2010.

Table 5 shows the effects of N treatment, irrigation, and variety on tuber yield and size distribution. In general, total tuber yield and tuber size increased with increasing N rate and this corresponded to increases in relative chlorophyll readings (See Fig. 8). The N treatment by variety interaction was significant for tuber yield and size, indicating that response to N was variety dependent. Moisture stress did not significantly affect tuber yield or size, but yields were greater with conventional than deficient water management.

<u>NEXT STEPS:</u>

Due to radiometric correction difficulties, the 6 August hyperspectral imagery has not yet been received from CALMIT. Once it is received, the hyperspectral and thermal imagery will be geo-rectified to a greater accuracy and data will be extracted for further analysis. Several vegetation indices and chemometric analysis methods will be applied to determine if hyperspectral and thermal data are related to potato quality and yields. The imagery will also be compared to ground-based measurements.

Field samples from 2010 that still need to be analyzed include petioles and leaflets for NO_3-N and total N, groundwater for NO_3, and soil samples for residual inorganic N. All field data (except tuber yield and quality) remain to be analyzed statistically. This experiment will be repeated in 2011 with the addition of plant water stress measurements. Also, Decagon soil moisture sensors will be used in addition to the Watermark sensors, in order to avoid possible errors associated with the Watermark sensors.

Table 5: Effect of N treatment, irrigation, and variety on tuber yield and size distribution.

Main Effects			Total yield	Total Marketable (> 85 g)	> 170 g	> 280 g
			Mt/ha		%	
Variety	Russet Burbank		58.1	48.9	42.2	9.2
	Alpine		59.0	55.4	68.6	28.4
		Significance[2]	NS	**	**	**
Irrigation	Conventional		59.8	53.4	57.3	20.4
	Stressed		57.4	50.9	53.6	17.2
		Significance[2]	NS	NS	NS	NS
N Treatment, P, E, PH[1]	34	34, 0, 0	48.2	39.0	36.7	7.3
	180	34, 78, 17*4	59.5	53.3	58.6	19.6
	270	34, 124, 28*4	61.9	56.2	60.4	23.2
	270	34, 124, 28*4 + Surfactant	63.0	57.4	61.4	23.0
	270	34, 124, 112	60.2	55.0	60.1	20.8
		Significance[2]	**	**	**	**
		LSD (0.1)	2.0	2.5	4.9	4.0
Interactions	Irrigation x Variety		NS	NS	++	**
	N Treatment x Irrigation		NS	NS	NS	NS
	N Treatment x Variety		NS	**	NS	*
	N Treatment x Irrigation x Variety		NS	NS	*	NS

[1]P, E, PH = Planting, Emergence, and Post-Hilling, respectively;

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.