Exploring the Potential of Combined Thermal and Spectral Remote Sensing for Irrigation Scheduling in Potato

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Abstract –We explore the feasibility of using remote sensing (RS) for scheduled irrigation of potato, focusing on the sensitivity of reflectance spectroscopy and infrared (IR) thermometry. Four deficit irrigation (DI) treatments; 100% (Control), 85%, 70% and 55%, were applied. Compared to control, the 55% DI treatment caused a 40.6% decrease in yield and 24.3% decrease in plant height, other treatments being sequential in response. An IR thermometer combined canopy measurements with wet and dry references, to calculate a stress index, I_G. DI had an almost immediate effect on treatments, with a highly significant (P<0.001) effect on I_G after 4 days. Using a spectroradiometer, treatments receiving greater DI were observed to have lower reflectance in both the visible (especially around 550nm) and throughout the near-infrared. Spectral changes were less sensitive than thermal responses; however a combination of both could be complimentary in irrigation scheduling, used to indicate instantaneous stress and stress longevity.

Keywords –, agriculture, I_G index, thermal, precision irrigation, potato, remote sensing, spectral.

1. INTRODUCTION

1.1 Global Water Security

Fresh water resources are limited; however, over 300 million hectares are equipped for irrigation worldwide (Loftas, 1995). Better global water management needs to be achieved to tackle water shortage in the face of climate change (Méndez-Barroso et al., 2008). It is estimated that 50% more food will be required by an increasing global population in the next 30 years. Generally, less than 50% of water extracted for irrigation is effectively used by crops (Hsiao et al., 2007) so greater water use efficiency, water management and legislation are required to manage water resources and increase irrigation efficiency (Loftas, 1995). To meet world food demands, a higher crop yield per unit of water input is required, such that we urgently need to deliver 'more crop per drop' (Grant et al., 2009).

1.2 Remote Sensing (RS) and Precision Agriculture

Over the last 20 years RS tools have become more commercially available and user friendly. The move away from space-borne and satellite sensors to include hand-held and unmanned aerial vehicles (UAV's) means their use in agriculture is becoming more plausible (Hunt and Rock, 1989; Jones et al., 2002). RS can be achieved at ground, air or space platforms/scales (Pinter et al., 2003) and allows the diagnosis of plant stress without using time-consuming, non-representative and/or destructive techniques (Chaves et al., 2003). The concept of precision irrigation is based on applying targeted amounts of water depending on spatial or temporal variation of a crop's requirement (Pinter et al, 2003). This is achieved by returning the same amount of water lost to evapo-transpiration by soil and a growing crop between irrigation events. To date, there has been much research into RS for precision agriculture; however much of the focus has been on higher value crops such as grapes and pipfruit at the expense of research into the use of RS for irrigation of more staple crops such as potatoes.

1.3 The potato

Potatoes are the fourth most consumed crop worldwide (Yuan et al., 2003) and are widely irrigated, making them a viable study crop. Potatoes are more sensitive to water stress than most other major crops and require frequent irrigation to supplement low rainfall (Achtymichuk, 2008). Crop quality and yields can be negatively affected by water stress, by restricting the growth of crop canopy, tuber quantity and tuber biomass. To deliver more water-efficient potato crops, research needs not only to develop more drought-resistant potato varieties, but in parallel to develop more targeted-irrigation techniques. Such an approach to irrigation could be tailored to satisfy specific water requirements and could be altered with growth rate and physiological requirements (Méndez-Barroso et al., 2008).

1.4 Remote sensing to detect water stress in plants

RS is a sensitive technique that can be used to detect spatially and temporally where water is required and in what quantities (Chaves et al., 2003), in the hope of maximizing crop yield and quality (Jones et al., 2002). Such monitoring allows us to quantify water loss via transpiration and photosynthetic efficiency during early stages of stress, well before visual symptoms of stress are apparent (Chaerle and Van Der Straeten, 2000). Although likely to be more expensive than traditional methods, advantages of RS include the quick and easy access and high accuracy across small or large scales, as well as being non-intrusive to crops and soil (Méndez-Barroso et al., 2008).

The main immediate physiological response to water deficit is stomatal closure and inhibition of leaf growth (King and Stark, 1997). These responses protect the plant from excessive water loss, preventing dehydration (Chaves et al., 2003). As transpiration of water occurs from plant leaves, heat is lost (Méndez-Barroso et al., 2008), therefore if there is sufficient water and stomata are free to perform gaseous exchange, leaf temperature will be cooler than that of the ambient air temperature (Yuan et al., 2003). Conversely if the plant is experiencing water stress and stomata are closed, there is less transpirational cooling and leaf temperature increases above ambient air temperature (King and Stark, 1997). Exploitation of these physiological responses can potentially be used to detect and quantify water stress in plants by thermal RS (Jones et al., 2002). IR thermometers determine the temperature of an object's surface by measuring the radiation emitted. Leaf temperature based on only a few point measurements would not allow for spatial variability across a field, whereas RS data could. The index, I_G (equation 1), is a crop water stress index used to describe the temperature of a canopy with consideration of dry and wet reference surfaces, accounting for current ambient temperatures and environmental conditions, (Jones et al., 2002). The closer the canopy temperature is to a dry reference, the more water stressed the plant is and the lower the I_G index.

$$I_G = (T_{dry} - T_1) / (T_1 - T_{wet}) \qquad (1)$$

T_1 = temperature of canopy
T_{wet} = temperature of wet reference surface
T_{dry} = temperature of dry surface (non-transpiring)

Water deficit can also affect the reflectance characteristics of leaves (Chaerle and Van Der Straeten, 2000). Limited water availability can cause structural changes to leaves, including reduced cell turgor and cellular structure, which can be detectable in the near infra-red (NIR) region. A change in actual leaf water content can also affect the amount of reflectance in shortwave IR. Longer term reflectance responses could include changes in pigment concentrations (such as chlorophyll) within leaves, and this would be noticeable in the visible part of the spectrum. The overall canopy structure can also change as a result of water stress. Wilting and changes to leaf angle can cause a decreased canopy area and decreased reflectance throughout the spectrum. Many of these changes are undetectable to the human eye and therefore such RS tools can provide an early detection system for the onset of detrimental environmental stresses such as drought (Chaerle and Van Der Straeten, 2000).

1.5 Aims

Developing precision irrigation techniques is one approach to sustainable water management to maintain future yields. Here, we explore the feasibility of using remote sensing for scheduled irrigation of potato, focusing on the sensitivity of reflectance spectroscopy and infrared (IR) thermometry. This research aims to determine if thermal and spectral reflectance can be used remotely to detect water stress in potatoes, with the objective that irrigation can be accurately scheduled to conserve water and achieve maximum yields.

2. MATERIALS AND METHODS

A preliminary experiment was performed to determine potato water usage through a full cropping cycle to assess optimal water requirement. This was achieved by the gravimetric weighing of pots on a daily basis, and returning the amount of water used in the preceding 24 hours. Further experiments relied on this understanding and the relationship between degree hours and actual water requirement, by calibrating an evaposensor and establishing a 100% control irrigation treatments and deficit (DI) treatments.

Four DI treatments; 100% (Control), 85%, 70% and 55%, were applied to established potato plants (*Solanum tuberosum L. cv Premier*). *Premier*s are a first early variety and do not show a particular resistance to drought. Plants were grown in 10L pots under glasshouse conditions at Lancaster University. Plant heights were recorded throughout and yields determined at the end of the experiment. The 100% (control) crop was grown and irrigated in accordance to accumulated degree hours. The other treatments were irrigated at a percentage of this 'optimal' control. Pots were arranged randomly in 2 blocks of 3 rows, with irrigation treatments applied via drippers. The amount of water given to each treatment was adjusted regularly in accordance to the accumulated degree hours.

Individual canopy temperatures were recorded using an infrared thermometer. In order to determine the I_G index, dry and wet reference temperatures (using leaves from separate control plants) were also recorded. Wet reference leaves were sprayed on both sides with water, to simulate a fully transpiring leaf. Dry reference leaves were coated on both sides with petroleum jelly, to fully inhibit cooling. Wet and dry reference temperatures were taken before and after each canopy temperature reading. Spectral reflectance measurements were also carried out on plants from all treatments every 2 to 3 days, in a darkroom, using a GER1500 field spectroradiometer, with a 500W lamp as a unidirectional light source. A spectral reference panel was used to measure irradiance prior to the target. The reference panel and target objects were placed in the same orientation and the panel level with the top of the canopy. The ratio of the target and reference panel reflectance was used to determine percentage reflectance for each canopy reading. Nine spectra were obtained for each canopy target and averaged, with eight repeats of this across each canopy, taking into account leaves nearest to (fully illuminated) and furthest from (in shade) the light source.

3. RESULTS

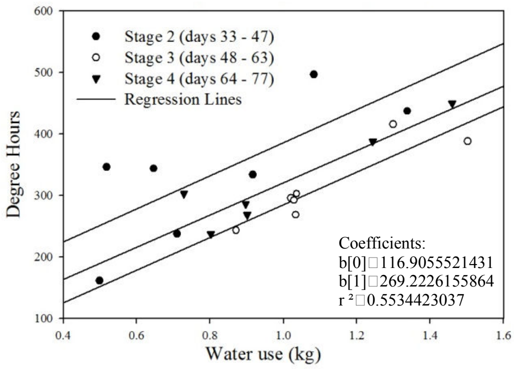

Figure 1. Relationship between accumulated degree hours and water-use at different stages of the potato crop development, as denoted by the key.

Preliminary experiments determined the relationship between degree hours and water use (figure 1). A linear relationship exists between water use and degree hours, with the relationship shifting throughout plant development. Plants in later stages of development used more water for a fixed number of degree hours. These relationships at different growth stages were used in subsequent experiments to schedule irrigation based on the accumulated degree hours.

For plants grown and irrigated as scheduled by the evaposensor and for the resultant DI treatments, yields and plant heights were determined. Compared to the control, the 55% DI treatment resulted in a 40.6% decrease in yield (figure 2) and a 24.3% decrease in plant height (figure 3), with other treatments being intermediate in response.

An IR thermometer combined canopy measurements with those of wet and dry reference surfaces, to calculate an index, I_G (equation 1). DI had an almost immediate effect, with a highly significant (P<0.001) negative effect on I_G in all three DI treatments, from 4 days onwards (figure 4). After this time, the 70 and 55% DI treatments remained largely indistinguishable from one another, with the significant offset throughout the remainder of the experiment. However, the 85% DI treatment had a much more variable response throughout.

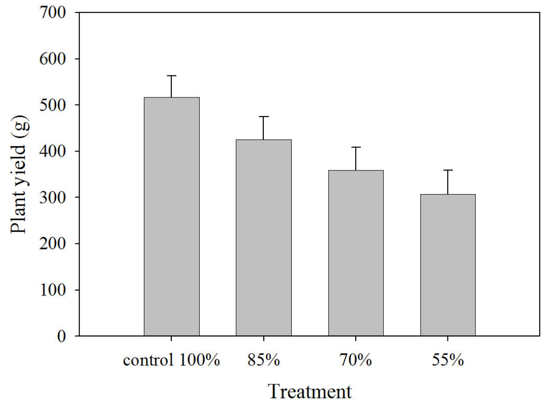

Figure 2. Effect of control and DI treatments on fresh weight yield of potato at final harvest (n = 10, bars = 1 SD).

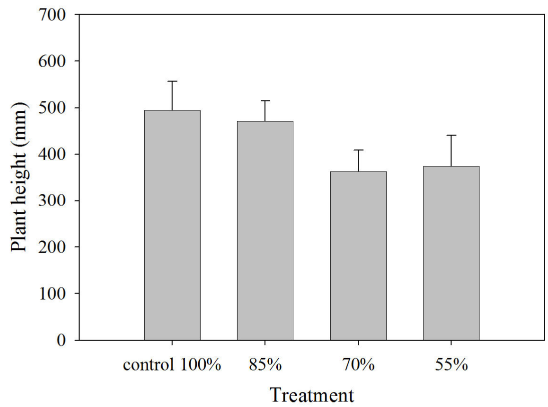

Figure 3. Effect of control and deficit irrigation treatments on the height (mm) of potato plants at 57 days after treatments applied (n = 10, bars = 1SD).

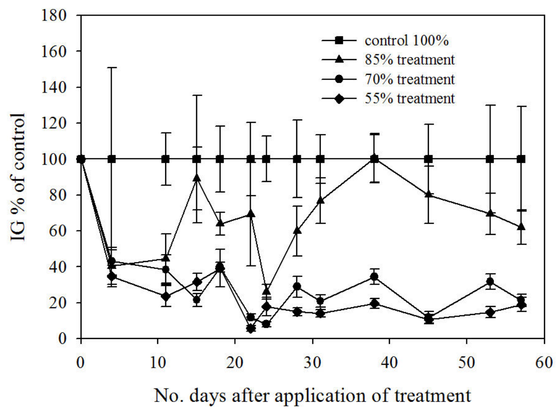

Figure 4. I_G stress index as percentage of control over time for deficit irrigated potatoes, with treatments as denoted by the key, (n = 10, bars = 1 x SE).

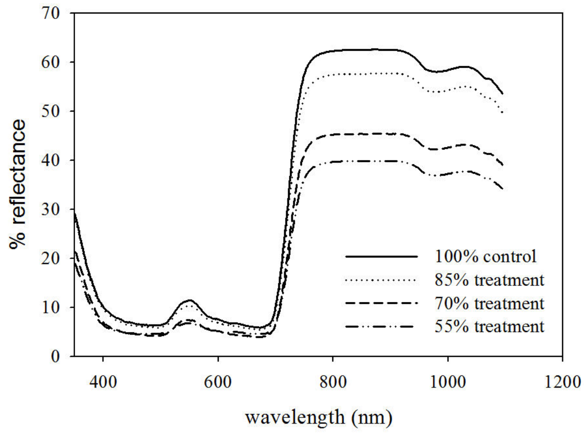

Figure 5. Mean reflectance spectra for control and deficit irrigated potatoes, (32 days after treatments commenced), with treatments as denoted by the key (n=10).

Using a spectroradiometer, treatments receiving greater water deficits were observed to have lower reflectance in both the visible (especially around 550nm, green region) and throughout the NIR region (figure 5).

The main response of reflectance to different irrigation treatments is a decrease across the NIR region. There are clear differences between treatments from approximately 15 days after commencement (figure 6), with more water stressed plants having a lower reflectance across the NIR. The deviation from the reflectance response for control plants grows stronger as time under DI increases, until approximately 45 days and onwards, when reflectance in the NIR appears to recover towards that of control plants.

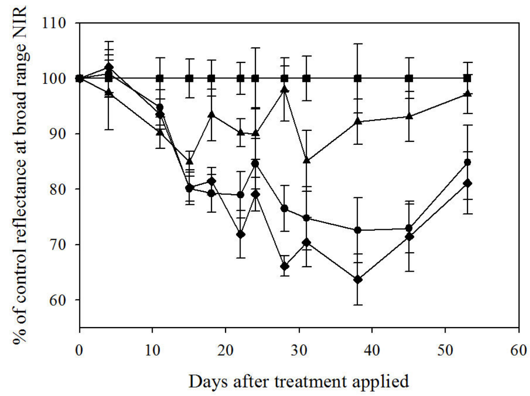

Figure 6. Broad band IR reflectance as a percentage of control over time for DI potatoes, with treatments as denoted in the key of figure 4. (n = 10, bars = 1 x SE).

4. DISCUSSION

Yields were maximised under the 100% irrigation (control) treatment (figure 2). This suggests that preliminary experiments were efficient in establishing the control and subsequent DI treatments and demonstrates that precision irrigation can maximise yields. It is also important to note the correlation between plant height and DI treatments (figure 3). Whilst not investigated in this project to date, height could be detected remotely through laser scanning and used as a tool in detecting longer term stress responses.

We were able to discriminate between treatments almost instantaneously using thermal sensing; indicating that thermal sensing can be used remotely for potato to detect stomatal closure and water stress in plants (Jones and Vaughan, 2010). There are large significant differences between control I_G index values and the highest DI treatments (55% and 70%). However results suggest that thermal sensing of the 85% DI treatment is not consistently sensitive enough to detect such a small deficit in water application. Figure 4 shows that a thermal sensing approach is sensitive enough to demonstrate when plants are stressed and when they have sufficient water (as the 85% treatment does at certain times). Under certain conditions it is likely that the 85% DI treatment is effectively receiving enough water so that it responds similarly to the control. There appears to be a threshold between the greater DI treatments, where further water stress appears to have no further negative effect on the I_G index values. This is supported by results, where the height of 55% DI treated plants was not significantly different from those receiving a 75% DI treatment.

Overall, spectral changes were less sensitive than thermal responses. Spectral reflectance techniques did not detect such immediate differences as IR thermometry, but responses started to develop after about 15 days of experiencing DI. Overall reflectance was actually decreased for water stressed plants, suggesting that differences in spectral responses are a response to longer term stress effects on the canopy characteristics, including degree of wilting, leaf structure, overall canopy shape, depth of canopy. In turn, these factors affect the amount of soil visible through the canopy and further alter spectral reflectance. It has been suggested previously that such factors can have a larger effect on reflectance then the internal leaf changes and actual leaf water content (Datt, 1999). This is most apparent in the NIR and is therefore the most suitable part of the spectrum to monitor. This is important because it demonstrates that thermally there may be differences between water stressed and non water stressed plants, but visually these differences may not be apparent (little change in plant colour/pigmentation). Therefore although a crop may look as healthy as a non water stressed plant, resulting yields may still nevertheless be negatively affected. The last few occasions plotted in figure 6 demonstrate that differences between control and DI plants diminish during plant senescence. During senescence the two least water stressed treatments display reflectance properties that would appear more like those of the water stressed plants (leaf angle and shrivelling leaves revealing more soil and causing a reduction in reflectance in the NIR) resulting in the convergence of responses by all four treatments.

5. CONCLUSION

Results from this experiment support the use of thermal and spectral RS in irrigation scheduling, rather than relying on traditional 'by eye' methods. A combination of both thermal and spectral techniques could be combined to detect water stress in a potato crop. This would indicate stress severity (thermal) and duration of the stress (spectral). However, in the work reported here, neither approach was able to discriminate at DI treatments less than 70% of control. In future work we will test the robustness of these techniques in a more naturally variable field environment.

The ultimate aim of this project is to create a tool for field based precision irrigation for potato crops, without the requirement of *in situ* reference plants within the field. This would require a RS method that could indicate quantitatively how much water a plant requires to return it to optimal functioning, supported by a thorough understanding of how this would be affected by developmental stage.

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