Water Savings through the Use of Wireless Sensor Networks in Irrigated Agriculture: Developing New Low Cost Plant-based sensing technologies

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1. Project Overview:

Novel approaches to irrigation scheduling are becoming critically important as water resources in the Basin come under increased scrutiny. It has been well known for a long time that through increased measurement of plant water requirements, one can dramatically improve yield and quality with less water. However, the challenge has been in implementing the science in a way that accurate and easy to use. This challenge clearly remains since the current uptake of smart irrigation scheduling system is less than 10%. One important reason for this is the lack of irrigation scheduling techniques that can be adapted or scaled across a range of cropping systems with consistent outcomes.

Between 2004 and 2008, the Victorian Government, through the STI grants, funded a joint research initiative between National ICT Australia, The University of Melbourne and Uniwater called Smart Irrigation. The purpose of this project was to develop low-cost wireless sensor networks and irrigation scheduling algorithms for dairy, viticulture and horticulture. This project demonstrated up to 30% water savings in dairy irrigation and up to 75% increases in yield in horticulture. The project laid the foundations for future research in the application of intelligent sensor networks and control algorithm to irrigation science.

Current approaches to irrigation scheduling rely on point-scale measurements of soil moisture. However, due to crop, soil and micro-climate variability, decisions based on point-scale data may not be optimal for the entire field. Overcoming this limitation requires a sensing system with a wider spatial coverage and a rethink of the algorithms that use this data, as well as existing point-scale measurements.

In this project, we propose to develop a new scalable approach to irrigation scheduling and innovative algorithm for developing field-scale water demand prediction models. Our algorithm will use more than one point-scale measurements of soil moisture combined with low-cost, low-resolution thermal images and local micro-climate data, to predict short-term water demand. By combing point-scale soil moisture data with spatial images, the algorithm will enables users to calculate water application rates that are optimum at the field-scale, rather than focused on a single plant. This approach avoids the bias towards a single measurement point that is common in most irrigation scheduling techniques in use today.

Due to the fact of long experimental turnarounds and wide spatial distribution of sensing devices, the approach to separate device management will raise the cost and complexity of experiment. Alternatively, our approach employs low-cost wireless sensor networks to establish a sensing system for data collection and remote storage. It provides user with a lower cost and more efficient way to real-time data access and remote monitoring in contrast with conventional ones.

a. Photosynthesis and NDVI:

The general equation for photosynthesis [5]:

$$2n\ CO_2 + 2n\ H2O + photons \rightarrow 2(CH2O)_n + n\ O2 + 2n\ A$$

Where A denotes oxidized electron donor. From this equation, the process of photosynthesis reaction directly associates with the supply of the water, solar irradiation (wavelength) and concentration of carbon dioxide. They are three main factors that affect the process of photosynthesis, which also can be reflected by the indicator of normalized difference vegetation index (NDVI).

NDVI is a numerical indicator that is used to assess whether there is live green vegetation within the observed region or not. The strong absorption of the solar radiation by live green plants occurs in visual spectral region from 400 to 700 nanometers, also known as the photosynthetically active radiation (PAR) region, where part of the energy required by the process of photosynthesis reaction sources. Therefore, by contrasting with other objects, live green plants appear relatively dark in the PAR region. However, they appear relatively bright in near-infrared spectral region (700 – 1100 nm), because leaf cells have evolved to scatter solar radiation at these wavelengths to prevent from overheating the plant and damaging the tissues and organisms. The NDVI is calculated as follows:

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

where VIS and NIR denote the reflectance measurements of solar radiation in the visual and near-infrared spectral regions, respectively. This spectral reflectance is the ratio of the reflected over the incoming radiation by itself, ranging between 0 and 1. Hence, the calculation of NDVI always varies between -1 and 1.

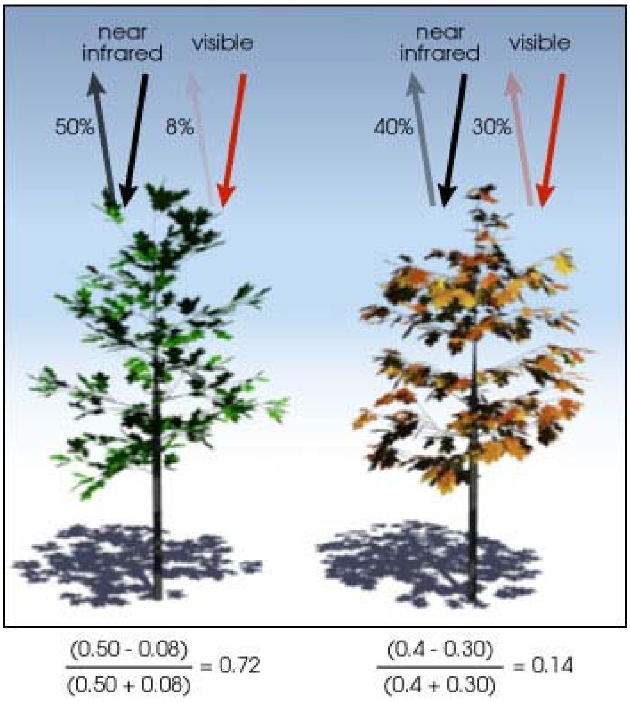

Figure 1 Reflection measurement of NDVI [2]

Instead of capturing the soil moisture that directly reveals the water demand of the plant, this project proposes an alternative approach to achieve this purpose by measuring NDVI, and investigate the relationship between the soil moisture and NDVI in order to develop field-scale water demand prediction models.

b. Cameras:

Professional near-infrared cameras are quite expensive devices that are used for the reflectance measurements of solar radiation in each spectral band individually. Moreover, due to the limitations of its working condition, complexity of configuration and sophisticated maintenance, it is not cost-efficient and realistic to mount them in remote farm fields. Therefore, we utilize low-resolution webcam as substitution because of its low price, compact size and easy usage.

Figure 2 Webcam

Webcam is designed for the general use of image capture. It only allows the visible light passing through by putting a filter behind the lens to prohibit IR light. In fact, webcam has a piece of silicon where there are lots of small sensors to detect light. Each of these sensors is a small diode, and the electronics is trying to push electric current wrong way through it. Normally, due to the nature of the diode, there is no free electron to be pushed wrong way. However, if a photon with enough energy hits the diode, a free electron will be separated from a silicon atom, and electronics measures the electric current produced by the electron movement and the light intensity. Any light with wavelength above middle infrared – near infrared, visible and ultraviolet, has enough energy to do this. Hence, it is feasible to adapt regular webcam to near-infrared camera by replacing the colored filter with near-infrared one. Fully exposed black photographic negative becomes an ideal candidate of the filter, providing its features of allowing near-infrared through and almost prevents all the visible light. Based on the rationale above, we apply both original and adapted webcams to measure the radiation reflectance of the plant, and expect to acquire the comparable quality of images.

c. Soil Moisture Sensors:

Figure 3 ECH2O Soil Moisture Probe

ECH2O soil moisture probe is deployed due to its low cost, high accuracy, low power requirement and easy maintenance. It measures the dielectric constant of the soil in order to find the volumetric water content expressed as the ratio of the volume of water over the total volume (water, soil and air). To accomplish this, ECH2O sensor applies the voltage between two electrodes burned in the soil, and measures its change rate.

d. Wireless sensor networks (WSNs):

Figure 4 NICTOR

The device attaching with sensors is called NICTOR®. It is a low-cost wireless platform that operates IEEE 802.15.4 protocol and provides user with standard I/O interfaces, programmable chip, memory and mechanical relays. Furthermore, build-in sleep/wake-up functionalities substantially prolong the battery's lifetime. This enables the development and customization of applications for diverse demands in commercial and research fields.

Mostly, wireless sensor networks consist of coordinator, transit devices and end devices. Coordinator is the centre node, responsible for coordinating and managing the entire network, whereas transit and end devices possess the same functionality except that the former has to forward the data received its child node to parent. When NICTOR devices are powered on, they will automatically form a network in certain topology. Each of them instructs the local sensors to make measurements by following the pre-installed program, and periodically transmits the data via certain path to the coordinator. Eventually, all the sensing measurements will be sent to the remote server by coordinator via GSM model, and then stored in database.

There is a remarkable enhancement in terms of experimental efficiency and flexibility, by piggybacking the sensors distributed in wide scale on the low-cost WSNs, while the overall expense is still kept in a reasonable level.

2. Experiments:

Figure 5 Glasshouse Complex

In order to minimize the factors that may disturb the sensing measurements, experiments were conducted in Glasshouse Complex [3] in University of Melbourne, which is a research facility catering for the environmental, scientific and legal requirements in the growing of a wide range of plants for various purposes.

It is well known that, photosynthesis of the plant takes place in chloroplasts residing in all the cells of green parts, and leaves are the places where it happens most often and absorbs the most of the energy. To ensure the captured images fully demonstrating this process, green leafy plant is used as the observed object. Experiment setup is shown as follows.

Two cameras (visual and NIR) are collocated and mounted on the top of plant, and sensor is vertically inserted in pot to measure the average value of soil moisture. Images are snapped and then stored in laptop for every one minute, while soil moisture sensor controlled by NICTOR makes measurements at the same sampling rate. A small piece of white paper is placed beside the plant as reference, and intensity in this area is treated as the one of incoming light as assumption.

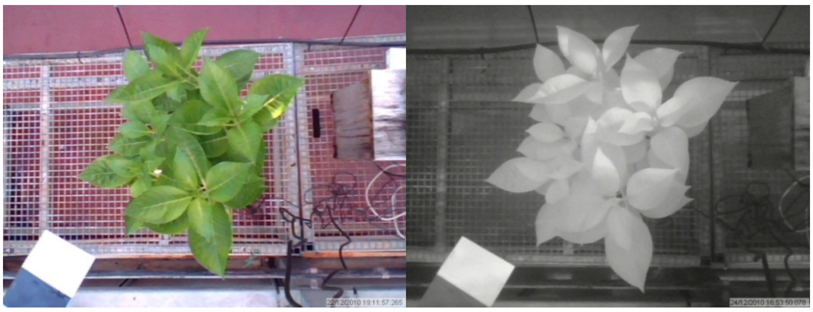

Figure 6 Visual (left) and NIR (right) image

The images taken by visual camera are saved in RGB format, whereas those from NIR camera are in Gray format. Each pixel in grayscale image is a single sample that carries only intensity information, ranging from 0 (black) to 255 (white). However, contrary to grayscale, RGB image is composed of three independent channels of red, green and blue primary color. Each color plane can be converted to grayscale with single intensity value. To calculate NDVI, a way to convert visual (RGB) to single intensity image has to be worked out first. According to the literatures, the formula of calculation of NDVI is not unique. For instance, in NDVI equation, the surface bidirectional reflectance in visual band is replaced with the one in red band [1]. Our approach utilizes red plane of RGB to calculate the surface bidirectional reflectance for visual band, and further investigation shows that close results are yielded by comparing among red, green, blue plane and their average.

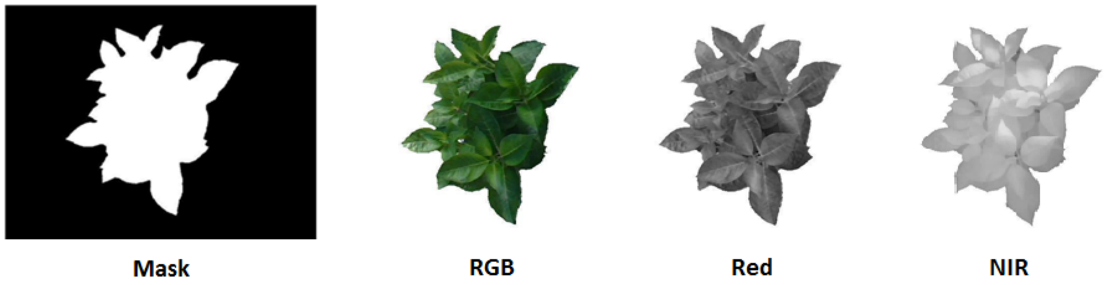

Figure 7

Each pair of pixels (visual and NIR) is of correspondence with a single numerical value of NDVI. To reflect the photosynthesis in overall, the average value of NDVI needs to be calculated within the leaf region. Through image processing, the region only containing leaves is extracted by logical operation between original image and a mask that marks leaves' outline. Finally, for both red and NIR images, average intensity in leaf region over reference intensity gives the reflectance measurement and corresponding NDVI value for that moment.

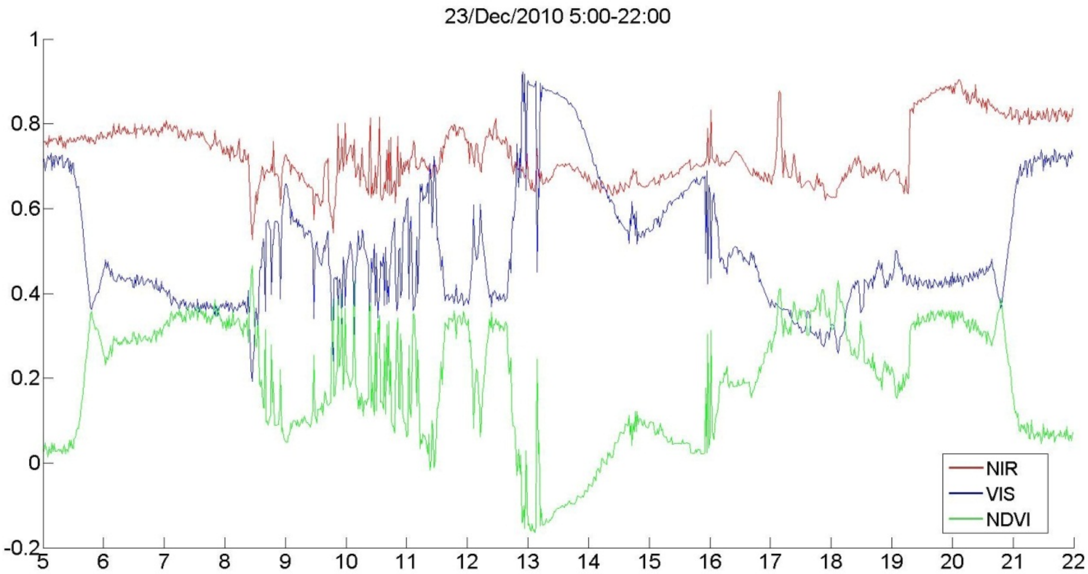

Figure 8

Based on the measurements over several days, it was observed that there is an exceptional leap of reflectance ratio from visual camera during mid-day. According to the knowledge of NDVI, it is an abnormal phenomenon that light reflectance measurements in visual band are much greater than in NIR band for green plant.

Figure 9 Overexposed image

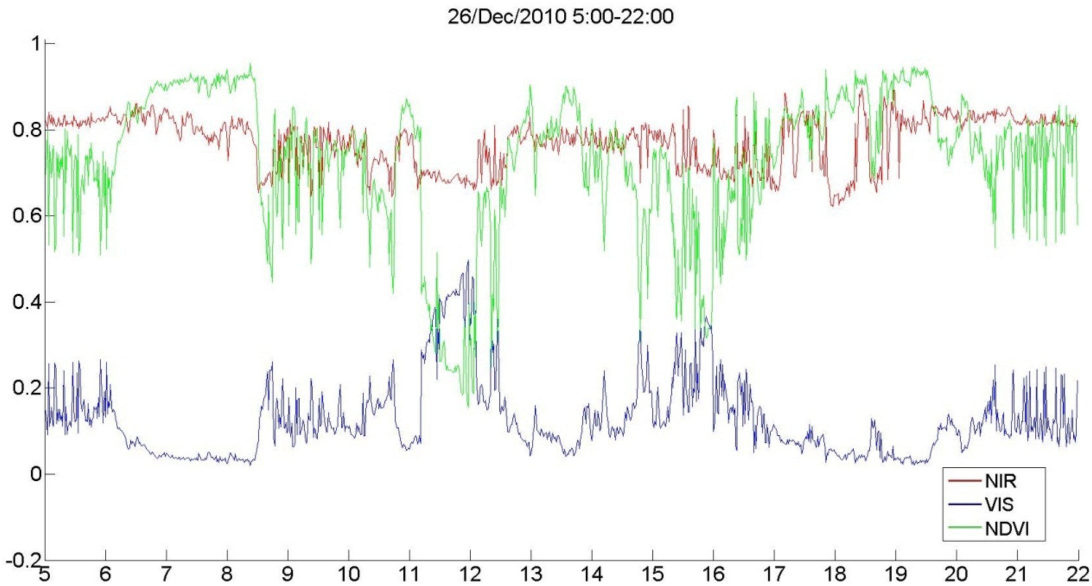

Figure 10

The most likely reason leading to such outcome is the over exposure of images from this period, duo to the limitation of narrow dynamic sensitivity scale of visual camera configured to auto adjustment. To eliminate this distortion, this configuration was changed to fixed brightness, contrast, color saturation etc., and the sensing measurements afterwards tend to have a more typical pattern.

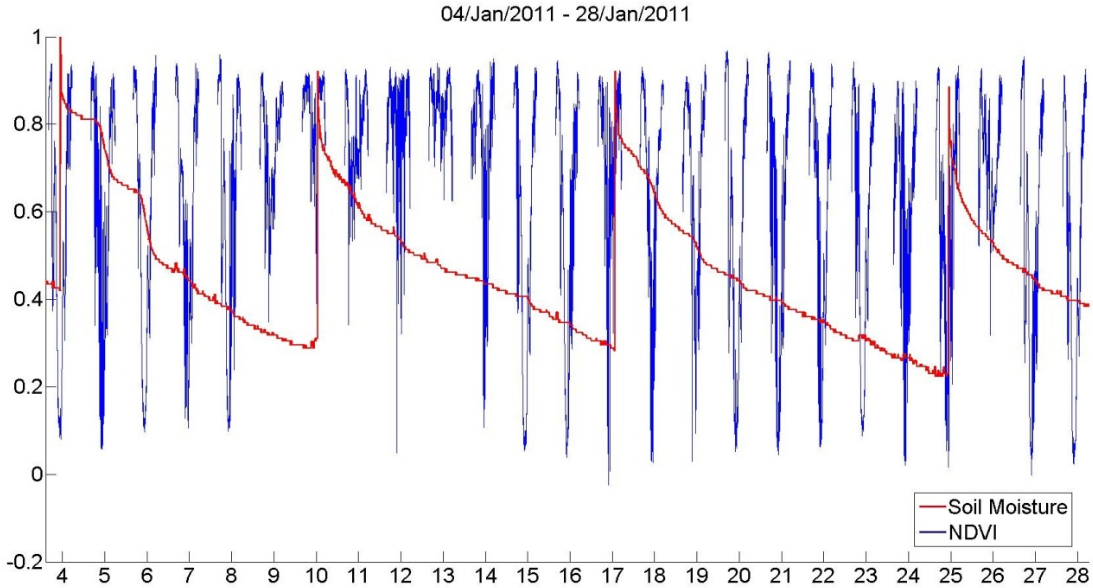

Figure 11

Figure 11 depicts the measurements of NDVI and normalized soil moisture from 4th to 28th in January 2011, where all segments of NDVI during night (9:00PM – 6:00AM) are removed. Total four irrigations were conducted during this experimental period, approximate once per week.

Figure 12

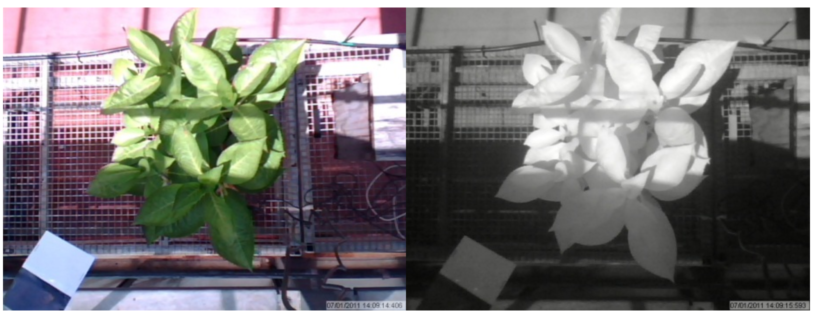

Figure 13 Projected shadows

To intuitively presenting the tendency of variations, the curve of average NDVI (average per day) is plotted as well. Through observation, any evident correlations between NDVI and soil moisture is not provided, so that it doesn't make any sense of applying mathematical models further. Although there seems to be similarity between the patterns of NDVI and soil moisture in some extent from figure 12, however, a more noteworthy fact is that, in figure 11, the values of NDVI fluctuate in a large wide scale for most of days, which far exceed the typical range for vegetation suggested in [2], [4] and [6]. By reviewing both visual and NIR images, we concluded that the source of noise distorting NDVI is likely to be the shadows projected on leaves, as a result of the obstruction of objects on top of plant, like canopy, cloud etc.

Figure 14 Constant Environment Room

Based on the previous experimental conclusion, there are still few uncertain factors existing in glasshouse. To eliminate these impacts, the second experiment was performed from 25th February to 8th March 2011 in constant environment room with temperature, lighting and relative humidity control. The same device setup and experimental approach were applied as the previous one described above.

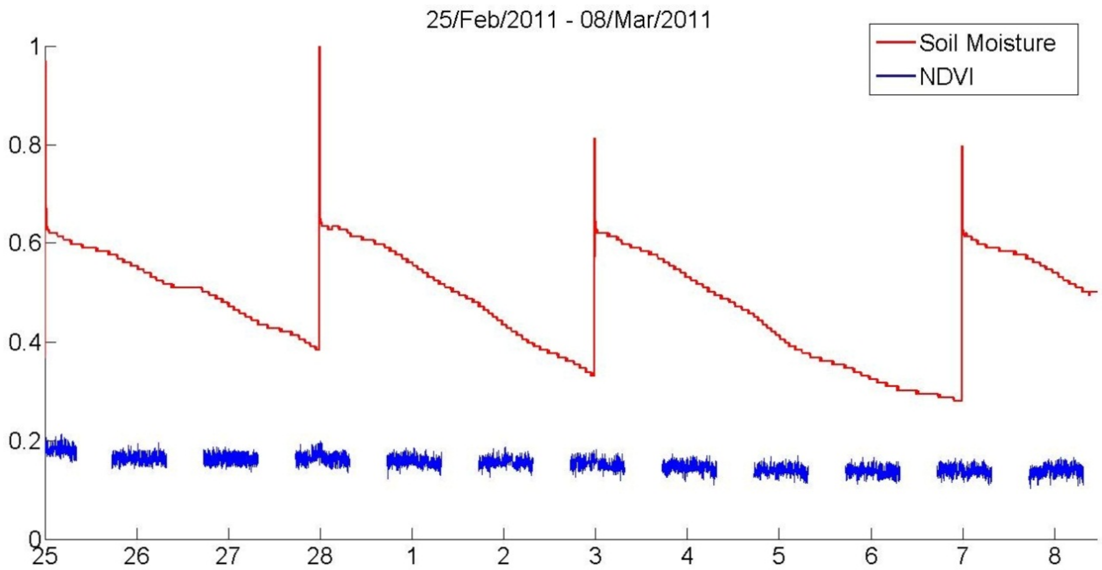

Figure 15

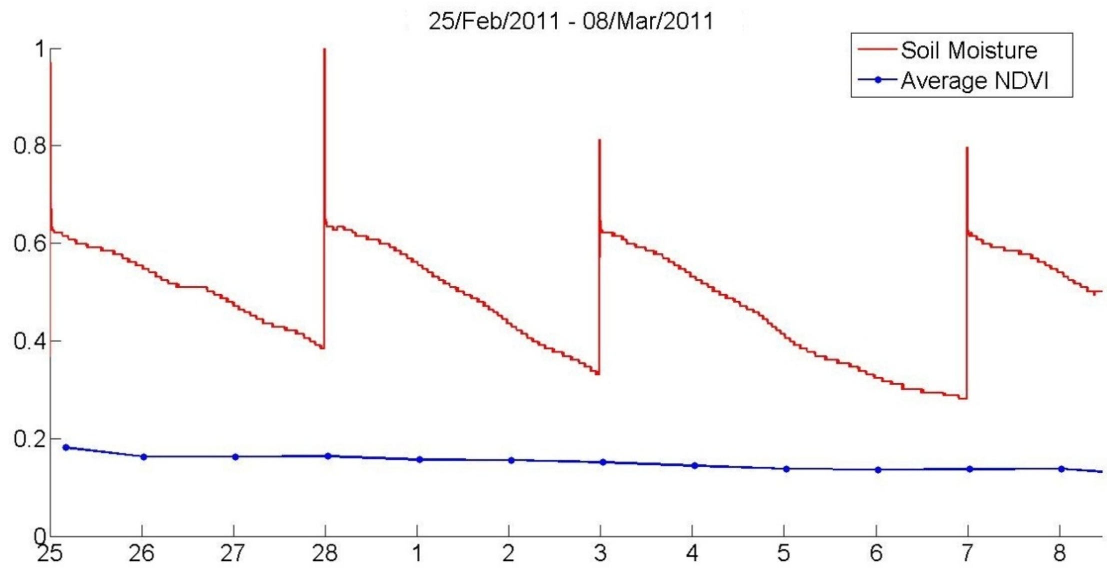

Figure 16

The normalized soil moisture with NDVI and average NDVI measured in controlled room are plotted in figure 15 and 16, respectively. From figure 16, as expected, NDVI varies within a much narrower range, fluctuating around 0.2. However, a critical issue appears that, NDVI indicator is still unable to reflect the impact of irrigation on the photosynthesis of plant, and gives the curve of unusual flatness. This illustrates that either the cameras are not sensitive enough to catch up the tiny changes of light reflectance on leaf surface during the process of photosynthesis, or they have limited ability of wavelength filtering.

3. Progress Conclusion:

Two individual experiments were conducted in glasshouse and constant environment room. According to the analytic outcomes of measurements, this progressive report is unable to give the final conclusions of our proposal and relative system models. We concluded that, the limitation of sensitivity and filtering of cameras is the key reason leading to the unexpected outcomes. For further experiments, are required and we are planning to replace the current cameras with a professional thermal camera with more dynamic sensitivity and well-designed filters, and insert another two soil moisture sensors horizontally with different levels so as to trace the variation of water distribution during the plant growth.

4. Acknowledgements

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