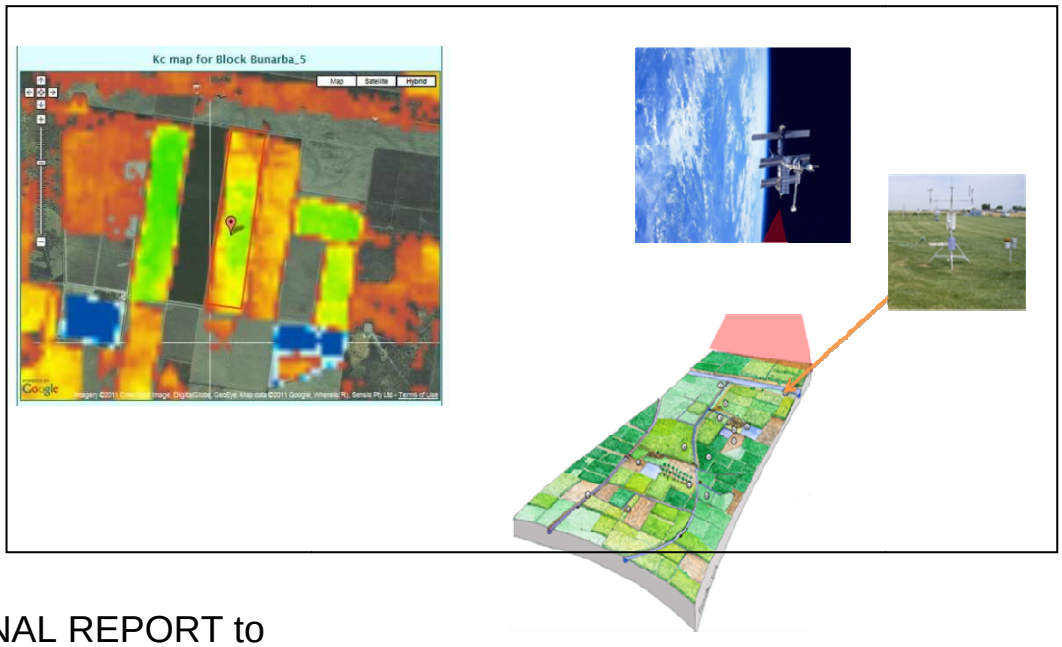
Vineyard Irrigation – delivering water savings through emerging technology



FINAL REPORT to

GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

Project Number: **CSL0901**

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Research Organisation: CSIRO Land and Water

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Abstract

Increasing costs associated with water and energy use and reduced water availability will see the Australian wine industry face major challenges in the coming years. Water use productivity improvements will continue to be critical to the industries long term survival and new methods and techniques for monitoring crop water use from the plant to the regional level will be important for benchmarking and improving water use productivity across the industry. This project developed and investigated the use of new emerging satellite water use monitoring technology combined with on-ground weather station data and seven day forecast reference evapotranspiration data for providing irrigators with estimated actual and forecast crop water use information using a range of information delivery platforms from mobile phones to web based platforms.

Executive summary

Irrigation scheduling is an important aspect in maximizing yields and improving water use efficiency but many irrigators still do not utilize quantitative tools for irrigation scheduling. This is due to a number of reasons related to cost and ease of use of equipment along with social aspects. At the last census only 20% of growers used some form of soil moisture monitoring device for irrigation scheduling with many still relying on 'gut feel' or non-quantitative measures.
This report outlines an irrigation water management approach using the reference evaporation (from weather stations) combined with satellite derived crop coefficients. While weather station determinations of reference evapotranspiration (ETo) are practical and easy to access in most irrigated regions, the difficultly has been in determining localized crop coefficient (Kc) information. Crop coefficients are affected by management (irrigation, fertiliser etc), soil type and varietal differences and often show variation even within crops in the same region due to these factors. This has proven a major limitation to applying a reference evaporation with crop coefficient approach for providing practical scheduling and water management information on a per paddock basis.

Recent advances in remote sensing have seen the use of visible and near infrared light wavelengths used for determining vegetation indexes. These indexes, particularly the Normalised Difference Vegetation Index (NDVI) have the potential to be used for providing site specific crop coefficient information. A number of authors have found linear relationships between NDVI and crop coefficients for a broad range of crops. These relationships allow a practical method which can be used to gain large scale, low cost, site specific crop coefficient information which can then be used with reference evapotranspiration from weather stations to provide paddock specific scheduling/water management information.

During this project these approaches where refined and tested with winegrape growers in the Murrumbidgee Irrigation Area and Northern Victoria wine growing region, with water management information provided in a number of delivery formats to irrigators including mobile phone and web based delivery platforms. Additionally, during this project a methodology was developed using the BoM Operational Consensus Forecast model data to provide a seven day ETo forecast. This forecast could be combined with the satellite derived crop coefficients and used to develop a 7 day crop water demand.

In order to extend the results the project team have also developed a training package using freely available easy to use software that allows end users to access the free satellite data and process it into useful water management information which can be used in a range of water management activities by irrigators to improve their water management. These packages have been presented in a series of workshops to irrigators, consultants and industry during the life of the project and are continuing to be delivered through the Irrigation Association Limited (IAL).

Introduction

Irrigation water management is an important aspect of many grape producing businesses within the Australian wine sector. Increasing pressure is being placed on growers to use water more efficiently due to increasing demands from the environment and also through an increasing awareness of the economic value of water. Current statistics show that less than 20% of growers are using some form of quantifiable irrigation scheduling system. The most significant barriers to adoption have been the high costs of systems from an economic and time/labor perspective. Recent advances in remote sensing technology and linking this data with crop performance and ultimately irrigation water requirement has provided an opportunity to combine this technology with low cost delivery mechanisms (mobile phone and web based) to provide site specific, individual water management information to irrigators to improve their decision making around irrigation water management.

Over the course of this project these remote sensing technologies have been refined and tailored into simple to use systems which provide irrigators with knowledge on site specific crop coefficients which can be used in water management. Additionally, this project has developed a robust seven day reference evapotranspiration forecast which allows a seven day crop water demand forecast to be developed on a daily basis which can be used for improving irrigation water management decisions. The approach of combining satellite remote sensing data and measured and forecast evapotranspiration as developed in this project has become known as the IrriSat approach.

Overview of the IrriSat approach to irrigation water management

The IrriSat system is a new approach of providing tailored but widely applicable irrigation water management services. This approach aims at delivering daily and 7 day forecast data to irrigators to support and facilitate their irrigation decision making process.

This IrriSat approach is based on the computation of crop water requirements based on weather data (measured and forecast) and crop related coefficients which can then be translated into a water balance and the required irrigation demand. A schematic representation of the IrriSat approach is given in Figure 1, showing the specific and main components of the system. The IrriSat approach undertakes calculations needed to convert weather station based reference evapotranspiration (ET_o) data and crop coefficient data (K_c) into useful water management information for the irrigator.
Additionally, the system can use seven day forecast evapotranspiration data to provide a 7 day forecast of crop water demands for the irrigator.

Crop coefficients are affected by management (irrigation, fertiliser), soil type and varietal differences and often show variation even within crops in the same region due to these factors. Satellite derived vegetation index images can potentially be used to derive site specific crop coefficient values, which can be used for determining site specific crop water use information, when combined with reference evapotranspiration (ETo) information. This reference evapotranspiration (from ground stations or forecast) is used to represent the climatic conditions under which evapotranspiration takes place, which is then used to calculate actual evapotranspiration (ETc) for specific crops by multiplying the ETo by a specific crop coefficient (kc). The crop coefficient takes into account differences in canopy cover, stomatal characteristics, aerodynamic properties and albedo, which affect the rate at which crops evapotranspire compared to the reference crop. Therefore, ETc for a specific crop is given by:

$$ETc = ETo \times Kc$$

This information on crop water use can then be packaged and delivered to irrigators in a number of delivery formats such as web based or through mobile phone based mechanisms. Additionally, by collecting basic information such as irrigation run times and rainfall this information can be used to provide a feedback loop that allows a simple waterbalance to be updated, which can be used for irrigation scheduling and management. Data collected by the IrriSat approach can also be used for benchmarking performance across a range of scales and coverage of areas is large and universally applied.

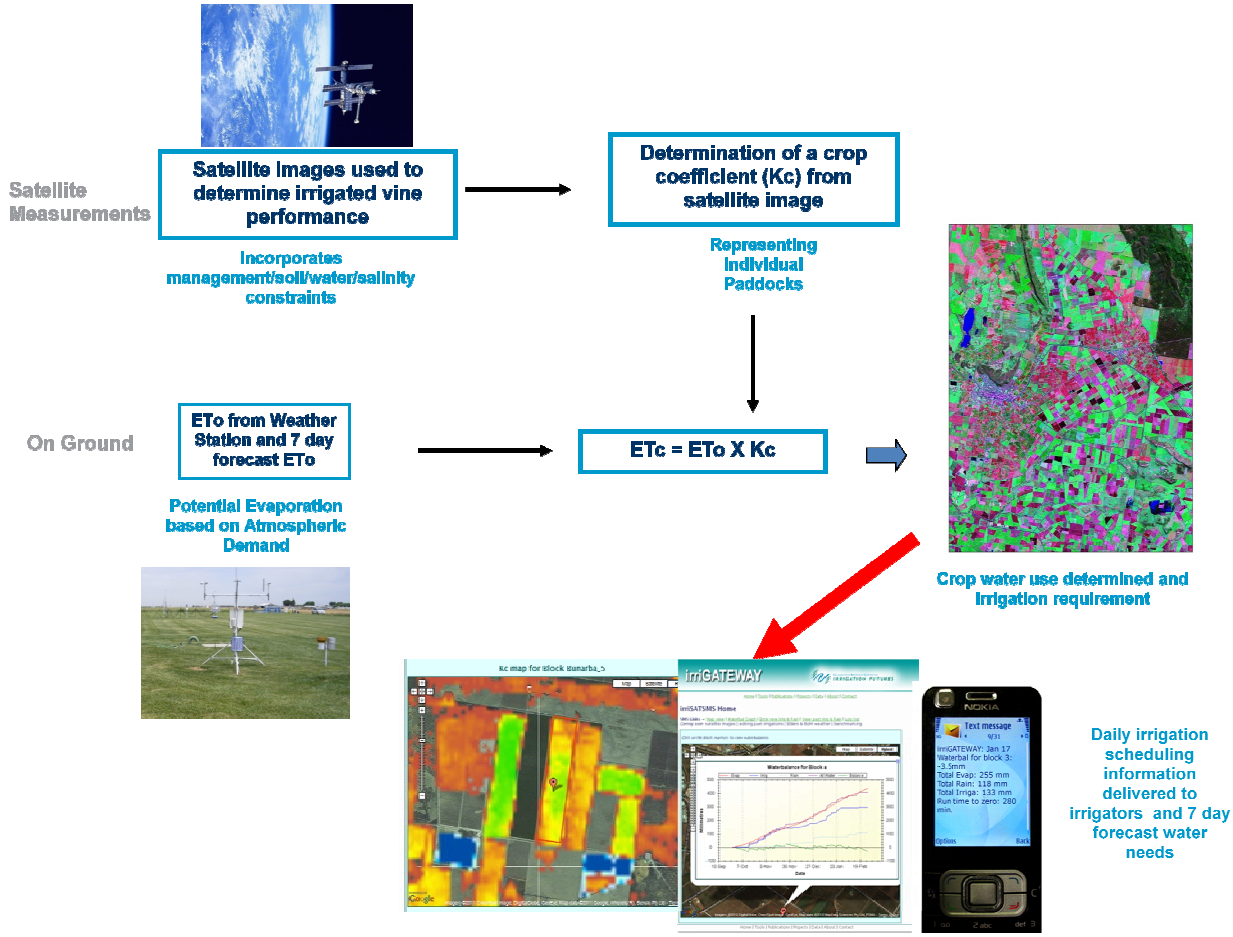


Figure 1 Overview of the IrriSat approach for providing crop water use information for irrigation management, showing information flows and linkages between sensing and information delivery platforms

All values can be centrally stored for further use allowing, for example, system benchmarking to be performed. All results can be presented on a web page instantly and may be securely accessed by the irrigators.

The IrriSat approach can have a number of mechanisms for communicating with irrigators, such as mobile phone based or through the web or a combination of approaches. The IrriSat approach is scalable, from single to hundreds of users and/or paddocks. The geographic spread of the area has little limitation as satellite coverage is universal with Landsat 7 and 8 coverage across Australia.

Project Aims

The overall aim of IrriSat approach is to provide irrigators with site specific, low cost and tailored water management information which can be used to increase water use productivity using the latest technologies in remote sensing and short-term weather forecasting. The aim of this project was to implement, test and tailor the IrriSat approach and associated tools across irrigated wine growing regions to enable the approach to be used by industry to improve water management. Objectives of the project were:

1. Develop/refine methods for derivation of NDVI to kc relationships in irrigated viticulture crops

2. Incorporate RDI / deficient irrigation scheduling capability to meet quality targets

3. Develop and investigate ways of incorporating seasonal water budgets, water accounting and 7 day weather forecasts

4. Collect evaluation data on the use of the technology and some quantification of actual on-farm water use productivity improvements achieved by using this technology.

Methods

Relating remote sensed images to irrigation scheduling and water management

A commercial vineyard in Yenda, NSW was selected for the field based investigation to refine Normalsied Difference Vegetation Index (NDVI) to crop coefficient (kc) relationships. The vineyard consisted of a 12 ha shiraz block with 15 year old vines on Ramsey rootstock on a double cordon trellis and a Semillon block of 13 ha. All rows were in an east-northeast direction with row spacing of 3.3m and plant spacing of 1.8m. Irrigation was applied through drip tape with 0.6m emitter spacings. Energy balance instrumentation as described in detail in Kerridge (2011) was used in the vineyard to directly measure crop evapotranspiration (ETc) this allowed a crop coefficient to be calculated when combined with reference evapotranspiration readings. The energy balance instruments were installed in the centre of each vineyard with a minimum fetch of 140m. Temperature and humidity gradients were measured above the crop and combined with net radiation and soil heat flux to get ½ hourly measurements of actual crop evapotranspiration. Reference Evapotranspiration was taken from the nearby CSIRO Griffith weather station http://weather.irrigateway.net/aws/index.php .

Remote sensing data was collected from the Landsat platforms over the life of the project. Freely available Landsat satellite data from USGS (http://earthexplorer.usgs.gov/) was used to develop relationships between satellite measured NDVI values and ground based measurements of kc values during periods of image acquisition over the growing season. The Landsat satellite images used were a combination of images from Landsat path 92 row 84 and path 93 row 84 which provided image coverage of the experimental site. Only images with cloud free conditions were used for analysis. Landsat image acquisition cycles were 16 days. Each individual Landsat image is approximately 180km x 180 km with individual pixels in the image 30 x 30m.

Normalised Difference Vegetation Index values were calculated from surface reflectance values of the red and near infrared satellite bands using the following relationship:

$$NDVI = (NIR - Red)/(NIR + Red)$$

The NDVI is an index generally expressed as a ratio between 0-1 of the red and near infrared reflectance by plants. Larger, greener canopies give higher NDVI values than smaller less healthy plant canopies. Figure 2 gives a visual indication of reflectance values and calculated NDVI values for two grape canopies typical of those found in the study. Landsat derived NDVI values were then compared with calculated crop coefficient values to investigate the NDVI to kc relationships, which could be used for wider scale applications.

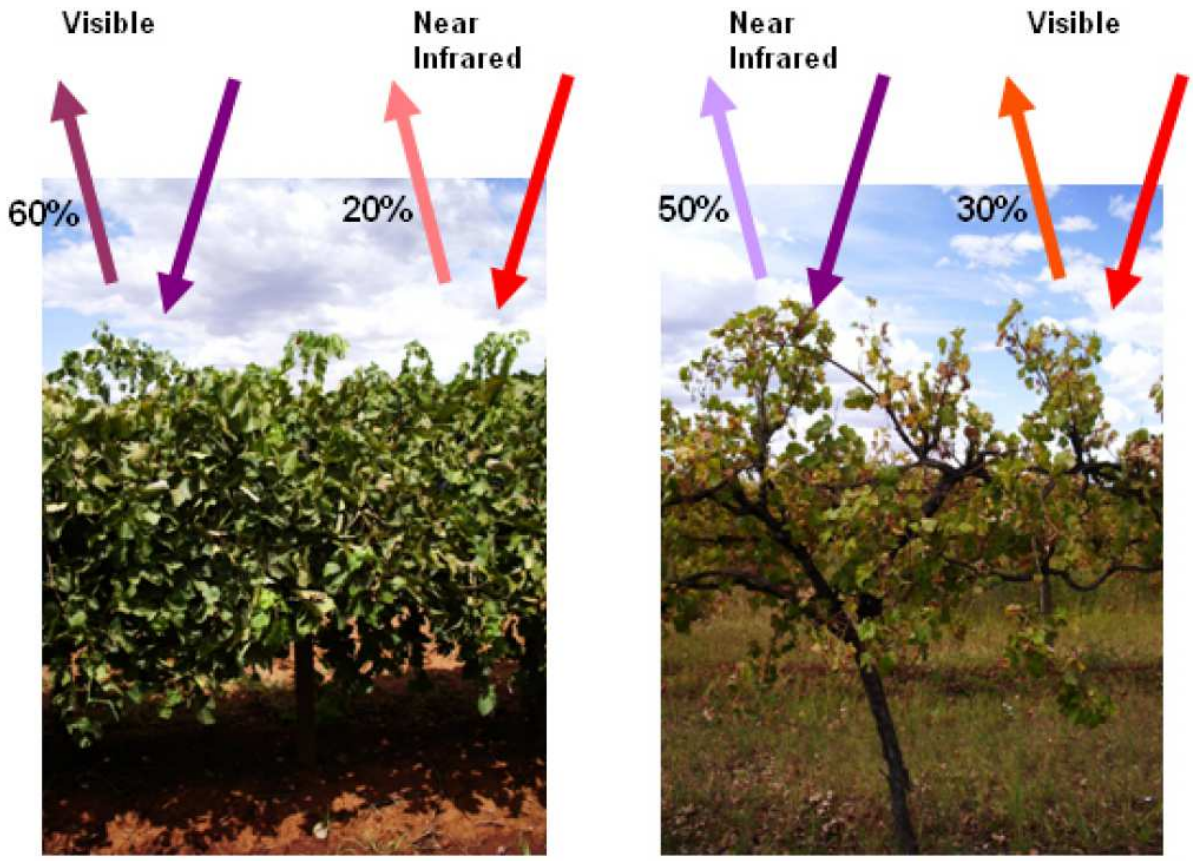


Figure 2 Grapevine canopies showing left – high NDVI (0.5) and right – low NDVI canopies (0.25)

Seven day forecasting of evapotranspiration

In order to develop and test a seven day reference evapotranspiration forecast the BoM Operational Consensus Forecast (OCF) data were collected from 6 August 2010 to 19th July 2011 on a daily basis. Multiple formats of collected data files were converted into a standard database table, one for each data source. This forecast data consisted of the individual parameters used to calculate reference evapotranspiration such as temperature, humidity, wind speed and solar radiation.

Forecast data have a multi-dimensional feature, since for each forecast day, a dataset of 7 forecast data are available, i.e. each day a forecast is available for that day+1, day+2 … day+7. The next day, the same set of forecast data. This means that for a one-week time frame, each day had 7 forecasts available (from day-7, day-6… day-1). The multi-dimensional aspect of forecast data allows for a large set of evaluations, each with its own validity of results. Note that a general expression that "the forecast was 70% correct" is a statement without value when the methods of evaluation are not included.

In order to test the stability and accuracy of the forecast data an evaluation for the Griffith area was undertaken. Two independent weather stations with complete Penman-FAO56 parameter collection are available for Griffith; CSIRO-automated weather station (AWS), and the BoM Griffith airport weather station. Previous comparison between these two stations indicated that most parameters are similar, with exception of the wind speed measurements. The wind speed at the airport is measured at 10m elevation, while the standard agricultural weather stations (including the CSIRO site) measured wind speed at 2m height. Standard adjustments are available to convert 10m measurements to 2m measurements, and these are applied to the BoM weather station when using data for the Penman-FAO56 ET_o. Even after the correction, the BoM wind speed measurements appear to measure approximately two times higher at the airport site than at the CSIRO site. Since the forecast data are likely based on the BoM measurements, we used both the CSIRO AWS and the

BoM weather station as a reference measurement, with the observation that we have more confidence in the wind speed measurements of the CSIRO station for hydro-agricultural applications.

1, 3, 5 and 7 day forecast periods were selected for evaluation against measured data. This allowed a comparison between measured data and forecast temperature (OCF and weather.com.au), humidity and wind speed (weather.com.au). The forecast data from the OCF were selected from the 12Z forecast hour, corresponding to the 10 PM AEST forecast of the previous day, while the forecast data from weather.com.au were collected between 4 and 5 AM AEST each day.

The global radiation forecast data (weather.com.au) required a multi-step extraction. Since only icons of the expected cloud conditions were available, a calibration of the type of icon against a daily transmissivity was undertaken. The transmissivity is a measure of the atmospheric filter of solar radiation available at the earth's surface. On a clear day, approximately 75-78% of the solar energy reaches the earth's surface, while on a cloudy day, only 25% of solar energy reaches the surface. To calibrate the expected transmissivity for each type of icons (33 different types of icons are in use by weather.com.au, although only 15 icons are applicable for Griffith weather conditions during the day) we included forecast data with the highest certainty (for weather.com.au, day+0, representing the day-time conditions for the day that the forecast was downloaded). Each type of icon was combined with the calculated transmissivity of observed data, resulting in an average transmissivity for each icon.

After evaluation of each of the ET_o components, the ET_o can be calculated using the standard Penman-FAO56 approach. To evaluate the results of the forecast with the actual ET_o. i.e. the daily values for a forecast period were evaluated, as were the cumulative values for a given period.

Note that the cumulative ET_o forecast has a composite set of variables and probabilities. ET_o for a seven day period uses the accuracy and probability of ET_o+1, ET_o+2 … ET_o+7. This means that a potential low probability for a 7 day forward forecast is only $1/7^{th}$ of the total cumulative ET_o for the week.

Uses and applications of the IrriSat technology

During the project, application of the IrriSat technology has focused on developing tools, knowledge and understanding for implementing the technology into the wine grape industry. Two approaches have been developed to test the use and application of the IrriSat technology. These approaches have largely been separated on the scale of the application.

Large scale application have focused on tailoring and implementing the IrriSat technology into regional scale approaches centered around a single entity providing information from IrriSat to multiple irrigators in standardized formats. This approach relies on an operator or providers of the service having sufficient revenue or resources to implement such an approach. The second scale has been focused on providing individual irrigators, consultants and smaller scale (less resourced) interested parties with the knowledge, know how and software tools to allow them to undertake their own analysis of satellite images and use the IrriSat approach within their individual business or application. This has involved collaboration with and BEAM Earth Observation Toolbox and Development Platform developed by European Space Agency. This has resulted in a freely available open source software platform which can be used to apply the IrriSat approach.

In order to access the applicability of the IrriSat system and gain evaluation data on the use of the technology, a subset of project participants were surveyed on the use of the system and its potential to change water management behavior. The survey group was followed with regular surveys before/ after and during the irrigation season on how they used the IrriSat information in their water management decisions and what affect it had on their decision making.

Results/Discussion

Relating remote sensing information to irrigation scheduling and water management (Obj 1,2)

Crop water use is related to the interception of incoming solar radiation and the amount of transpiring leaf surface. A number of previous studies (Johnson et al. 2005; Williams and Ayars, 2005) have related both leaf area index and crop light inception to crop transpiration. Previous studies have shown that various spectral vegetation indices, calculated from visible and near infrared reflectance data, are related to crop evapotranspiration. Functional relationships between remotely sensed vegetation indices and crop coefficients have been given by authors in the United States and Europe using two different approaches to develop these relationships. Trout et al. (2007) presented an NDVI to kc relationship using a 2 step approach. This relationship was based on lysimeter measured data from lettuce and pepper crops grown in California. The two step approach used NDVI values to determine a canopy cover which was then converted to a crop coefficient using the relationship below:

$$CC = 1.22 * NDVI - 0.21$$

$$kc = 1.13 * CC + 0.4$$

The two step approach can be converted to a single empirical relationship given by:

$$kc = 1.37 * NDVI - 0.086$$

Vine specific relationships have also been developed by Campos et al. (2010) using measured crop evapotranspiration measured with an eddy-covariance flux tower in south east Spain. The authors developed a relationship between crop coefficient and NDVI from Landsat 5 satellite data. The relationship was given by:

$$kc = 1.44 * \mathrm{NDVI} - 0.1$$

Tasumi et al. (2006) also developed a NDVI to crop coefficient relationship based off satellite derived estimates of actual evapotranspiration using the thermal imaging bands of Landsat in the Colorado River basin. The relationship was given by:

$$kc = 1.1875 * NDVI + 0.05$$

This approach was also undertaken in Idaho by Rafn et al. (2008) which for the study area yielded an NDVI to kc relationship given below:

$$kc = 1.063 * NDVI + 0.29$$

In both of the above studies the developed relationships were generated from broadacre crops.

These relationships were used in the field trials as starting points for investigating the relationship between NDVI and Kc for irrigated grape vines grown under Australian conditions in the semi-arid Riverina area of New South Wales.

In order to develop NDVI to Kc relationships energy balance instrumentation (Figure 3) outlined in the previous section was used to determine actual ETc throughout the growing season on a Shiraz and Semillon drip irrigated vineyards. Local ETo data collected from the CSIRO reference weather station was then used to calculate crop coefficients.

$$kc = \mathrm{ETc}/\mathrm{ETo}$$

Throughout the season these crop coefficients were then compared to the remote sensed satellite NDVI data so functional relationships between NDVI and Kc could be developed (Figure 4).



Figure 3 Energy balance instrumentation for determining ETc.

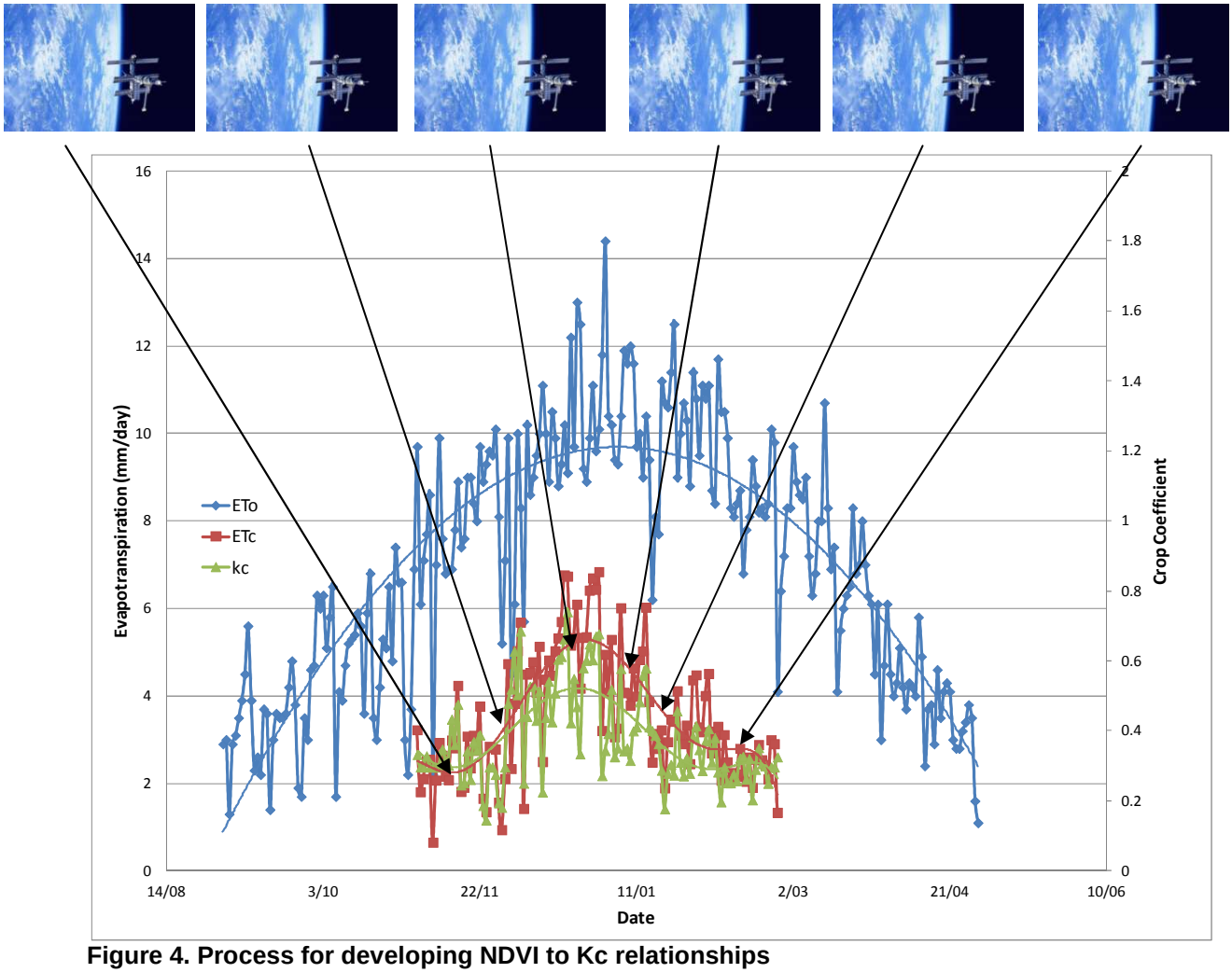


Figure 4. Process for developing NDVI to Kc relationships

Figure 5 shows results from the field experimentation and the four model NDVI to kc relationships mentioned previously. It can be seen that there is a strong correlation between measured kc values determined from the energy balance instrumentation and reference ETo and the satellite derived NDVI values at overpass times. What is also interesting is the close fit of all four models to the experimental data and indeed each other. The Tasumi relationship had a tendency to overestimate kc compared with the other models particularly at lower NDVI values. Over the typical NDVI measurement range the Trout, Rafn and Campos models all gave similar results. This is interesting considering the Trout and Rafn models were developed on non-vine crops and also using very different approaches to developing the NDVI to kc relationships. Rather than recommend another NDVI to kc model to fit the data it is clear that either the Trout, Rafn or Campos models provide a very good fit to the experimental data and could comfortably be used to determine kc values over the ranges typically found in irrigated vineyards.

Due to the good fit of the Trout NDVI to kc model and the authors experience in using this model and its initial development, this model has been the default model which has generally been applied when implementing IrriSat. However, as can be seen selection of an alternative NDVI to kc model as shown would also be appropriate with little practical difference when used in generating information for irrigation decisions.

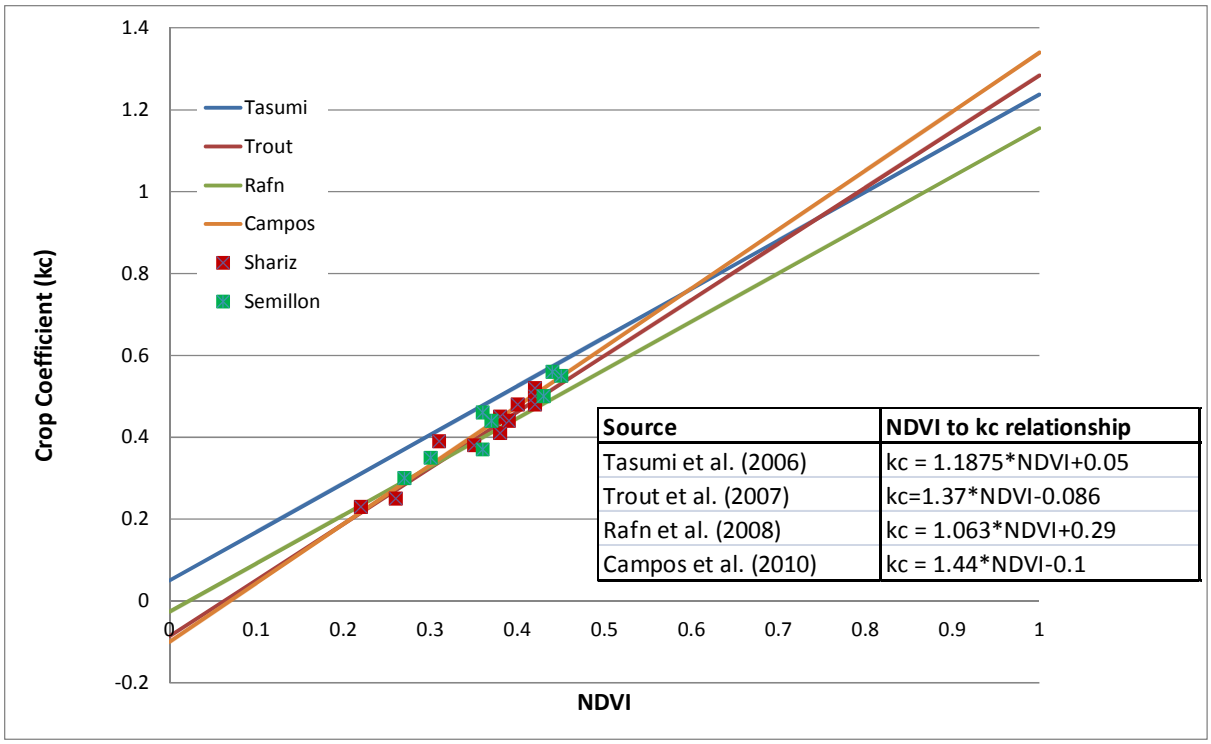


Figure 5 Measured crop coefficients and satellite derived NDVI with fitted NDVI to kc models

The advantage of using an NDVI to kc relationship is that it allows easy, consistent collection of site specific crop coefficient data which has previously been difficult and time consuming to collect. These relationships can then be applied across a region and Kc data updated on a regular basis based on the satellite derived NDVI data. Trout *et al.,* (2008) have also shown that these NDVI to Kc relationships appear quiet robust both temporally and even over different crops. The use of this approach allows Kc coverage's down to a 30x30m resolution to be developed across a whole irrigation region (Figure 6) with useful resolution down to an individual paddock level (Figure 7). As the NDVI model is simple and easy to implement kc maps across entire irrigation areas can be constructed using satellite derived NDVI values and easily updated with each new satellite overpass.

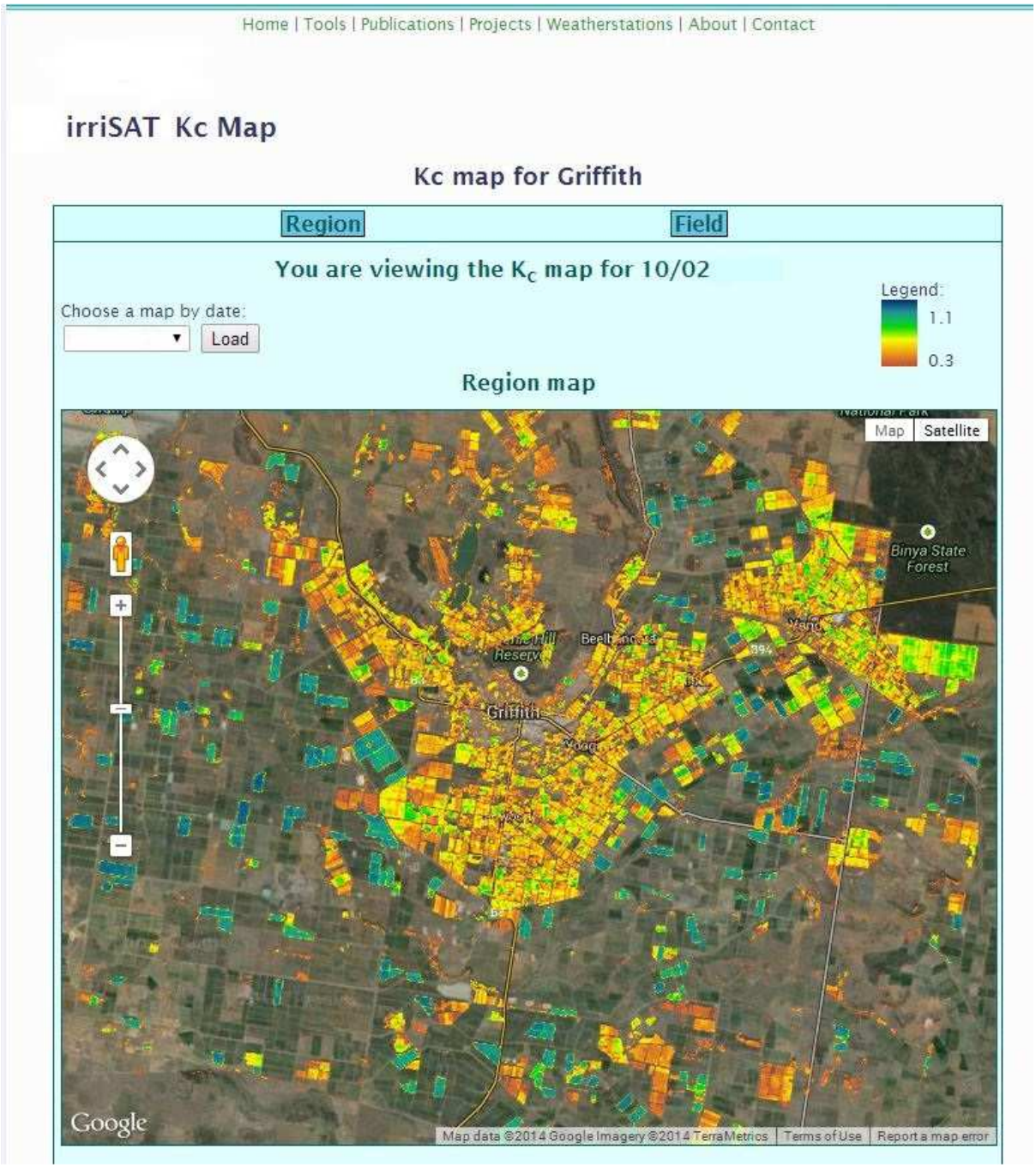


Figure 6 Regional crop coefficient (kc) data shown across the Murrumbidgee Irrigation Area, derived from Landsat satellite NDVI measurements. Non irrigated crops are shown not coloured.

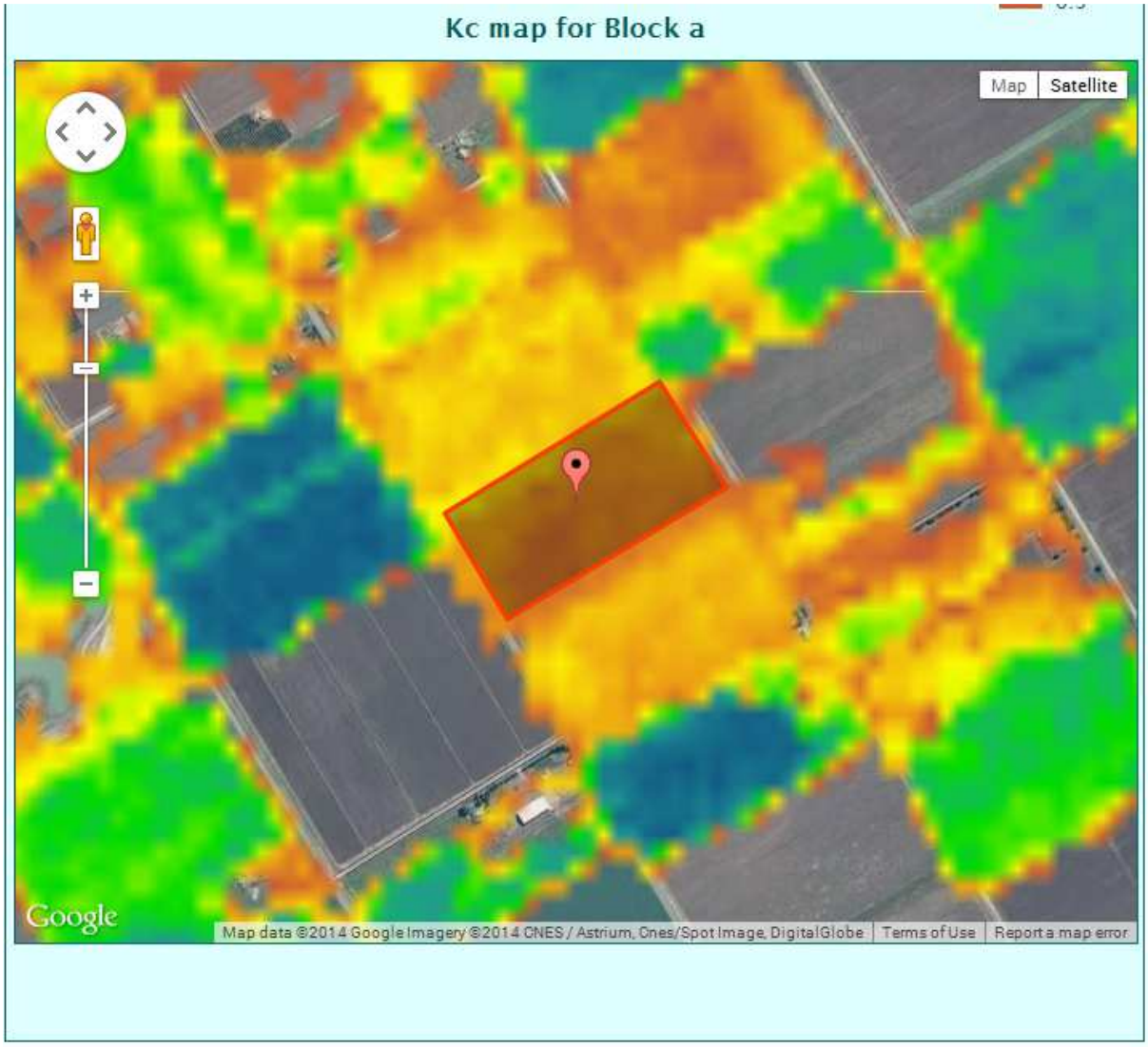


Figure 7 Paddock scale crop coefficient (kc) data as shown in the IrriSat system for an individual user. Non- coloured areas are non-irrigated.

Incorporation of RDI

In order to allow the implementation of RDI into the IrriSat approach a simple method based on modification of the crop coefficient was developed. Table 1 from Goodwin (per comm.) updated from the crop factor tables given in Kriedemann and Goodwin (2003) shows crop coefficients for irrigated grapevines with medium vigor under both no stress and RDI irrigation regimes. When the % reduction in kc between these regimes is calculated (Table 1) it can be seen that upon implementation of RDI kc is reduced by 50% from no stress or fully watered conditions. The NDVI to kc relationships developed above are for fully watered conditions. In order to implement or calculate kc values to be used in RDI strategies then the approach taken is simply to reduce the calculated kc values by a specified % reduction. This approach can allow for various levels of RDI to be implemented using the NDVI to kc approach, as a starting point.

Table 1 No stress and RDI crop coefficients (Goodwin Pers. Comm.)

	No Stress	RDI	% reduction in Kc
September	0.1	0.1	0%
October	0.3	0.3	0%
November	0.5	0.5/0.3	0%-50%
December	0.6	0.3	50%
January	0.6	0.3	50%
February	0.6	0.3	50%
March	0.6	0.3	50%
April	0.4	0.2	50%

NB: Medium vigour vineyard (Canopy cover ~ 40%)

Seven day weather forecasting of Evapotranspiration (Obj. 3)

Forecasting reference evapotranspiration (ET_o) is highly dependent on the accuracy of weather parameter forecasting, especially air temperature, humidity, wind speed and radiation. Once the weather parameters have a reasonable expectation of accuracy, the ET_o can be calculated using the standard Penman-FAO56 equation.

The Bureau of Meteorology (BoM) is the main source of forecast data for Australia. The BoM is in the process of changing their data-forecast from point source-based models to grid-based models. This application has been implemented in Victoria, and is planned to be expanded to other states in Australia. For the forecast data to be used in the ET_o forecast, they need be made readily available into a forecast database. Currently, the BoM meteogram available through the web is not automatically extractable.
Data availability is better for the Operational Consensus Forecast (OCF) model made publicly available by the BoM. The OCF model is a combination of eight weather forecast models, weighted and combined into a model that is applied to Australia specifically. For our forecast purposes, the parameters "air temperature" and "sunshine hours" are included in the OCF output, in addition to expected rainfall and probability of rainfall. The probability is expressed as a percentage of the number of models agreeing on the precipitation depth.

Sunshine hours are only predicted for the larger towns (manned weather stations, approximately 55 in Australia), and not available for Griffith, NSW. This results in only the air temperature available as an input into the ET_o calculations, and the rainfall as part of the water balance forecast.

Additional forecast data were found from the website www.weather.com.au which is owned and operated by Australian based Weather.com.au Pty Ltd. This site is based on a set of proprietary computer models developed from various sources including international weather organizations and the Australian BoM. It provides forecast data for temperature, expected humidity, wind speed, and an icon representing the cloud conditions.

Air temperature

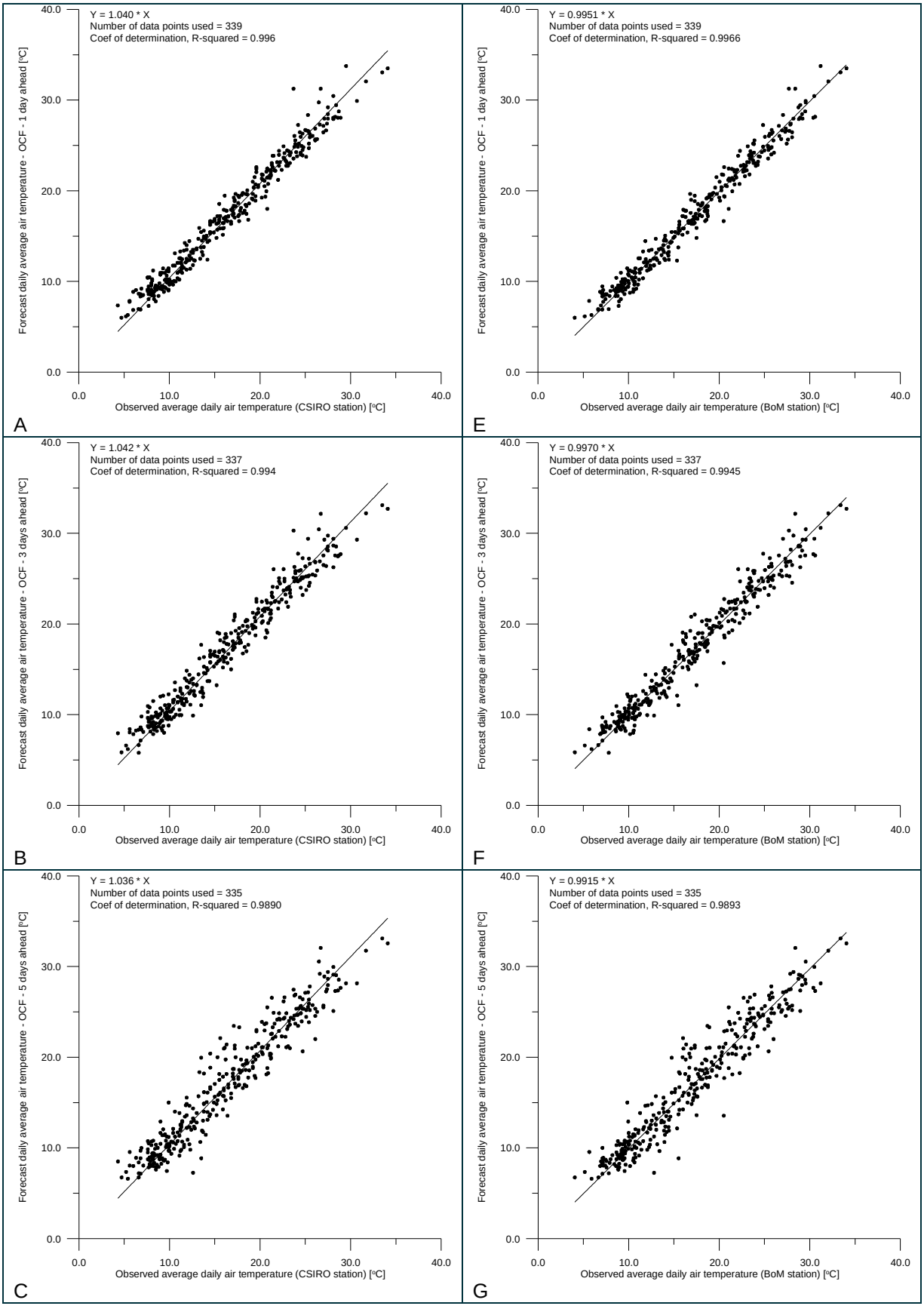
Air temperature was collected from both OCF and weather.com.au with a 7 day forecast period (day+1 … day+7). OCF 12Z was used, and the current forecast for weather.com.au was collected between 4 and 5 AM AEST. Observations for actual air temperature were available from both CSIRO and the BoM weather station. Data analysis was applied on forecast "day+1", "day+3", "day+5" and "day+7" (Figure 5)

Data were collected between 6-Aug-2010 and 19-July-2011. A total of 339 data were included in the analysis for forecast day+1. Forecast for day+3, day+5 and day+7 contained 337, 335 and 333 data, respectively. A set of 9 data was missing from September-October 2010 due to the lack of automated processes for download and power-outages.

From Figure 8 it can be seen that the relation between forecast (OCF) data and observed data deteriorates when the period of forward forecast increases. This is not surprising, as the influence of random meteorological aspects increases over longer time periods. In general, the relation between observations and predictions is very strong. Using the BoM weather observations as a reference results in a slope very close to a 1:1 line, while when using the CSIRO-Griffith station as a reference results in a 3-4% overestimation of the forecast data. The coefficient of determination (r^2) is for each combination more than 0.97, thus indicating that the slope of the regression line is valid for the data.

Although small differences exist between the correlations with the CSIRO and the BoM weather station, both indicate that predicted vs observed data have a strong correlation, thus that the forecast temperature values from OCF are representative of the actual expected values, even for a forecast 7-days ahead.

The website weather.com.au also provided temperature forecast data. These predications were compared with observed data using the same method as the OCF data, but only for the CSIRO weather station. The period of analysis is from 27-Aug-2010 until 1-Aug-2011. Similar relations were found, and regression slope and r^2 data for these comparisons are shown in Table 2.


Y = 1.040 * X
Number of data points used = 339
Coef of determination, R-squared = 0.996
Forecast daily average air temperature - OCF - 1 day ahead [ºC]
Observed average daily air temperature (CSIRO station) [ºC]
A
Y = 0.9951 * X
Number of data points used = 339
Coef of determination, R-squared = 0.9966
Forecast daily average air temperature - OCF - 1 day ahead [ºC]
Observed average daily air temperature (BoM station) [ºC]
E
Y = 1.042 * X
Number of data points used = 337
Coef of determination, R-squared = 0.994
Forecast daily average air temperature - OCF - 3 days ahead [ºC]
Observed average daily air temperature (CSIRO station) [ºC]
B
Y = 0.9970 * X
Number of data points used = 337
Coef of determination, R-squared = 0.9945
Forecast daily average air temperature - OCF - 3 days ahead [ºC]
Observed average daily air temperature (BoM station) [ºC]
F
Y = 1.036 * X
Number of data points used = 335
Coef of determination, R-squared = 0.9890
Forecast daily average air temperature - OCF - 5 days ahead [ºC]
Observed average daily air temperature (CSIRO station) [ºC]
C
Y = 0.9915 * X
Number of data points used = 335
Coef of determination, R-squared = 0.9893
Forecast daily average air temperature - OCF - 5 days ahead [ºC]
Observed average daily air temperature (BoM station) [ºC]
G

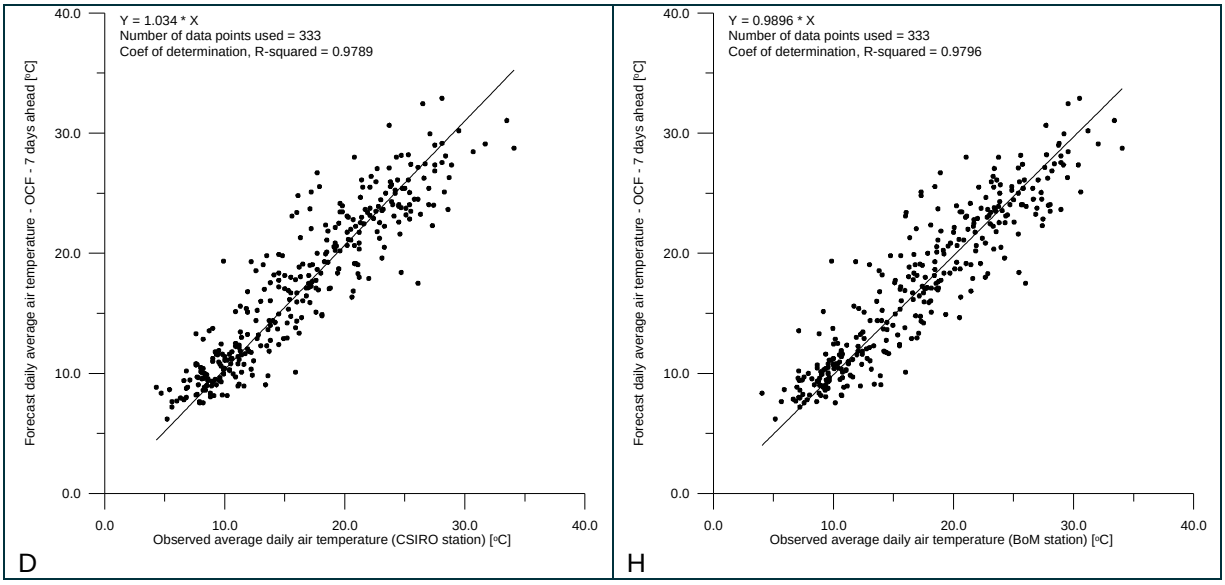


Figure 8 Observed average daily temperature forecast at CSIRO weather station (A-D) and BoM weather station (E-H) compared to the forecasted temperature from OCF using 1, 3, 5 and 7 day forecast periods[1].

Table 2 Slope of the correlation and coefficient of determination (r^2) between observed (CSIRO weather station) vs predicted (weather.com.au) average daily temperature.

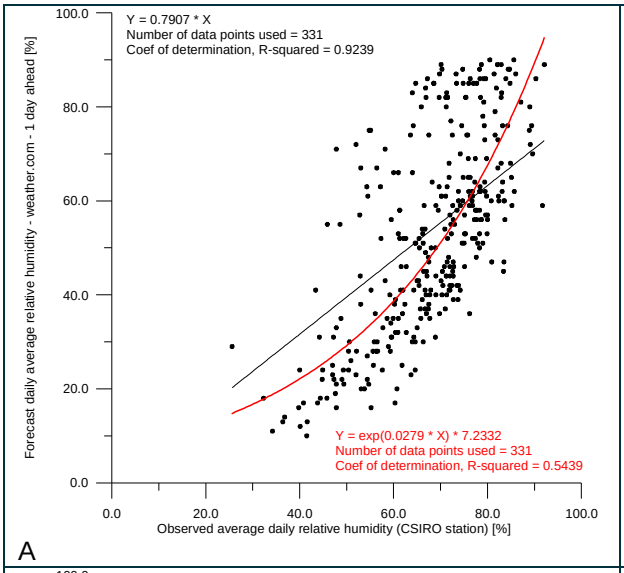
	slope	r^2	number of observations
Forecast day+1	1.066	0.9941	n=331
Forecast day+3	1.067	0.9918	n=329
Forecast day+5	1.075	0.9867	n=327
Forecast day+7	1.081	0.9779	n=325

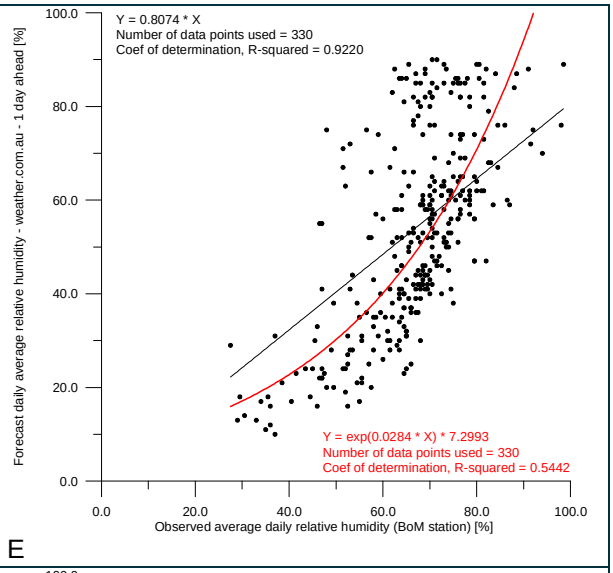
The average daily air temperature has a good correlation between observed and predicted values. For the period of analysis, the weather.com.au dataset appears to overestimate the temperature between 6% and 8% compared to the CSIRO temperature measurements. The coefficient of determination for each of the correlations for all calculations is more than 0.97.

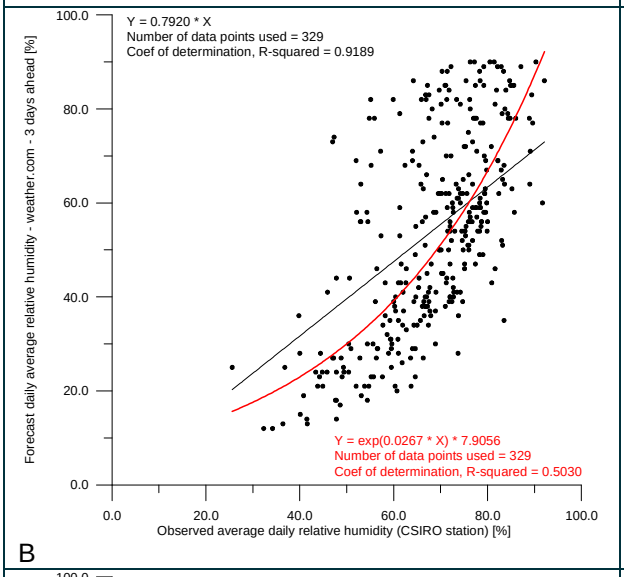
Relative humidity

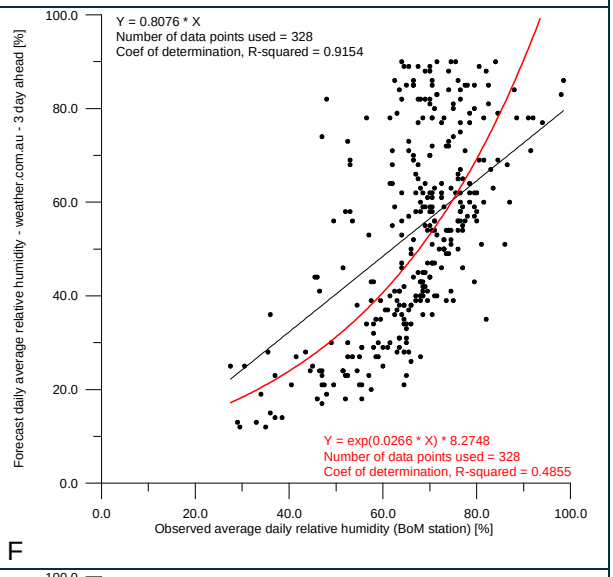
Relative humidity is a common measurement of the actual water vapor pressure in the air. This is an input to the Penman-FAO56 equation, and provides, in combination with the potential water vapor pressure in the air at a specific air temperature (the saturated vapor pressure) one of the two gradient drivers for evapotranspiration (the other gradient being temperature).

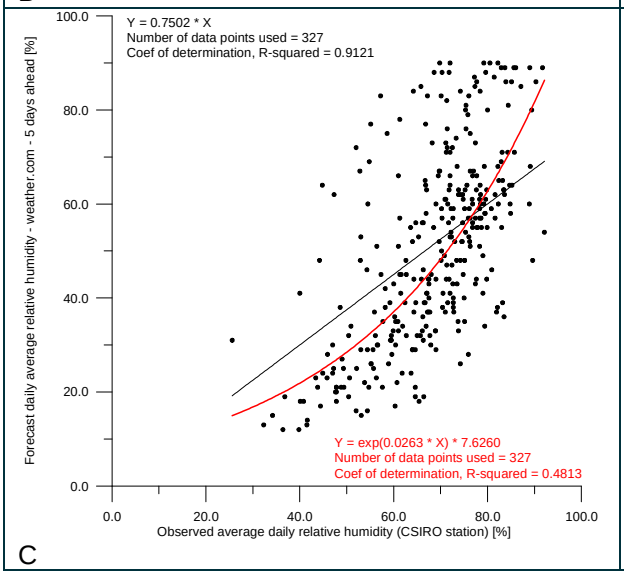
OCF forecast does not provide humidity forecast, and data were only collected from the weather.com.au site. Comparison was done against observed CSIRO weather station and BoM station data for the period from 27-Aug-2010 until 1-Aug-2011 (Figure 9).

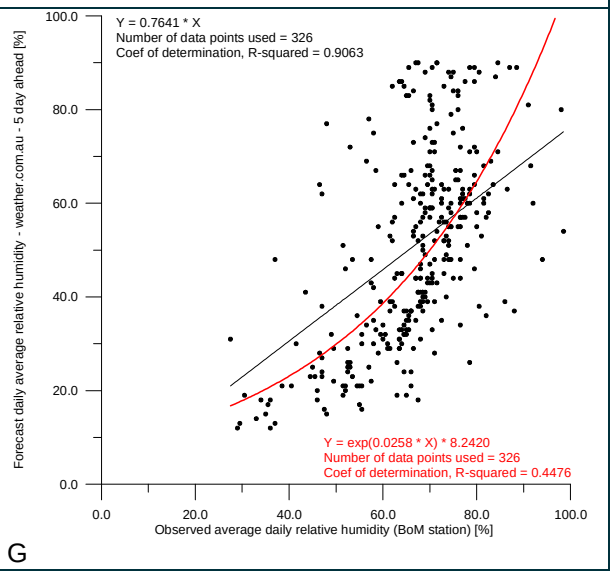

Y = 0.7907 * X
Number of data points used = 331
Coef of determination, R-squared = 0.9239
Y = exp(0.0279 * X) * 7.2332
Number of data points used = 331
Coef of determination, R-squared = 0.5439
Forecast daily average relative humidity - weather.com - 1 day ahead [%]
Observed average daily relative humidity (CSIRO station) [%]
A


Y = 0.8074 * X
Number of data points used = 330
Coef of determination, R-squared = 0.9220
Y = exp(0.0284 * X) * 7.2993
Number of data points used = 330
Coef of determination, R-squared = 0.5442
Forecast daily average relative humidity - weather.com.au - 1 day ahead [%]
Observed average daily relative humidity (BoM station) [%]
E


Y = 0.7920 * X
Number of data points used = 329
Coef of determination, R-squared = 0.9189
Y = exp(0.0267 * X) * 7.9056
Number of data points used = 329
Coef of determination, R-squared = 0.5030
Forecast daily average relative humidity - weather.com - 3 days ahead [%]
Observed average daily relative humidity (CSIRO station) [%]
B


Y = 0.8076 * X
Number of data points used = 328
Coef of determination, R-squared = 0.9154
Y = exp(0.0266 * X) * 8.2748
Number of data points used = 328
Coef of determination, R-squared = 0.4855
Forecast daily average relative humidity - weather.com.au - 3 day ahead [%]
Observed average daily relative humidity (BoM station) [%]
F


Y = 0.7502 * X
Number of data points used = 327
Coef of determination, R-squared = 0.9121
Y = exp(0.0263 * X) * 7.6260
Number of data points used = 327
Coef of determination, R-squared = 0.4813
Forecast daily average relative humidity - weather.com - 5 days ahead [%]
Observed average daily relative humidity (CSIRO station) [%]
C


Y = 0.7641 * X
Number of data points used = 326
Coef of determination, R-squared = 0.9063
Y = exp(0.0258 * X) * 8.2420
Number of data points used = 326
Coef of determination, R-squared = 0.4476
Forecast daily average relative humidity - weather.com.au - 5 day ahead [%]
Observed average daily relative humidity (BoM station) [%]
G

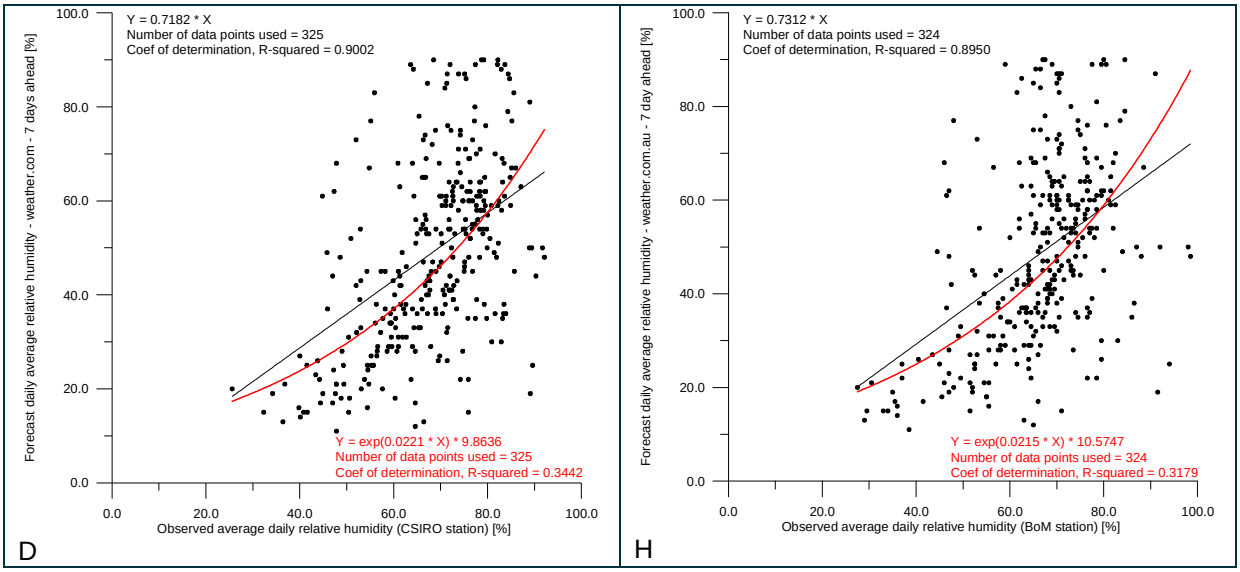


Figure 9 Observed average daily (24hr) relative humidity at CSIRO weather station (A-D) and BoM weather station (E-H) compared with the forecasted daily relative humidity from weather.com.au using 1, 3, 5 and 7 day forecast periods.

Figure 9 shows the differences in comparison between the CSIRO (A-D) and BoM station (E-H). Two "best-fit" lines are added to the datasets. The first is a straight line through the origin, since that is the type of relation that would be expected (1:1), while the other is an exponential function. The exponential "best-fit" had higher values for the coefficient of determination than the straight line with an intercept (not through origin). Note that the two coefficients of determination between the "best-fit" lines cannot be compared, since a different method is used to calculate the r^2 (see appendix).

Earlier comparisons of relative humidity measurements between the CSIRO and BoM weather station (not shown) indicated the high variability of observations for the same day at two different locations. This variability of the observations is found back in the comparison between BoM observations and predicted values. The BoM measurements appear to measure higher relative humidity values than the CSIRO on days with a lower forecast. This results in a lower correlation of measurements with forecast data for the BoM than for the CSIRO station.

Humidity is difficult to forecast, as can be seen from the correlations in Figure 9 A-H. General trends (low and high humidity) are captured, but with less accuracy than the temperature. The slope of the linear correlation between observed and predicted varies from 0.71 to 0.79, indicating an average under-prediction of relative humidity. Using an exponential correlation captures the shape of the measured values, but some bias remains at the low values (over-predicted) and the high values (under-predicted). However, the exponential relation appears to capture the relation between forecast data and measured data better than the linear relation, and hence was used to adjust the forecast humidity data to better represent actual expected values.

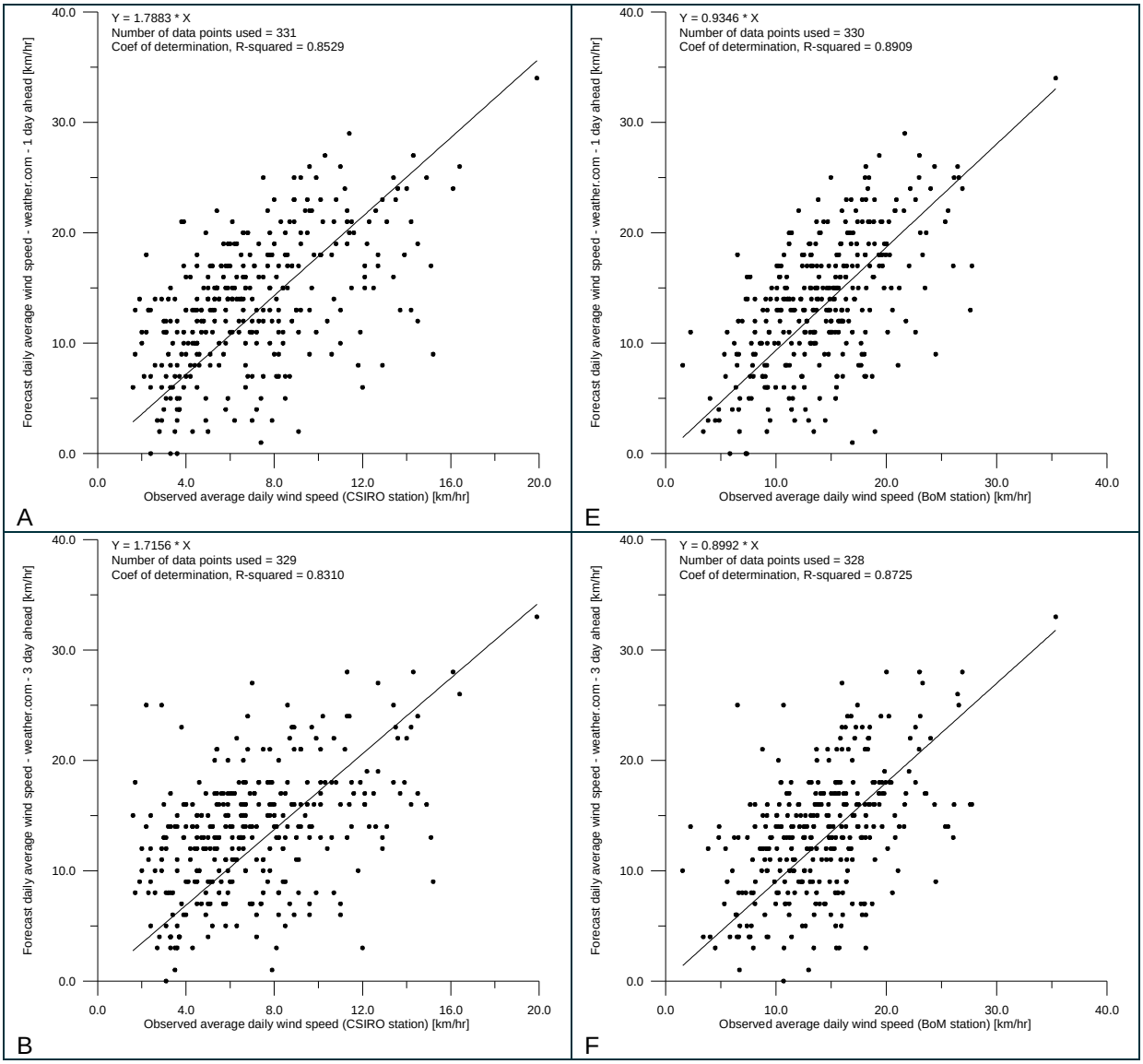
The higher variability in relative humidity forecast is not unexpected. The forecast data do indicate the expected relative humidity, albeit with a higher uncertainty than the temperature data. Relative humidity observation are also highly affected by the ground cover around a weather station, which, under optimal conditions, should have at least a 100-200 m well-watered grass cover in all directions to measure the relative humidity under FAO56 guidelines. The difference in conditions for the BoM and the CSIRO stations reflect part of the variability in the measurements as well. The CSIRO station appears to perform (slightly) better in measurements when compared to forecast than the BoM measurements.

Wind Speed

Wind speed measurements between the CSIRO and the BoM station have shown discrepancies. Discussions between CSIRO and BoM are ongoing to find the cause of the differences. Based on manual observations of average daily wind speed and the measurements from CSIRO weather

station, these are considered more representative than the values obtained from the BoM station. However, since it is likely that observations from the official BoM station are included in the weather forecast models, we do include the comparison of forecast outputs with the BoM station as well.

OCF does not provide a wind speed forecast, thus only weather.com.au data were available for analysis. Figure 10 shows the comparison of wind speed measured at CSIRO and BoM stations with the forecast data from weather.com.au for 1, 3, 5 and 7 day forecast. Note that the CSIRO measurements are taken at 2 m height, and the BoM data are collected at 10m height.



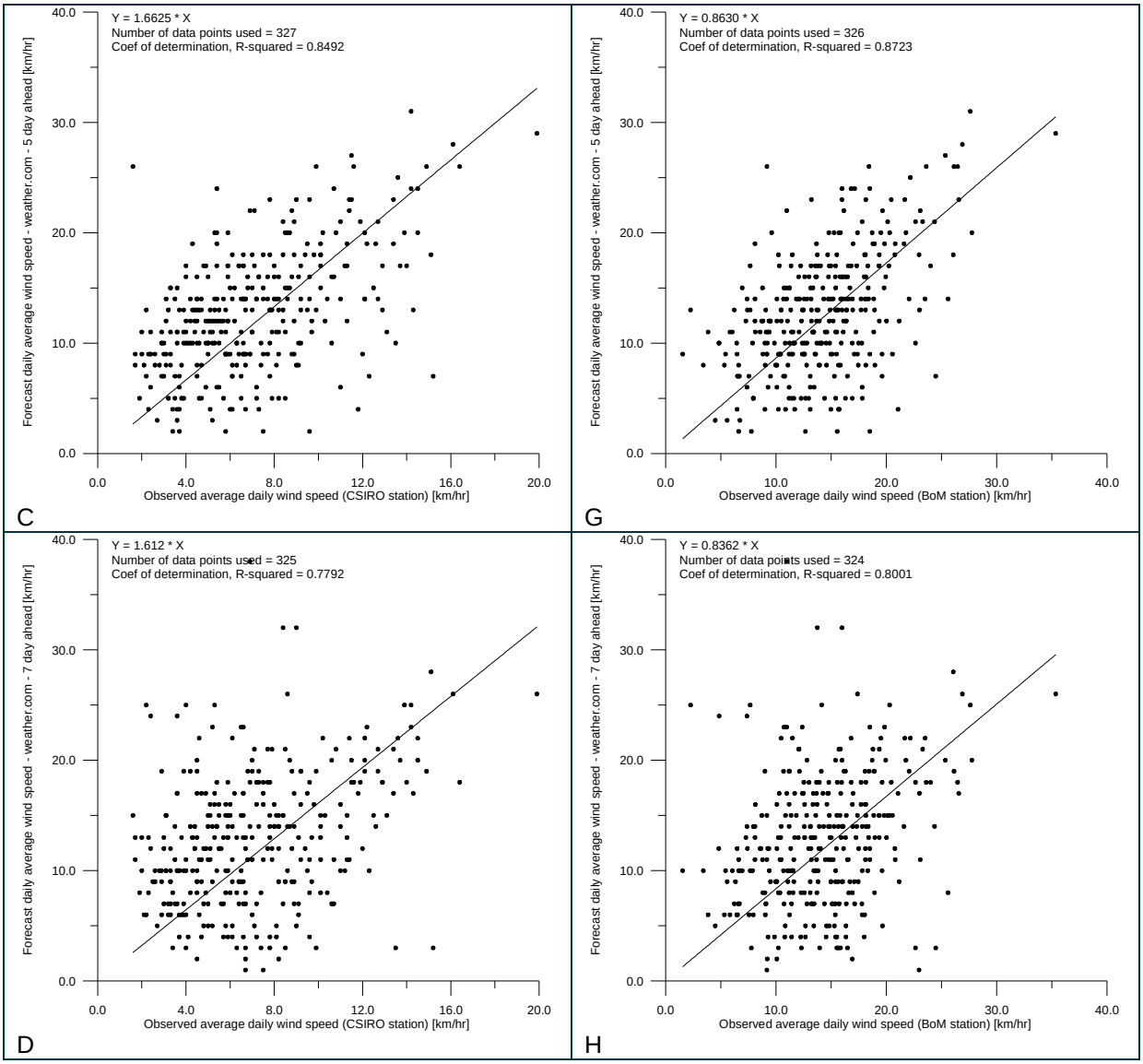


Figure 10 Observed average daily (24hr) wind speed at 2 m height at CSIRO weather station (A-D) and BoM weather station (E-H) compared with the forecasted wind speed from weather.com.au using 1, 3, 5 and 7 day forecast periods.

It can be seen from Figure 10 (A-H) that the relation between wind speed observations and forecast data is not very strong. Figure 10 shows a slope for the correlation between CSIRO measurements (A-D) and weather.com.au predictions in the range of 1.6-1.8. This indicates that the predicted wind speed is more than 60-70% as high as the actual observed wind speed. Several reasons could be causing this. It is unclear for which height the forecast is applicable. There is no immediate information available, although similar weather sites show that predicted wind speed is valid for "the height that is usually screened for observations". Most likely, the forecast is for a 10m height. To adjust the 10m forecast to a 2m forecast, a conversion factor can be applied, based on the equation

$$u_2 = u_{10} * \frac{4.87}{\ln(67.8 * 10 - 5.42)} = u_{10} * 0.75$$

Multiplying the observations with a factor 0.75 would reduce the slope of the correlation from 1.7 to 1.3, thus still resulting in a forecasted wind speed that is 30% higher than expected.

Similar to the relative humidity, a general trend between forecast and observed data exits, although the relation is less pronounced, as indicated by the coefficient of determination (r^2) not higher than 0.89.

Global radiation

Global radiation is not a directly forecasted parameter, yet an important input in the Penman-FAO56 equation. The global radiation is an indication of the amount of energy available at the earth's surface for heating the air, the soil and evapotranspiration.

OCF does not provide radiation parameters, except sunshine hours for a limited number of stations in Australia. In written descriptions, an indication is given on the cloud expectations for the duration of the forecast. The weather.com.au site provides a visual interpretation of the number of clouds through the use of icons. Weather.com.au uses a total of 33 icons to describe the atmospheric conditions, although several are applicable only on night-time conditions. The daytime conditions are crucial to calculate global radiation and are described by 15 different icons.

Figure 10 shows a summary of the most commonly used icons for Griffith, during the period of analysis (27-Aug-2010 until 15-Aug-2011).

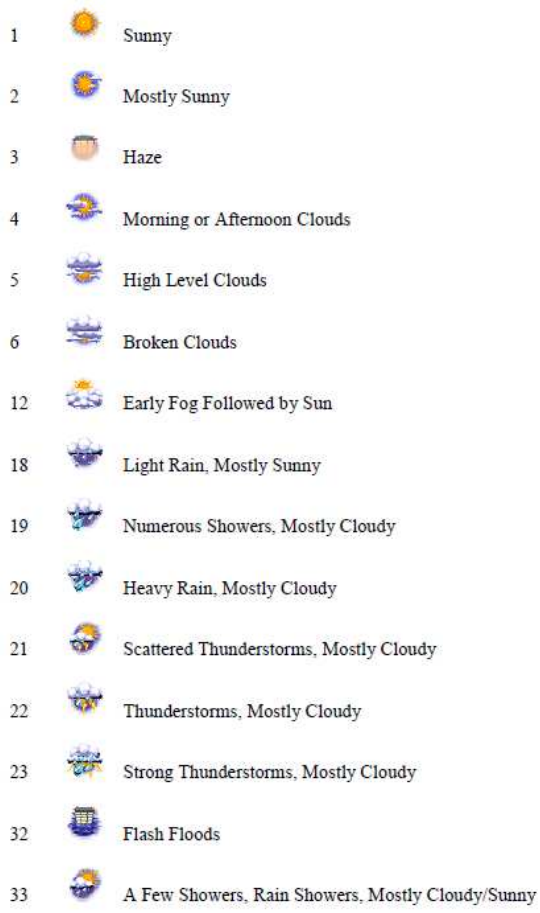


Figure 10 Overview of the icons and weather conditions represented at weather.com.au

To translate the icons into global radiation, a multi-step approach was used. The day+1 forecast icon was coupled with the calculated transmissivity from observations from CSIRO stations and calculated extraterrestrial radiation. Each of the transmissivities was then averaged for each icon, resulting in the values in Table 3.

Table 3 Average transmissivity values representing each icon used at weather.com.au

Cloud icon number	Transmissivity (τ)	Number of observations (n)
1	0.73	131
2	0.64	354
3	0.66	2
4	0.57	248
5	0.59	35
6	0.49	30
12	0.66	70
18	0.44	110
19	0.41	117
20	0.27	21
21	0.46	22
22	0.49	19
23	0.28	5
32	0.35	3
33	0.35	107

The calculated values approach expected values. One generic method to estimate transmissivity from cloud cover is expressed as:

$$\tau = 0.25 + 0.50\,\frac{n}{N}$$

Where τ = daily average transmissivity of the atmosphere, n = actual duration of sunshine (hr) and N is maximum possible duration of sunshine (hr). This shows that when the actual sunshine hours equal the potential duration (a clear day), the transmissivity has a value of 0.75. On a fully clouded day (sunshine hours equal zero), the transmissivity would have a value of 0.25.

Comparing Table 3 with the weather conditions as described in Figure 10, the two extremes (icon 1 and icon 20) are represented by an average transmissivity value of 0.73 and 0.27 respectively. This corresponds well with values expected for these conditions. Other cloud conditions identified by the icons also follow the pattern that would be expected. Note that icons 3, 23 and 32 only represent values of 2, 5 and 3 observation days respectively. This is a low number of observations, but the calculated values correspond with expectations, and the low number of observations is also an indication that these weather conditions do not occur frequently.

When each icon represents a transmissivity value, and the extraterrestrial radiation for each day of the year is known, we can compare forecast global radiation data with observed data (Figure 11). Note that the comparison with day+1 is biased, since this is a subset of the data that were used to calibrate the transmissivity data. The comparison of these data shows in a sense the variability of the days that contributed to the average value of transmissivity.

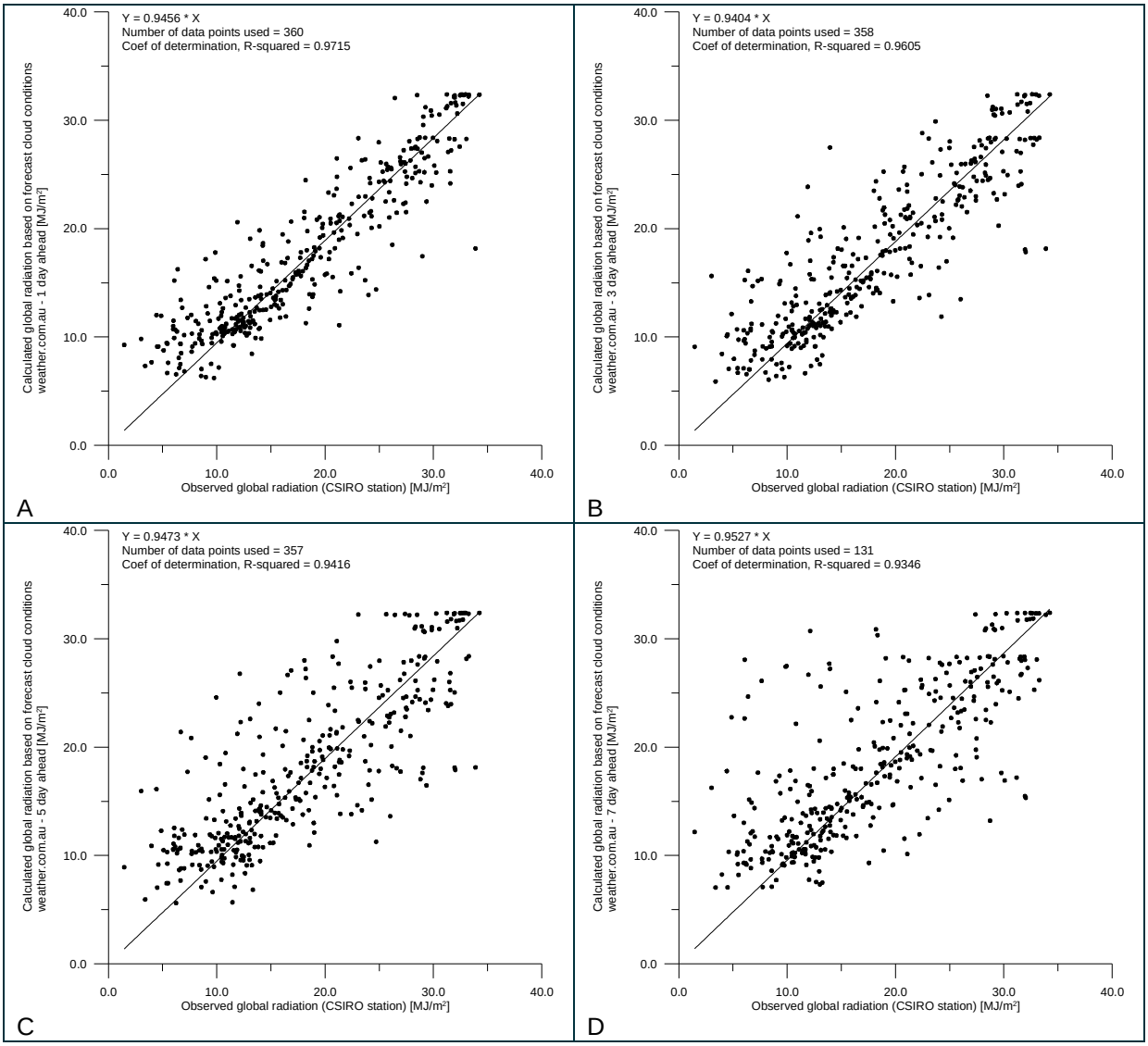


Figure 11 Observed global radiation at CSIRO weather station (A-D) compared with the forecasted global radiation based on cloud indications from weather.com.au using 1, 3, 5 and 7 day forecast periods.

Some bias appears for the lower radiation observations (less than 10 MJ/m^2), where the forecasted values appear to level off around 15 MJ/m^2. This may be related to a lower number of observations for clouded, low transmissivity data. It is expected that this may improve once more forecast data can be used to re-calibrate the icons.

It can again be observed that the forecast for day+7 is less correlated with observations than the forecast for day+1. However, the same relation between observations and forecast data is valid.

ETo

With the four variables available, the reference evapotranspiration can be calculated using the Penman-FAO56 equation:

$$\lambda E = \frac{\Delta(R_n - G) + \left(\rho_a c_p \frac{(e_s - e_a)}{r_a}\right) * 86400}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

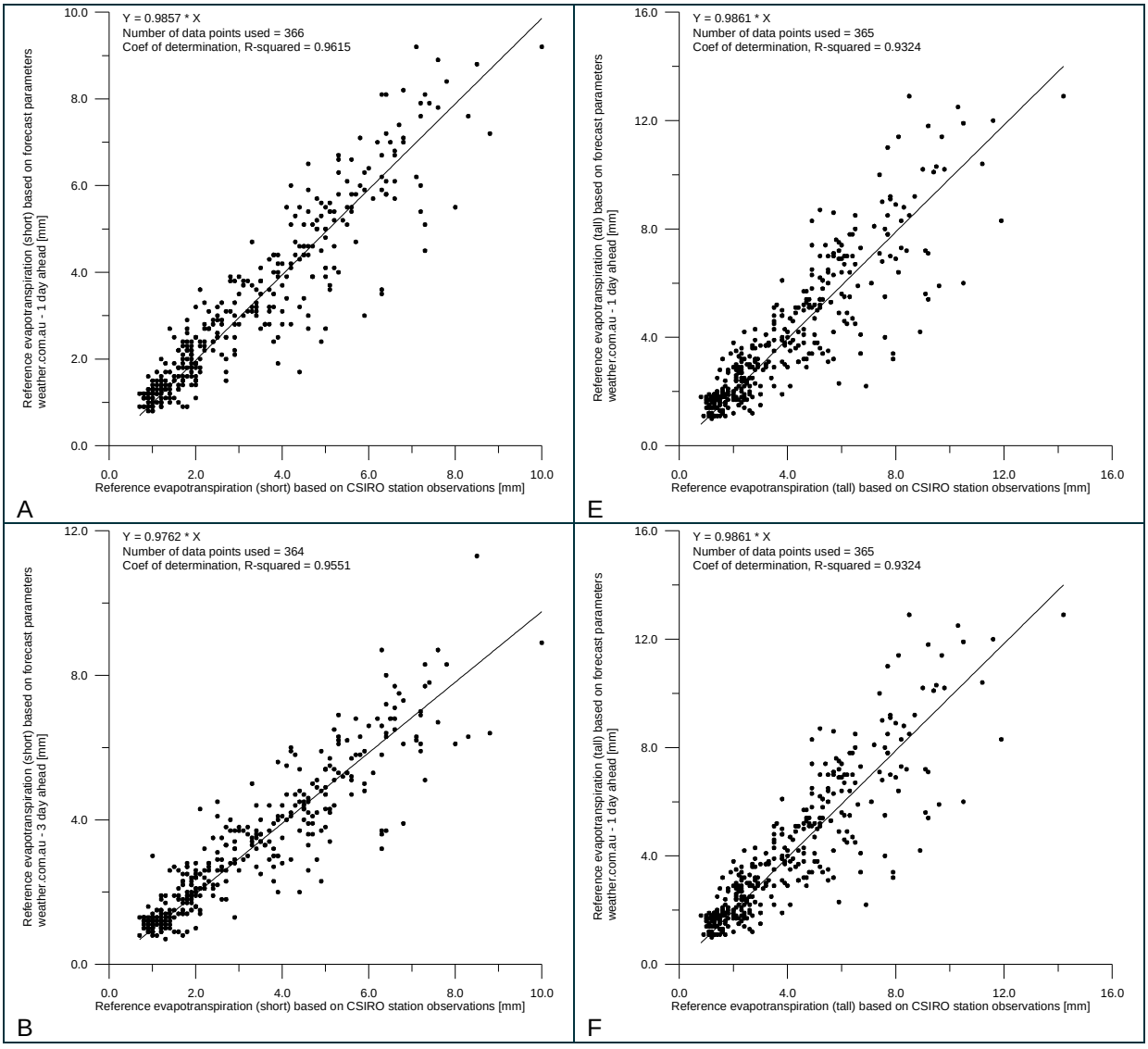
Where λE= latent energy (energy needed to evaporate water) [MJ/(m^2 day)], Δ = slope of the saturation vapour pressure temperature relationship [kPa/^{o}C], R_n = net radiation [MJ/(m^2 day)], G =

soil heat flux [MJ/(m^2 day)], ρ_a = mean air density at constant pressure [kg/m^3], c_p = specific heat of air [MJ/(kg ^{o}C)], γ = psychometric constant [kPa/^{o}C], r_s = bulk surface resistance [s/m] and r_s = aerodynamic resistance [s/m].

We use the short and tall reference crop to compare daily reference evapotranspiration based on observed and forecasted input data. For the theoretical grass reference crop (short reference), the bulk surface resistance is defined as 70 s/m, while the tall reference crop uses a bulk surface resistance of 50 s/m. The albedo is in both cases defined as 0.23.

Forecast wind speed and humidity values were adjusted with the linear through origin and exponential "best-fit" lines, respectively, (using day+1 forecast) to use the 'most likely' values.

Forecast data are compared with calculated values from observed weather parameters for the period from 27-Aug-2010 until 5-Sep-2011 (Figure 12). In September 2010, 7 days are missing, and in October 2010, 2 days are missing. The corresponding ET_{ref} values from the missing dates would be expected in the lower range.



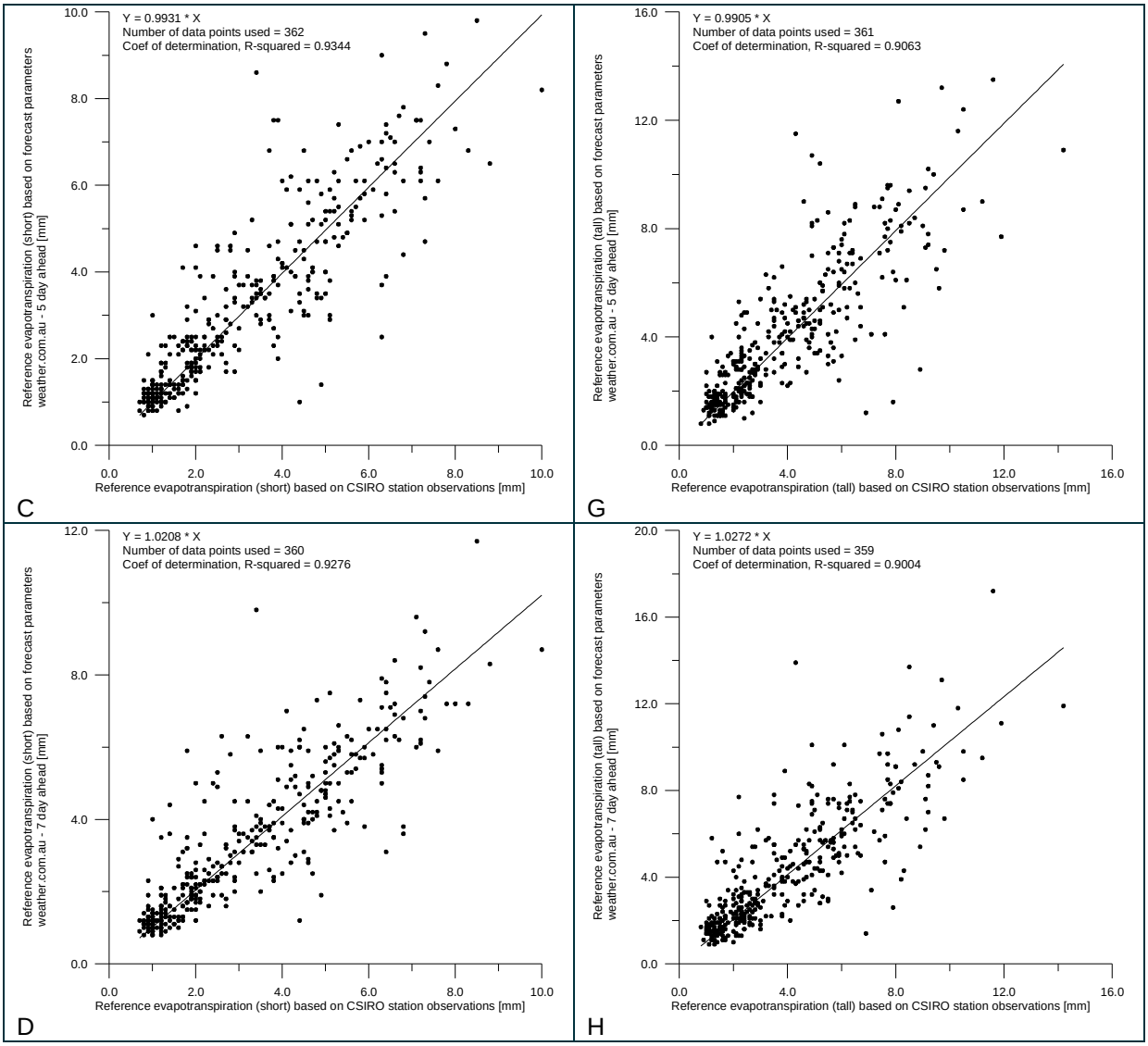


Figure 12 Short reference evapotranspiration (A-D) and tall reference evapotranspiration (E-H) based on CSIRO weather station parameters compared with the values calculated based on forecast data from weather.com.au

Figure 12 shows a good comparison between evapotranspiration based on measured and forecast data for a 1-day ahead forecast. The correlation is reduced when the forecast is farther ahead in time. This effect is expected based on the increased variability between observed and forecast data of the meteorological input data. The calculations for the tall reference evapotranspiration have a very similar correlation between measured and forecast data as the short reference evapotranspiration.

The slope of the fitted line indicates that in general the method to forecast the ET_{ref} is well calibrated with the actual measurements. A sensitivity analysis on the meteorological inputs into the evapotranspiration calculations for the climate in Griffith shows that solar radiation has the largest influence, followed by temperature, wind speed and humidity (See Appendix).

Figure 12 can also be represented as a time series. Data from September 2010 to September 2011 are shown in Figure 13, for the actual measured values (orange line), the 1-day forecast data (dark green) and the 7-day forecast data (blue). Note that during the summer season, many of the peaks and troughs are captured by both the 1-day and 7-day forecast data. In August 2011 and early September 2011, two peaks in the measured values were less captured. These two peaks represent a period of warm weather with high wind speeds where temperature and wind speed was not well captured in the forecasted meteorological data.

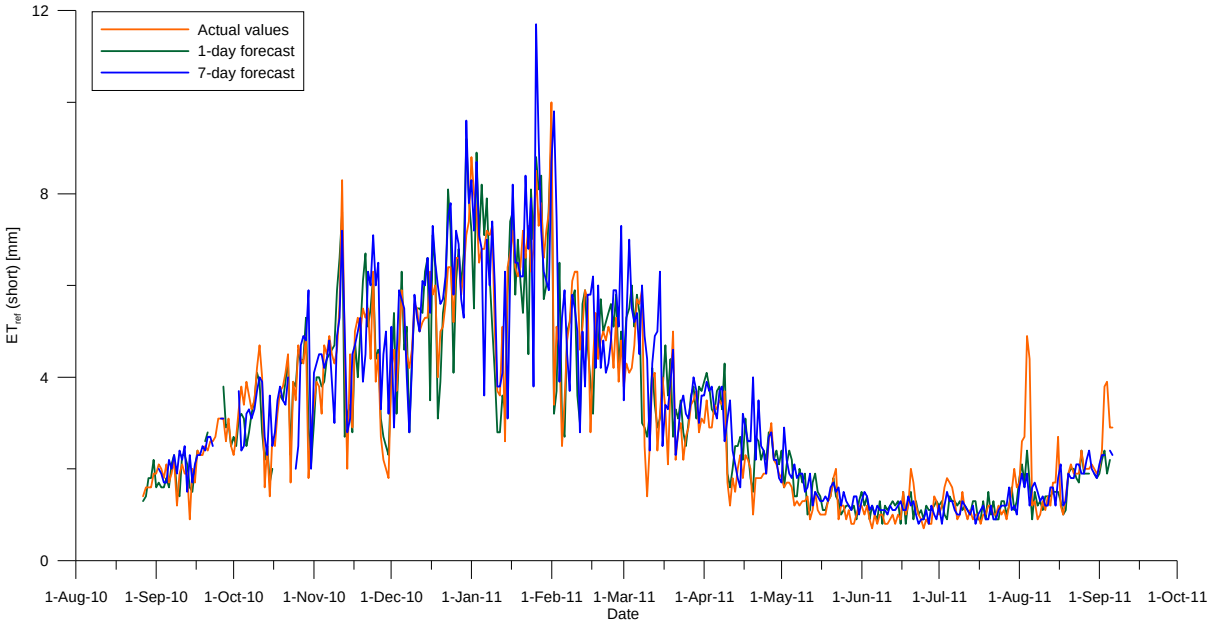


Figure 13 Measured daily evapotranspiration compared with 1-day forecast and 7-day forecast calculated short reference evapotranspiration.

For the application of forecast ET_{ref} to irrigation management, the variability increases once the forecast duration increases although Figure 12 D and H still show a strong relation for the 7-day ahead forecast. For irrigation water demand planning, the ET will likely be used cumulatively for the forecast period. Thus, the cumulative 7-day forecast will include a value for day+1, day+2 … day+7. The 7-day ahead forecast in this analysis is presented as the worst case, but will practically only be the worst case when the ET_{ref} specifically for day+7 is used as a single number.

A comparison of cumulative values from forecast data and observed data is shown for a 3-day and 7-day period. The 25-year average is shown to compare forecast based calculations with statistical based methods (Figure 14).

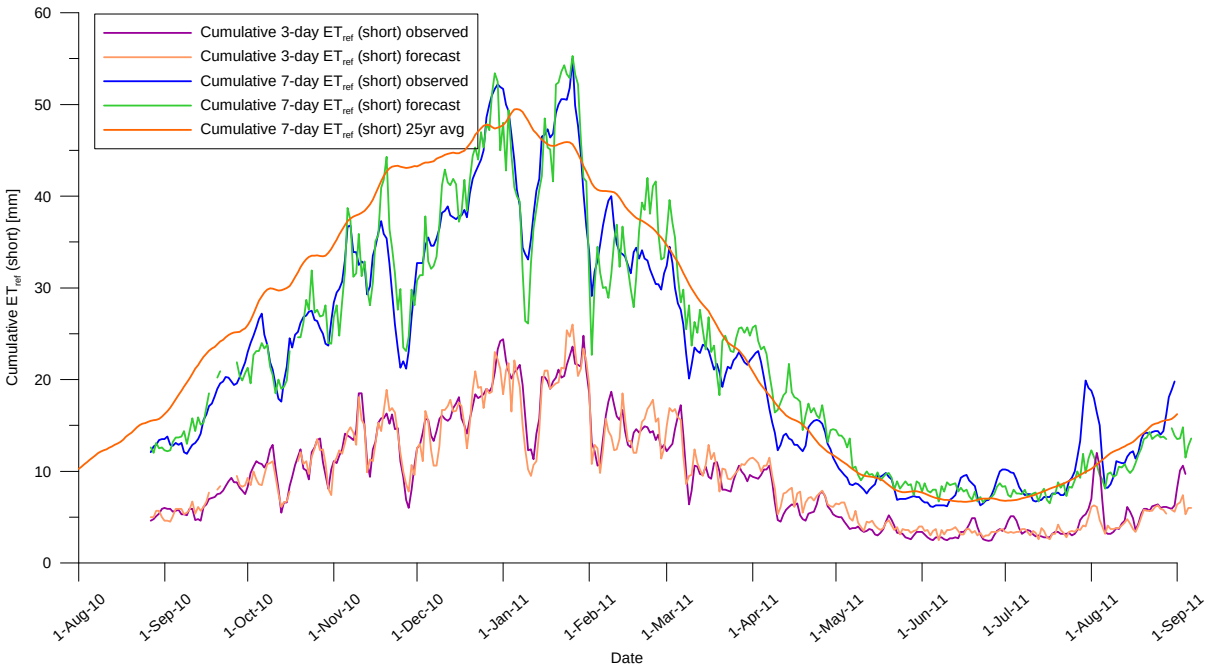
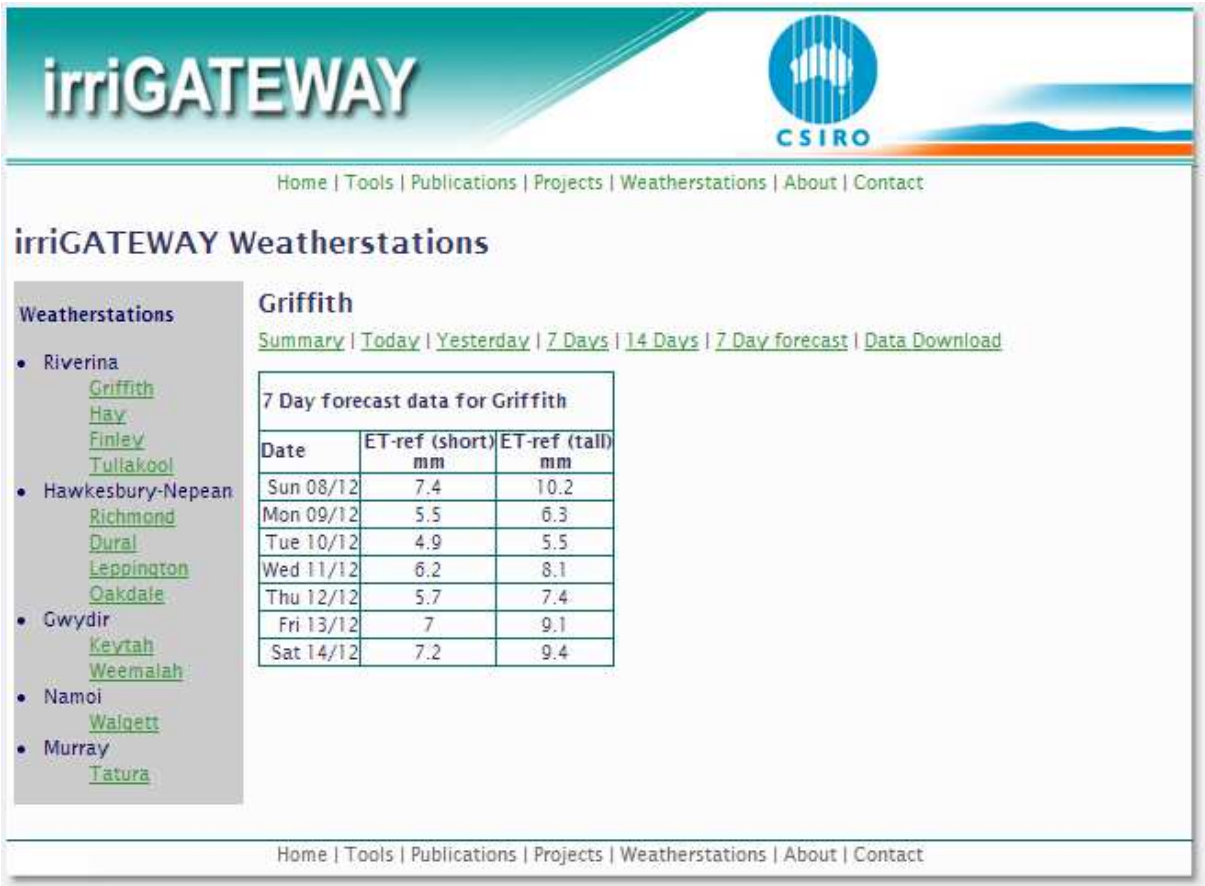


Figure 14 Three and seven day cumulative forecast and observed short reference evapotranspiration based on data from CSIRO weather station and weather.com.au forecast. The 25-year average is shown to compare forecast based calculations with statistical based methods.

Figure 14 shows that the 3-day cumulative forecast (orange) follows the 3-day cumulative observed (purple) closer than the 7-day cumulative values, as expected. The 7-day cumulative values follow the variability over time well, which is a large improvement over an alternative to use average historical data. It appears that the current (calibrated) forecast for Griffith would provide sufficient reliability to be used for irrigation water management up to 7 days in advance.

In order to make this forecast data available to irrigators in the study regions (Murrumbidgee and Northern Victoria) an automated system was developed and data displayed to the web daily with open access, through the Irrigateway website. Data from this web site is used in IrriSat, but is also available free for use by other interested parties. Figure 15 shows the web interface and forecast data for Griffith and Tatura. Forecast data can be automatically harvested into an Excel spreadsheet from the website using a simple Excel web Query which requires no specific programming. The addition of the developed ETo seven day forecast allows the IrriSat derived crop coefficients and forecast derived ETo to be used to provide seven day future prediction of crop water demands which can be used in a range of scheduling and water management planning activities. Tutorials on using this information is shown in the attached appendices.



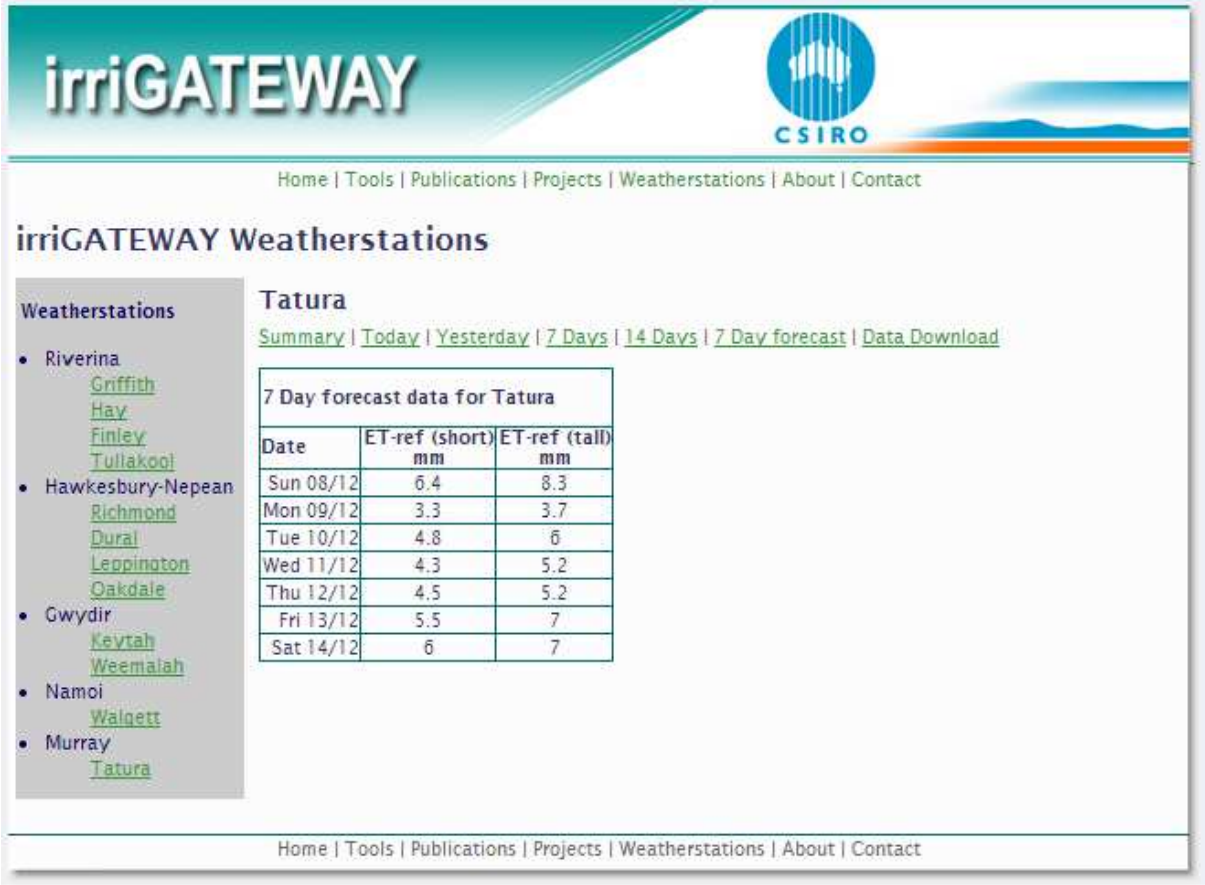


Figure 15 Seven day forecast data as available through the web at http://weather.irrigateway.net/aws/index.php

Uses and applications of the IrriSat technology (Obj. 4)

Assessing IrriSat system Utility

In order to fully evaluate and assess how irrigators were using the IrriSat technology a sample group of 72 trial irrigators were selected and provided with IrriSat derived data in the same format, delivered through both a mobile phone sms service and web service. Participants were wine grape growers selected for their use of drip irrigation systems and mobile phone ownership. Mobile phone ownership was close to ubiquitous amongst all irrigators in the region so this was not a limitation. They were also selected to be representative of the range of drip irrigators in the region by the local Wine Grapes Marketing Board (WGMB) grower association technical officers. The reason for this was to ensure as representative cross section of the local irrigation community as possible was used in the trial. The sizes of the grape farms, participant ages and years of irrigation experience are shown in Figure 16.

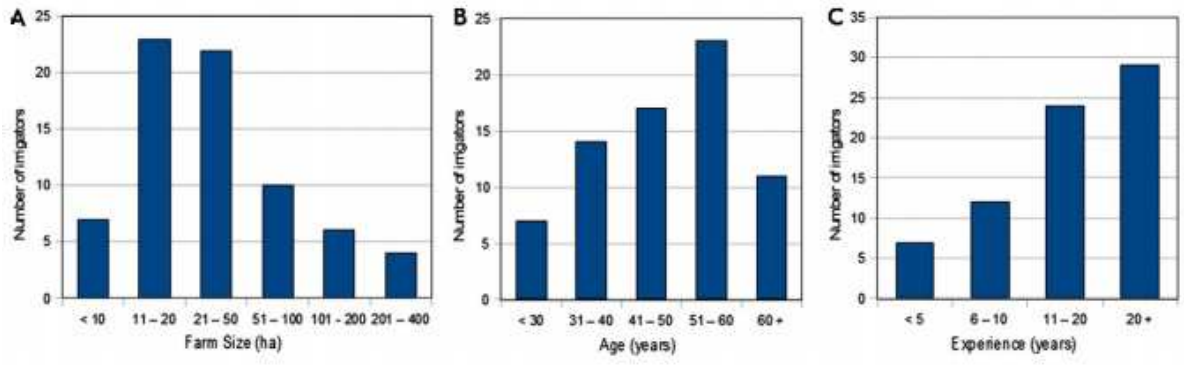


Figure 16 (A) Participating irrigator farm sizes. (B) Participating irrigator ages and (C) participating irrigators experience.

During initial interviews irrigators were asked about their irrigation systems and their use of mobile phones, computers and the Internet. They were then asked about their irrigation scheduling techniques in general and their experience with evapotranspiration in more depth. Table 4 gives the number of irrigators who used various methods and various tools to schedule before the trial. Irrigators often used more than one method or tool to determine when and how much to irrigate. Some common combinations were visual inspection of the vine and soil moisture determined by digging and soil moisture probe readings with weather forecasts.

Irrigator's previous use of evapotranspiration based methods for scheduling was very limited, indeed only one irrigator could demonstrate use of a water balance approach. To ensure irrigators understood the information they received throughout the season, they had training in evapotranspiration basics (how a simple crop water balance is driven by water in (rainfall and irrigation) and water out (evapotranspiration and drainage) and that the evapotranspiration of particular crop fields can be estimated through measured reference evapotranspiration and satellite imagery of the crop i.e. the IrriSat approach. They also had the phone data they received explained to them on several occasions. It was intended that they should easily understand the information they received. Additionally, in order to run an individual waterbalance for each irrigator they were required to send a text message in with the time they irrigated for and also any rainfall amounts. This data was stored on a central server and used to provide daily updated water use information to the participants.

All irrigators spent 15 min or less, on average, deciding on their irrigation application volume for each Irrigation Management Unit (IMU), each day, including the time taken to use scheduling tools listed in Table 4.

Table 4 Irrigation scheduling methods used

Tool/method	No. of irrigators[a]
Experience	66[b]
Moisture probes	45
Shovel – to inspect soil moisture	28
Visual plant inspection	26[c]
Fixed schedule	19
Weather (irrigator's estimations of crop water demand)	18
ET_0 – growers using reference ET from a local weather station	5
ET_c – a grower using local weather station ET and his own estimates of crop coefficients	1
Infra-red probe – a grower using an IR camera to tell when vine leaves reach background temperature	1

Most irrigators had between one and several (2–5) IMUs meaning a total irrigation decision time of less than an hour was normal. Irrigators all approached the task of deciding how much to irrigate each day having an approximate figure in mind due to the time of the season, a pre-existing schedule, previous experience with that crop or system limitations. In this trial the IrriSat derived crop water use data was provided to irrigators as both a web based graphical interface showing water balance data and also a daily sms test message sent to users mobile phones. The sms messages contained water use information to that point in the season along with a dripper run time in minutes which was determined based on the IrriSat derived crop water use and the irrigators drip system application rates measured at the time of initial interviews (Figure 17). Almost all irrigators immediately understood that the dripper run times derived from the water balance were to be used in the context of multiple scheduling data sources (such as shovel inspections and weather forecasts) and thus used the dripper run times as a guide, rather than absolute figures to be followed exactly.



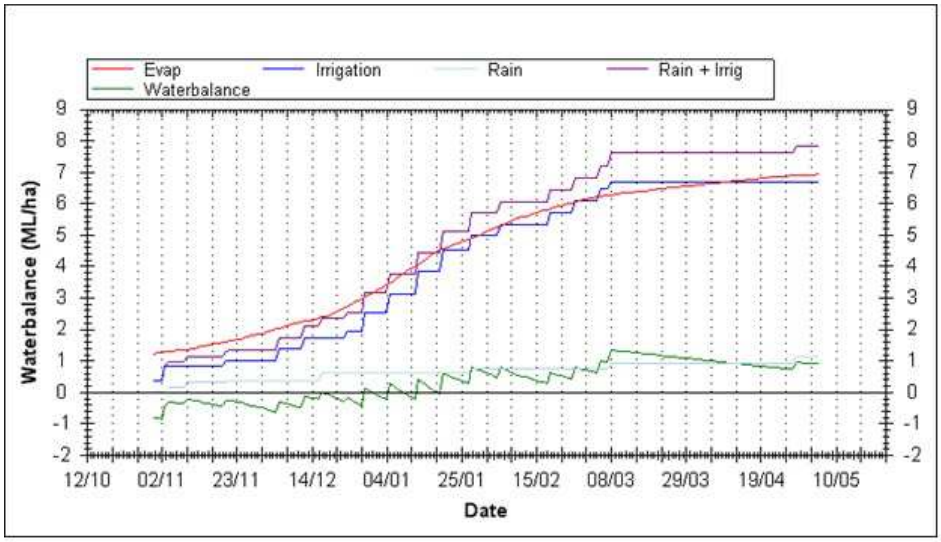
Figure 17 Mobile phone screen showing typical sms message

Figure 18 shows the daily Crop Water Demand (CWD) values for 3 irrigators over the full season. The 3 irrigators followed irrigation patterns that resulted in them using either more than, close to, or less water than recommended. However, in all three cases the information provided was useful to the irrigators based on their survey responses. We can see that for the 'more' irrigator, once the rainfall in December had been evapotranspired, his negative cumulative CWD continued to grow slowly for the rest of the season but he engaged with the system until the end of the season nonetheless. This irrigator grew a large Colombard crop and was comfortable using what he considered to be a large

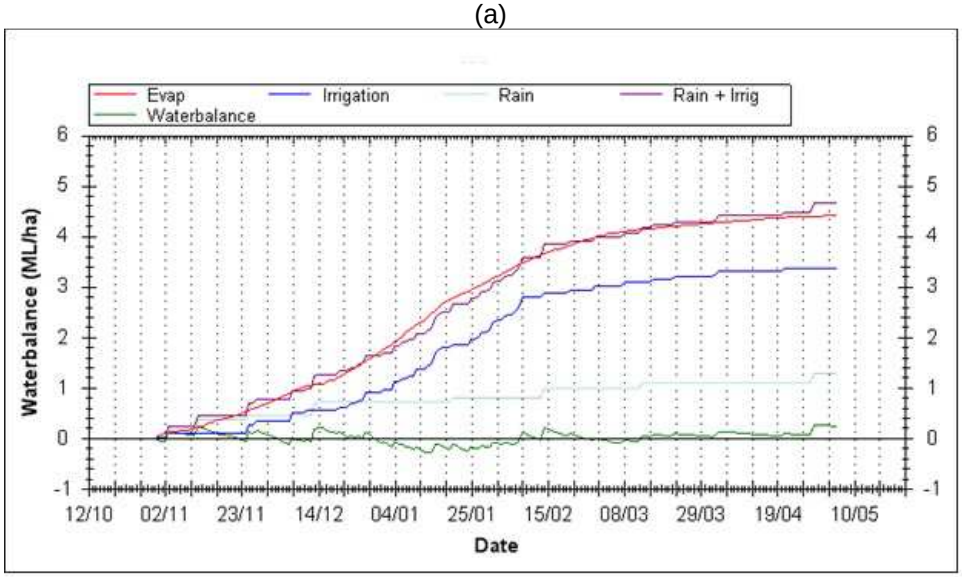
amount of water as he was aiming for maximum yield with quality being of minimal importance. In interviews he stated that he was able to use the IrriSat information as a relative guide as to how much to irrigate, due to weather effects and crop life cycle, even though the absolute value recommended was not the same as his practice. The ‘close’ irrigator used the IrriSat information as his main scheduling tool. It was his first year using a drip system and so he looked to the SMS messages to provide him with guidance. The ‘less’ irrigator did not follow the advice of the system during the January heat wave in which the IrriSat information recommended more water be applied than he was comfortable doing, but then did so for the rest of the season even though there was a legacy of approximately 50mm cumulative CWD that he was not able to recover. He found the advice post heat wave useful in determining exact irrigation volumes taking 50 mm cumulative CWD as a new zero point.

All three representative irrigators continued to interact with the tool until the end of the season despite their differing cumulative CWDs and associated suggested dripper run times. All three also chose to participate with using the tool again for the following season which confirms their perceived utility of it.

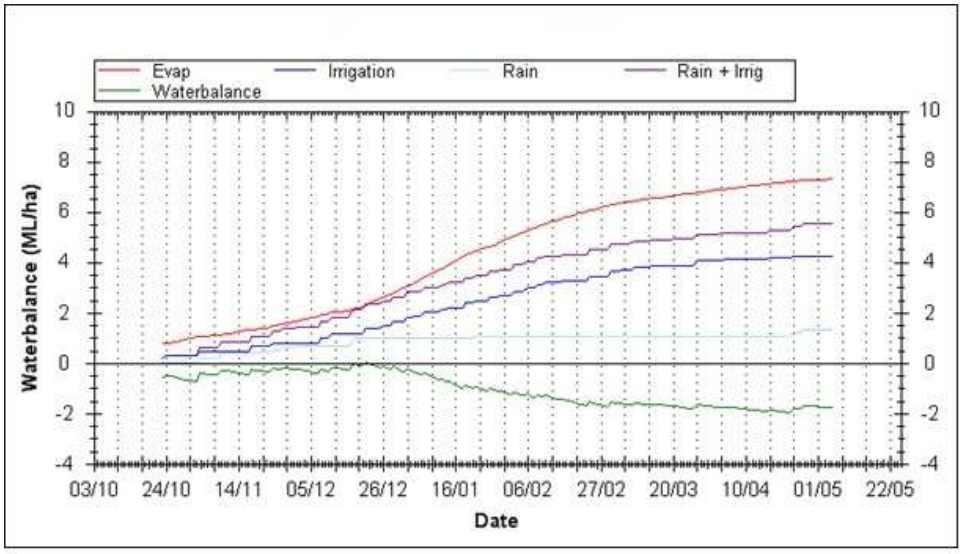
From the interviews it was clear that the IrriSat information use ranged from a direct to an indirect scheduling guide and that irrigators were able to interpret and use the information received from the tool in ways that benefited their situation.



(a)



(b)



(c)

Figure 18 Representative irrigation behaviour patterns from users of the IrriSat derived data

From the IrriSat daily CWD graphs, usage could be placed into six named groups:

1. **Close throughout** – those who followed IrriSat recommended dripper run time closely, irrigating within 10% of the recommended minutes throughout the season.
2. **Close mostly** – those who followed the IrriSat recommended runtime closely until late December, then applied less than recommended for 3–4 weeks co-responding with a time of very high evaporative demand (heat wave), and then applied as recommended for rest of season.
3. **More throughout** – those who applied more than recommended consistently across the season. Note this was only up to 15% more than the total recommended number of minutes.
4. **Less throughout** –those who applied much less than suggested.
5. **Stopped sending** – those who followed the recommended amounts until late December mid January and then stopped sending input data
6. **Never sent** – irrigators who never sent in any data.

The number of irrigators in each of group is given in Table 4.

Table 5 Percentage of irrigators per water balance group

Group	%
1. Close throughout	36
2. Close mostly	10
3. More throughout	4
4. Less throughout	18
5. Stopped sending	8
6. Never sent	24
Total	**100**

Irrigators in Groups 1–4 (68%) can be collectively grouped as full system participants. They engaged with the system until the end of the season, albeit with different watering preferences.
Irrigators in Group 4, less throughout, did not ascribe to a single motive for doing so in end-of-season interviews. Two said that they deliberately reduced their watering to stress their crops for quality reasons, two said they did not think it was economically viable to fully water their crop and two said their crop was 'happy' with the amount of water that they had given it.

Group 5, stopped sending, or ceased sending messages as they saw their suggested dripper run times increase beyond what they perceived to be reasonable and so did not persevere. It would seem they lost confidence in the system. Half the irrigators in this group stopped after some usage as they felt the system offered them no benefits. Three stopped for reasons unrelated to irrigation such as personal and other issues such as sale of the farm.

Some irrigators who were generally happy with their involvement in the trial and whose actual dripper run times differed from the suggested dripper run times, but did not change their behavior, explained that the differences between the volumes were necessarily so due to their blocks being non-standard. One irrigator who watered much more than the suggested dripper run times said that his block was steeply sloped and had unusually sandy soils. Others who watered much less said it was due to their heavy clay soils.

The important message from these responses is that no irrigators that followed the advice were unhappy with having done so and no irrigators that received the advice and monitored it through to the end of the season were unhappy about having done so, indeed some wished they and followed the advice, not just monitored it. This realisation was corroborated both at the post irrigation season group meetings as many irrigators, particularly in group 2 and 4, reported reduced yields below targets and sun burn issues. Figure 19 shows a typical CWD's of group 2 irrigators during the trial. It can be seen that for these irrigators there was a significant period (3-4 weeks) in which applied water was not able to maintain the water balance resulting in a sustained period of water deficit. This group reported that after this period they had difficulties 'catching up' and felt that they had suffered reduced yields because of this water stress.

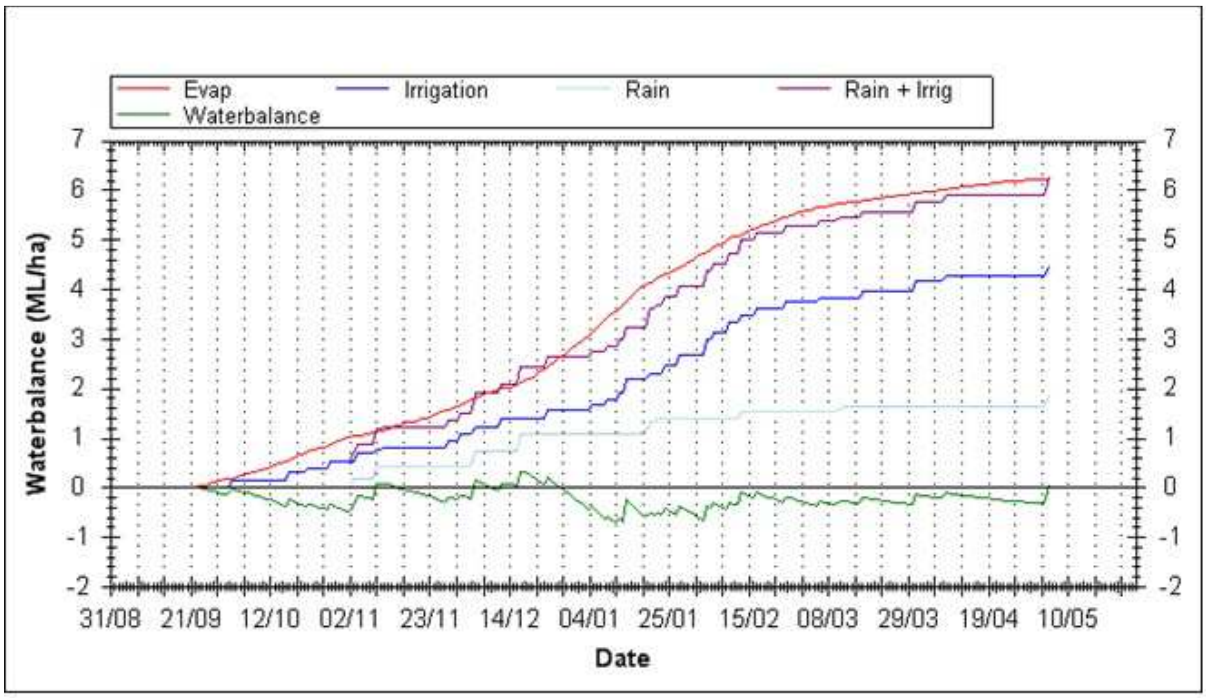


Figure 19 Typical pattern of group irrigators

At the end of the season interviewed irrigators were asked how they used the IrriSat information in their decision making on water management in their vineyards over the trial period. When asked how irrigators translated the IrriSat advice into action, 25% answered that they allowed dripper run time minutes to accumulate for a number of days and then irrigated for a time close to that number. The majority (79%) said they took advice from several data sources (such as weather forecast, auger results, vine inspection) and would then come to a final decision based on a fusion of this type of information with the IrriSat information. None of these irrigators could quantify the implicit weight they ascribed to each data source. Only 6% of the irrigators wrote down approximate dripper run times from each source before making a decision, all the rest carried out this process semi subconsciously in a matter of a few minutes each day. In response to direct questioning, all irrigators stated that the total irrigation decision making process occupied only a few minutes per day. For the whole group of 72 irrigators, 53 (74%) said they actively considered information from IrriSat in their scheduling decision making.

Of the irrigators actively involved in the trial, 40 irrigators answered the open ended question ‘‘How did the tool affect your scheduling behaviour over all?’’. Their answers followed 5 similar behaviour themes which were:

Small: The dripper run times were close to what they were doing so observing and/or following it resulted in little change in their former practice. The tool was still seen as valuable in that it gave them confidence in their current practice and acted as a back-up. IrriSat did thus influence their practice by positive reinforcement and resulted in a small change in behaviour whereby a new irrigation data source was considered in coming to a decision.

Large: They perceived the dripper run times to be higher than they believed necessary but they still followed them on trust, resulting in a large change to their practice.

Significant: They used IrriSat as their main irrigation scheduling tool but could not describe how this may have changed their practice. Thus the tool can be deemed to have influenced their practice, but the behaviour change is unknown.

Marginal: The IrriSat information was interesting and educative to them and changed their understanding but did not change their behaviour.

None: They perceived the dripper run times to be too high/low and did not follow them, resulting in no change to their behaviour.

Table 5 gives the percentage of respondents who subscribed to the various views described above.

Table 6 Number of irrigators per behaviour change

Group	% of respondents
1. Small	27
2. Large	24
3. Significant	22
4. None	20
5. Marginal	7
Total	100

When assessing the total effect of the system on irrigator behaviour we can sum Group 2 and 3 giving 46% as those for whom IrriSat had significant effect on their behavior. We can then add Group 1 to this as those for whom there was some influence on behaviour (73%). Beyond that we can add Group 5 to this to give 80% as those who were educated in some form by using IrriSat. However, further discussion with Group 4 irrigators found that their post season analysis told them that they could have benefited from following the IrriSat recommendations, and would do so in future seasons. As such we can see that IrriSat had a level of influence on behaviour and educative capability.
After discussing the effect of IrriSat on their behavior the irrigators were asked to reflect upon this. Group 1 all said that using the tool gave them confidence in their current method of operation.
No one from Group 2 who had followed the advice of the tool and put on more water than they initially thought necessary was unhappy with having done so in retrospect as they felt it positively affected yields. Group 3 irrigators could not articulate their behaviour change due to:

- inter-seasonal changes in circumstance (e.g. crop age, financial returns, weather variations);
- lack of previous seasons' experience with that particular block; this being their first year using drip irrigation;
- insufficient records from previous years.

This confounded efforts to draw comparisons between the trial season and previous seasons however, all of these irrigators thought the IrriSat information useful and did not regret having followed it. Several Group 4 irrigators said that in retrospect they wished that they had followed the suggested irrigation times that they originally did not follow due to thinking them too high. Group 5 irrigators stated they found the involvement with IrriSat system interesting for a number of reasons such as learning about crop/weather interactions and quantitatively comparing rainfall and irrigation, but it had significantly influenced them to change their behavior. It was clear from the survey results that group 2 irrigators where able to improve their water use productivity through use of an information system such as IrriSat. It can be seen that across most groups there is the potential for irrigators to improve their farm water use productivity using this type of technology and many irrigators were able to do this.

Packaging and deploying IrriSat information

Over the course of the project a number of changes in technology and fundamental changes to access of satellite data have occurred. Two of the bigger changes have been the freely available access to NASA Landsat satellite data, which allows anyone completely free access to satellite images covering all of Australia. Secondly, the emergence of open-source (free) software in intuitive desktop applications which allows users with little or no previous experience with remote sensing software to rapidly access, analysis and use remote sensing data.

The original IrriSat system made use of the commercial Erdas Imagine remote sensing software for image analysis, which is a considerable barrier for smaller interested parties to incorporate the technology into their applications due to costs of this specialized software suite. During the course of the project it was clear that a range of users of the IrriSat technology (consultants, industry groups and individual irrigators) were interested in being able to access the technology in a way which allowed then to 'fit' or integrate the IrriSat approach with other technologies such as soil moisture monitoring or using the remote sensing data for other purposes i.e. understanding/managing variability. The project has investigated ways of being able to provide the IrriSat approaches to a range of end users from individual consultants to large water management providers.

Large IrriSat nodes

Development of large IrriSat nodes run in a commercial independent setting or by an agency tasked with water use efficiency offers a number of benefits. This was one of the initial models which was proposed for the application of IrriSat. It offers an industry or commodity base the ability to offer services to end users that assist in water management and also potentially collect data on benchmarking which can be used in a number of ways such improving performance across an industry. This approach has been successful in the Murrumbidgee where IrriSat has been used by a large number of growers during the project which have contributed to the development of the system and understanding key functionality and user needs. In order to continue to provide this information to users the project has been working on a joint project with Murrumbidgee Irrigation Ltd which supplies water to all horticultural irrigators in the MIA and ultimately hopes to offer the knowledge generated from the IrriSat approaches to all their irrigators through the EasyWater ordering system. All irrigators are required to order water before they receive it from the irrigation company and incorporating the IrriSat water use forecasts into the water ordering process for irrigators will help irrigators better understand their water use needs and also additionally, help the irrigation company manage water releases from larger storage dams which have a 7 day time lag between release and availability to irrigation farmers in the MIA.

Smaller independent IrriSat users

The project has also worked with smaller independent consults to allow them to access and use the technology with their individual clients at a smaller scale. This system relies on remote sensing software the project team has been involved in developing with the European Space Agency (ESA) and also access to free satellite images from the Landsat platform, through the USGS.

During the project a workshop program has been developed that teaches participants how to set up small scale IrriSat networks, at a local scale. Participants learn how to access free satellite images, use remote sensing software to manipulate images and then to disseminate water management information through a range of mediums. These workshops have been run with Irrigation Australia Limited (IAL) as part of the evapotranspiration masterclass series and also independently with interested end users. Tutorials and training materials used in these workshops have been included in the appendices of this report. The tutorials and training package provide information on how to implement the IrriSat approaches across a range of scales and for various end uses.

Outcome/Conclusion:

The IrriSat approach has the potential to provide a significant benefit for the Australian winegrape industry. This project has shown the potential of the IrriSat approach for providing site specific irrigation water management information. From this trial it was clear that there is significant interest in the approach by water managers in the winegrape industry and clear benefits for water management. Continued use and expansion of the IrriSat approach has the potential to lead to wide scale change in water use management across a range of scales from individual fields to regions which in turn will have positive economic flow on effects to the industry. The approaches, tools and packages developed in this project can be practically applied by the industry.

Within this project the project team has worked to develop a 7 day forecast and practical methods for gaining site specific crop coefficients across large areas at low cost. This information can then be used in a range of water management activities such as scheduling and water planning. Training packages to allow a range of end users access to the technology and to be able to apply this knowledge in their own situations has also been developed and a series of formal workshops has been run in conjunction with Irrigation Australia Limited (IAL) as part of the Evapotranspiration Master class series, along with informal training with interested end users such as consultants.

With increasing pressure being placed on water resources within the irrigation sector in the Murray Darling Basin, having an industry standard water use productivity benchmarking and water management tool is particularly important, that is accurately directly measuring crop water use. Applications such as IrriSat provide actual site specific water use management information across large area's at low cost at various time and spatial scales which have been shown to be potentially very useful in winegrape production systems. Future research within this area should focus on providing a consistent and sustainable approach for providing this information across the industry. Potential also exists to further refine the technology and its accuracy and also to link this water use information to other areas of interest for growers. The NDVI data, combined with IrriSat derived water use and other on ground measurements, such as bunch and berry counts, could also potentially improve yield forecasting. Additionally, the information derived by IrriSat lays a solid platform for implementing precision irrigation techniques, which may offer growers the opportunity to reduce input costs and increase profitability.

Recommendations:

There is a large opportunity to further extend this research and application within the wine grape industry. Project participants have provided feedback that they see value in the information provided with the technology and also value in the ability of the system to provide industry wide and inter region water use management information which can be used to improve water management. With increase access to satellite data and ease of use of this information there will continue to be opportunities to rapidly incorporate this information to aid water management decisions. In early 2015 the European space agency will launch the Sentinel 2 satellite which will provide 10m resolution NDVI data on a 5 day repeat cycle, with free global access. Additionally, large international commercial agencies are working of extremely simple to access to near real time global NDVI maps. For instance Google is developing the 'Earth Engine' https://earthengine.google.org/#intro which already in Beta version providing 8 day composite NDVI images across the globe using the Landsat satellite data. We are currently an active beta user and see great potential in this technology for further increasing access to satellite data and methods for using this information in on-farm water management. This ease of use and access to high resolution satellite information will provide further opportunities in irrigation management that focus on spatial aspects of irrigation management and further embed approaches such as IrriSat into irrigation water management activities.

Training material developed in the project for smaller independent IrriSat users have the potential to be delivered to a wider audience, through various grower information initiatives and extension networks and provide practical tools which can be used by water managers.

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Appendix A: Notes on method to determine slope and coefficient of determination.

The coefficient of determination (r^2) used in this report is different than the r^2 reported by the software package Microsoft Excel. Note that the r^2 in our report often appears higher than what we obtained from Excel. However, r^2, as the symbol indicates, would be hard-pressed to be negative. Yet many of the analyses in the report, especially about the forecast data, resulted in a negative r^2 as reported by Excel.

This may not be a large problem, since we mainly use the coefficient of determination as a relative value for comparison. However, to develop a better understanding of the (simple) statistics that we use, we provide the background on the differences between the r^2 reported by Excel and the r^2 we use in this report.

An internet search reveals that Excel 2003 contained some changes to the method used to calculate best-fit line statistics. Previous versions used a wrong method for cases where the "fit through origin" option was used. (http://support.microsoft.com/default.aspx?scid=kb;en-us;829208). Other discussion groups appear to seriously discuss the lack of transparency of the methods Excel uses (e.g. http://groups.google.com/group/microsoft.public.excel.worksheet.functions/browse_frm/thread /1622331fff22c235/c58cdd63033f6a2f#c58cdd63033f6a2f; http://sci.tech-archive.net/Archive/ sci.stat.math/2007-02/msg00078.html)

A search on Wikipedia reveals that multiple definitions to calculate the r^2 are available, including an adjusted r^2. (http://en.wikipedia.org/wiki/Coefficient_of_determination).

The graphing package (Golden Software Grapher) used for this report defines the coefficient of determination as:

Coefficient of determination, R-squared shows how well the data are explained by the best-fit line.

$$r^2 = 1 - \frac{SSe}{SSe + SSr}$$

When using a *Through origin* fit, R-squared is calculated with

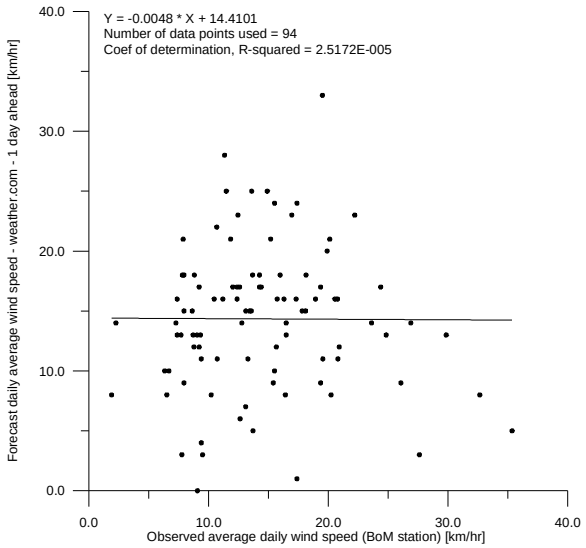
$$r^2 = 1 - \frac{SSe}{Syy}$$

where Syy is the sum of y * y.

The last definition (through origin) is the method we use in this report.

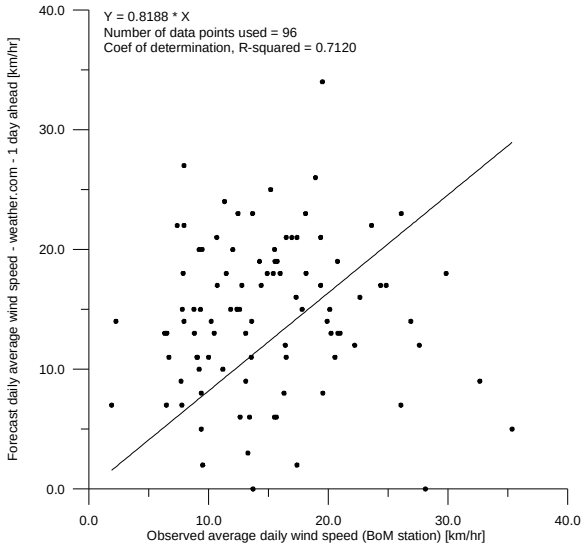
The reason we use a fit through the origin is that we are trying to assess the accuracy of the forecast compared with the measurements. We are not only looking for the best relation to convert forecast data into most likely measurements. We assume that the forecast data are going to fit a 1:1 line, and evaluate that assumption through the use of a linear fit through the origin. The slope of the line indicates how close the forecast is to the 1:1 line, while the r^2 provides us with information how well the assumed relation (with the off-set slope from the 1:1 line) fits with the set of observations.

As an example, we can evaluate the relation between daily wind speed measured by the BoM, and the 1 day ahead forecast provided by weather.com.au.



The best fit linear solution shows a flat line with an r^2 of 0. This shows that there is no statistical relation between measurements of wind at the BoM station, and the forecast made the previous day. Although this information provides us with information about either the quality of the forecast, or the quality of the measurements, this analysis does not provide us with the accuracy (or lack thereof) when we use the forecast data in the calculation for the reference evapotranspiration.

When we fix the origin for the best fit line, we force a relation that we assume will have a slope of 1.



In reality, the best fit line has a slope of 0.82, thus indicating that, with the assumption of linearity through the origin, we are underestimating the wind speed by 18%. Using this new –assumed– relation, we find a coefficient of determination of 0.71. This is a very low coefficient of determination (using the definition and method we selected, a value of less than 0.8 would indicate a bad fit).
In this specific case, we use this analysis to discard the BoM weather station, and continue with the analysis of the CSIRO weather station to evaluate the wind speed forecast.

Using the relation between the CSIRO weather station and the forecast data, we find that if we divide the forecast data by the slope of the graph, we are now estimating a wind speed that is more likely to represent the values that we are measuring.

To be able to analyze the forecast data, and the best method to use these data in the evapotranspiration equation, we use the best fit line forced through the origin, and thus the related coefficient of determination defined by the graphing package, instead of the one obtained through Excel.

Appendix B: Sensitivity of input data to the Penman-FAO56 equation

Despite the variability of weather forecast data, especially when considering day+7 forecast, the ET_{ref} based on these variables appears to be a reasonable estimate. From the individual analysis, relative humidity and wind speed forecast appear to be weak in the forecast. Through some simple variations of parameters for a standard winter and summer day, we evaluate the sensitivity to the separate parameters.

For a typical winter day the dataset for 1-Sept-2010 is selected, and for a representative summer day, the dataset for 1-Jan-2011 is selected.

	Max air temp	Min air temp	transmissivity	Windspeed [km/hr]	Humidity [%]
1-Sept-2010	20	9	0.47	3	85
1-Jan-2011	43	26	0.63	7	29

For the sensitivity analysis, each of the variables is varied by 20% (both negative and positive), and the resulting effect on the short reference evapotranspiration is measured.

Variation	ET-ref (short)	change in ET-ref
Base data set 1-Sept-2010	1.63	0
Max temp + 20%	1.78	+ 9 %
Max temp - 20%	1.47	- 10 %
Min temp +20%	1.70	+ 4 %
Min temp - 20%	1.56	- 4 %
Wind speed + 20%	1.62	- 1 %
Wind speed - 20%	1.64	+ 1 %
Humidity +18% (100% max)	1.62	- 1 %
Humidity -20%	1.71	+ 5%
Transmissivity +20%	1.86	+ 14%
Transmissivity - 20%	1.40	- 14%

Variation	ET-ref (short)	change in ET-ref
Base data set 1-Jan-2011	6.89	0
Max temp + 20%	7.29	+ 6 %
Max temp - 20%	6.37	- 7 %
Min temp +20%	7.15	+ 4 %
Min temp - 20%	6.58	- 4 %
Wind speed + 20%	7.15	+ 4 %
Wind speed - 20%	6.06	- 4 %
Humidity +20%	6.90	0 %
Humidity -20%	6.83	-1 %
Transmissivity +20%	7.75	+ 13 %
Transmissivity - 20%	6.00	- 13 %

Note that the sensitivity analysis shows large influence of the transmissivity (radiation) both in winter and summer conditions. Relative humidity appears to have more influence on the reference evapotranspiration in winter conditions, but barely any effect is measured under summer conditions. Overall, the effect of a 20% change in RH input does not appear to have more than 6% effect on the final calculations. Wind speed under winter conditions has less effect than under summer conditions. It is important to note that a change in either direction appears to reduce the calculated reference evapotranspiration. This is a result of the aerodynamic resistance (r_a) present in the numerator as well as in the denominator. The effect of a 20% change is in both cases less than 20% on the final result.

$$\lambda E = \frac{\Delta(R_n - G) + \left(\rho_a c_p \frac{(e_s - e_a)}{r_a}\right) * 86400}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

The resulting effect of a change in minimum temperature is relatively small, although a change in the maximum temperature has a larger effect in the summer conditions. This is caused by the temperature having an effect on the saturated vapor pressure, as well as the slope of the vapor pressure – temperature value. The temperature, however, has the highest accuracy in the forecast data, and a 20% difference with observed temperatures is unlikely.

An improvement of the relation between the weather icon and the transmissivity most likely will have the largest effect on the forecast ET-ref. The temperature already shows good correlations between observed and forecast data, therefore an improvement of the wind forecast, especially for summer conditions, could refine the ET-ref forecast even more.

Appendix 1: Communication

Journal articles

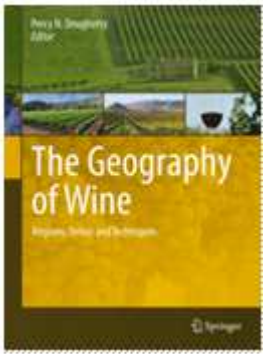
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*Invited Speaker at the Spatial Precision Agricultural Association Annual Conference: "Innovative Irrigation- PA tools in use in the horticulture, viticulture and cotton industries". Dr John Hornbuckle, Technology Park, Mawson Lakes, SA

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‘Mobile irrigation’ – ABC Rural News Wednesday 9th June, 2010

‘Crop revolution earns John gong’ – Area News 18th June, 2010

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‘Making the most of not enough water in irrigated vineyards’ Tony Proffitt, Australian & NZ Grapegrower & Winemaker, 01 Dec, 2013

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Appendix 2: Staff

Staff that have been engaged on the project

Dr Evan Christen
Dr John Hornbuckle
Dr Richard Soppe
Roy Zandona
Dr Belinda Kerridge
Nick Car
David Smith

CSIRO LAND AND WATER/SUSTAINABLE AGRICULTURE FLAGSHIP
www.csiro.au

IrriSAT approaches implemented in BEAM VISAT

Supporting Tutorials

Dr John Hornbuckle

IRRIGATION AUSTRALIA

gwrdc
GRAPE AND WINE RESEARCH AND DEVELOPMENT CORPORATION

The material contained in this document is supporting material for the IrriSAT component of the evapotranspiration masterclass. This guide provides a step by step tutorial for using the freely available BEAM VISAT software (http://www.brockmann-consult.de/cms/web/beam/software) for extracting NDVI from Geotif images supplied freely by USGS http://earthexplorer.usgs.gov/ and subsequent methods for use of this data for irrigation water management.

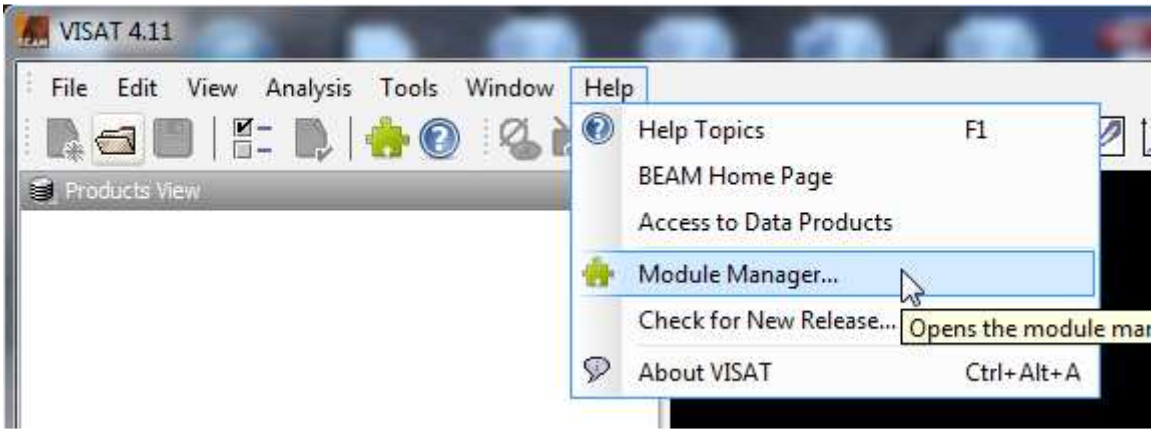
Three mini tutorials are included in this document.

1. Calculation of NDVI values from satellite images
2. Development of crop coefficient maps and 7 day water use forecast maps across irrigation areas
3. Extraction of multiple individual irrigator data on water use

These are designed to give the reader an understanding of the use of Landsat images in irrigation management, including how to do analysis on the images and extract and display data which can be used in various irrigation water management activities such as irrigation scheduling or investigating irrigation system distribution uniformity for instance.

The Landsat 8 image used in this tutorial is from Path 92, Row 84 taken on the 08/09/2013, which can be freely downloaded from the USGS website, along with all historical and future Landsat images. The tutorial can be undertaken with any Landsat image from Landsat 5, 7 or 8. However, images shown will be different, but the process the same! Instructions and a simple guide showing how to download images is included in the appendix.

Download the latest version of the BEAM VISAT software from http://www.brockmann-consult.de/cms/web/beam/software. For this tutorial version 4.11 was used. You will need to check that you have the Landsat 8 product reader installed. From the Help menu select Module Manager as shown below.



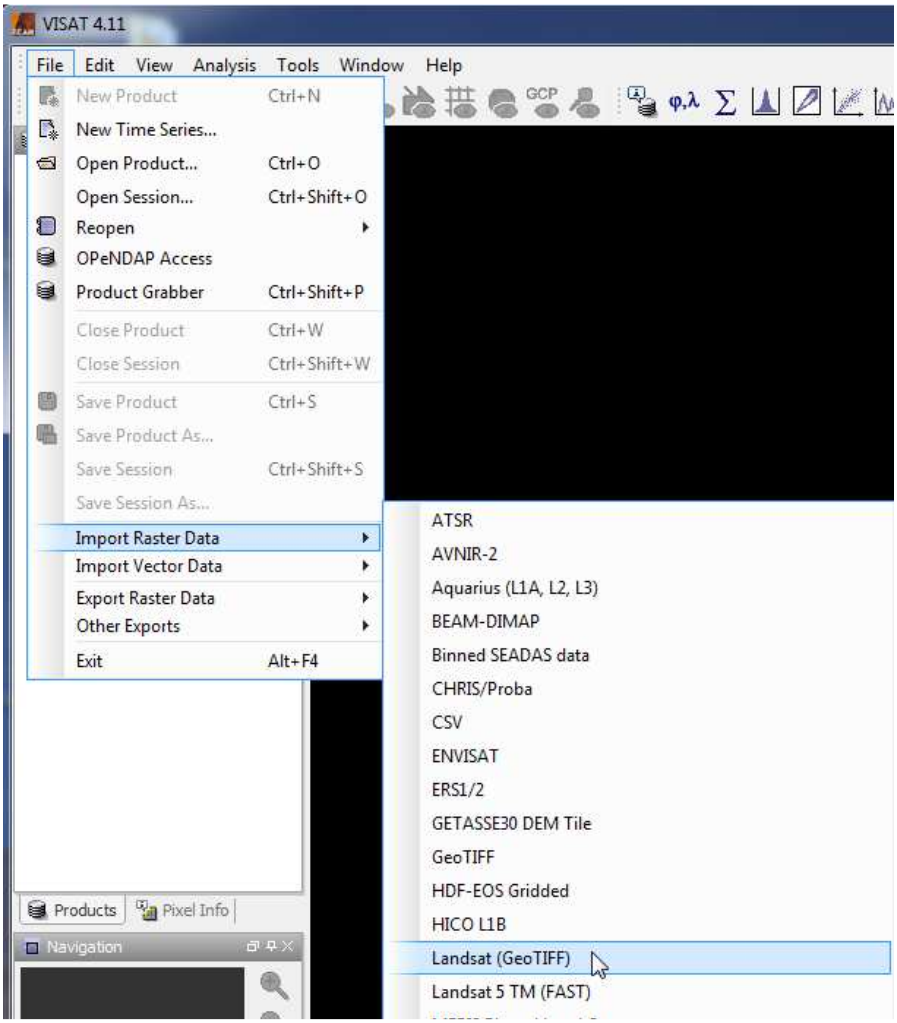
Now in the installed modules check to see the 'Landsat Product Reader' is at least version 1.4.1. If not then please update the module.

You are now ready to undertake the tutorials!

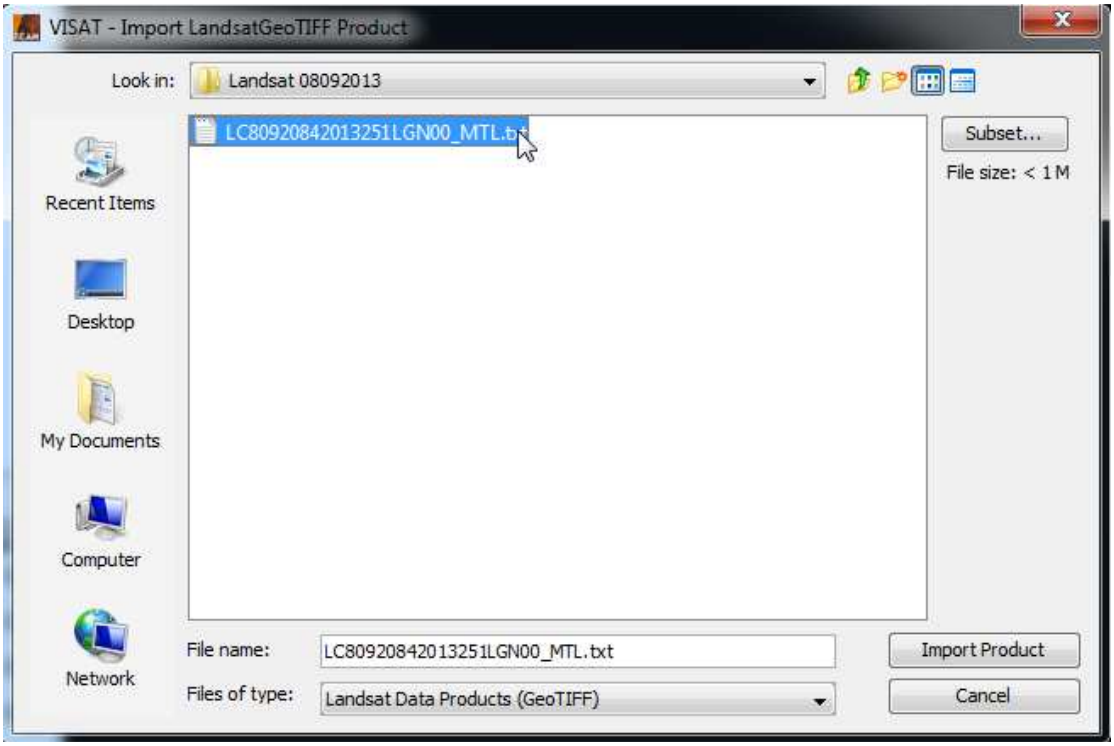
Tutorial 1: Calculation of NDVI values from satellite images

In this first tutorial we will step through the process of calculating NDVI values from satellite images and get familiar with the Beam VISAT software.

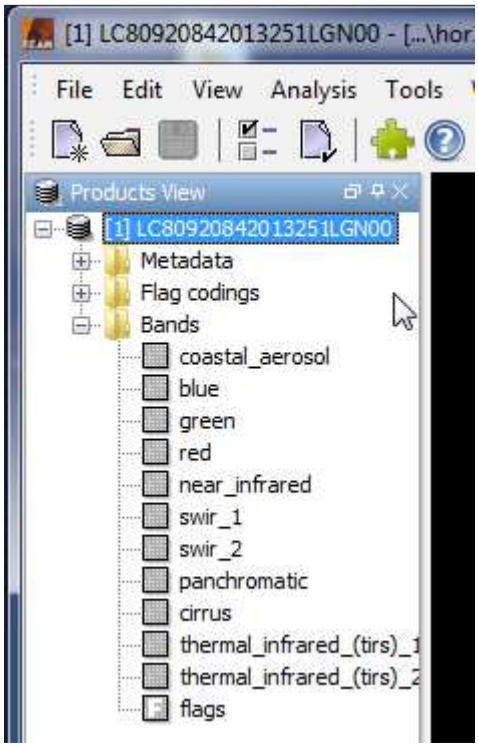
Step 1: Open the VISAT software and select 'File' and then 'Import Raster Data'>'Landsat (GeoTIFF)' You will now be presented with an open dialog box. Navigate to the folder containing your GeoTIFF image.



Now navigate to the folder that contains your downloaded Landsat image. You will have the option to select a .txt file which will import all Landsat bands into VISAT. Select this .txt file as shown below and click 'Import Product'.

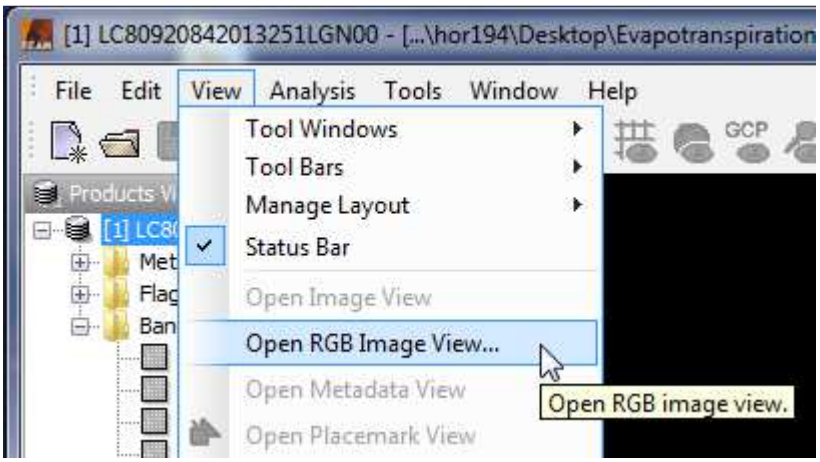


You will now see all yours Landsat data in the 'Products view' window as shown below.

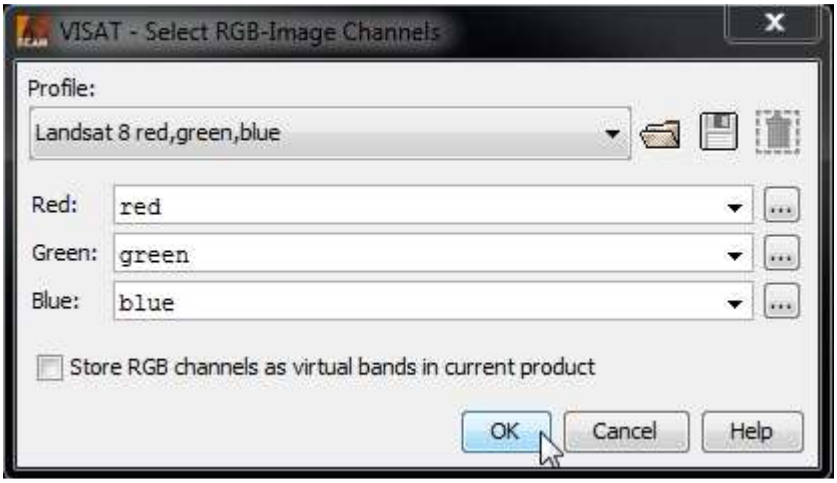


You can re-name these bands with a more descriptive heading if you like, this particularly applies to earlier Landsat images (5, 7 etc) which may not automatically have descriptive headings for each of the bands. In this tutorial since we are using Landsat 8 data the band descriptions are instructive so we will leave them as they imported.

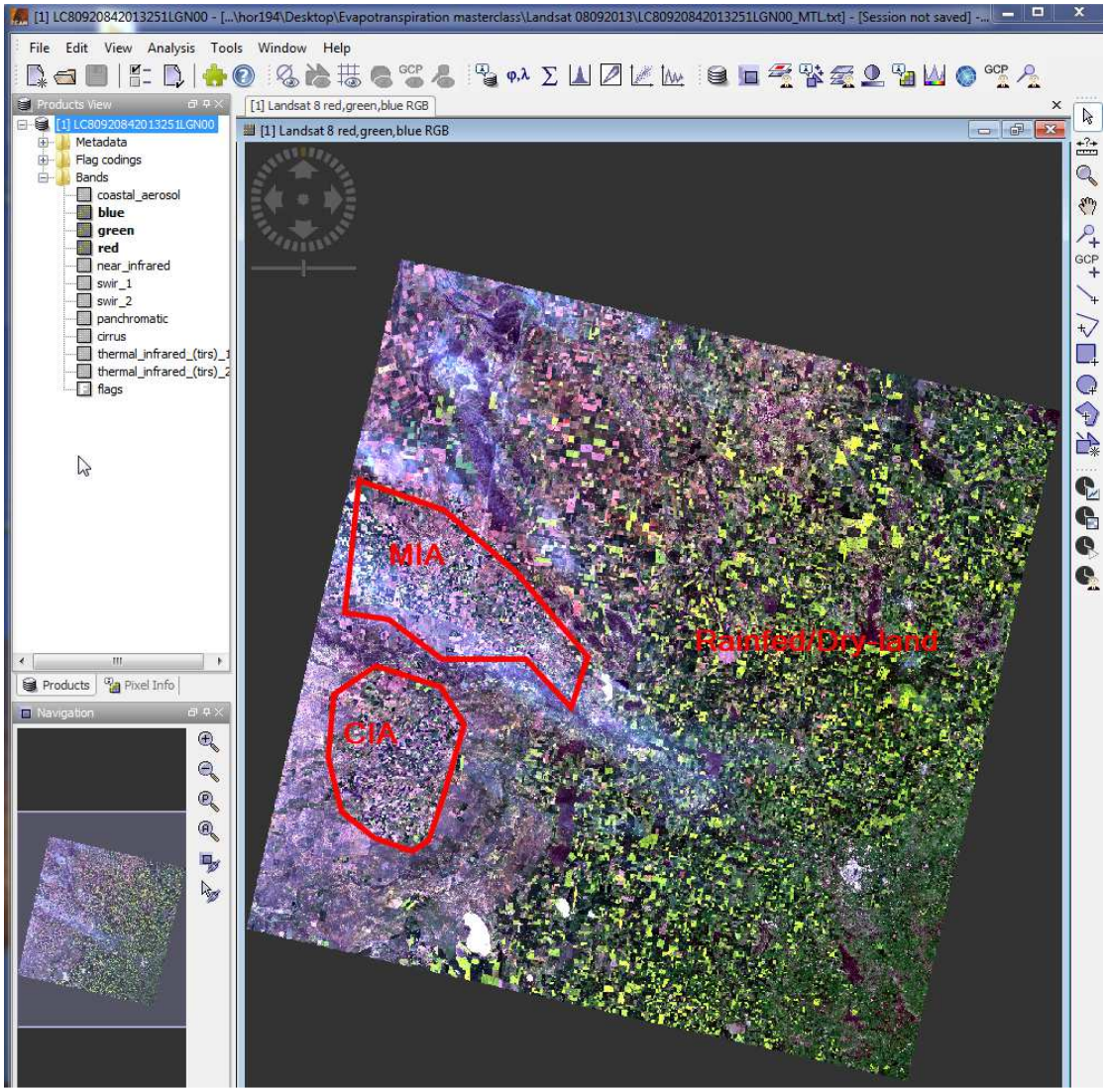
Step 2: Now we can have a look at what the image looks like in a Red, Green, Blue image which is slightly similar to what the eye would see. Simply click on 'View' then 'Open RGB Image View' as shown below.



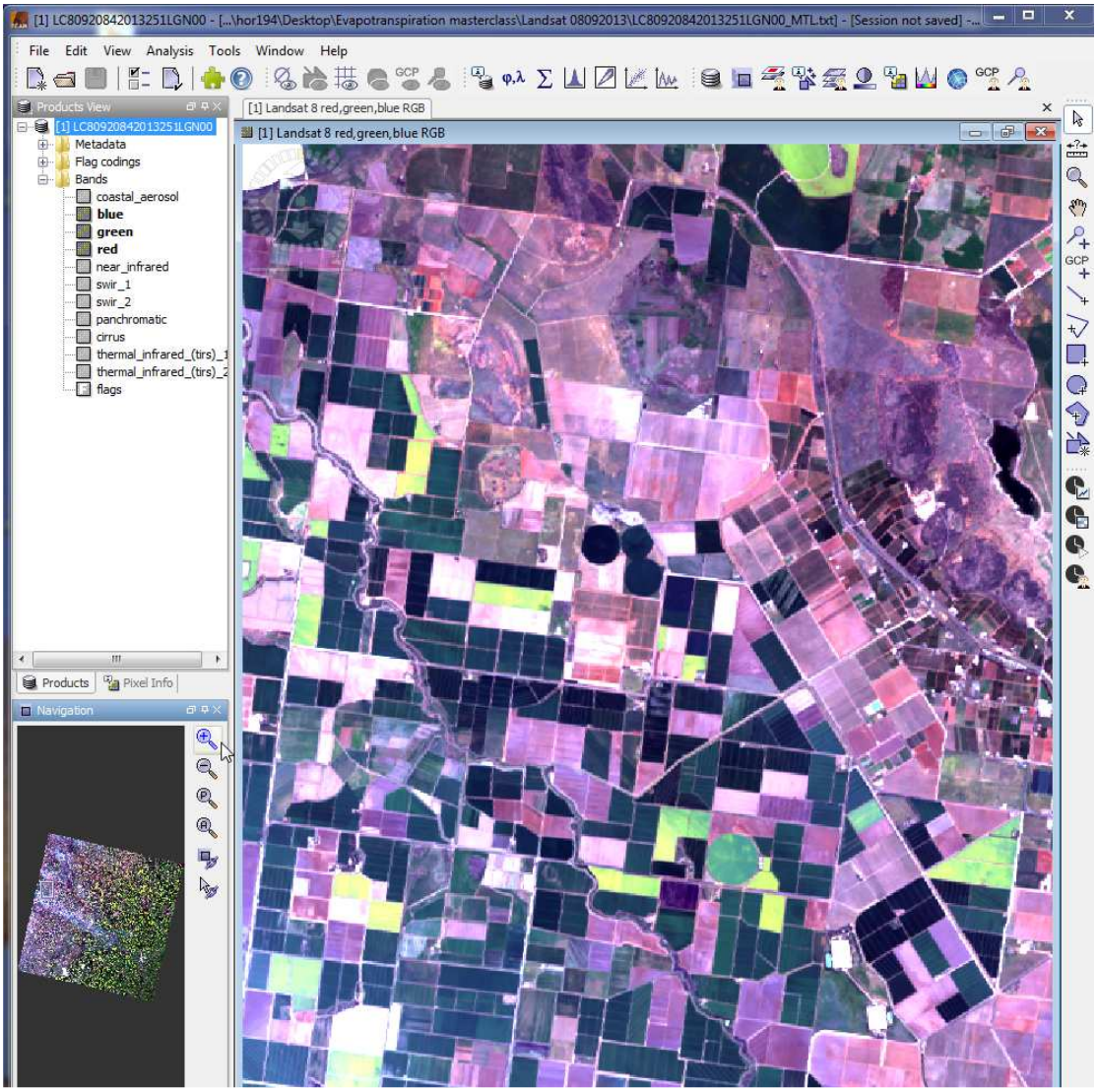
You will then be asked to select the red, green and blue bands to create the image. Select the correct bands of the drop down menu's as shown below. If using Landsat 8 images, these should be automatically selected. But double check.



You will now get an RGB image which will be helpful for determining key features.
For example, we will work with a Landsat 8 image taken in August 2013 with a center at approximately Leeton, NSW. You can see the Murrumbidgee and Coleambally Irrigation areas as shown and also dryland cropping activities. Also notice cloud cover issues on some parts of the image and even a jet trail running approximately north/south through the MIA and CIA areas!



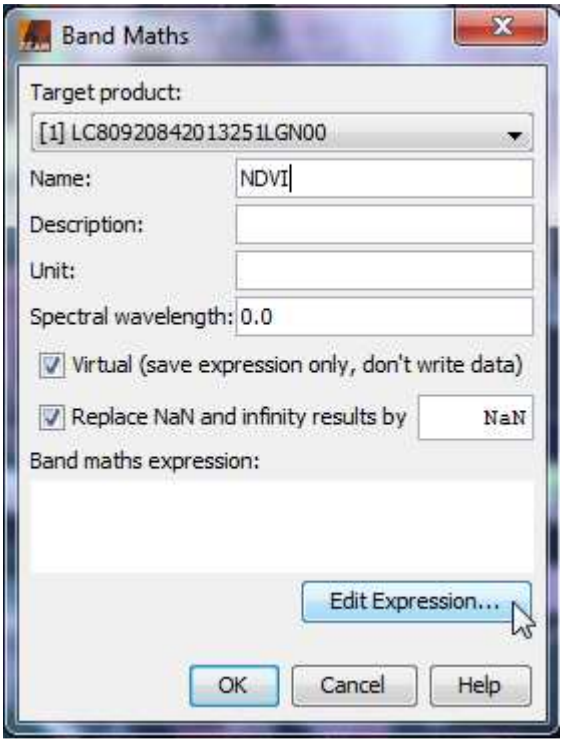
Feel free to zoom areas on the image and pan using the controls located in the lower left hand corner titled ‘Navigation’ and the tools on the right hand side of the image which also allow you to pan and zoom. Shown below is a zoomed image just west of Griffith in the Murrumbidgee Irrigation Area showing smaller horticultural farms on the right and larger broadacre farms on the left. You will also see some centre pivots in the image.



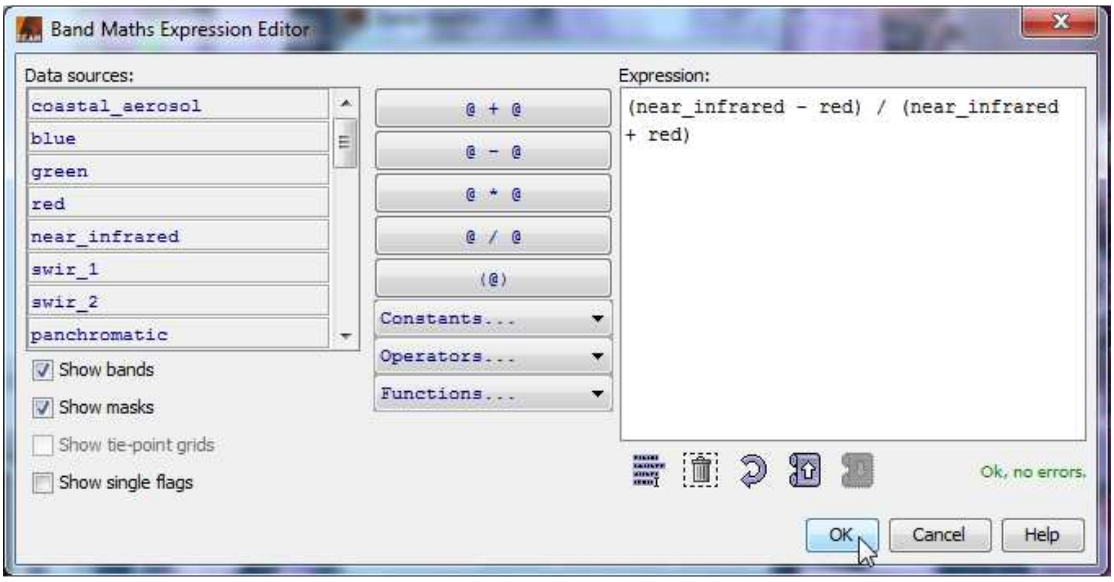
Step 3: Now we have had a brief explore with the Landsat 8 image it's time to turn that image into useful information! What we now want to do is create an NDVI band with the red and near infra-red band data in the image. Select the 'Tools' menu and then 'Create Band by Band Maths...'.



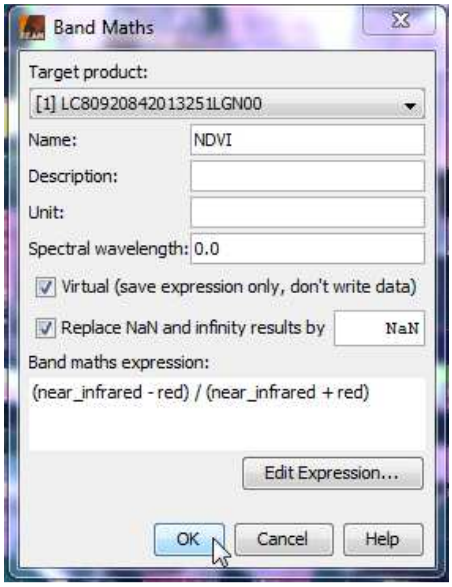
Rename the band 'NDVI' as shown and the click 'Edit Expression' as shown below.



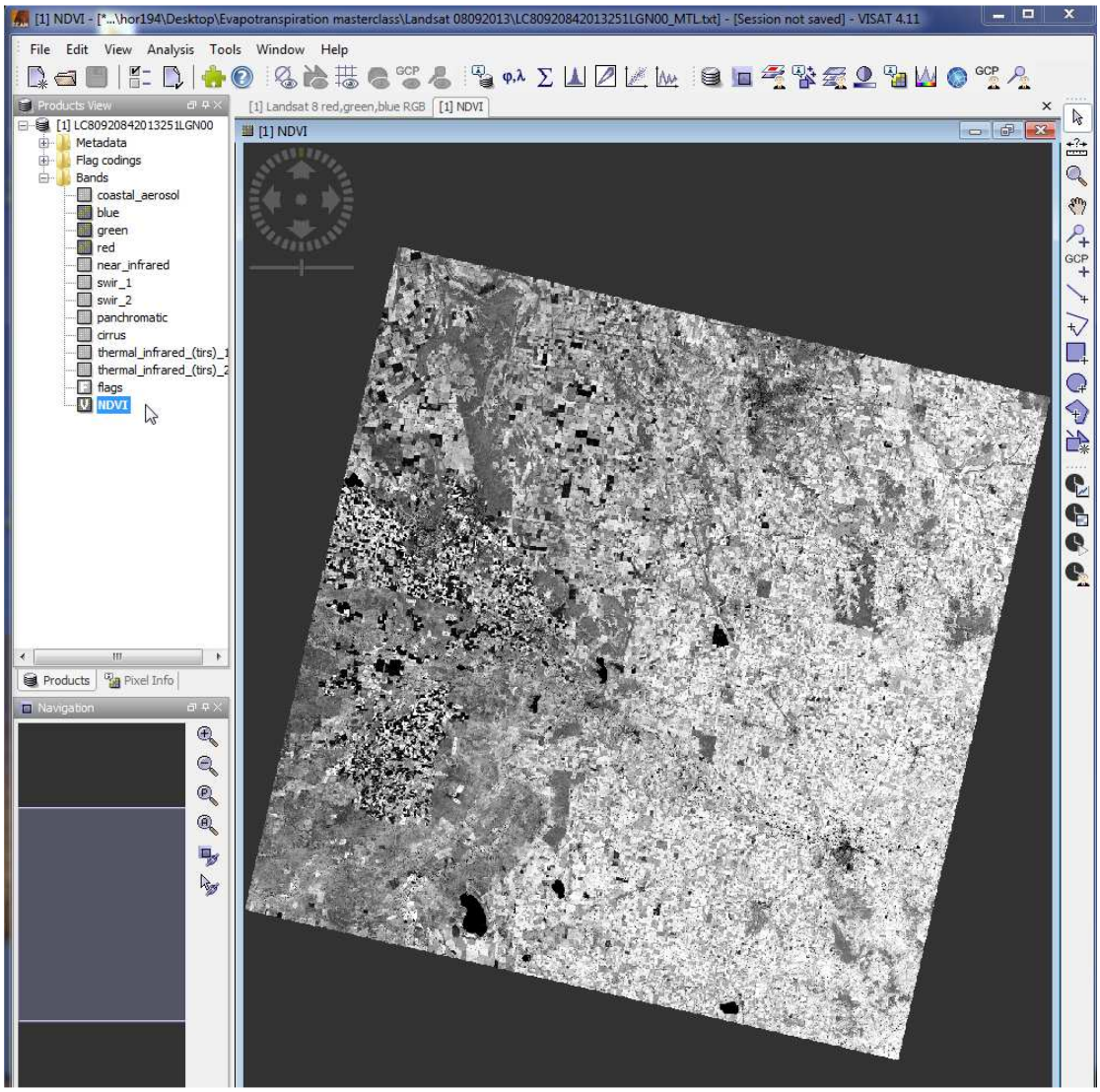
Step 4: You now need to create the NDVI band by using the red and near infra red bands with the following expression NDVI = (NIR-RED)/(NIR +RED). Click on the Data Sources and math to add them to the expression. Your expression should look like the expression shown in the window below. Click OK.



Click OK again and OK on the band maths screen.



Step 7: You should now see the NDVI band displayed as shown below and available for selection as a virtual layer in the 'Products view' window on the left had side of the screen. Low NDVI values are black and high NDVI values are shown in white.

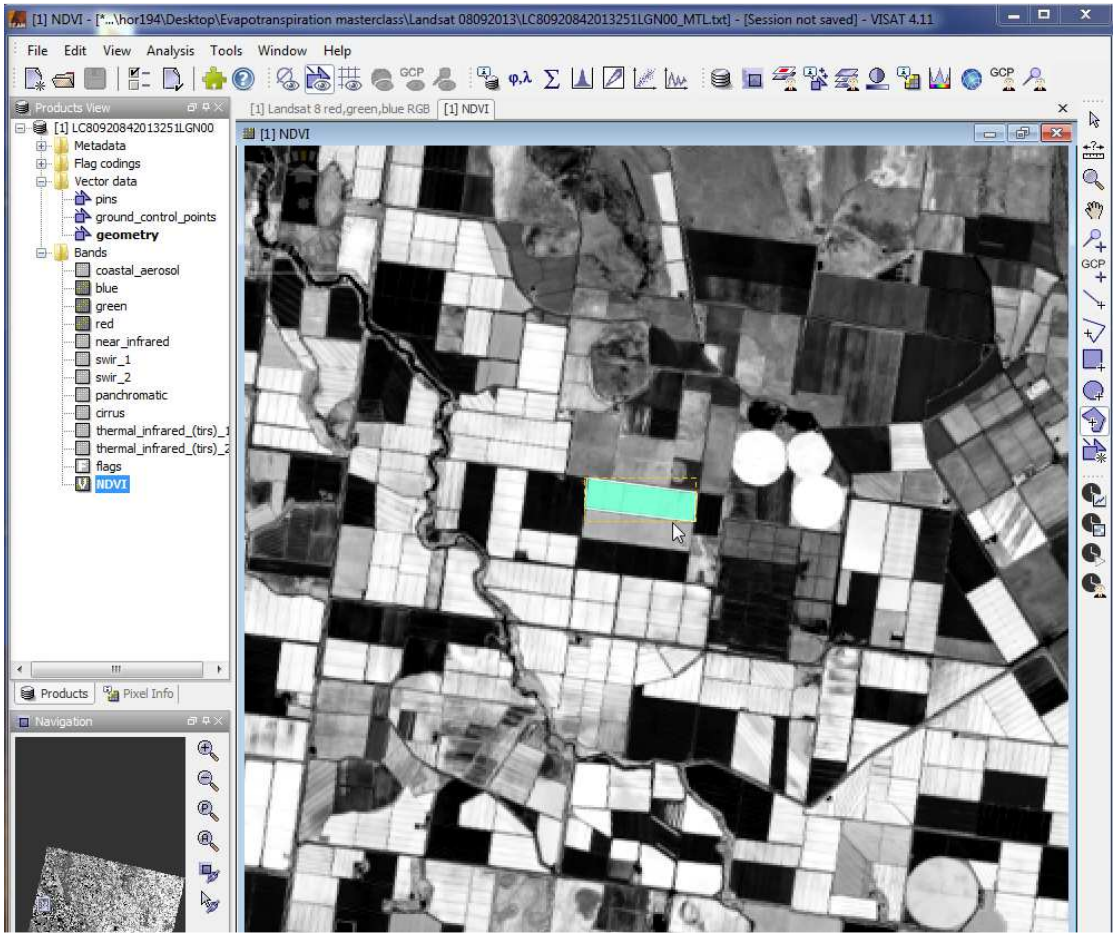


Step 8: Now to extract the data use either the NDVI image to identify the paddocks or display the RGB image again using the previous steps. The RGB image is slightly easier to identify paddocks. Zoom to the location or paddock you are interested in.

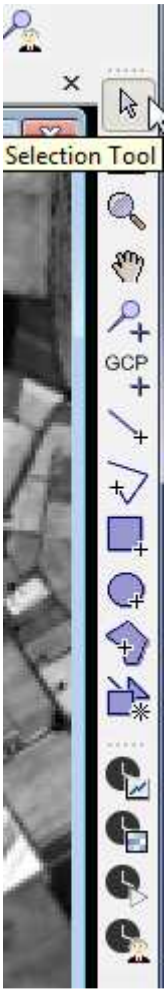
Step 9: Now select the 'Draw Polygon' tool located on the right hand side toolbar.



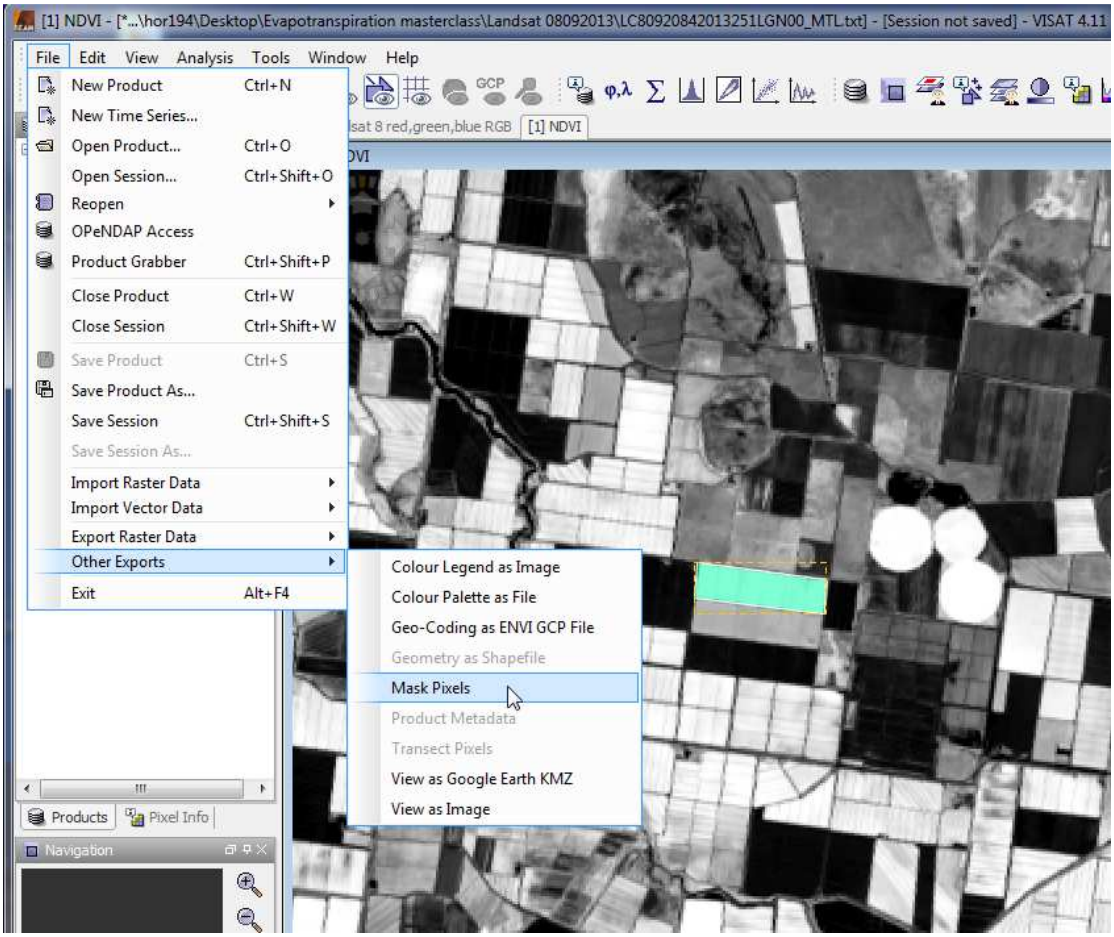
Step 10: Now left mouse click in each corner of the selected paddock and double click to finish. A polygon will now be shown over the paddock.



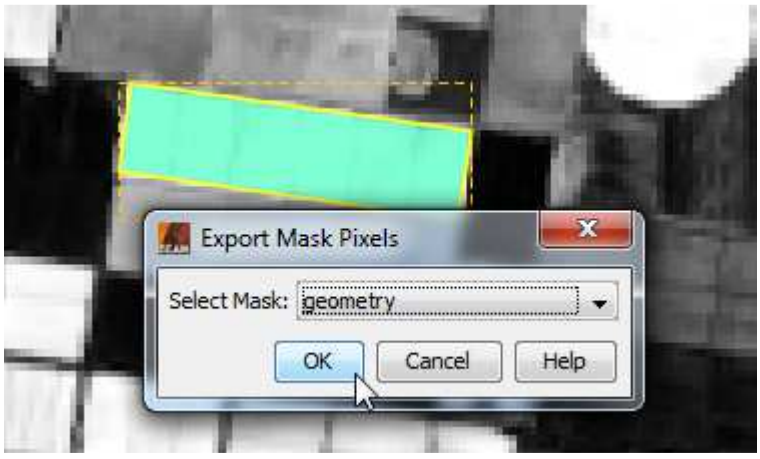
Now select the selection tool from the right hand menu and then click on the polygon you have just created.



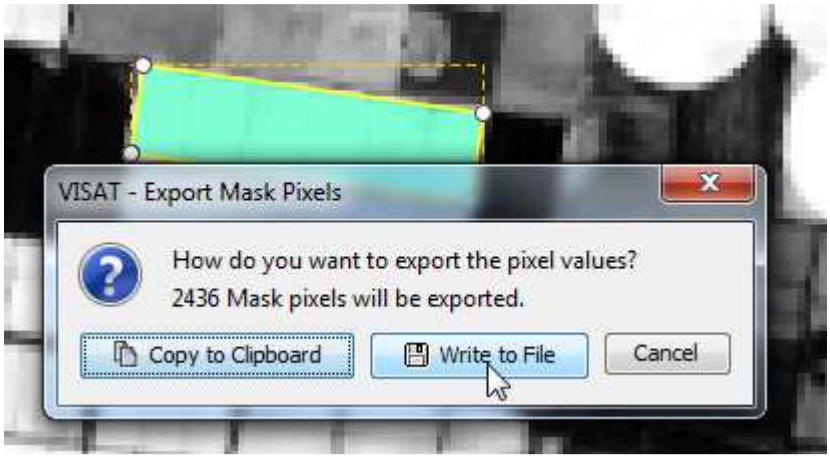
Step 12: Now you want to export the pixels containing the band and NDVI data for each co-ordinate in the paddock to Excel or a text editor. To do this select 'File' from the main toolbar and then 'Other Exports' then ‘Mask Pixels’ as shown below.



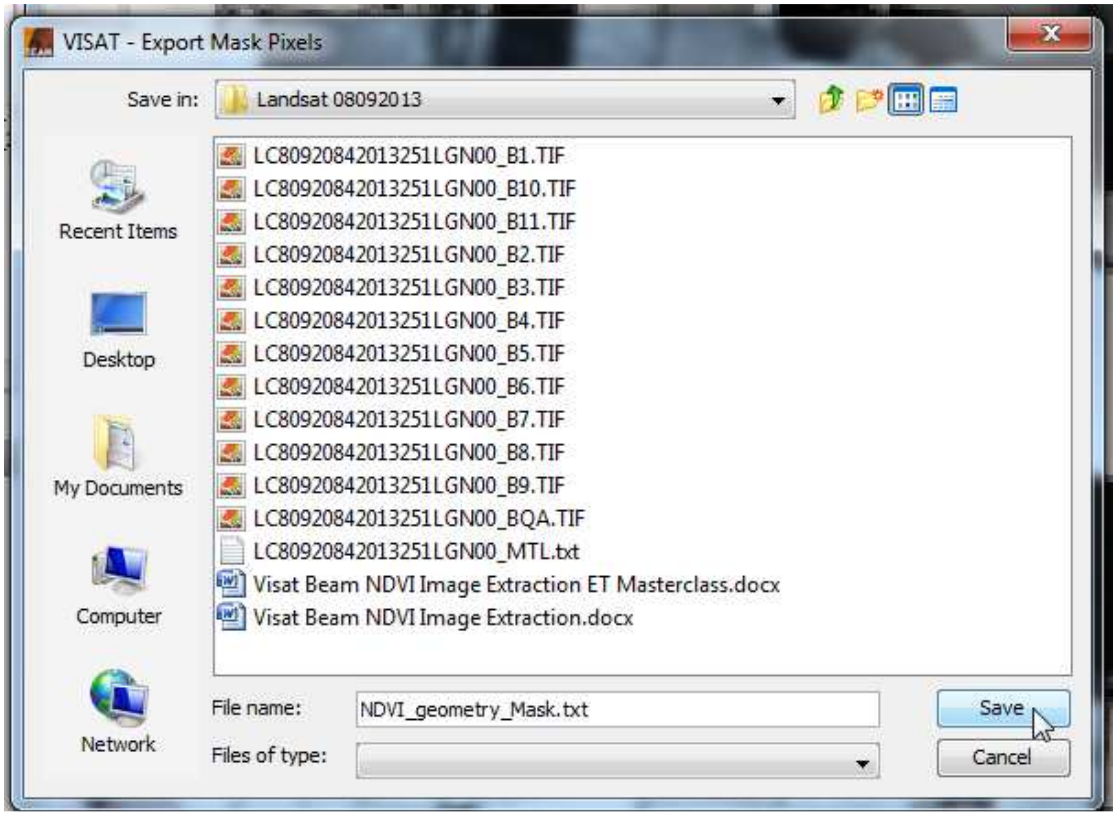
Step 13: You will now see then screen below that gives options for selecting a mask. From the drop down menu select geometry and click OK, for saving as a file or to the clipboard. Click on 'Write to File'.



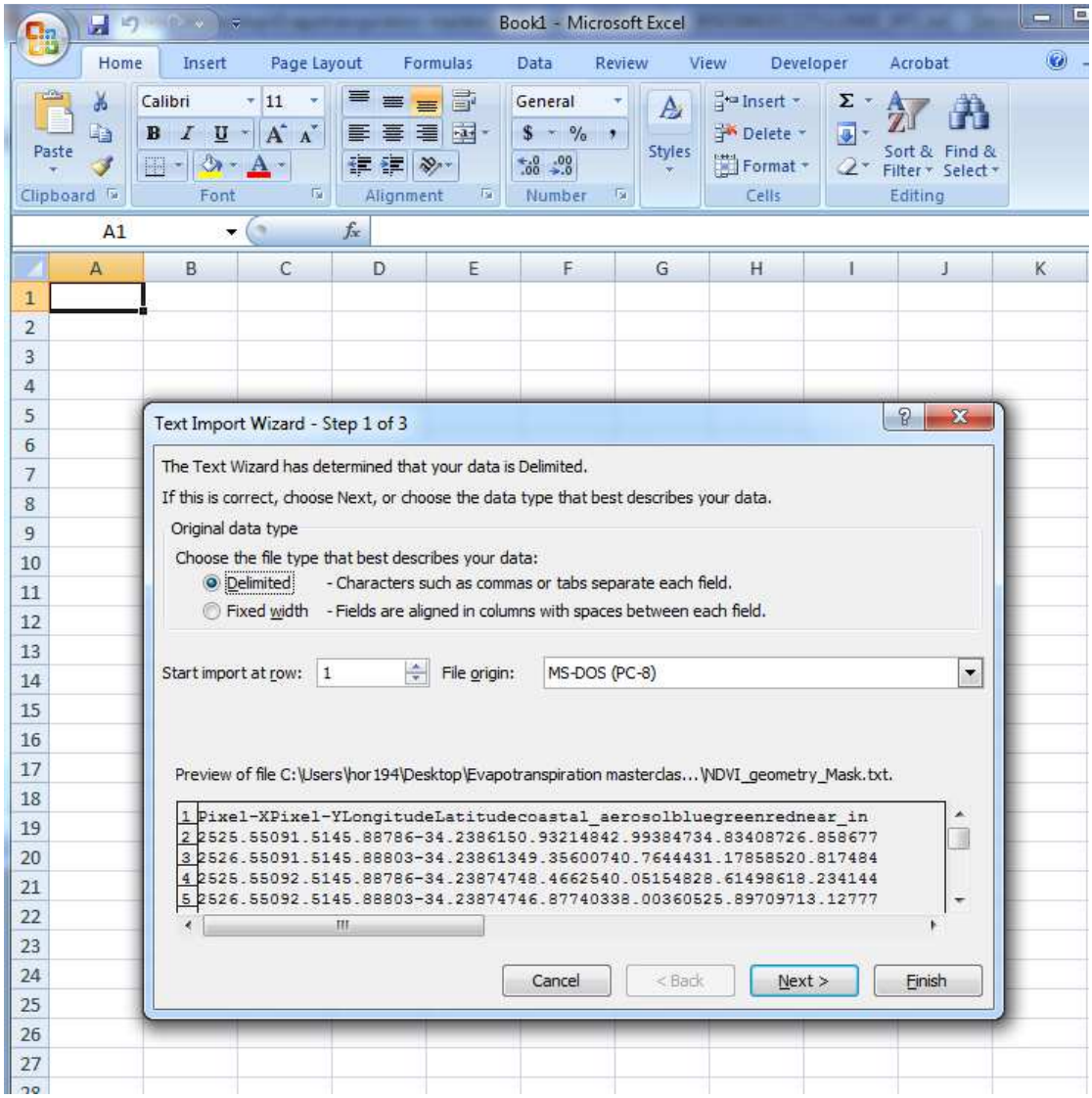
You will now see the export options for your selected data. Select ‘Write to File’.



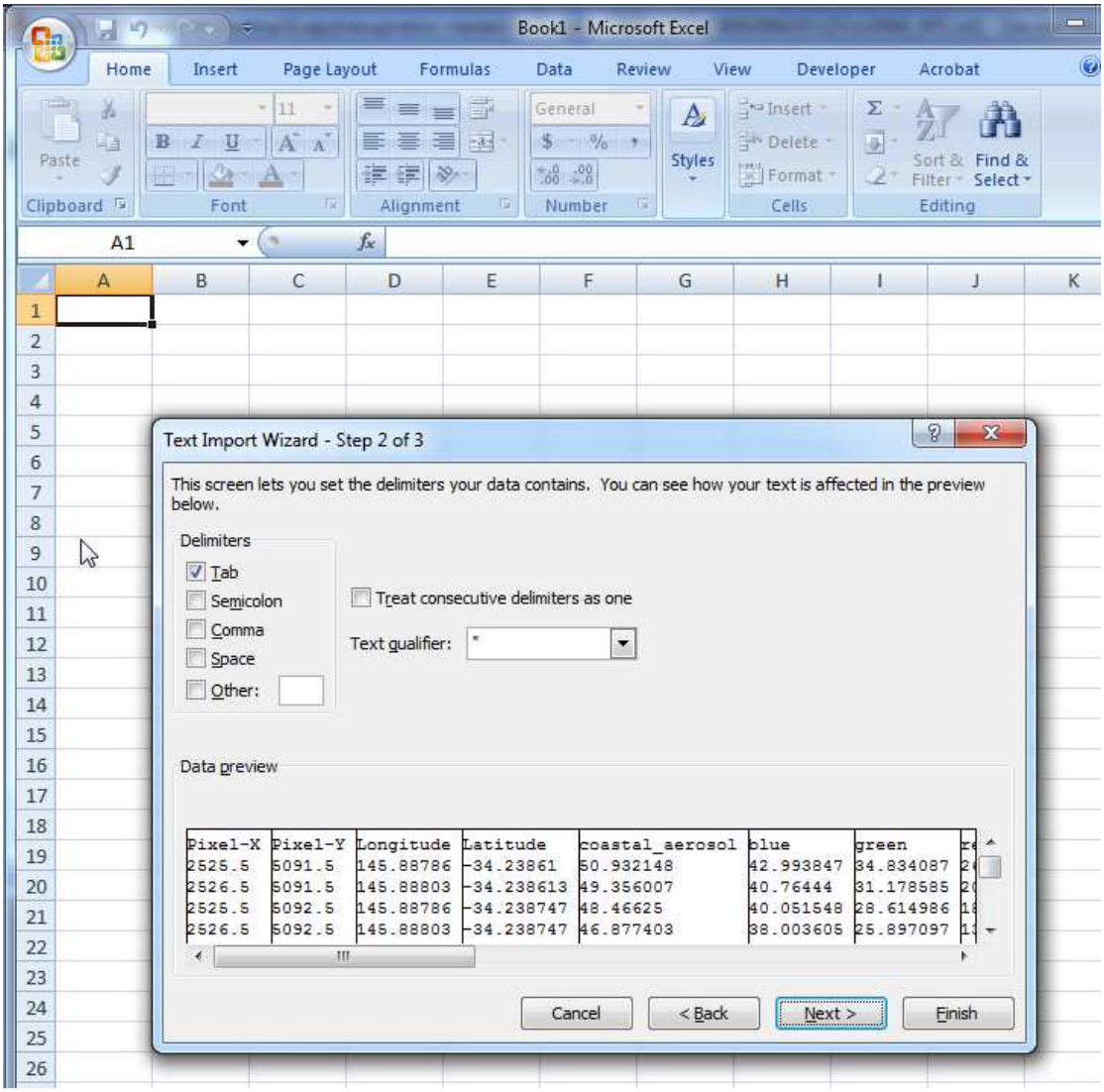
You will now be able to name the file and select where to save it as shown below.



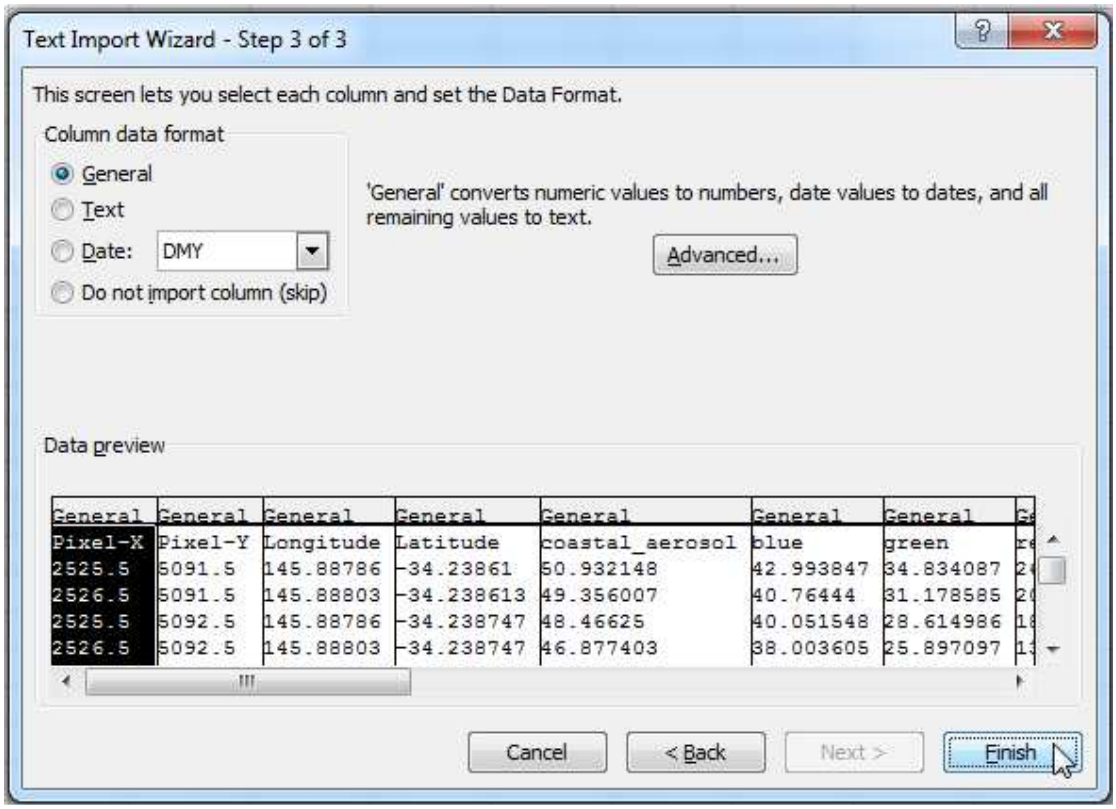
Step 14: Now open Excel and then click on 'File' and then 'Open' in the main toolbar. Select the file we have just saved in the previous step and open in Excel. Note: You may need to select the option to show all file types. Now select the file you just saved above. You will now be presented with the text import wizard in Excel. Select ‘Delimited’ as shown below and click ‘Next’.



Now Select ‘Tab’ and lick ‘Next’ as shown below.



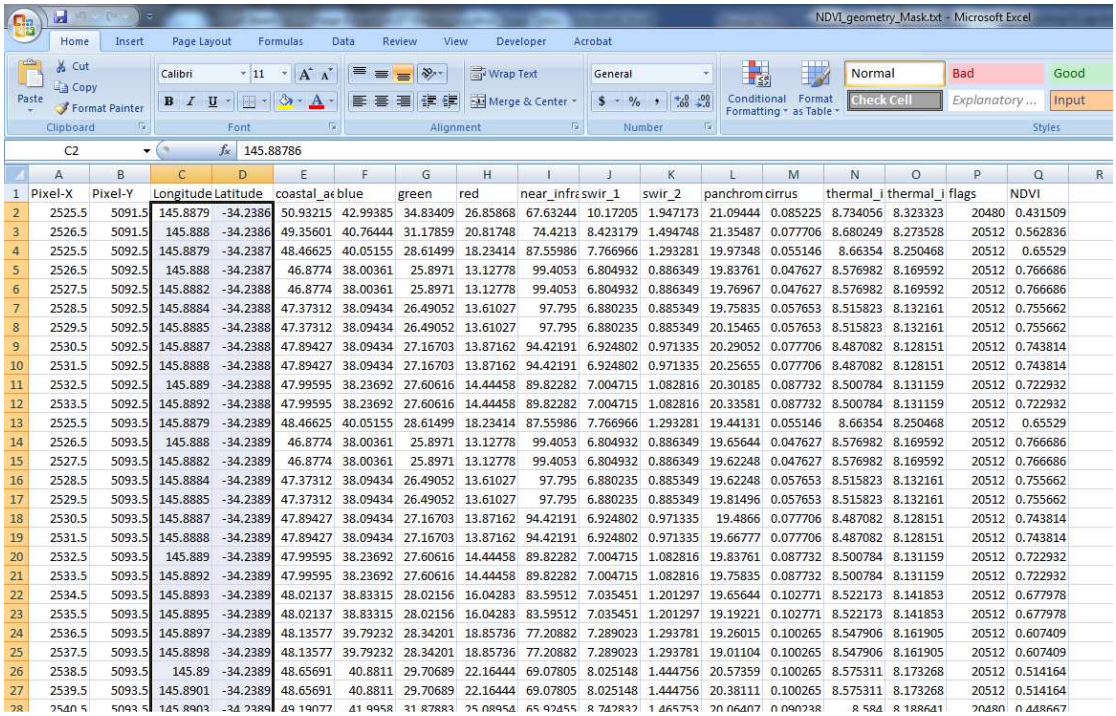
Now select ‘General’ and click ‘Finish’ as shown below. Your data will now appear in Excel as a spreadsheet.



Step 15: To quickly check positioning of data select the Lat. and long. Data and then create a XY Scatter chart as shown to make sure the areas are the same. Once you are satisfied you can play with the Remote Sensing data in Excel to calculate a crop coefficient using the relationships between NDVI and Kc we have discussed, determine an average/min/max crop coefficient for the selected area or export to a 3rd party application i.e. for mapping such as Surfer http://www.goldensoftware.com/products/surfer but there are a number of products available to plot xyz surfaces/maps.

In the next tutorial we will use this NDVI data with BEAM to develop some spatial maps of crop water demand and us the BEAM software to create exportable maps.

Note: You can also calculate NDVI values from the individual red and infrared bands here in Excel as an alternate to doing it in BEAM.

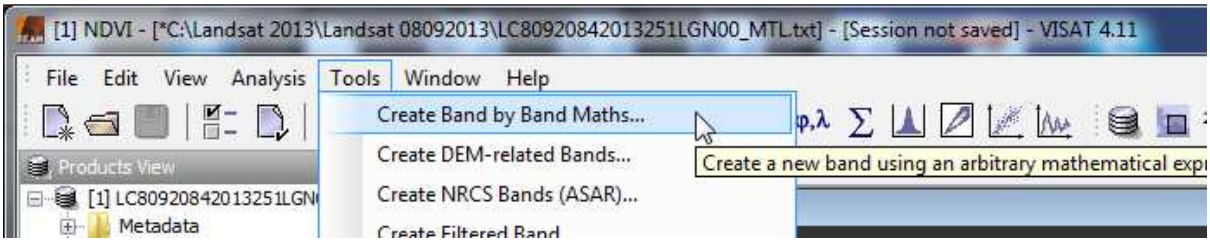


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Pixel-X	Pixel-Y	Longitude	Latitude	coastal_ae	blue	green	red	near_infra	swir_1	swir_2	panchrom	cirrus	thermal_i	thermal_i	flags	NDVI	
2	2525.5	5091.5	145.8879	-34.2386	50.93215	42.99385	34.83409	26.85868	67.63244	10.17205	1.947173	21.09444	0.085225	8.734056	8.323323	20480	0.431509	
3	2526.5	5091.5	145.888	-34.2386	49.35601	40.76444	31.17859	20.81748	74.4213	8.423179	1.494748	21.35487	0.077706	8.680249	8.273528	20512	0.562836	
4	2525.5	5092.5	145.8879	-34.2387	48.46625	40.05155	28.61499	18.23414	87.55986	7.766966	1.293281	19.97348	0.055146	8.66354	8.250468	20512	0.65529	
5	2526.5	5092.5	145.888	-34.2387	46.8774	38.00361	25.8971	13.12778	99.4053	6.804932	0.886349	19.83761	0.047627	8.576982	8.169592	20512	0.766686	
6	2527.5	5092.5	145.8882	-34.2388	46.8774	38.00361	25.8971	13.12778	99.4053	6.804932	0.886349	19.76967	0.047627	8.576982	8.169592	20512	0.766686	
7	2528.5	5092.5	145.8884	-34.2388	47.37312	38.09434	26.49052	13.61027	97.795	6.880235	0.885349	19.75835	0.057653	8.515823	8.132161	20512	0.755662	
8	2529.5	5092.5	145.8885	-34.2388	47.37312	38.09434	26.49052	13.61027	97.795	6.880235	0.885349	20.15465	0.057653	8.515823	8.132161	20512	0.755662	
9	2530.5	5092.5	145.8887	-34.2388	47.89427	38.09434	27.16703	13.87162	94.42191	6.924802	0.971335	20.29052	0.077706	8.487082	8.128151	20512	0.743814	
10	2531.5	5092.5	145.8888	-34.2388	47.89427	38.09434	27.16703	13.87162	94.42191	6.924802	0.971335	20.25655	0.077706	8.487082	8.128151	20512	0.743814	
11	2532.5	5092.5	145.889	-34.2388	47.99595	38.23692	27.60616	14.44458	89.82282	7.004715	1.082816	20.30185	0.087732	8.500784	8.131159	20512	0.722932	
12	2533.5	5092.5	145.8892	-34.2388	47.99595	38.23692	27.60616	14.44458	89.82282	7.004715	1.082816	20.33581	0.087732	8.500784	8.131159	20512	0.722932	
13	2525.5	5093.5	145.8879	-34.2389	48.46625	40.05155	28.61499	18.23414	87.55986	7.766966	1.293281	19.44131	0.055146	8.66354	8.250468	20512	0.65529	
14	2526.5	5093.5	145.888	-34.2389	46.8774	38.00361	25.8971	13.12778	99.4053	6.804932	0.886349	19.65644	0.047627	8.576982	8.169592	20512	0.766686	
15	2527.5	5093.5	145.8882	-34.2389	46.8774	38.00361	25.8971	13.12778	99.4053	6.804932	0.886349	19.62248	0.047627	8.576982	8.169592	20512	0.766686	
16	2528.5	5093.5	145.8884	-34.2389	47.37312	38.09434	26.49052	13.61027	97.795	6.880235	0.885349	19.62248	0.057653	8.515823	8.132161	20512	0.755662	
17	2529.5	5093.5	145.8885	-34.2389	47.37312	38.09434	26.49052	13.61027	97.795	6.880235	0.885349	19.81496	0.057653	8.515823	8.132161	20512	0.755662	
18	2530.5	5093.5	145.8887	-34.2389	47.89427	38.09434	27.16703	13.87162	94.42191	6.924802	0.971335	19.4866	0.077706	8.487082	8.128151	20512	0.743814	
19	2531.5	5093.5	145.8888	-34.2389	47.89427	38.09434	27.16703	13.87162	94.42191	6.924802	0.971335	19.66777	0.077706	8.487082	8.128151	20512	0.743814	
20	2532.5	5093.5	145.889	-34.2389	47.99595	38.23692	27.60616	14.44458	89.82282	7.004715	1.082816	19.83761	0.087732	8.500784	8.131159	20512	0.722932	
21	2533.5	5093.5	145.8892	-34.2389	47.99595	38.23692	27.60616	14.44458	89.82282	7.004715	1.082816	19.75835	0.087732	8.500784	8.131159	20512	0.722932	
22	2534.5	5093.5	145.8893	-34.2389	48.02137	38.83315	28.02156	16.04283	83.59512	7.035451	1.201297	19.65644	0.102771	8.522173	8.141853	20512	0.677978	
23	2535.5	5093.5	145.8895	-34.2389	48.02137	38.83315	28.02156	16.04283	83.59512	7.035451	1.201297	19.19221	0.102771	8.522173	8.141853	20512	0.677978	
24	2536.5	5093.5	145.8897	-34.2389	48.13577	39.79232	28.34201	18.85736	77.20882	7.289023	1.293781	19.26015	0.100265	8.547906	8.161905	20512	0.607409	
25	2537.5	5093.5	145.8898	-34.2389	48.13577	39.79232	28.34201	18.85736	77.20882	7.289023	1.293781	19.01104	0.100265	8.547906	8.161905	20512	0.607409	
26	2538.5	5093.5	145.89	-34.2389	48.65691	40.8811	29.70689	22.16444	69.07805	8.025148	1.444756	20.57359	0.100265	8.575311	8.173268	20512	0.514164	
27	2539.5	5093.5	145.8901	-34.2389	48.65691	40.8811	29.70689	22.16444	69.07805	8.025148	1.444756	20.38111	0.100265	8.575311	8.173268	20512	0.514164	
28	2540.5	5093.5	145.8903	-34.2389	49.19077	41.9958	31.87883	25.08954	65.92455	8.742832	1.465753	20.06407	0.090238	8.584	8.188641	20480	0.448667	

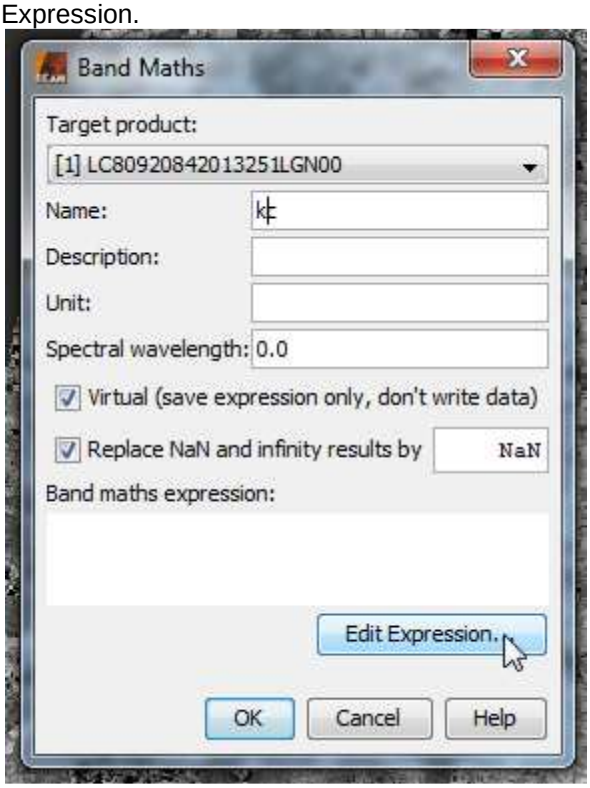
Note: The calculated NDVI values shown in this tutorial are not atmospherically corrected due to time limitations for this tutorial. For research work and temporal analysis it is recommended to use Top of Atmosphere (TOA) corrected NDVI values. This simply involves a further simple step to convert the raw band values using supplied information from the downloaded Landsat files. This can be done in either VISAT using the band maths functions or in Excel. Details on TOA correction can be found here http://landsat.usgs.gov/Landsat8_Using_Product.php

Tutorial 2: Development of crop coefficient maps and 7 day water use forecast maps across irrigation areas

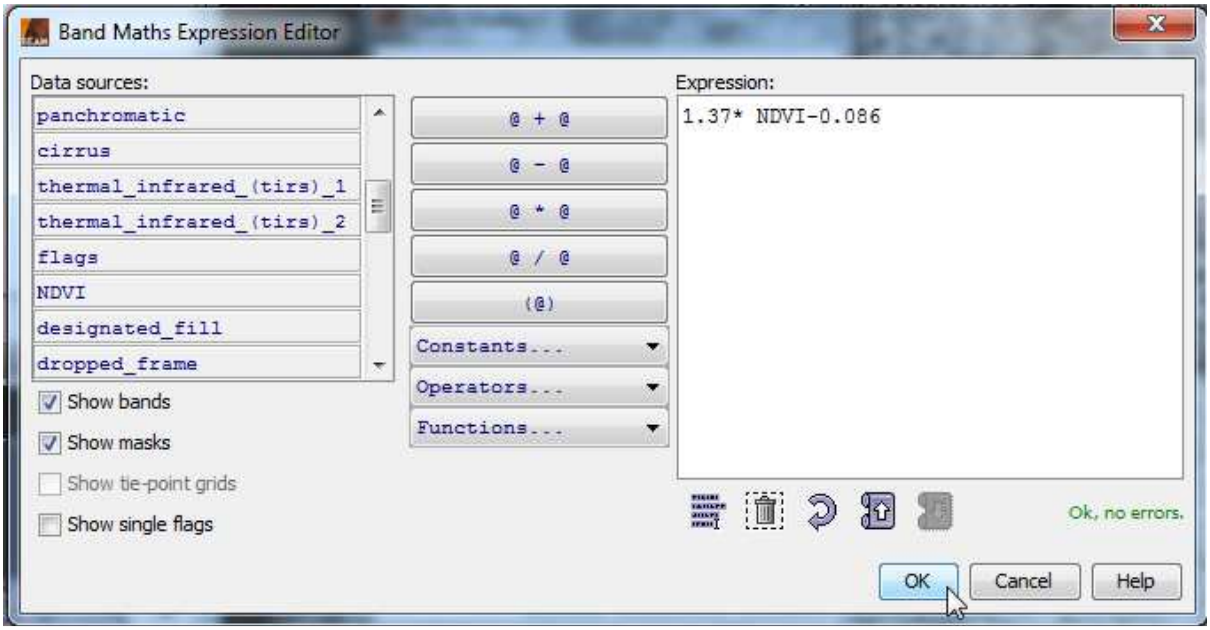
Step 1: Now from our calculated NDVI layer we are going to determine crop coefficients for each pixel in the image and hence a kc map across the satellite image. Click on the Tools menu and select Create Band by Band Maths as shown below.



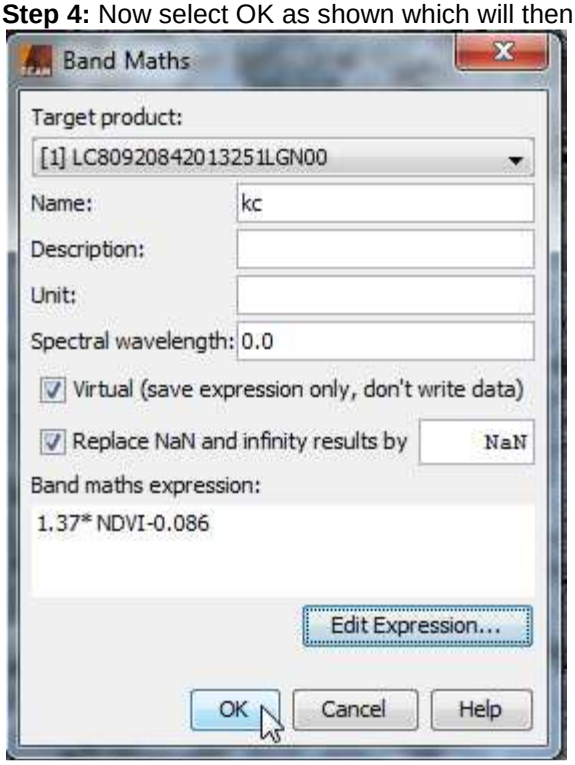
Step 2: Now rename the band we are going to create kc (Crop coefficient) and select Edit Expression.

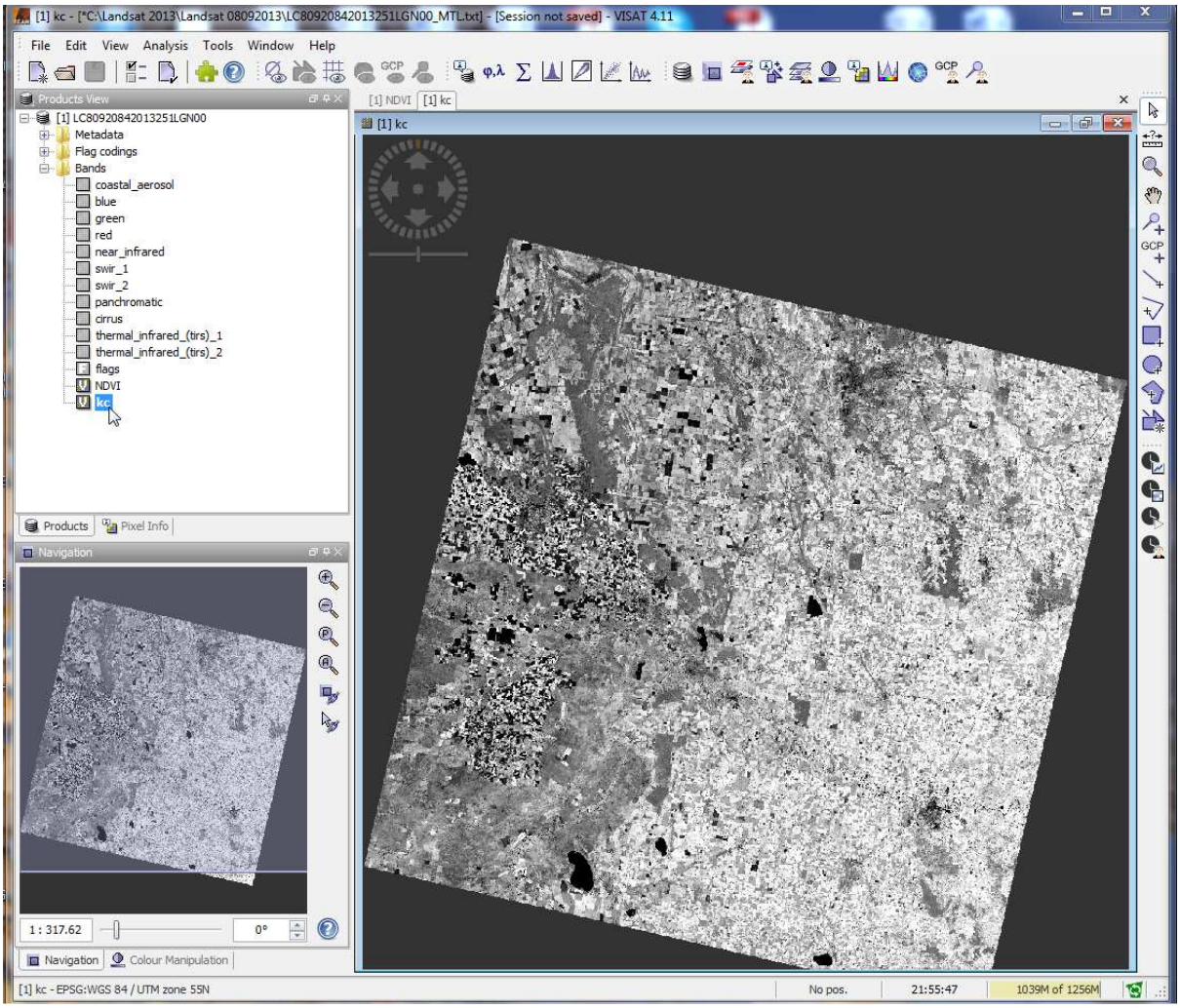


Step 3: Now we will use an empirical relationship to convert the NDVI values into crop coefficient values. In this tutorial we will use the relationship given by Trout et al. 2007, which has been extensively used by IrriSAT and found to apply to a wide range of Australian crops. This relationship is given by kc=1.37*NDVI-0.086. In the Expression Editor create this expression as shown below and select OK.

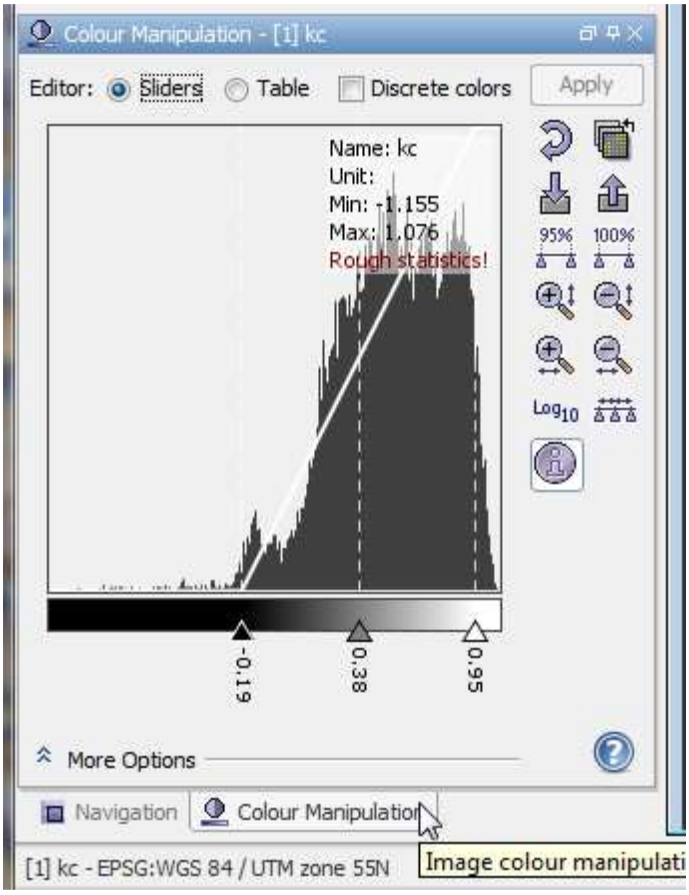


Step 4: Now select OK as shown which will then create the crop coefficient band.

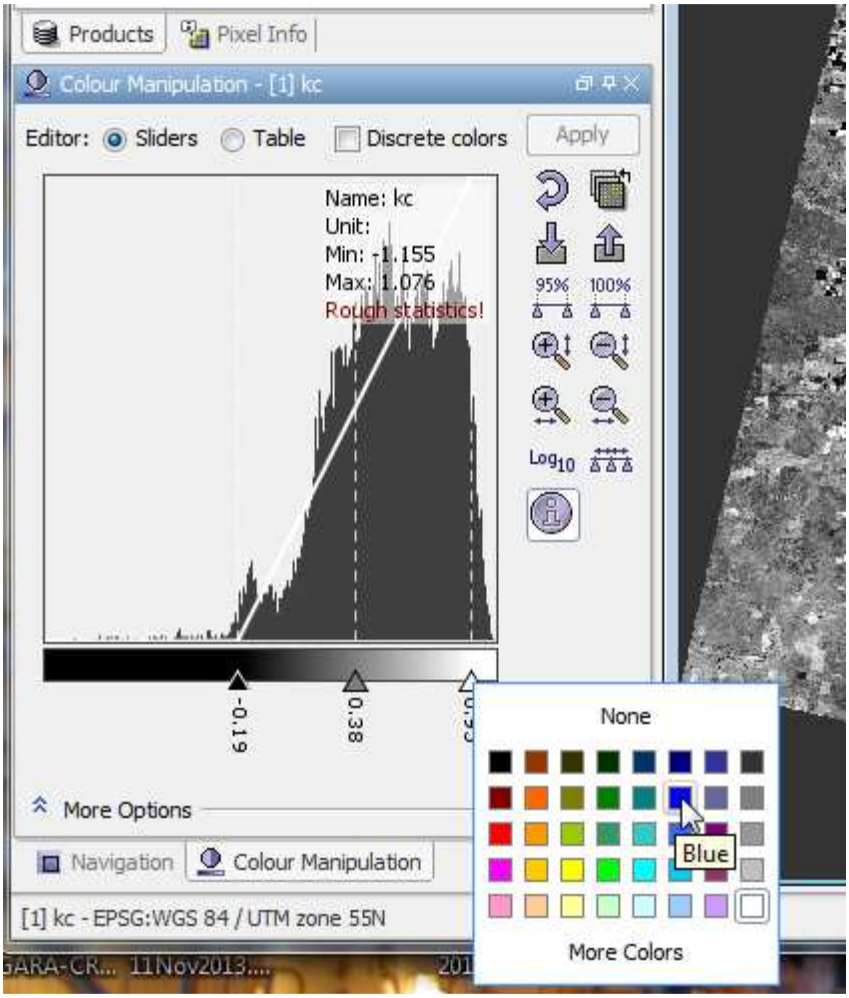




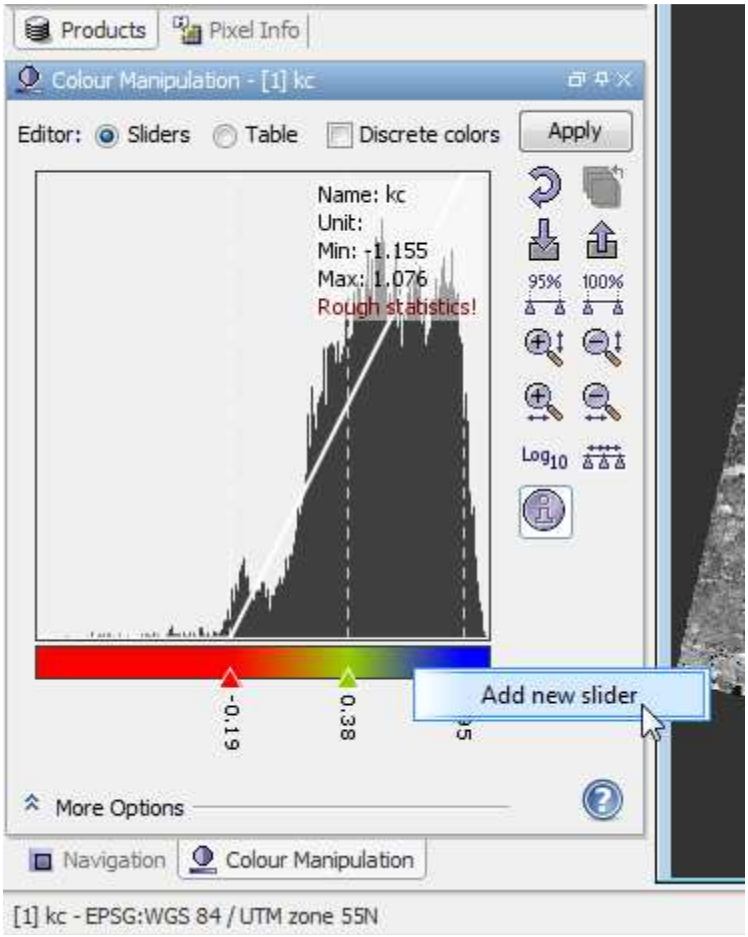
Step 5: Now we are going to add some colour to the image. Select the ‘kc’ band from the menu tree on the left hand side and the click on the ‘Colour Manipulation’ Tab as shown below.



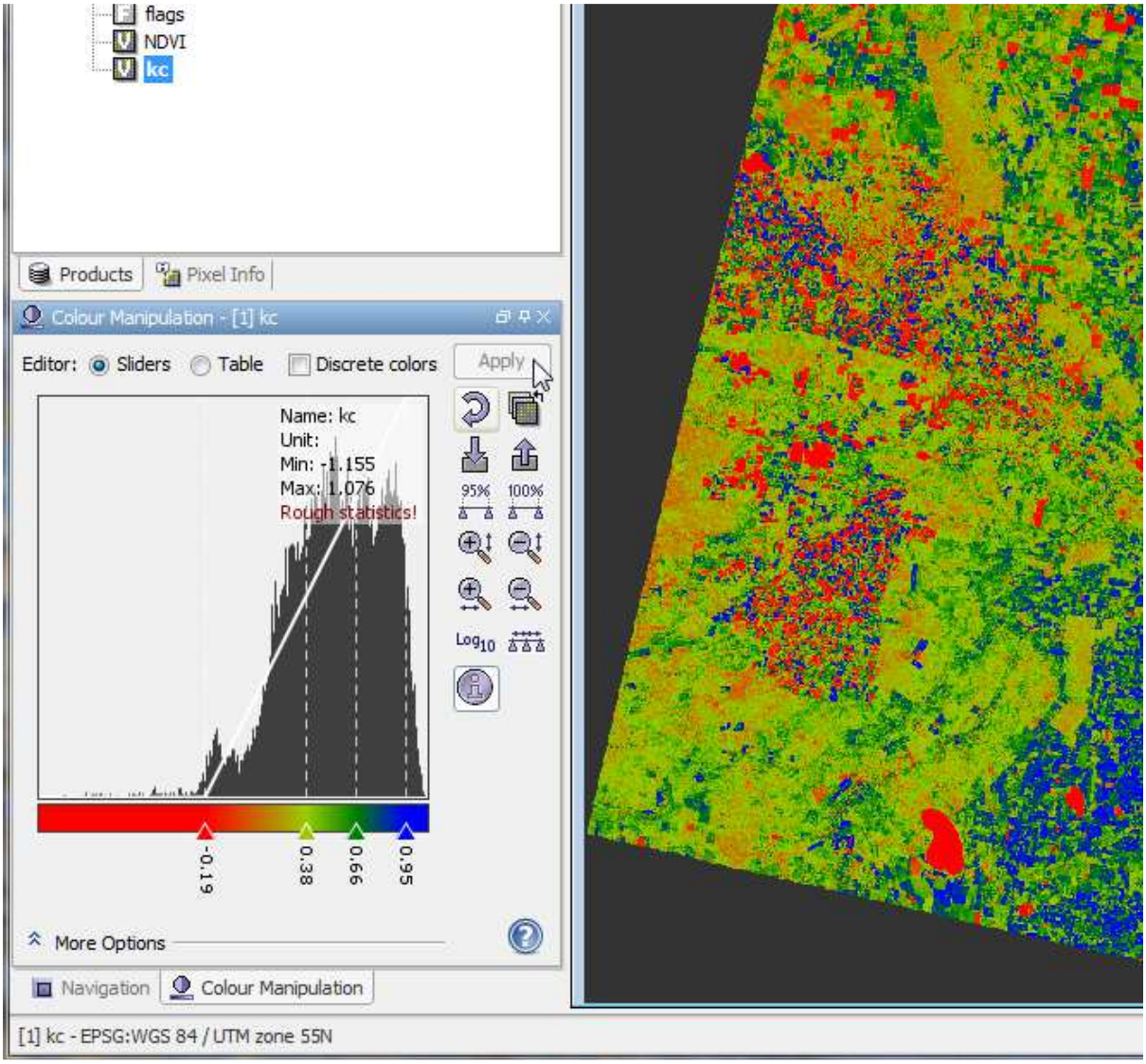
Step 6: Click on the triangles as shown below and change the colours. For the lower values choose red and blue for the higher values. Use a dark green for the mid range.



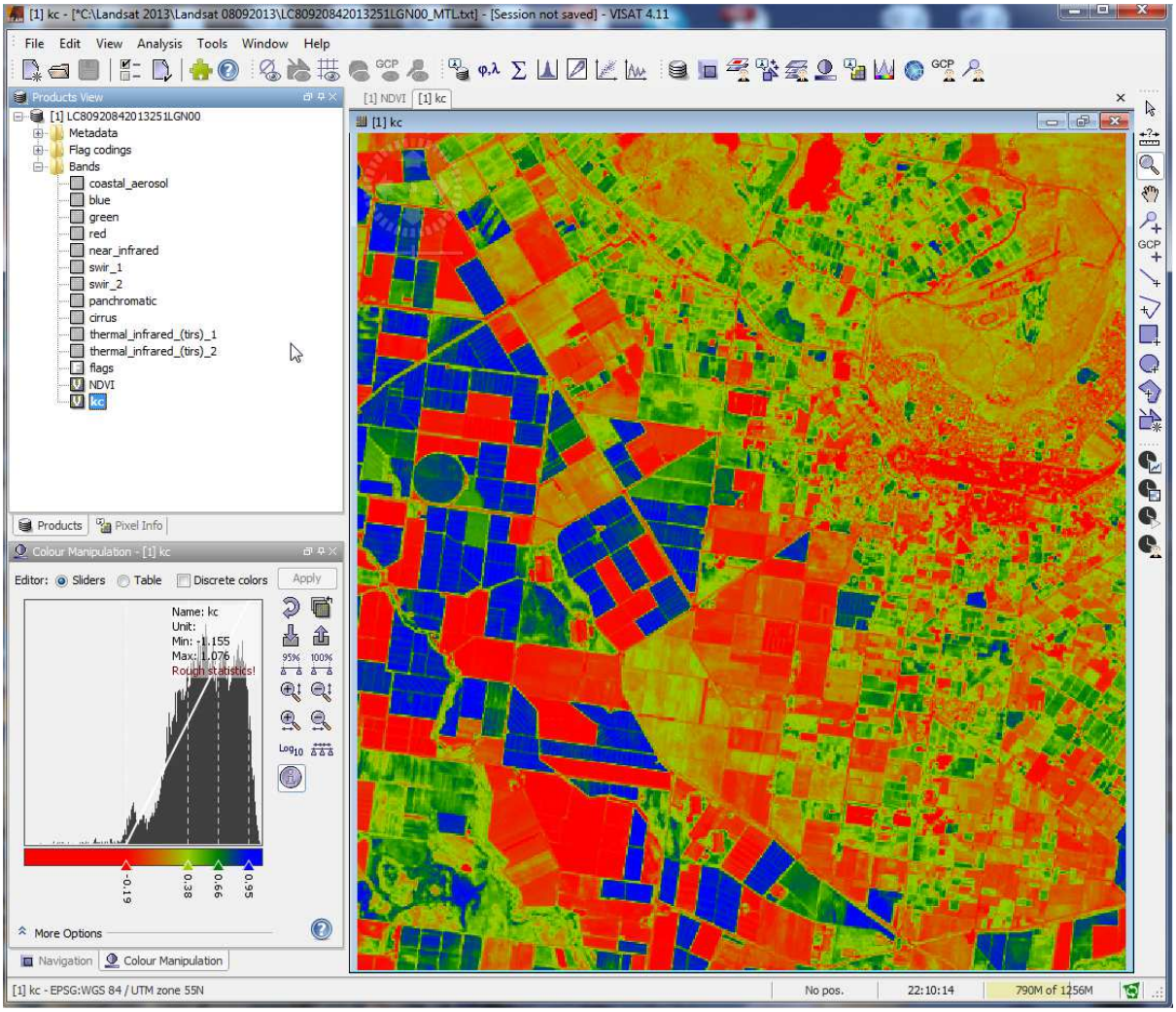
Step 7: Now add some additional sliders to the colour range. Using the right mouse click on the chart range and select ‘Add New Slider’.



Step 8: Now once you have a colour scheme across the range click on apply as shown. The kc band will now be updated.



Step 9: Feel free to zoom around the image and have a look at the variability in crop coefficients across districts, across paddocks and within paddocks. The colour scale can be further changed to focus in on ranges of kc that you may want more resolution in.

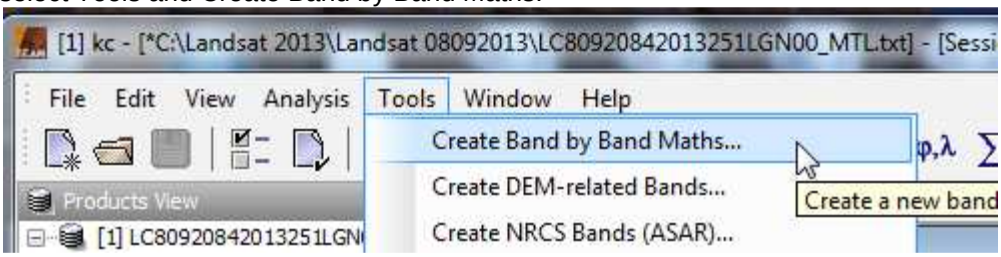


Step 9: Now that we have kc data we are going to combine this with a seven day reference evapotranspiration forecast so we can create some irrigation water use demand maps for the coming seven days. Seven day ETo forecast data is available from http://weather.irrigateway.net/aws/index.php for the Murrumbidgee and Murray valleys. For this exercise we will use the Murrumbidgee Valley forecast and specifically the Griffith, NSW ETo forecast from http://weather.irrigateway.net/aws/index.php?aws_id=8&view=7dayforecast this data is updated daily. An image of the webpage is shown below.

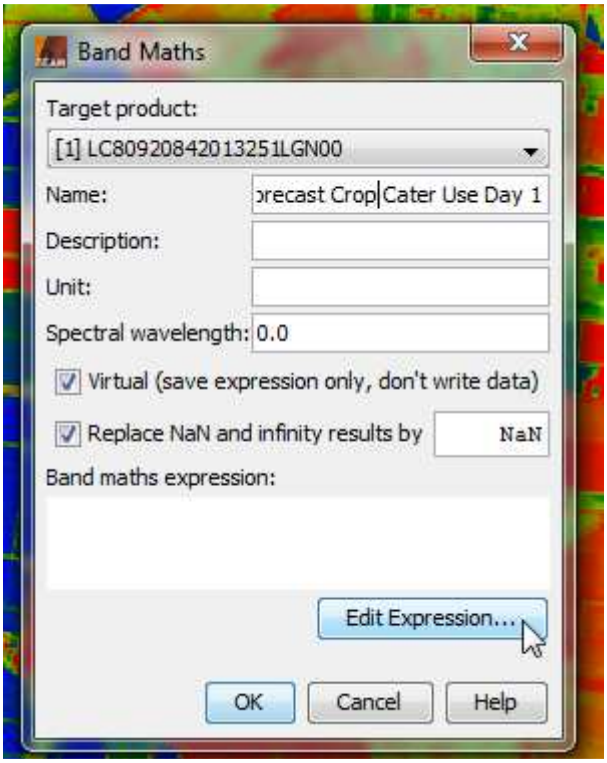


So for the next seven days we have a forecast reference water use of 7.4, 5.5, 4.9, 6.2, 5.7, 7, 7.2 mm/day.

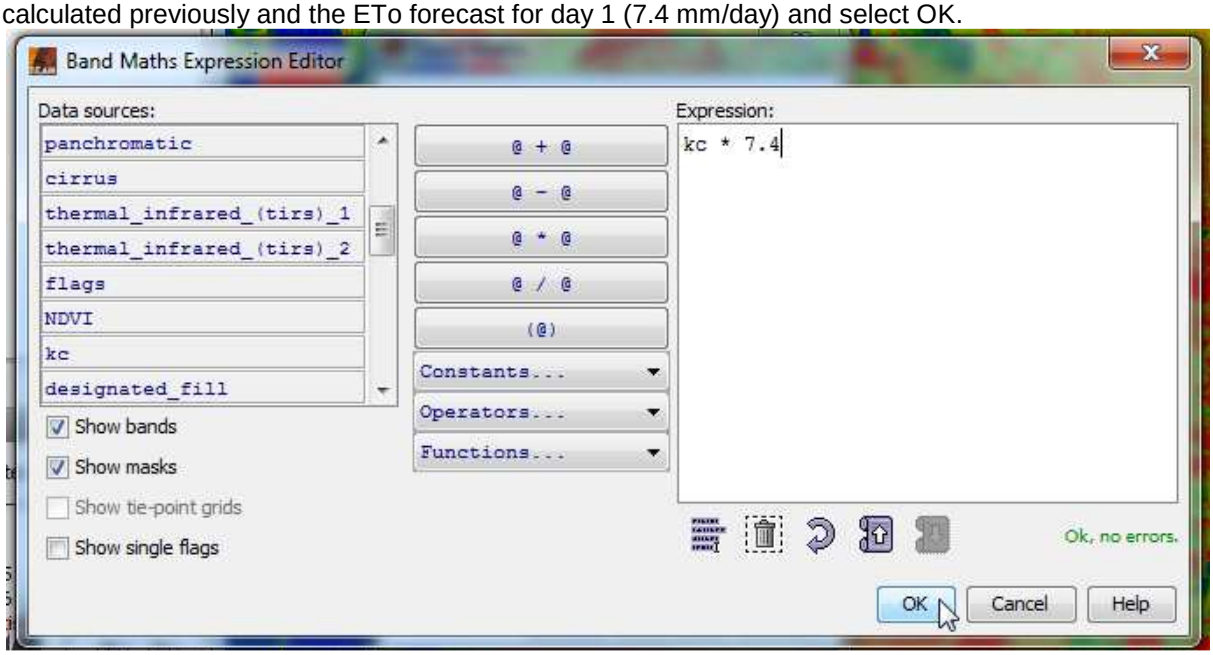
Step 10: Now for each of these days we want to create a forecast crop water use map. So again select Tools and Create Band by Band Maths.



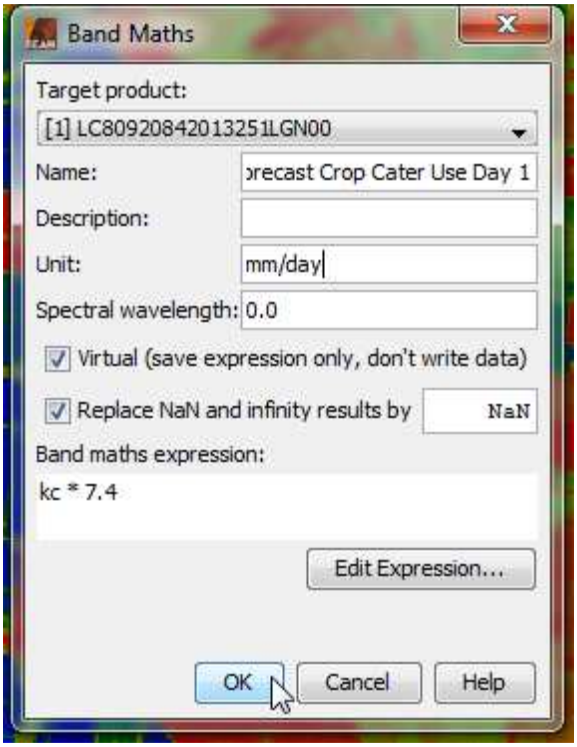
Step 11: Now rename the band to ‘Forecast Crop Water Use Day 1’ and select Edit Expression as shown.



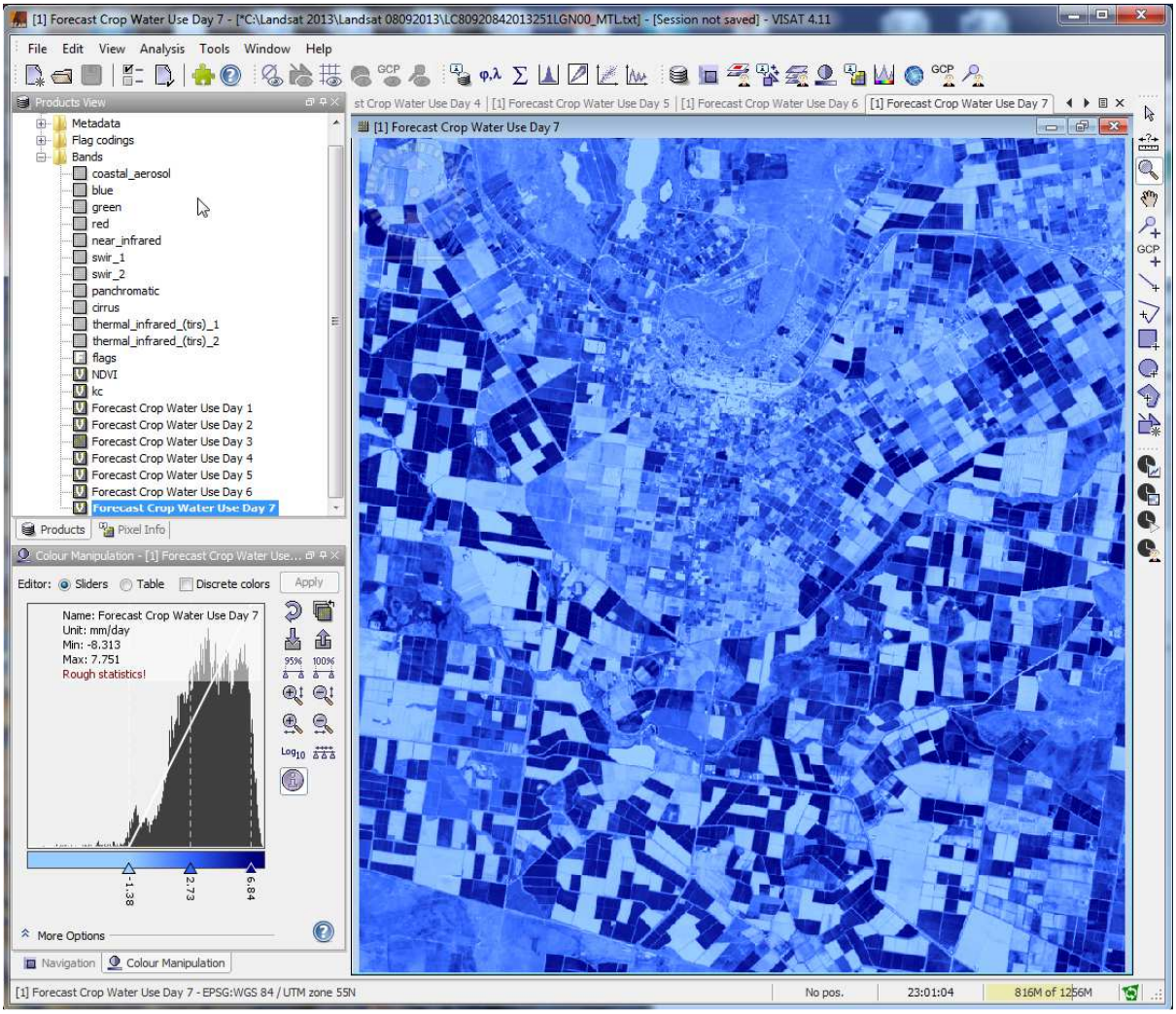
Step 12: Now using the universal expression relating actual crop water use to reference crop water use given by ETc =ETo*kc edit the expression to calculate forecast crop water use, using our kc band calculated previously and the ETo forecast for day 1 (7.4 mm/day) and select OK.



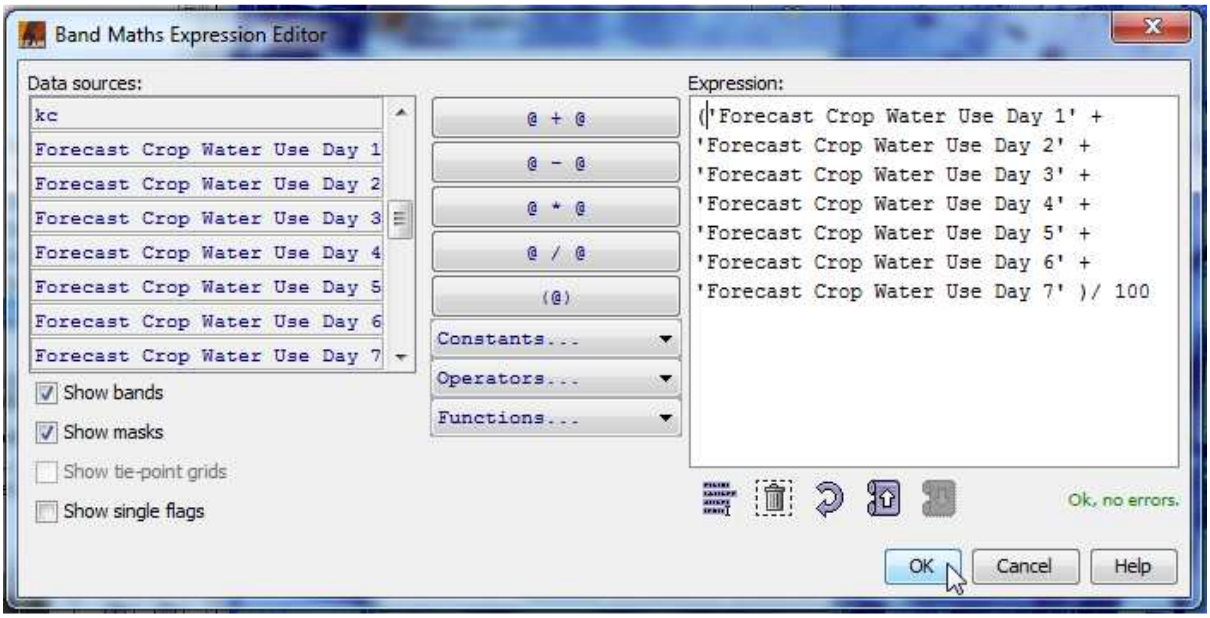
Step 13: Now in the Unit: text box for the Band, add the unit of mm/day as shown and select OK.



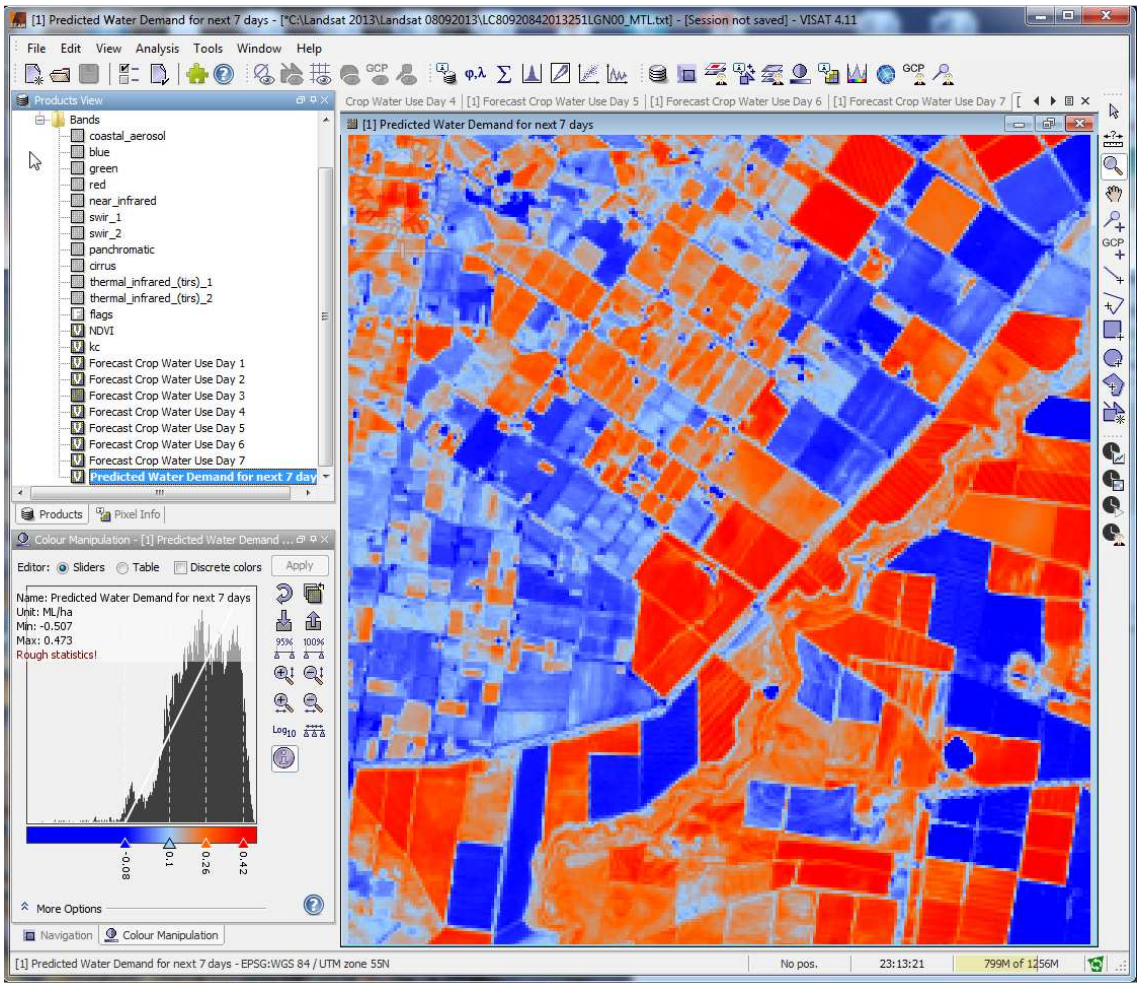
Step 14: Now repeat the above steps to create Forecast crop water use maps for the coming seven days. These images as shown below shown forecast crop water use in mm/day.



Step 15: We can also use the forecast data to develop predicted water need for the coming week. We will do this by creating another band that is simply the cumulative daily crop water use forecasts divided by 100 to convert to ML /ha. So create another band and edit the expression as shown below.



Step 16: We now have a water demand for the coming seven days shown in ML/ha.



These created layers can then be exported in a range of formats such as Google Earth KMZ, Geotif, image files etc. To view the range of available options see export options from the file menu.

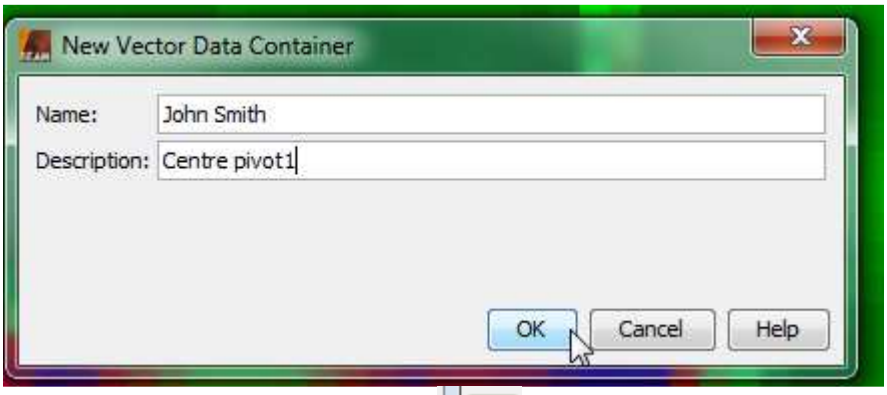
Tutorial 3: Extraction of multiple individual irrigator data on water use

In this tutorial we will extract multiple water use data for a group of irrigators. This process can be used to extract data from a group of paddocks or a group of irrigators for instance. The created 'masks' known as 'Region Of Interests' (ROI) can be saved and used to easily extract data from specific areas in created maps as new satellite images and maps become available.

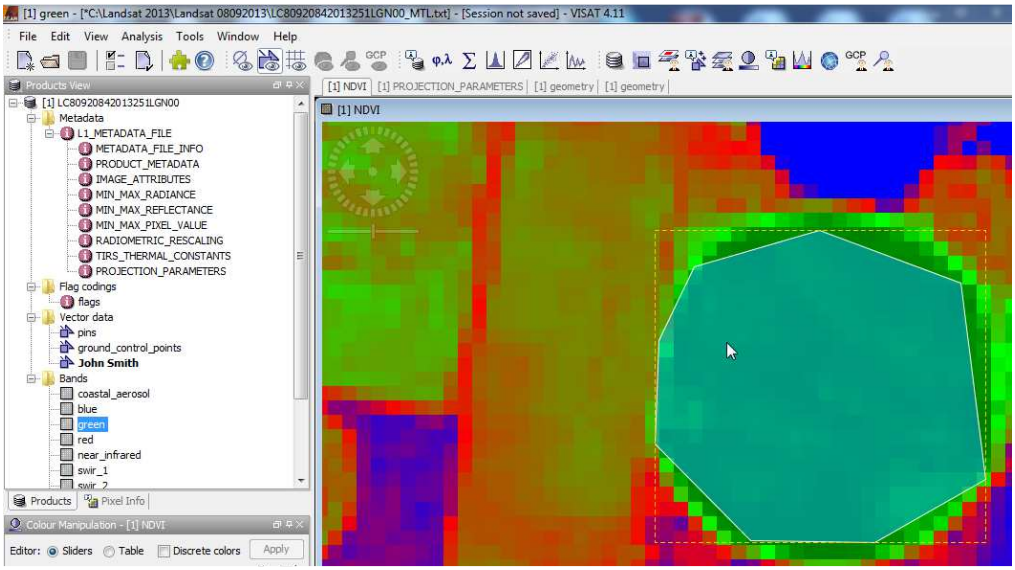
Step 1: Click on the 'Create a new vector data container' button on the right hand toolbar



Step 2: Now rename the vector data container to something meaning full i.e. Name of irrigator and the field. Then Click OK



Step 3: Now select the polygon tool  and draw your field boundary on. You will now see in the vector data a John Smith Polygon.



Step 4: Click on the ‘Create a new vector data container’ button again on the right hand toolbar

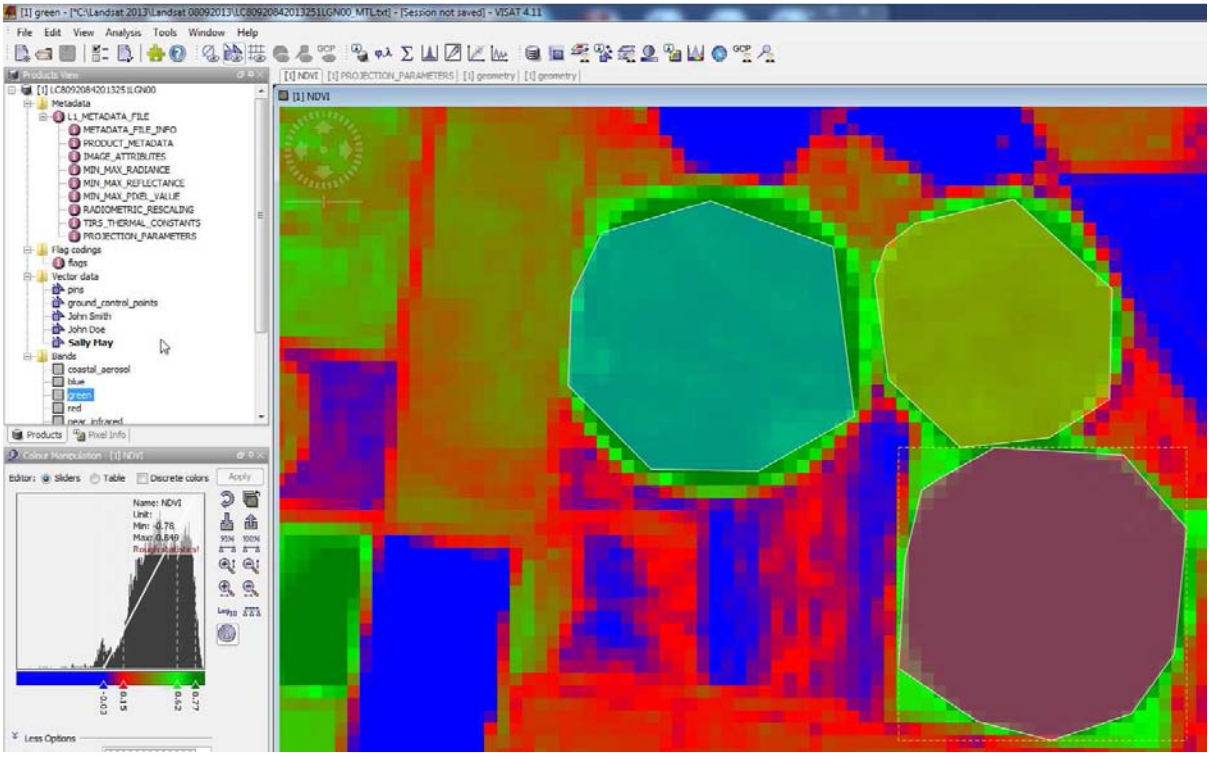


Step 5: Now add additional irrigators to the Vector Data Container and their fields.

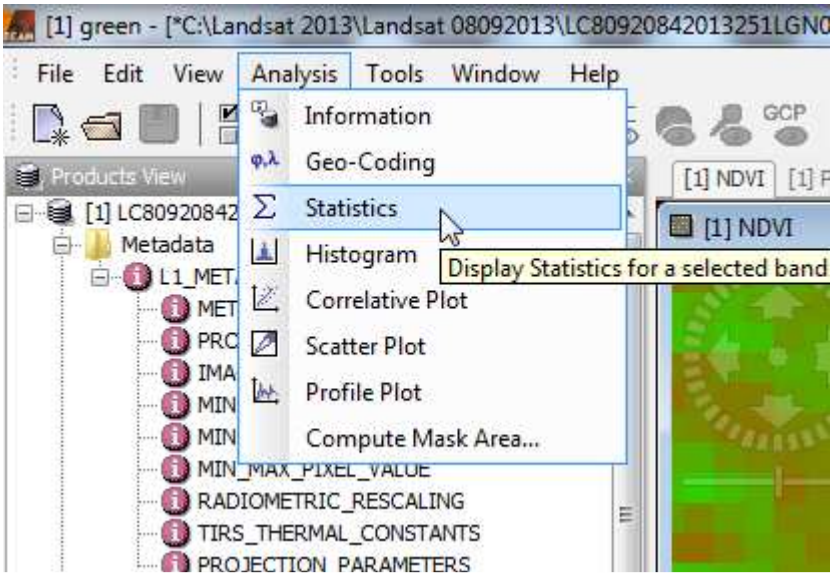


Click on the draw polygon button  and draw the new field

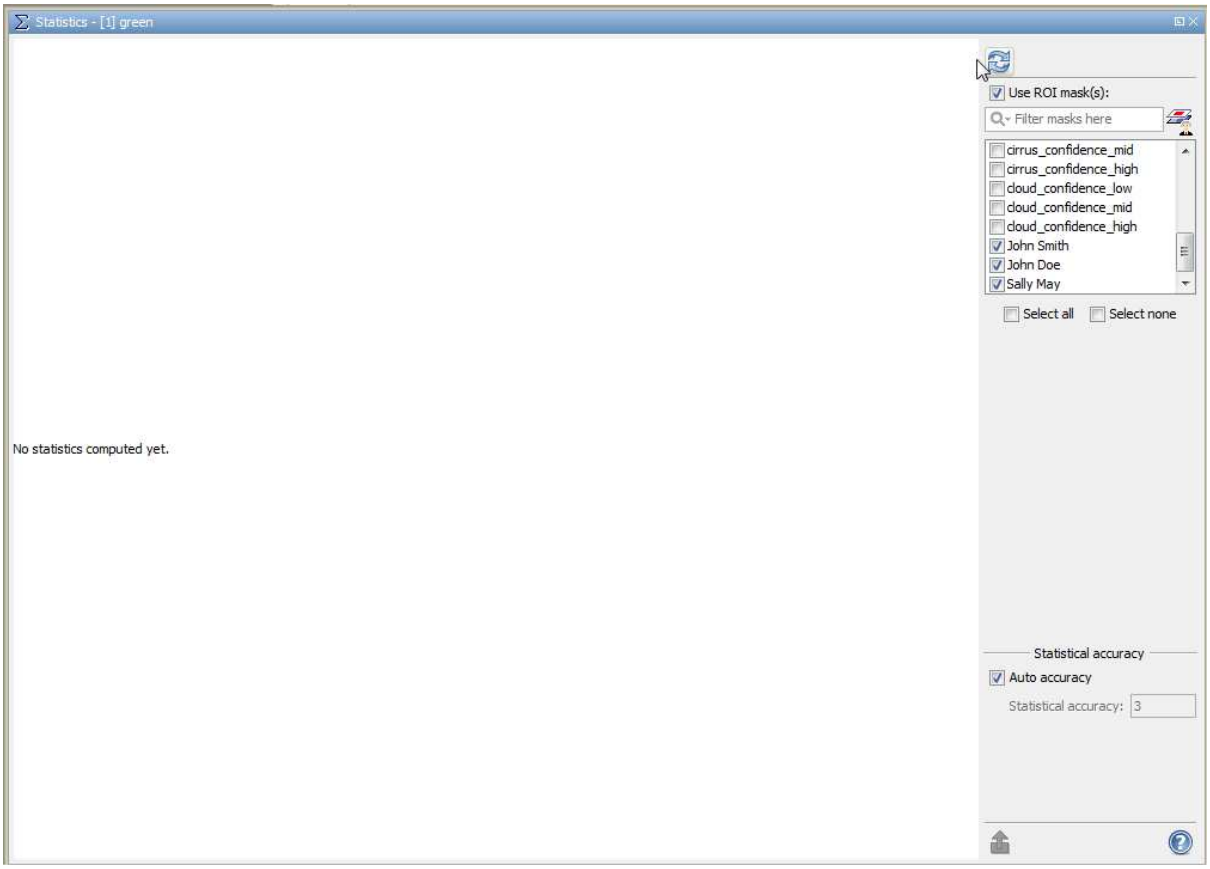
Step 6: Repeat above two steps to add additional irrigators that you are interested in. I’ve gone ahead and added one more irrigator. So in total I have three irrigators.



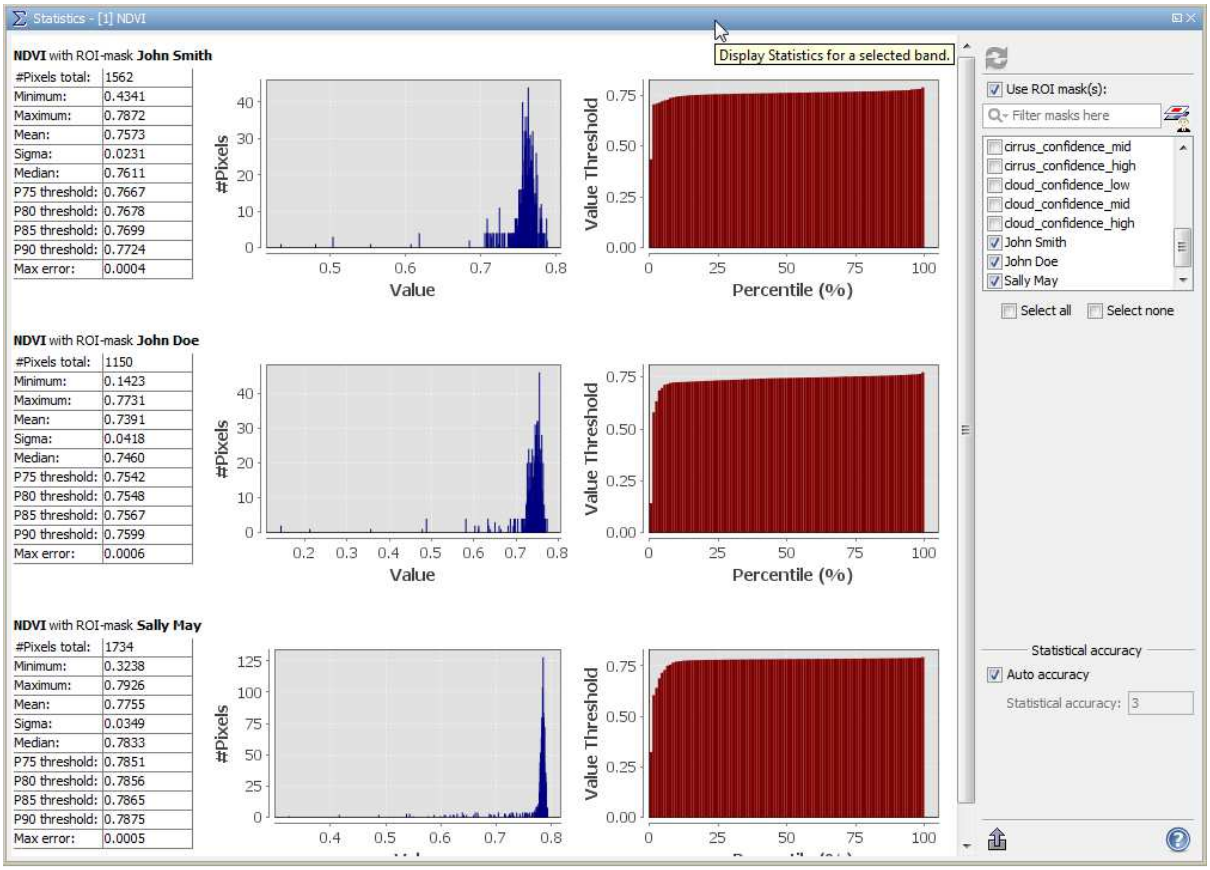
Step 7: Now select the NDVI band in the left menu tree view. In the main menu bar Click on Analysis and then Statistics as shown below.



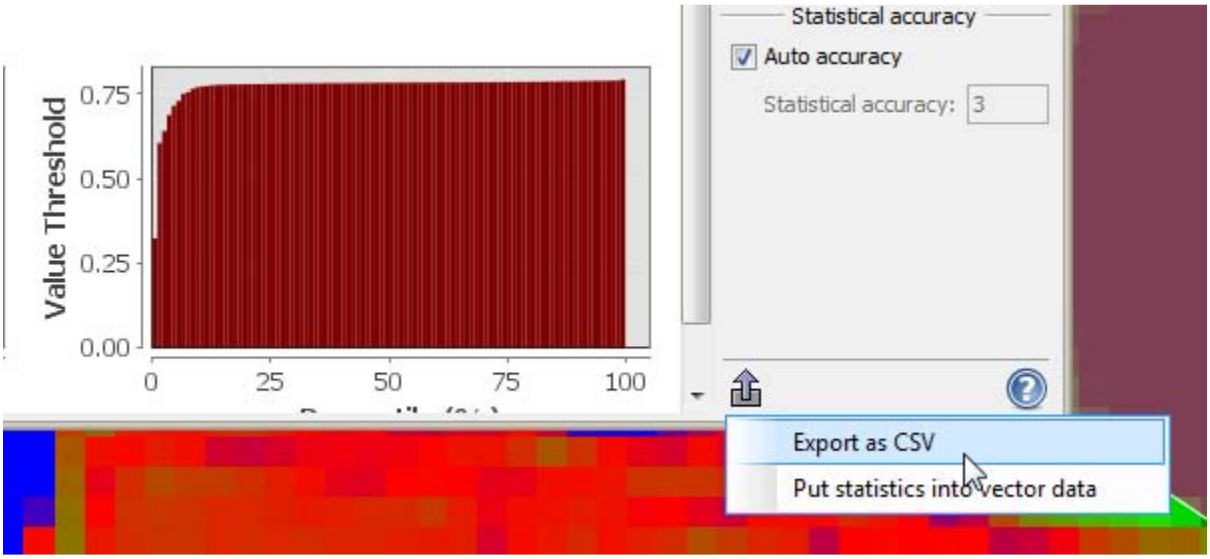
Step 8: Now in the statistics window select the 'Use ROI mask(S) check box and select the irrigators we are interested in as shown. Now click on the refresh button as shown.



You will now see the average NDVI for each of the paddocks displayed along with other statistics, such as minimum, maximum etc.



Step 9: Now to export to Excel click on the Up arrow box as shown below and select 'Export as CSV'. The CSV can now be saved and imported into Excel for further analysis.

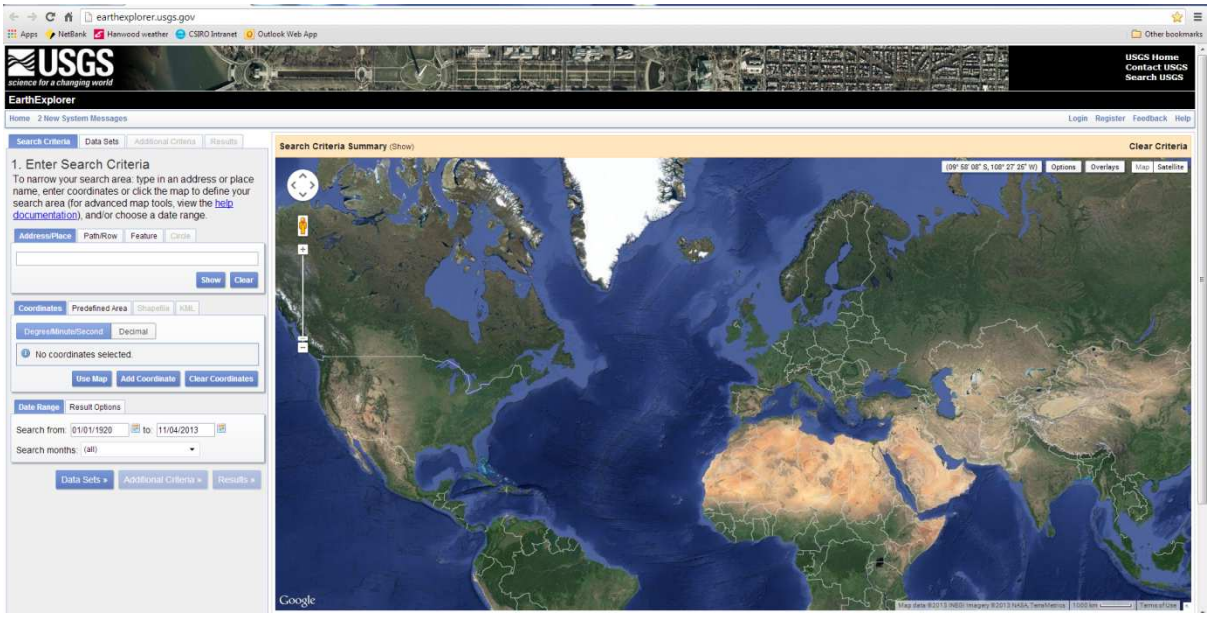


These ROI masks can be saved and used to very quickly extract areas of interest from new satellite data and created maps. For instance average crop coefficients can be extracted and combined with forecast ETo to send crop water demand information or run a simple waterbalance for irrigation scheduling.

Appendix

The Landsat 8 image has been supplied on participants USB stick for these tutorials. The guide below provides step by step details on how to gain access to Landsat images you maybe interested in through the USGS.

Step 1: Navigate to http://earthexplorer.usgs.gov/ as shown below.



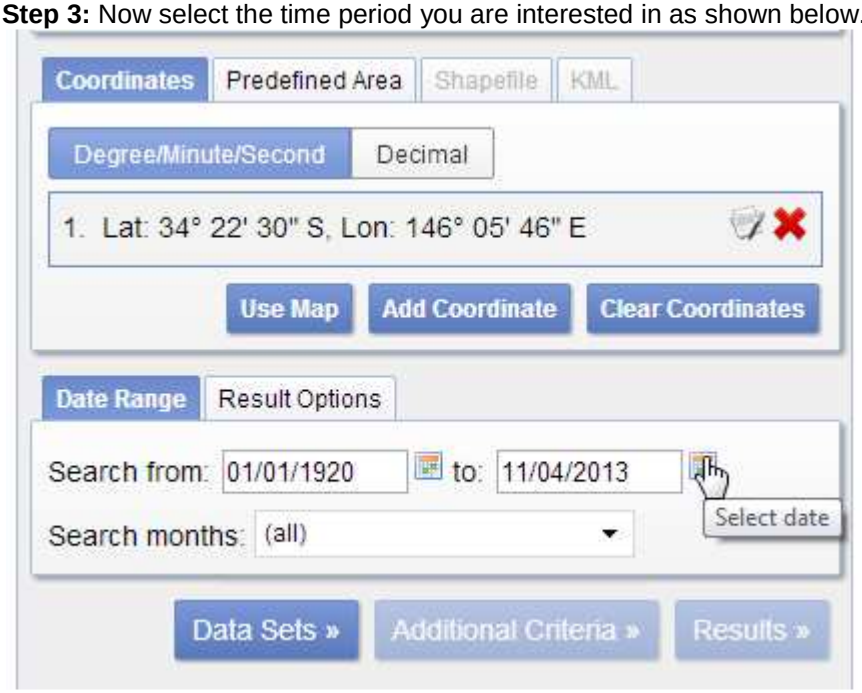
Now right click on the register button as shown and follow the steps to register as a user and complete the registration process.



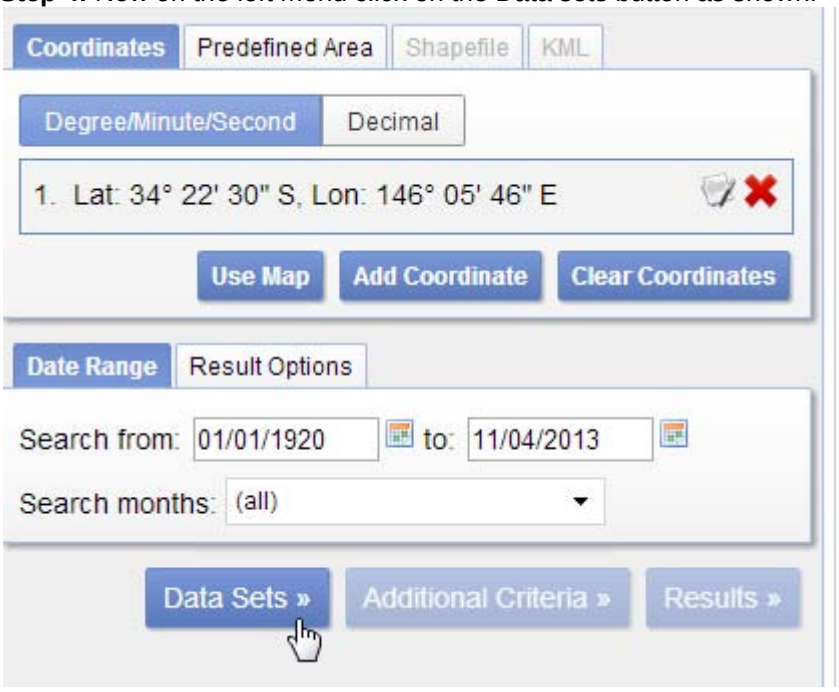
Step 2: Now navigate to the area of interest on the map. You can either use the map itself or enter in GPS co-ordinates you are interested in. The map interface uses Google Earth/maps interface so you can zoom in and out using the navigation bars the same you would with google earth to identify your location. Click on your area of interest which will put a place mark on the map as shown below and add the co-ordinates to your search on the left hand menu as shown.



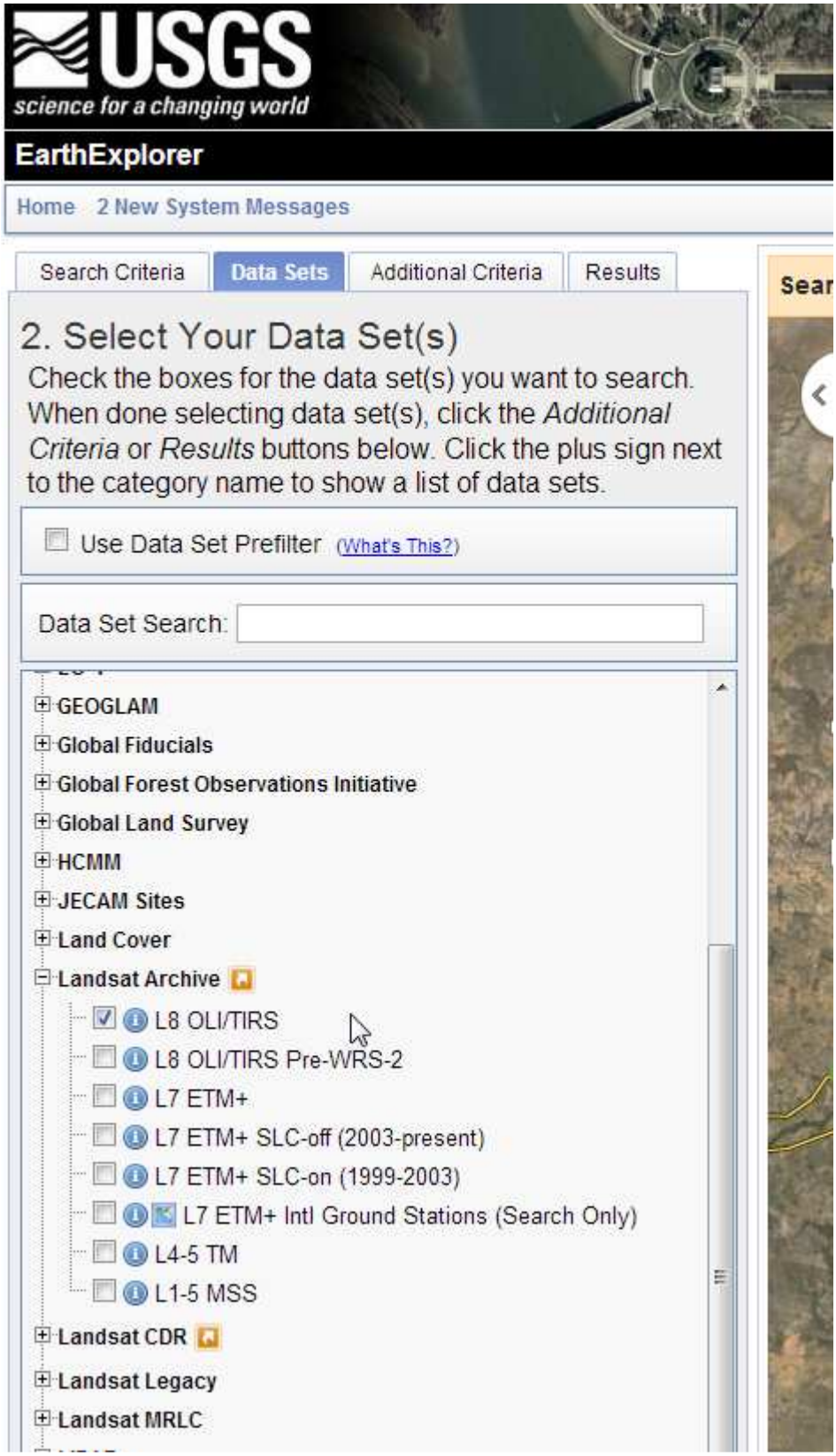
Step 3: Now select the time period you are interested in as shown below.



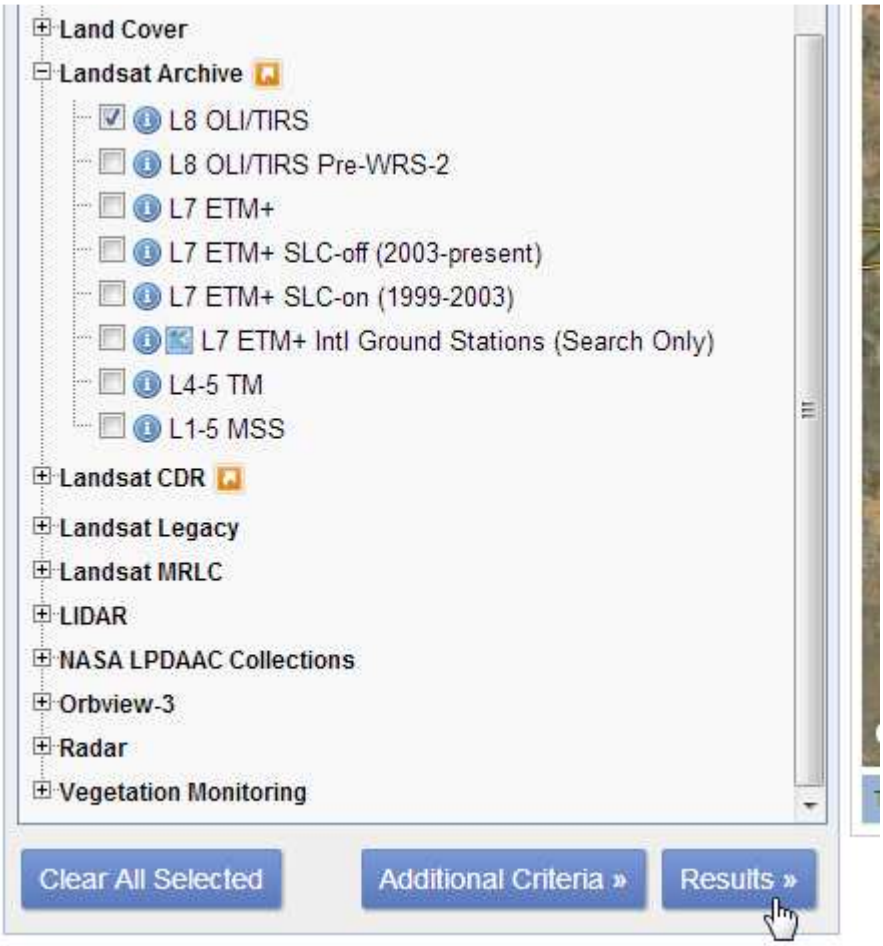
Step 4: Now on the left menu click on the Data sets button as shown.



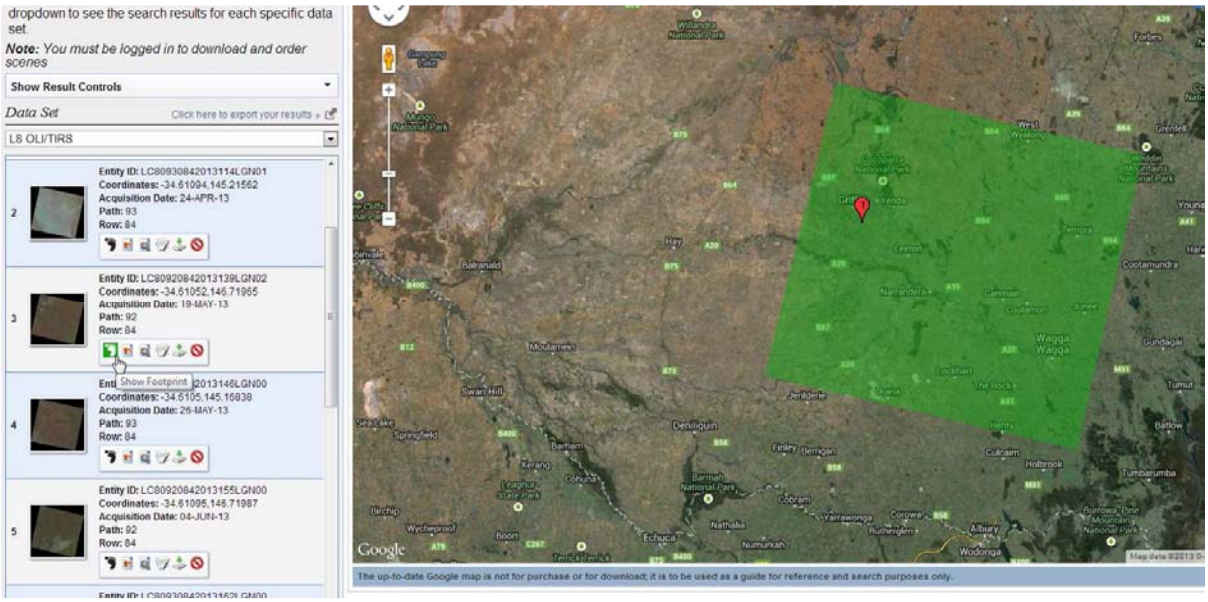
Step 5: Now select the Landsat archive and the Landsat satellite you are interested in. In this case we will look at Landsat 8 so select it as shown.



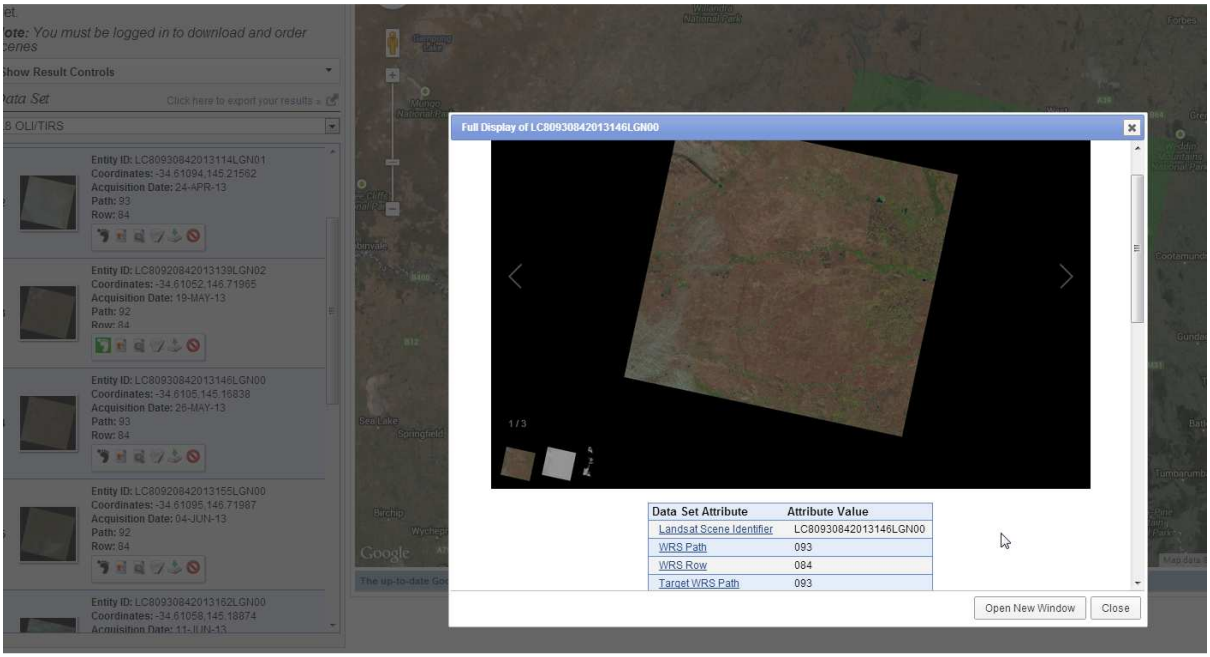
Step 6: Now click on the results button.



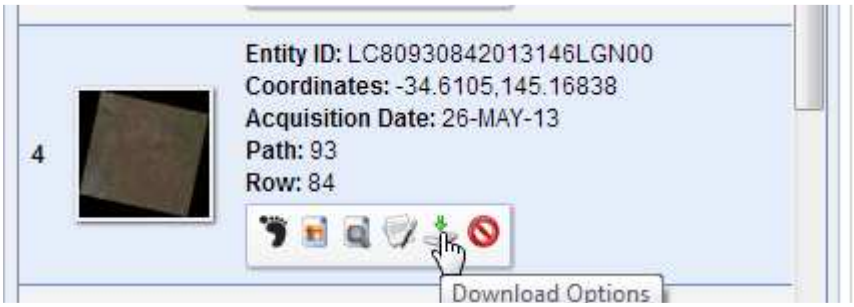
Step 7: You will now be presented with a series of images that meet your search criteria. Select the footprint icon next to an image to show its footprint and coverage over your area of interest.



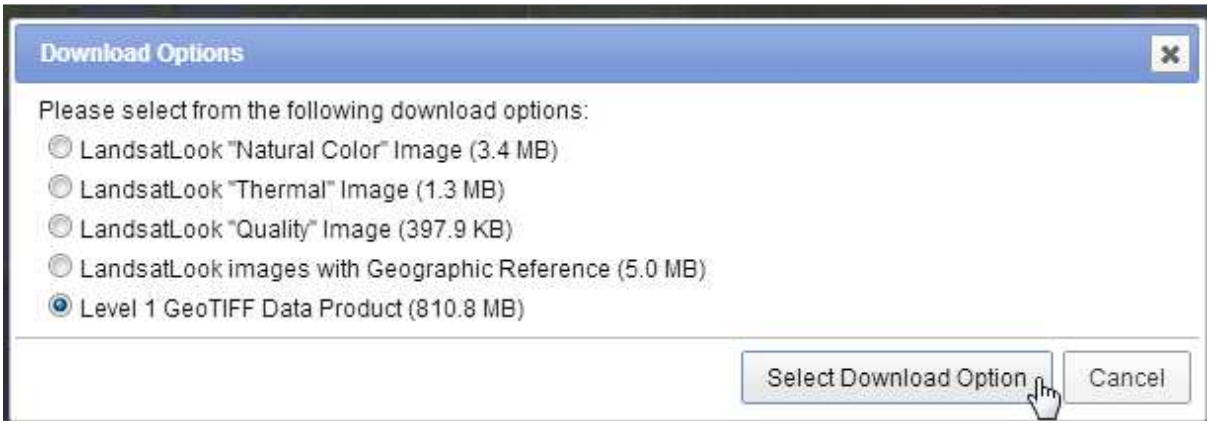
Step 8: Now double click on the image to have a quick look at it. It will show cloud cover in the image and also give attribute values of the image.



Step 9: Now if you want to download the image and its sensor band data as geotifs click on the download icon as shown.



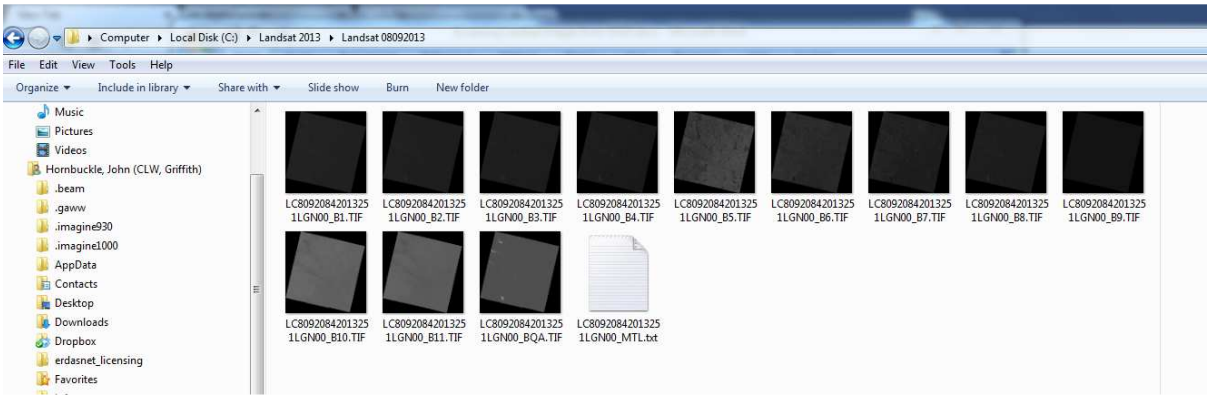
Step 10: Now if you not logged in you will need to. Select the GeoTIFF data product as shown and the 'Select Download Option' button as shown.



Step 11: Now you will be able to download the GeoTIFF file by clicking download as shown below.



Step 12: The downloaded file is zipped. I use the program http://www.7-zip.org/ to unzip the file. Note: It needs to be unzipped twice. Once unzipped you should get a file folder and files that look like below and contains the individual bands as GeoTIFF files and a .txt file.



You are now ready to use these files in BEAM VISAT for analysis.

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