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Vegetation water content mapping in a diverse agricultural landscape: National Airborne Field Experiment 2006

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Abstract. Mapping land cover and vegetation characteristics on a regional scale is critical to soil moisture retrieval using microwave remote sensing. In aircraft-based experiments such as the National Airborne Field Experiment 2006 (NAFE'06), it is challenging to provide accurate high resolution vegetation information, especially on a daily basis. A technique proposed in previous studies was adapted here to the heterogenous conditions encountered in NAFE'06, which included a hydrologically complex landscape consisting of both irrigated and dryland agriculture. Using field vegetation sampling and ground-based reflectance measurements, the knowledge base for relating the Normalized Difference Water Index (NDWI) and the vegetation water content was extended to a greater diversity of agricultural crops, which included dryland and irrigated wheat, alfalfa, and canola. Critical to the generation of vegetation water content maps, the land cover for this region was determined from satellite visible/infrared imagery and ground surveys with an accuracy of 95.5% and a kappa coefficient of 0.95. The vegetation water content was estimated with a root mean square error of 0.33 kg/m². The results of this investigation contribute to a more robust database of global vegetation water content observations and demonstrate that the approach can be applied with high accuracy.

Keywords: Vegetation, field experimentation, thematic mapper, NDWI, agriculture.

1 INTRODUCTION

The science goals of the National Airborne Field Experiment 2006 (NAFE'06) focused on retrieving surface soil moisture using an airborne L-band passive microwave radiometer. This research would contribute to the development of algorithms used on the upcoming Soil Moisture and Ocean Salinity Mission (SMOS) [1], in addition to evaluations of satellite products from the higher frequency Advanced Microwave Scanning Radiometer, AMSR-E [2]. NAFE'06 was conducted from October 29 – November 20, 2006 in the Murrumbidgee catchment in southeastern Australia. Field sampling and instrumentation monitored soil moisture conditions in coordination with aircraft and satellite observations. Other types of sampling were also conducted, including soil and vegetation characterization, to support the overall objectives of soil moisture retrieval on a large spatial scale.

A critical element of soil moisture estimation using microwave remote sensing is accounting for the effects of vegetation [3]. Providing vegetation information, typically vegetation type and vegetation water content (VWC), in an experiment such as NAFE, is necessary for vegetation parameterization and modeling as it contributes to the microwave signal. As a parameter for use in soil moisture remote sensing, VWC is a quantification of the

quantity of water per unit area and it is used to calculate the attenuation of the microwave signal by the vegetation canopy. We recognize that there are more sophisticated ways of quantifying the VWC. However, for the purposes of soil moisture retrieval using coarse passive microwave data (typically 50 km) it is quite difficult to implement in an experimental framework. If more advanced products are readily available these would offer an improvement and would be adopted in retrievals. In this investigation we extended a technique developed for primarily for croplands in the U.S. to the NAFE domain. This approach utilizes ground-based reflectance and vegetation water content sampling combined with indices derived from high resolution satellite reflectance data to map daily vegetation types and water content over the NAFE domain.

2 BASIS OF THE VEGETATION WATER CONTENT MAPPING APPROACH

Studies have explored the utility of satellite reflectance data in estimating VWC [4, 5, 6], which is defined as the ratio of mass of water per unit area of land surface. The satellite reflectance data can often be reduced to an index or ratio of bands upon which relationships to VWC can be developed. Several vegetation indices have been investigated. The Normalized Difference Water Index (NDWI) [7] has been shown to be the most robust to the variations in vegetation biomass and water content [4,5,6].

NDWI is defined as:

$$NDWI = \frac{R_{NIR} - R_{SWIR}}{R_{NIR} + R_{SWIR}} \quad (1)$$

where R_{NIR} is the reflectance in the near-infrared channel (0.78-0.90 μm TM/ETM+) and R_{SWIR} is the reflectance in the short wave infrared channel (1.2-2.5 μm TM/ETM+) [7]. During the Soil Moisture Experiment in 2002 (SMEX02) [6], NDWI maintained a relationship with VWC late into the growing season. The more widely available Normalized Difference Vegetation Index (NDVI) [8] often saturates for high biomass crops such as corn, as seen in SMEX02 [6]. Previous studies have also shown that another limitation of NDVI as an indicator of vegetation water content is that it's more an index of canopy structure and leaf area [9]. Therefore, as an alternative in this study, NDWI will be used to estimate VWC across the broad range of vegetation conditions found in the NAFE study region.

The procedure developed in SMEX02 will be adapted and verified here and consists of the following steps:

1. Collect ground-based observations of spectral reflectance and compute NDWI
2. Collect ground-based measurements of VWC concurrent with the spectral data
3. Establish land cover type specific relationships between NDWI and VWC
4. Obtain multi-temporal high-resolution satellite data (Landsat TM) and compute NDWI for each image.
5. Perform land cover classification
6. For each image, compute VWC using land cover, NDWI, and the relationship developed from ground sampling and the radiometric signatures of the surface
7. Interpolate/extrapolate the available VWC information for satellite overpass days to each day of NAFE'06.

3 DATA SOURCES

3.1 Ground Sampling Results from NAFE'06

For NAFE '06, three regions were selected as intensive study sites. The Yanco study region was 60 km by 60 km in size and is dominated by agriculture, such as rice, canola, maize, wheat, barley, and pasture and rangeland during the summer months with substantial amounts of land in irrigation. The second area was the Kyeamba watershed that is approximately 600 km² in the eastern highlands of the Murrumbidgee catchment. This region is used for rangeland and pasturing of cattle, but some irrigation exists in the southern portion. The third study region, Yenda, is the smallest watershed studied and consists of a 26 hectare experimental farm of vineyards. Full details of NAFE '06 can be found in Merlin et al. [10].

Much of the experiment was conducted during drought conditions. There was no precipitation in the preceding five weeks. Only two precipitation events occurred during the 3 week experiment in October/November, 2006. All of the physical sampling of vegetation occurred in the Yanco region, so this domain will be the basis for developing the NDWI-VWC relationships. These equations will then be applied throughout the NAFE domain. Physical sampling of vegetation began with selecting fields in order to include the dominant crop types. Within each field, five locations were sampled approximately weekly during the experiment. At each location, a small area (0.25 m²) was randomly selected and all the vegetation within the area was trimmed at the surface, weighed, oven dried, and weighed again, to calculate vegetation water content. A ground-based radiometer (CROPSCAN-MSR16) and LiCor LAI-2000 were used to collect surface radiometric data at the sample sites as well. There was limited LAI data collected, but this data was not adequate for this analysis. From these coincident measurements, regression relationships were developed between NDWI and vegetation water content.

3.2 Satellite Data Sets

Our primary satellite data resource was the Landsat 5 Thematic Mapper (TM) that provided a very good basis for land cover and vegetation studies due to good sky conditions on the overpass days and the timing of these relative to the campaign. Three days were retrieved for NAFE'06: October 6, November 7, and November 23, 2006 (Path 92, Row 84). Initial tasks included georeferencing each of the Landsat TM scenes to the same grid. No significant errors were detected between the scenes, but subtle corrections of 15-30 m were made based on distinctive stationary features found in each of the scenes. The TM reflectance values were then atmospherically corrected using MODTRAN 4 [13] to generate surface reflectance. The results of this correction were compared to ground-based multi-spectral radiometer (CROPSCAN-MSR16) data collected during the one overpass date at various locations in the Yanco study region on November 7.

4 LAND COVER CLASSIFICATION

The approach used for land cover classification is based upon a decision tree developed in previous studies [11, 12]. Utilizing the three dates; the beginning, middle, and late stages of the growing season improves the likelihood of success. Figure 1 shows that the corrected radiance (reflectance) values are highly correlated to ground-based measurements.

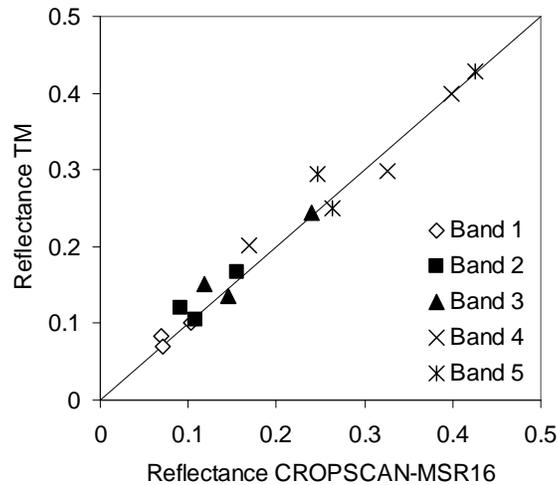


Fig. 1. Reflectance from the ground-based multi-spectral radiometer compared to atmospherically corrected reflectance from the Landsat Thematic Mapper on November 7, 2006. The RMSE is 0.019 reflectance.

As a check of the ground versus satellite reflectance observations, we compared data obtained concurrently, after making the atmospheric corrections to Landsat TM data. Three samples were available, respectively bare soil, cut wheat and canola. In order to compare the reflectance band by band, the reflectance at 485nm of CROPSCAN-MSR16 was corresponding to band 1 of TM, 560nm corresponding to band 2, the average of 650nm and 660nm corresponding to band 3, the average of 830nm and 850nm corresponding to band 4, and the average of 1640nm and 1650nm corresponding to band 5. The low RMSE (0.019) of reflectance guarantees the good accuracy of water index. Note that the ground data were not used in calibration, only in validation. Also, it should be noted that we are comparing spatially distributed point averages on the ground to spatially integrated pixel values.

Additional processing was conducted to insure that no clouds were present in the imagery (cloud and shadow masking). During the campaign, field surveys were conducted to collect land cover and land use (LC/LU) information across the domain. The resulting dataset of locations and LC/LU were partitioned into a training dataset (2/3 of the locations) and testing dataset (1/3 of the locations).

A decision tree classification system was developed using a combination of ground-based reflectance measurements for known LC/LU, the training dataset, and histograms of the reflectances. The decision tree method uses a sequence of rules to establish how an individual pixel within the LC/LU image is classified [11]. A key component of this analysis is the use of the three available Landsat scenes, which capture different stages of vegetative growth. Each crop type will exhibit individualized growth or greenness patterns during the study period providing additional information for the decision making process. Generally, the irrigated crops exhibit the typical green vegetation spectral characteristic at peak growth, with high reflectance in the near infrared, low reflectance in the red band, and relatively low reflectance in the short wave infrared, while the reflectance of dry crops with increasing wavelength so NDVI and NDWI or other combination of reflectance at different wavelengths can be used as indicators to distinguish crops.

Table 1. Confusion matrix for the land cover classification using a decision tree.

Class	Bare soil	Alfalfa	Canola & Wheat	Maize	Rice	Forest & Shrub	Water & Swamp	Other Crop	Dry wheat	Range & Barley
Bare soil	62	0	0	0	0	0	0	1	1	1
Alfalfa	0	58	0	0	0	0	0	0	0	0
Canola & Wheat	0	0	79	0	0	0	1	0	1	2
Maize	0	0	0	54	0	0	0	0	0	0
Rice	0	0	0	0	46	3	8	0	0	0
Forest & Shrub	0	0	0	0	0	56	0	0	0	0
Water & Swamp	0	0	0	0	0	1	55	0	0	0
Other Crop	0	0	0	0	0	0	0	43	2	1
Dry wheat	0	0	0	0	0	0	0	0	38	0
Range & Barley	0	0	0	0	0	0	0	6	0	98
Total	62	58	79	54	46	60	64	50	42	102

Post classification processing was conducted to improve the overall accuracy and remove subtle errors that often occur with satellite-based classification. The imagery was sieved to remove isolated pixels of dissimilar land cover types; for example, a single pixel of rice within a field of maize is very likely misclassified. Clumping takes unclassified pixels and reclassifies them to adjacent or nearby pixels. The resulting LC/LU image was determined to have an accuracy of 95.5 % and a kappa coefficient of 0.95. A kappa coefficient is a method of measuring agreement in categorical data [14]. A kappa coefficient of 1.0 is perfect agreement, and a kappa of 0.0 is a measure of no agreement. Table 1 shows the confusion matrix for the classification. Figure 2 is the classified image. The Yanco study region is outlined and the diversity of irrigated (red) and dryland (green) agriculture is apparent. The Kyeamba and Kenda study regions are also shown in this figure.

5 VWC MAPPING

The next step in developing VWC products for soil moisture analyses is to establish relationships between ground-based NDWI and physically sampled vegetation water content. Figure 3 is a plot of the observed VWC as a function of ground-based NDWI measurements. Regression equations for the dominant land cover types were developed from this data set (see Table 2). Several of the crops exhibited very similar relationships between NDWI and VWC; therefore, they were grouped together. One group was alfalfa, canola, and wheat. The other was rangeland, barley and dry wheat. Generally irrigated crops share the same regression relationship while dryland crops share another. Maize has a unique relationship due to large range of VWC that occurs during the growing season. Forests and shrubs were not sampled and as a result were assigned a fixed VWC for this study based upon previous experiences.

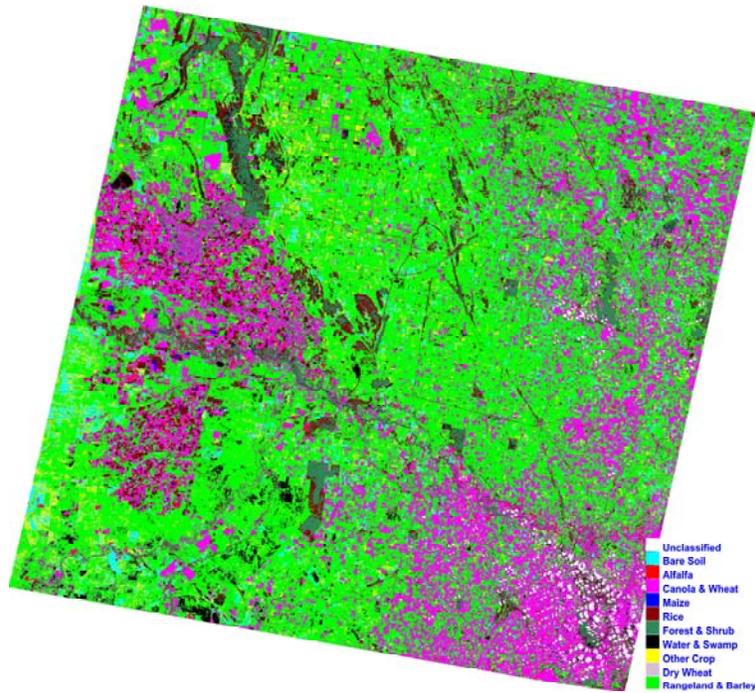


Fig. 2. Land cover classification based on the Landsat 5 TM (Path 92/Row 84).

Table 2. Regression equations for NAFE land cover/land use.

Landcover	Equation or Value (kg/m ²)	RMSE (kg/m ²)
Alfalfa, Canola & Wheat	$VWC = 2.1014 * NDWI + 0.5085$	0.1730
Maize	$VWC = 9.3897 * NDWI + 1.2583$	0.3351
Other Crop, Dry Wheat, and Rangeland & Barley	$VWC = 0.9825 * NDWI + 0.2801$	0.0631
Unclassified, Bare soil, Water & Swamp, Rice	0	-
Forest & Shrub	3	-

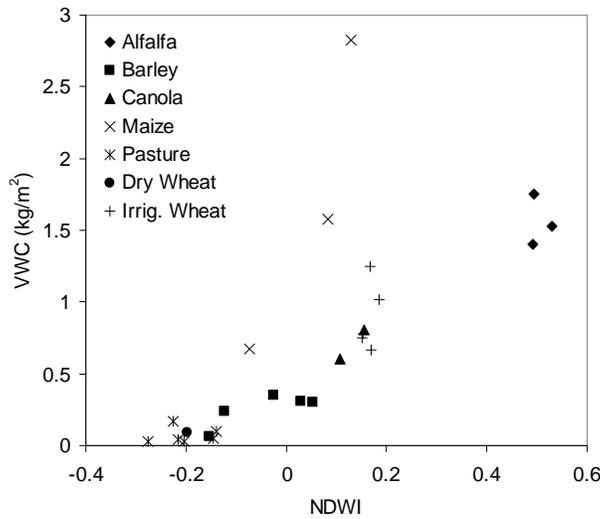


Fig. 3. Vegetation water content ground sampling data compared to ground-based NDWI measurements.

Figure 4 shows the results of applying the regression equations to the three available Landsat TM scenes. It is readily apparent from the figure that overall VWC was decreasing during the study period, which was confirmed in the field. This is likely the result of the ongoing drought. Average estimates of vegetation water content for the major crop types are shown in Fig. 5. Most of the crops dried out over the study period, with the exception of corn, which increased as a result of irrigation.

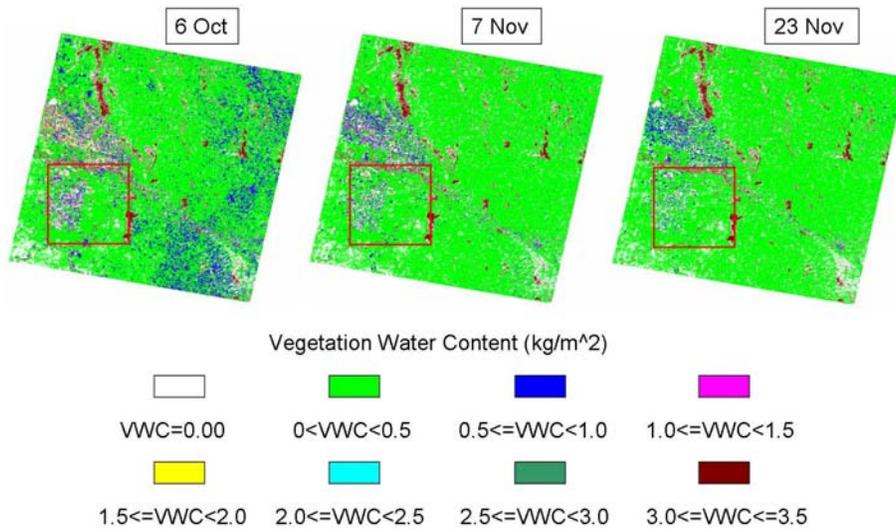


Fig. 4. Vegetation water content for the three TM satellite scenes for the NAFE'06 study region.

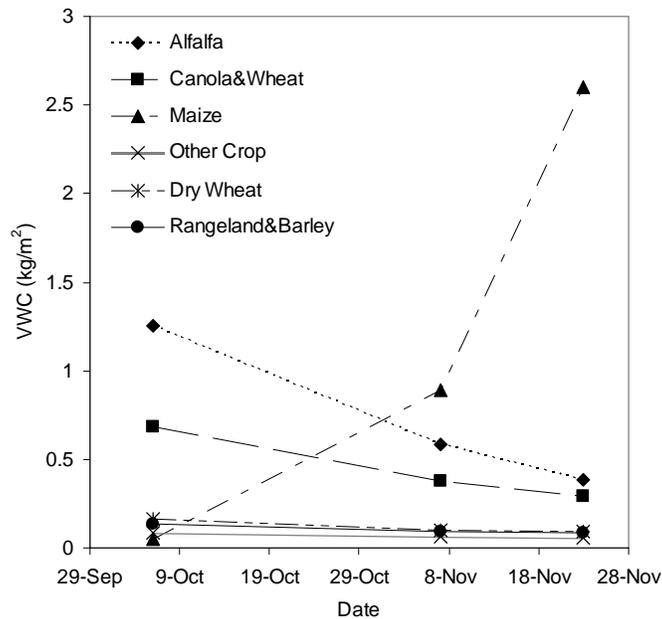


Fig. 5. Temporal changes in vegetation water content by land cover type.

The three TM-based scenes of NDWI were then used to linearly interpolate imagery for each day of the study when there was no satellite overpass from October 6 to November 23. Using the linearly interpolated VWC satellite scenes, estimates were retrieved for each ground-sampled pixel for each day of sampling. Figure 6 shows the estimates versus ground data. The overall agreement is quite good. Table 3 contains the biases and root mean squared errors (RMSEs) for the various crop categories in the study region. Overall bias in the study for VWC was -0.03 kg/m^2 and the RMSE was 0.33 kg/m^2 . The crops which were either very wet or very dry tended to have the largest errors due to the sensitivity of the regression equations develop using NDWI.

Table 3. Evaluation statistics for the vegetation water content results in NAFE'06.

Landcover	RMSE (kg/m^2)
Alfalfa	0.30
Barley	0.08
Canola	0.10
Cut Wheat	0.35
Maize	0.06
Pasture	0.28
Wheat	0.82

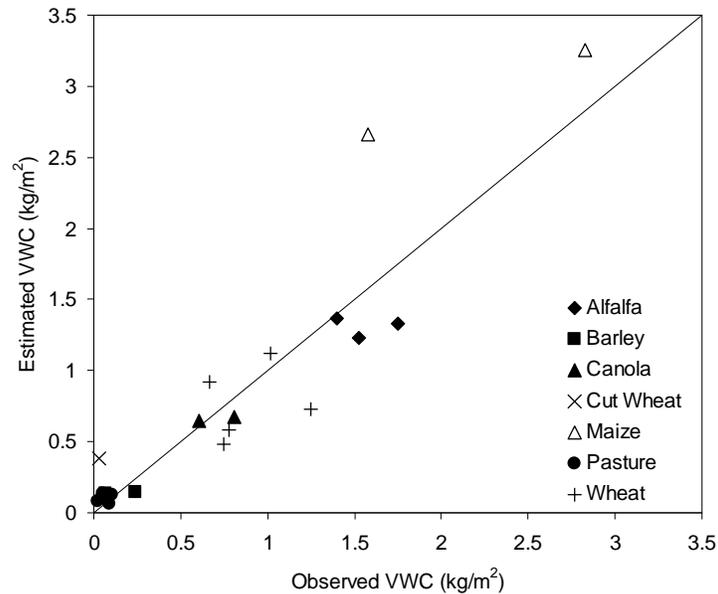


Fig. 6. Verification of estimated VWC from satellite interpolation and the observed VWC from ground sampling.

6 CONCLUSIONS

For the hydrologically diverse NAFE'06 study region, containing both dryland and irrigated agriculture, a previously developed technique [6] was adopted land cover and vegetation water content mapping. The results showed that VWC could be estimated from visible/infrared satellite imagery with a high degree of accuracy. However, this approach is dependent on supplementary ground-based sampling of reflectances and VWC and the availability of good satellite-derived reflectances in the near-infrared and shortwave infrared bands. Significant variation was a result of the irrigated agriculture in the area. The robust use of NDWI to predict VWC in this study extends the land cover types, as well as soil climate regimes for which this type of prediction is possible. These results support the development of robust approaches to support passive microwave soil moisture algorithms developed for AMSR-E and SMOS. Future application of this technique to other satellite NIR and SWIR bands, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) or the Advanced Wide Field Sensor (AWiFS), would be useful and extend the utility of this approach beyond the life of the Landsat satellite program.

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