Mapping Variations in Crop Conditions Using Airborne Videography

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Abstract

Videographic observations can provide useful information at a scale intermediate between the large-scale data collected on the ground and the regional scale data available from satellite imagery. Previous work on agricultural, hydrologic and forestry applications report multi-spectral video as a non-invasive and rapid method for generating timely information that can be integrated with other ancillary data for better management strategies. Accordingly, this study investigates the potential of digital multi-spectral video to identify variations in crop conditions related to farm management, soil types, and terrain conditions. Specific spectral, spatial and temporal remote sensing requirements for mapping variations in crop conditions are addressed as well.

Vegetation indices were applied to map different crop types and conditions. The NDVI, plant pigment ratio, plant vigour index and cell density ratio were used to this end. The study examines whether the spectral variability observed in the vegetation indices of paddocks under crops are associated with terrain attributes such as slope and aspect, different soil-landscape types, waterlogging, and crop conditions such as the presence of weeds.

It is concluded that qualitative images as provided by the vegetation indices implemented in this study can provide useful information for identifying zones that perform differently within or between paddocks. The indices showed sensitive to variations in drainage conditions, soil-landscape units (e.g. and associated terrain attributes such as slope) and the presence of weeds within a paddock. Thus, it is concluded that rapid mapping of the occurrence of field variations by applying vegetation indices derived from high resolution airborne videography would enable farmers to identify the causes of variability (e.g. waterlogging, weeds, insufficient fertilisers, etc.), helping to decide on appropriate management practices for improving farming conditions.

1. INTRODUCTION

Precision crop management is defined as an information and technology based agricultural management system to identify, analyse and manage site-soil spatial and temporal variability within paddocks for optimum profitability, sustainability and protection of the environment. Site-specific management recognises that variations occur within paddocks, and involves recognising the spatial location and extent of such variations, assessing the causes so that the right thing, in the right way, at the right place and in the right time is done (Berry, 1998).

The major functional components involved in precision-farming technologies include sensors (field or remote based), locationers, controllers, and a field information system, which is essentially a geographic information system (GIS) at the paddock level (Han et al., 1994). The overall approach involves assessing and reacting to field variability by tailoring management actions, including fertilisation levels, seeding rates and variety selection, and pesticides to match changing field conditions. It assumes that managing paddock variability leads to cost savings (international and Australian research work suggest potential increase of net profits by more than A$50 per hectare), and production increases as well as improved management and environmental benefits.

A common approach to precision farming termed ‘zone or patch management’ was developed in the United States and Europe. This approach consists of dividing fields into relatively homogenous management zones that can be treated differently. Continuous sensors to map crop yield and soil properties, and intensive sampling are frequently used to determine these within-field management units. But they tend to be expensive and time-consuming. Thus, an alternative approach of using remote sensing technologies to reduce the cost and time of data collection (a high priority in precision farming) has been undertaken in different countries, including Australia, during the last decade.

Accordingly, this paper examines the potential of airborne videography as a remote sensing tool for rapid assessment of crop conditions in the agricultural region of Western Australia. This implies a close examination to the requirement for image-based precision farming, and image processing techniques that could be applied for deriving value-added information easy to use by farmers and land planners interested to know where and why field variations occur in their paddocks. The relationship between variations in the reflectance values of the DMSV data and terrain attributes such as slope and aspect, and different soil-landscape types (often associated to field variability), was investigated as well. Likewise, spatial and statistical analysis was undertaken to analyse the relationship between variations in crop and field conditions (e.g. weeds, waterlogging, sowing dates) and the digital values of vegetation indices derived from the DMSV data set.

1.1 Spectral, spatial and temporal remote sensing requirements for mapping crop variations

Rapid image turnaround and near-real time delivery of information are critical to retrieve crop and soil information relevant to farm management (Moran et al., 1997). For instance, decisions on optimum times to spray or to fertilise need to be taken within a short time span (e.g. usually no longer than a week). Robert (1996) mentions that in most agronomic applications, the imagery should be received on the farm within one day, as a detected plant stress needs to be corrected very promptly to reduce its impact on yield losses and crop quality. Satellite-based imagery has a turnaround of three days for archive data of most satellite-based imagery, while new data acquisitions can take up to three months (e.g. high precision multi-spectral or panchromatic Ikonos products commercialised by Carterra).

Frequency of coverage is another key issue in remote sensing based precision farming. High value crops have critical times during which they need frequent coverage to identify and minimise crop stress conditions. The monitoring requirements tend to change throughout the year and the growing season, with crucial, rigid data acquisitions dates (e.g. linked to crop phenology). To this end, satellite-based coverage needs to account for cloud cover periods and the revisiting cycle capability. Current multi-spectral Earth observation satellites, with fix revisiting cycles and generally coarse temporal resolution (e.g. not better than 3 days for Ikonos data or 16 days for Landsat 7 ETM) are unable to cater for these monitoring needs. Though the flexibility of pointable satellite-based sensors such as SPOT allows shorter repeating cycles, clashes among customers’ request are common (Moran et al, 1997), and the additional charges for these requests may make the final products cost-prohibitive for farmers.

Airborne videography has been tested and applied for detection and mapping of weed infestation and diseases in rangelands and mixed farming (Lamb, 2000), and for identification of site-variability in cropped areas (Yang and Anderson, 1996; Moran et al., 1996; Hageman and Metternicht, 2000; Metternicht et al., 2000). Because it provides greater levels of spatial detail than current satellite technology (e.g. between 0.25 and 4 m pixel size), it is possible to delineate variations of vegetation or soil surface conditions more precisely. Atkinson (1997) reports that a spatial resolution between 0.5 and 3 m is required for mapping spatial variation in agricultural field using remotely sensed data. Additionally, the flexibility in the frequency and time (e.g. conditioned to the needs of the phenomena being assessed) of data acquisition enables farmers or managers to detect signs of stress damage in vegetation, and to quickly assess its causes by looking in the field at places where variations in spectral responses occur. As result farmers have new tools to predict the outcome of site-specific management, weather permitting. Climate still remains as the main variable farmers deal with every day, and cannot control. However, as mentioned by Berry (1998) they can seek to understand how to plan and manage variability as a fact of business.

One of the most successful uses of airborne videography in Australia has been in helping farmers (particularly in extensive farms), to carry out rapid assessment on conditions of paddocks during the growing season. In Queensland, sugar cane growers have applied fertilisers and pesticides using 'output maps' from processed video images as their field-guide. In Western Australia, farmers in the Wheatbelt have assessed the conditions of crops during the growing season, identifying areas that were performing poorly, and used the output images as a field guide to locate and analyse the causes of variability within or between paddocks.

1.2 Identification of changes on vegetation condition using remote sensing

Remote sensing of changes in vegetation condition requires knowing the spectral behaviour of the landscape components of interest in the range of the spectrum in which the sensor gathers information. Likewise, it is important to know what constitutes remote sensing evidences of vegetation damage and the effects on spectral reflectance (Murtha, 1978), so that techniques to interpret and assess the condition of the vegetation can be derived.

Changes in plant morphology such as defoliation, stunted growth, loss of branches in trees and cellular collapse are indicated by variations in texture and shape, whereas physiological changes such as decrease in photosynthesis, deterioration of chloroplasts, interruption of translocates including water, are associated with changes in spectral reflectance patterns. Because morphological damage affects spectral reflectance only when new surfaces are exposed (e.g. increased shadow component in the vegetation canopy), they are better described on the basis of form, texture and boundary patterns (Murtha, 1978).

Remote determination of chlorophyll content constitutes a useful tool for detection of physiological states and stress in plants (Gitelson and Merzlyak, 1996). Chlorophyll content in leaves changes throughout the different stages of plant development, with the content of leaf pigments being affected by exposure of terrestrial vegetation to various kinds of natural (e.g. water stress, senescence, waterlogging, soil salinity) and anthropogenic stresses (e.g. release of toxic substances such as heavy metals into the soil, herbicides) as reported in previous works by Carter (1993 and 1994) and Gitelson and Merzlyak (1996). Investigating the responses of leaf spectral reflectance to plant stress agents of biological (e.g. plant competition, senescence) and physicochemical (herbicide, salinity, ozone) origin, Carter (1993), found the visible (e.g. 535 to 640 nm, 685 to 700 nm) rather than infrared reflectance, to be the most reliable indicator of plant stress.

1.3 Interpreting variations in the vegetation condition using vegetation indices

Based on the positions of the spectral bands relative to the spectral features mentioned above, specific band ratios and indices can be applied to assess the conditions of vegetation in agricultural landscapes. Vegetation indices are multispectral transformations of image data, usually involving addition, subtraction, multiplication and/or ratio of the pixel brightness from two image bands to derive a new image. The advantage of using ratios is the normalisation of data, reducing the influence of illumination conditions and topography. Discrimination of crop growth and plant status (e.g. disease, crop nutrient deficiency, water stress) is generally accomplished by computing a ratio or linear combination of visible and near-infrared reflectance such as that done in the NIR to red ratio (VI), the normalised difference vegetation index (NDVI), the soil adjusted vegetation index (SAVI), and other indices for chlorophyll assessment like the ones proposed by Gitelson and Merzlyak (1994, 1996) and Carter, (1994). Comprehensive reviews of vegetation indices can be found in (Cohen, 1991; Jackson and Huete, 1991; Moran et al., 1997).

2. Study area and data set

A farm located eastern of the Balgarup River in the Shire of Kojonup, in the South-west Region of Western Australia was chosen as the study area. The farm is characterised by gently undulating to undulating rises and low hills. The soils formed from granitic parent materials are deep sandy and shallow duplex soils, often with loamy sand or clayey sand surface textures. Doleritic parent materials produced shallow sandy duplex or loamy duplex soils. Shallow sandy duplexes dominate in the valley flats, and are slightly saline.

Most of the native vegetation in the farm has been cleared for agricultural purposes. Only 11.8% of the farm area is occupied by native forest, the remaining area being used for pasture and cereal and legume crops in a system of rotation. The pastures are used as grazing paddocks for livestock. Some paddocks are periodically fenced-off for silage production. Wheat, oats, lupins, and canola covering an area of 212 hectares were main crops sown in the year the airborne data was collected.

3. Method and techniques

The research comprised:

a) Field and remote sensing data collection, including in situ interview with the farmer to gather information about field conditions relevant to the study;
b) Manipulation of existing topographic and land use vector layers;
c) Generation of a DEM from the elevation data, and derivation of slope and aspect information for the entire farm;
d) Computation of selected vegetation indices (VIs). These indices were derived from the DMSV data to assess whether this remotely sensed information could be used to detect paddock features such as irregular planting patterns, weed infestation, waterlogging and differences in crop management such as sowing date. Likewise, investigations focussed on the ability of these indices to detect variations in terrain attributes such as slope, aspect and different soil-landscape units;
e) Generation of field layers. This included zonation of selected paddocks according to variations reported by field data supplied by the farmer, and the masking out of features such as dams, drains, trees, and exposed rocks within the fields;
f) Spatial and statistical analysis to determine relationships between the output images of the vegetation indices and variations in crop and field conditions (e.g. weed infestation, crop management, planting patterns, waterlogging), and terrain attributes (slope and aspect). Spatial analysis involved spatial intersection (e.g. area cross-tabulation) between the vegetation indices, and the slope and aspect images to obtain the mean, standard deviation, minimum and maximum index values characterising these attributes. Univariate descriptive statistics (e.g. mean, range, and standard deviation) were applied to find the typical index values for selected field and crop conditions and terrain attributes. Two-sample Z-tests were conducted to analyse whether the difference among index values typical of different crop and field conditions were statistically significant;
g) Analysing the practical significance of the results and their implication for deriving information useful for improved farm management.

3.1 <u>Field and remote sensing data collection</u>

Digital multispectral video data at 2m resolution was acquired over the farm in September 1998, about 14 to 15 weeks after the crops were sown. The digital multi-spectral video (DMSV) system developed by SpecTerra Systems was used to this end. The system acquires images in preset spectral bands determined by an interchangeable narrow (25 nm) band-pass interference filters centred at: 450 nm (band 1, blue), 550 nm (band 2, green), 650 nm (band 3, red), and 750 nm (band4, near-infrared). Individual frames are acquired sequentially along GPS controlled flight paths. The frames were corrected for camera distortion and brightness, to minimise vignetting and bi-directional reflectance effects. Radiometrically corrected frames were subsequently geo-referenced to an orthophoto of the study area, and mosaiced to generate a single 4-bands image covering the entire farm area.

The farmers were interviewed to gather information on crop types, varieties, planting time, fertiliser input, and additional information such as areas affected by weeds, waterlogging, salinity, and fencing conditions at the time the video data was acquired over the farm. Farm records kept by the owner, maps of paddocks and large scale video images were used during the interview. Areas identified by the farmer as weed-infested, waterlogged, and salt-affected were later digitised in ArcView to generate geo-referenced attribute information, for further spatial analysis of the relationship between variations in crop conditions and spectral reflectance. Other relevant data such as government reports, colour aerial photographs, meteorological data providing information on the volume and distribution of rainfall during the 1998's growing season were used as well.

Digital land management unit maps, soil-landscape maps and elevation data were provided by the Department of Agriculture of Western Australia. These data were converted to ArcInfo in order to be compatible with the image processing software used in this study (ERDAS Imagine).

3.2 <u>Generation of the DEM</u>

A Triangular Irregular Network technique, involving a non-linear, fifth order polynomial interpolation as implemented in ERDAS Imagine (ERDAS, 1997) was used to generate a 20m resolution DEM from the contour data set. Grid-based methods of terrain analysis were used to estimate slope and aspect using the algorithms described in ERDAS (1997). The aspect was expressed in degrees from North, from 0 to 360 degrees. A value of 361 degrees was used to identify flat areas. Additional models were implemented to classify the slope image into 15 classes, ranging from one to 14 percent slope, and nine aspect classes (N, NE, E, SE, S, SW, W, NW, and flat).

3.3 <u>Deriving vegetation indices</u>

The relationship between variations in crop, field conditions, and terrain attributes, and four vegetation indices, namely plant pigment ratio (PPR), photosynthetic vigour ratio (PVR), cell density ratio (CDR) and the NDVI computed using the DMSV data were assessed in this study. The first three indices use the green region as a reference band because of its lower soil-green vegetation reflectance contrast, as mentioned by Tucker (1977). Graphical models were created within the Model Maker module of ERDAS Imagine for each index using equations (1) to (4) described hereafter, and the outputs are presented in Figure 1.

a) The plant pigment ratio (PPR) = $(DMSV_{green} – DMSV_{blue}) / (DMSV_{green} + DMSV_{blue})$ (1)

This index produces an output image where strongly pigmented foliage present a high PPR, while weakly pigmented foliage presents low values. The higher the pigmentation in the leaves, the stronger the absorption in the blue band, translated as lower digital numbers in this channel. Conversely, weakly pigmented leaves, absorbing less energy, will present higher reflectance values in this band.

b) The photosynthetic vigour ratio (PVR)= $(DMSV_{green} – DMSV_{red}) / (DMSV_{green} + DMSV_{red})$ (2)

This index is high for leaves or green canopies with strong chlorophyll absorption, that is, photosynthetically very active, with strong absorption of energy in the red band; and low for weakly active vegetation. The use of this ratio may be compared to the observation of chlorosis on plants with nutrient deficiency or under stress due to some plant diseases, or with onset of senescence. This index will show high values for photosynthetically very active vegetation, lowering as the chlorophyll content of the vegetation canopy decreases due to factors such as chemical stress or plant senescence.

c) The cell density ratio (CDR)= $(DMSV_{IR} – DMSV_{green}) / (DMSV_{IR} + DMSV_{green})$ (3)

This ratio is thought to provide a qualitative indication of quantity of leaves in a pixel and the density of healthy plant cells in the leaves, as the response of vegetation in the NIR is dominated by the cells' structure. Thus, for instance, moderately sparse distribution of very healthy plants may show a CDR similar to a dense distribution of plants with fewer leaves and/or less healthy cells in the leaves. In a grey scale image, the healthy plant tissues will reflect strongly in the NIR, exhibiting light grey values. Deterioration of the plant cell structure will translate in darker image values.

Gitelson and Merzlyak (1996) report this index as a good indicator of chlorophyll contents in yellowish-green to dark-green vegetation. They found the reflectance near 700 nm and in the range from 530 to 630 nm to be highly sensitive to chlorophyll variations. Thus, taking into account that the range of $(550nm)^{-1}$ is directly proportional to chlorophyll, and that the NIR region virtually does not depend on chlorophyll, they developed a so called 'green NDVI' to assess chlorophyll contents.

d) The NDVI= $(DMSV_{IR} – DMSV_{red}) / (DMSV_{IR} + DMSV_{red})$ (4)

Sensitive to vegetation parameters such as green leaf area index, and percent of the ground surface covered by green vegetation (Jackson and Huete, 1991). The index represents the aggregation of two phenomena, the high reflectance in the NIR due to healthy plant cells, and the low reflectance in the red region due to chlorophyll absorption (Honey, 1997).

3.4 Generation of field layers

Two paddocks showing high variability in field and crops conditions, as well as variations in slope and aspect were selected for analysing the sensitivity of the above mentioned indices to these factors. One paddock was sown with oats (*Avena byzantina*), and the other with wheat (*Triticum aestivum)*. The oats paddock was infested with rygrass (*Loliun spp*) and wild oats (*Avena spp)*, and thus three polygons, namely 'best area', 'ryegrass infested', and 'wild oats infested' were generated to analyse spectral differences in the vegetation indices.

Both paddocks showed evidence of waterlogging, and were composed of different soil-landscape units (LMU) as shown by the spatial analysis performed between the soil-landscape and the land use maps. Buffer areas of 15m inside the field boundaries were generated to avoid including variations due to parcel boundaries, and to mask out trees, exposed rocks, dams, drains.

3.5 Spatial and statistical analysis to determine relationships between the output images of the vegetation indices and variations in crop and field conditions

Spatial intersection between the digital vector layers of the fields and each of the vegetation indices derived from the DMSV data set was performed afterwards. Descriptive statistics such as minimum, maximum, mean and standard deviation and the *z*-test of significance were computed for each paddock.

Significance tests were applied to the difference of the means of the VIs of each portion of the oats field used for detecting weed infestation, differences in crop growth due to sowing date, and soil types. Because for large sample sizes, the sampling distribution can be approximated to a normal probability distribution, the two-sample Z statistics was applied as described in Moore and McCabe (1999). The values of z were calculated for each pair of means and the hypothesis of 'no difference' between the means was tested using a 95% (α=0.05) confidence level. The null hypothesis (Ho) assumes no difference between the means ($\mu_1=\mu_2$) and the alternative hypotheses Ha tests the difference between the means ($\mu_1\neq\mu_2$).

To detect spectral differences due to crop management (e.g. sowing date), digital vector layers of two oasts field sown two weeks apart were spatially overlayed with the vegetation indices using zonal operations (ERDAS, 1997). Likewise, descriptive statistics and correlation analysis (Pearson's correlation coefficient) were used to investigate the relationship between terrain attributes and the vegetation indices of the two paddocks. Two hundred points were selected from the oats and wheat fields using the random point selection function in ERDAS Imagine. The point were used to extract the pixel values from the slope maps and the vegetation indices, to calculate the Pearson's correlation coefficient. The results are discussed in the next section.

4. Discussion of results

4.1 Detection of weed-infested areas

Area cross-tabulations between the three zones of the oats field (i.e., best area, wild oats and ryegrass infested) and the vegetation indices (VIs) indicated the highest mean values in all the VIs occurred in areas infested with wild oats (Table 1). Table 1 also shows that, on average, weed-infested areas exhibit higher VIs as compared to weed-free zones. These results also suggest that caution should be exercised when using vegetation indices such as NDVI or PVR to draw conclusion about crop yield and crop vigour. Denser canopies due to the presence of weeds would show higher reflectance values in the IR, and strong absorption in the red region of the spectrum.

Table 1 Vegetation indices means and standard deviation for each area of the oats field. The standard deviations are shown between brackets.

VEGETATION INDICES	VEGETATION INDICES MEANS (STANDARD DEVIATION)		
	BEST PORTION OF FIELD	RYEGRASS -AFFECTED	WILD OATS-AFFECTED
NDVI	53.85 (8.39)	54.54 (6.40)	59.44 (5.92)
PVR	50.34 (4.77)	51.05 (3.71)	53.66 (3.46)
CDR	53.58 (4.24)	53.56 (3.17)	55.95 (3.00)
PPR	44.42 (1.51)	44.30 (1.51)	44.88 (1.29)

Table 2: Z-values computed for the difference between the means of the VIs

DIFFERENCE BETWEEN MEANS	CALCULATED Z VALUES			
	NDVI	PVR	CDR	PPR
(Best area - wild oats area)	-60.42**	-62.10**	-50.40**	-24.20**
(Best area - ryegrass area)	-6.34**	-11.37**	0.44*	4.96**
(Wild oats area – ryegrass area)	-41.45**	38.02**	40.32**	21.34**

** : Reject Ho; *: accept Ho.

The Z-values shown in Table 2 indicate a significant difference between the means of all VIs and the three subdivisions created in the oats field, except between the means of the Plant Cell Density ratio corresponding to the 'best area of the paddock' and the 'ryegrass infested area'. From these results it is inferred that NDVI, PVR and PPR to a lesser extent, can be used to isolate areas affected by weeds (e.g. ryegrass and wild oats) within a paddock. These results agree with previous findings by Lamb (2000), reporting that weed populations greater than 19 plants/m^2 could be reliably discriminated from weed-free areas when using NDVI.

4.2 Detection differences in crop growth due to management

The two oats fields chosen for this analysis were sown 15 days apart (e.g. 25 May and 10 June). They were under similar management, except for a slightly higher level of fertiliser (e.g. 20 extra kg of urea) applied on the field sown later. Area cross-tabulation performed between the fields and the VI images indicated higher mean values in all the indices corresponding to the field with slightly higher levels of fertiliser. This might indicate that the difference in sowing time is not as significant as the difference in fertilisers applied to the fields. However, other factors could have contributed to increased VI mean values in the field sown later. For instance, slightly waterlogging conditions were reported in certain areas of the field sown in May, which would lower the overall reflectance values on the DMSV data set. Likewise, the presence of weeds in the field sown in June could have increased the canopy density, thus yielding to higher VI values. The equality of the fields' means for each vegetation index was tested using the normal probability hypothesis. The values shown in Table 3 indicate a significant difference between the NDVI, PVR and PPR mean values of the fields. However, research under more controlled environment such as an agricultural research plot would be necessary in order to better understand and estimate the impact of different factors on the spectral reflectance of the DMSV data set.

Table 3: Z-values calculated for the means of the VIs and results of hypotheses testing

Vegetation indices	Z-value	Hypotheses testing (α = 0.05)	Hypotheses testing α= 0.01)
NDVI	-7.204	Reject Ho	Reject Ho
PVR	-15.099	Reject Ho	Reject Ho
CDR	1.194	Accept Ho	Accept Ho
PPR	-98.802	Reject Ho	Reject Ho

4.3 Detecting the impact of soil-landscape variations and terrain attributes in agricultural fields

Table 4 shows a positive correlation between the VIs and the slope values in both fields, that is, increases in slope are related to higher vegetation index values, particularly in the oats-sown field. This is probably due to better drainage conditions in the more inclined areas favouring better plant development. For instance, in the oats' paddock, flatter areas were waterlogged. However, not clear results were obtained when analysing the relationship between terrain aspect and the vegetation indices (Hageman, 2001). Additionally, a Z-test was conducted to evaluate whether there was a significant difference between the mean values of the VIs corresponding to different soil-landscape units. The procedure and findings are fully discussed in Hageman (2001). The difference between the means of the VIs for the different soil-landscape units was significant at a 95% confidence level. The lowest vegetation indices' means are reported for the soil landscape unit dominant on footslopes and lower slopes of the fields, while the highest VI mean values corresponded to a unit dominating steeper slopes. Likewise, the Z-test indicated significant differences amongst the all the VI mean values corresponding to poorly drained, moderately drained and well drained soils. Well drained soils exhibited consistently higher mean values in the NDVI, PRV and CDR indices.

Table 4: Pearson's correlation coefficient between slope and oats and wheat fields

	Vegetation indices		
	NDVI	PVR	CDR
Oats and slope	0.579	0.515	0.586
Wheat and slope	0.216	0.174	0.247

Conclusions:

This study has shown that qualitative images as provided by the vegetation indices implemented in this study can provide useful information for identifying zones that perform differently within or between paddocks. Lamb (2000) and Yang and Anderson (1996) report similar findings for wheat and triticale crop areas, and for sorghum crops. The indices applied showed sensitive to variations in drainage conditions, soil-landscape units (e.g. and associated terrain attributes such as slope), and the presence of weeds within a paddock. The capability of DMSV derived indices such as the PVR and NDVI to detect variations in plant vigour/biomass as related to fertiliser input or different sowing dates was not clear in this study, and deserves further research under more controlled conditions. Caution should be exercised when relating vegetation indices such as NDVI and PVR to vigour/biomass and crop yield estimation. This study shows that increases in vigour/biomass as shown in the indices could be related to the presence of weeds within the paddocks, and this in turn could mislead inferences on crop yield estimations drawn from NDVI or PVR.

However, the DMSV-data could be used in purposive sampling procedures to isolate areas that under similar management are performing differently, so that field sampling for a better understanding on the causes of variability could be easily undertaken. As DMSV has an image turnaround capability of about two days, it could also be utilised as a rapid tool for early detection of variations within fields, so that appropriate management measures can be adopted at the right place and in the right time.

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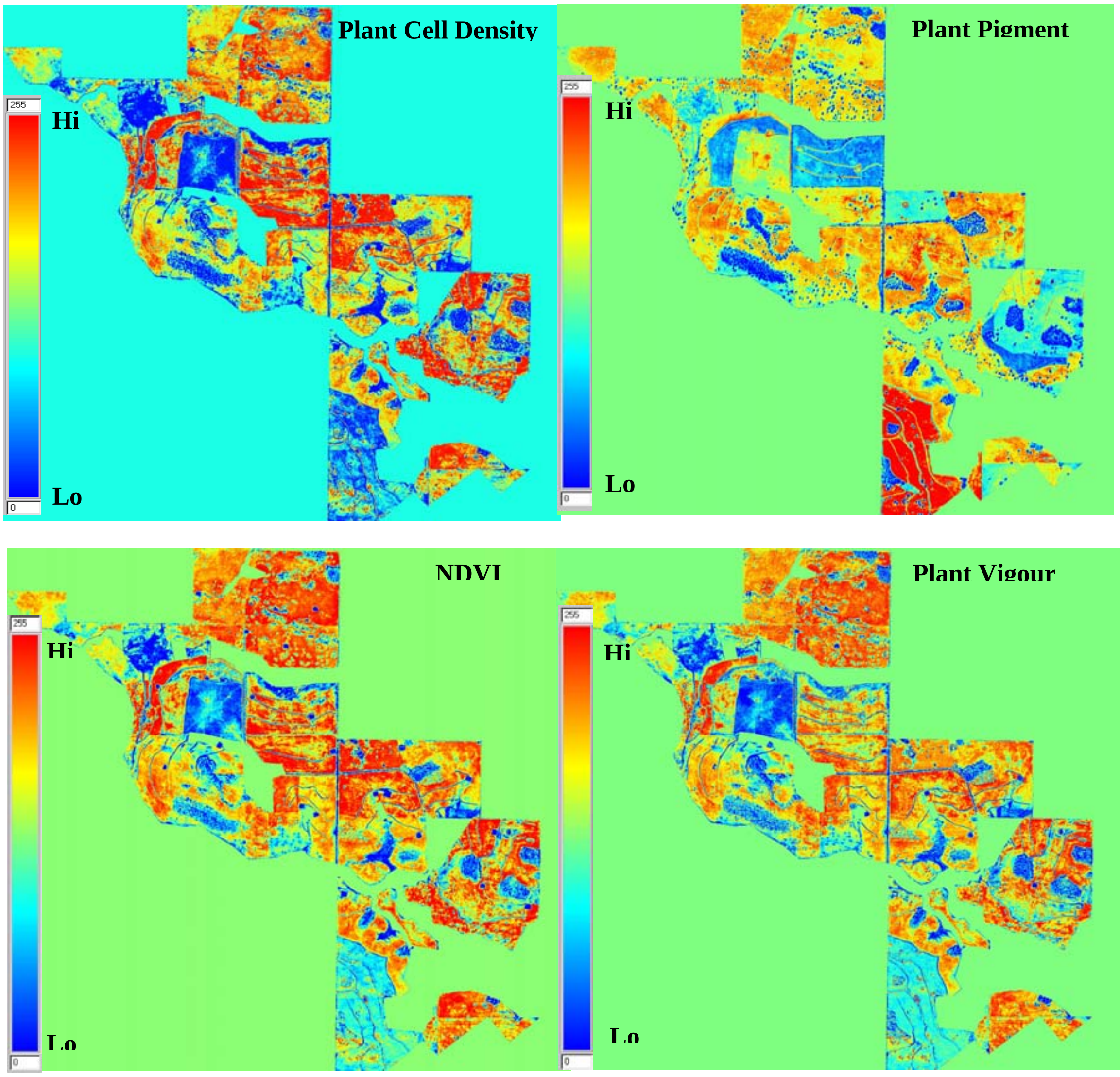

Figure 1: Qualitative images of the Cell Density Ratio, Plant Pigment Ratio, Normalised Difference Vegetation Index and Plant Vigour Index derived from the DMSV data set. The lowest ratio values correspond to a blue colour (Lo in the colour table), while red relates to the highest values (Hi in the colour table) recorded for a particular index (or ratio). Section 3.3 explains the formula and meaning of high and low values.