TELEDETECCIÓN - Hacia un mejor entendimiento de la dinámica global y regional
Ed. Martin, 2007, ISBN: 978-987-543-126-3

Geospatial Technologies and the Management of Noxious Weeds in Agricultural and Rangelands Areas of Australia.

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RESUMEN

Las malezas representan una seria amenaza para la producción agrícola y la biodiversidad de los pastizales en Australia. Este trabajo describe investigaciones conducidas en Western Australia para el desarrollo de herramientas costo-efectivas en el mapeo y modelado de la distribución de malezas basadas en el uso de teledeteccion, SIG y modelamiento espacial.

Palabras clave: Sensor remoto, detección de malezas, tecnologoía geoespacial

ABSTRACT

Exotic weeds pose a significant threat to primary production, biodiversity and conservation of Australian rangelands and agricultural areas. This paper describes research being conducted in Western Australia for the development of cost-effective tools for mapping and modelling the spatial distribution of weeds, and predict their likely spread on the landscape, using geospatial technologies like remote sensing, GIS and spatial modelling.

Keywords:Remote sensing, weed detection, geospatial technologies

Introduction

Weeds are a significant threat to primary production, biodiversity and conservation in Australia. Weeds increase the risk of fire and the cost of infrastructure maintenance, and reduce the amenity of recreation areas. According to a CSIRO report, weeds are costing Australia around $3.3 billion a year in control cost, lost production and contamination (Hutchinson, 2000). This does not include the effect on Australia's biodiversity, which is very difficult to quantify in financial terms, but is considered significant.

Mapping of even the most important weeds is often incomplete, and rarely at the resolution required for developing and evaluating regional-scale management strategies. A major reason for this is that weed mapping is typically a time consuming and expensive exercise that relies heavily on ground-based surveys and/or visual surveys from aircraft.

The use of remote sensing offers a potential alternative, but has not yet been adopted as a standard survey tool because of past problems in spatial and/or spectral resolution, signal processing, and cost. However, a new generation of remote sensing tools (such as Ikonos, ASTER, high resolution digital multispectral imagery and unmanned aerial vehicles or UAV), advanced analytical tools (e.g. artificial neural networks and new spectral indices) may overcome some these problems.

This paper describes applied research being undertaken jointly with the Department of Agriculture and Food, Western Australia to develop practical approaches for routinely mapping and monitoring the distribution, density and spread of two contrasting noxious weed species that are both serious issues in Western Australia. One species, Paterson's curse (*Echium plantegineum L*.) (Figure 2) is an annual/biennial herbaceous weed common in agricultural areas of Western Australia. The other species, either Mesquite (*Prosopis spp*.) or parkinsonia (*Parkinsonia aculeata*) (Figure 1). is a woody, perennial weed of the rangeland Western Australia.

Figure 1: Aerial view of mesquite infestation.

Figure 2: Paterson's curse during flowering period.

Finding remote sensing data with suitable spectral, spatial, temporal resolutions and developing optimal digital image processing techniques is one of the challenges set in this research.

The tools developed during this investigation will complement and add efficiency to current mapping approaches applied at the Department of Agriculture Western Australia, and other groups such as the Pilbara Mesquite Management Committee.

Success in the development of tools for consistently mapping spatial distribution and spread over time will allow addressing questions such as:

- How can these technologies help decision-makers and policy advisers formulate better weed management policies?
- What kind of decisions (e.g. priority of intervention) can be made using information gathered through their use?
- What are the financial advantages/disadvantages of using these technologies for weed mapping?
- When are remote sensing technologies appropriate, and when are they likely to under-perform?

Hereafter the paper describes some of the issues surrounding remote mapping of weeds, and prediction of potential spatial distributions on the landscape, as found through the 2 years research project financed by the Australian Research Council and the Department of Agriculture and Food, Western Australia.

Mapping weed distribution

Accurate and cost-effective mapping of weeds at the property, catchment or regional scale is becoming increasingly important as a basis for developing weed management strategies, and subsequently, to evaluate their effectiveness. Mapping at this scale is also important to understand spread and impact of weed invasions. The significance of the geographic scale of mapping, the sensors' spatial and/or spectral resolution is discussed hereafter.

Geographic scale of mapping and Sensor's resolution

The objective of the mapping task usually drives the scale of mapping. National maps at small scale are valuable for national prioritisation of wees, and development of national weed management strategies (Thorpe and Lynch, 2000). Conversely, large scale maps at paddock level are usually needed for tasks related to eradication and containment programmes (Dixon et al., 2003).

In turn, the geographic scale of the study drives the type of mapping technique to be applied. For instance, the spectral and spatial characteristics of most well known remote sensing satellites like Landsat are very effective for monitoring general vegetation health and progress of crops in medium to large fields (50-plus acres), but monitoring weed distributions within these fields is extremely difficult (Bulman, 2000). Satellites like Landsat simply cannot 'see' weeds in fields, ie, paddock-scale mapping. The spatial resolution, or the area of the ground represented as a single unit (e.g. 30m x 30m) is too coarse for the purpose of weed mapping.

The relatively few studies undertaken in Australia and overseas on the mapping of weeds such as Paterson's curse have been conducted using Landsat TM and hyperspectral CASI data. Because of the coarse spatial resolution (e.g. Landsat), and the high cost of implementation of hyperspectral remote sensors over large areas (e.g. CASI), none of these systems have been so far recommended for operational use in the mapping of this noxious weed.

Other techniques used in the mapping of woody weeds in rangelands of Australia and the USA include expert opinion, systematic ground-based surveys, aerial surveys, including the use of Unmanned Aerial Vehicles (UAV), aerial photographs, high spatial resolution digital multispectral cameras, imagery from passive satellite sensors (e.g. Landsat TM, SPOT). None of the techniques are yet operational for high resolution, broad scale coverage applications.

Limitations for operational mapping of weeds are dependant on the technique, weed type and distributions patterns over the landscape, extending to cost, the ability to discriminate weeds from surrounding vegetation types, and capability to quantify weed density or cover.

For instance, UAV technologies are promising in the USA for mapping weeds at very large scale (e.g. individual plants). Laliberte and Rango (2006) report successful mapping of individual mesquite plants, and their discrimination from other species like sagebrush. However, because of the cost, time associated to data processing, such data collection is limited to localised areas.

On the other hand, van Klienken et al (2005) reports on the use of a systematic helicopter survey (grid cell size of 16ha), whereby experts on board of the helicopter record weeds density in a 5-level scale (Figure 3). This type of survey enables covering large areas with a relatively high accuracy of discrimination, even at low densities where traditional satellites like Landsat TM fail because of their coarse spatial resolution that hinders mapping of weeds with low projective foliage cover and sparse densities.

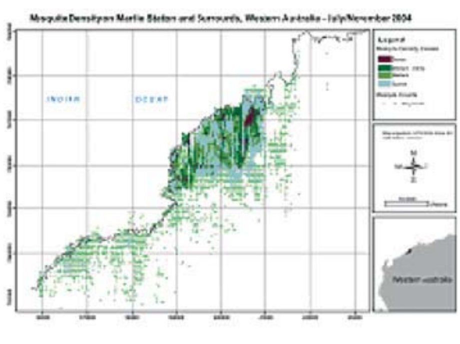

Figure 3: Draft map of mesquite in the Pilbara region determined by a systematic helicopter survey (Source: van Klienken et al., 2005).

Requirements for remote mapping of weeds

To successfully apply remote sensing technology to weed mapping, there must be some characteristic of the weed of interest that permits its spectral discrimination from other species with which it is associated. Such features as distinctive leaf shape, floral characteristics or phenological or morphological attributes need to be defined so that the target weed can be distinguished from its surroundings at certain stages during its life cycle, or under certain environmental conditions (Bulman, 2000). Additionally, consideration must be given to the spatial arrangements of weed patches (e.g. small regular patches, linear distributions, isolated emergence).

The spectral signal from vegetation that grows in patches smaller than the spatial resolution of the remote sensing imagery can get 'mixed' with the signal of other land covers occurring within a pixel, thus reducing its ability to be detected. Hereafter follows a summary of some tests conducted using multi- and hyperspectral imagery at different spatial resolutions.

The significance of spatial resolution over spectral resolution: mapping weeds in rangelands.

In some cases, the morphology of weeds and their spatial arrangement, as well as other relevant phenological attributes can be used to determine an optimal temporal, spatial and spectral resolution of its mapping. The majority of successful studies designed to detect individual weed species have used imagery with very high spatial resolution (<5m) in both the visible and near infrared part of the spectrum. We have conducted a test on the ability of digital multispectral imagery (DMSI), for discriminating mesquite from coexisting species (Robinson et al., 2006). This study tested the use of four-band (red, green, blue and near infrared) digital multispectral imagery (DMSI) acquired at a resolution of one meter for mapping mesquite (*Prosopis spp*.), which is a highly invasive, exotic shrub in the northwest Pilbara region of Western Australia. Various per-crown statistics were computed for all bands. Two approaches were taken for identifying the statistics offering the greatest information for classification using a multilayer perceptron (MLP) artificial neural network. In the first case, we sought to optimise overall error by choosing the statistics offering the greatest overall separation from coexisting species. In the second case, a series of binary classifications were carried out comparing mesquite to each of the non-mesquite classes. Conditional kappa values represented a strong agreement for the mesquite class using both approaches, with a slight improvement using the second case (0.79 to 0.82, respectively). However, only a moderate agreement was found using the first approach for the non-mesquite class (0.60). This was significantly improved using the second approach (0.81; Z=16.55). These encouraging results highlight the ability of the MLP for weed mapping and can be tailored to a wide range of high-resolution remotely sensed datasets.

Over the same area, Robinson (2007) conducted an artificial neural network (ANN) classification of hyperspectral Hymap data (126 bands covering the visible, near and mid-infrared) acquired at 3 m spatial resolution. Despite the higher spectral resolution, the accuracy of mapping reported by Hymap is similar to the one obtained using 4-spectral bands DMSI data. From this test we concluded that:

a) The higher cost (e.g. Hymap is about twice as costly as DMSI) of hyper-spectral data does not conduct to a significant improvement in the accuracy of weed detection, particularly at low projective foliage covers;

b) At sparse weed densities the spatial resolution of the sensor has higher impact in accuracy of detection than the spectral resolution (e.g. DMSI was acquired at one meter spatial resolution, while Hymap has a pixel size of 3 m).

These findings are in agreement with work conducted in rangelands of USA by Laliberte and Rango (2006) using UAV imagery (e.g. 0.05 meter spatial resolution, colour imagery acquired with a Sony DSC P200 7 MP camera). They report such imagery (e.g. RGB colour) allows for observation of individual plants, patches, gaps, and patterns over the landscape, which were not previously possible.

The importance of spectral and spatial resolutions: weeds in agricultural areas.

The applicability of remote sensing for determining the spatial distribution of weeds within arable fields has been examined for satellite (Fitzpartrick et al., 1990) airborne (Lamb, 2000a; Lamb, 2000b; Lamb et al., 1999; McGowan, 2000) and field scanner (Robins, 1998) systems. For the remote sensing technology to be successful in the detection and subsequent mapping of weeds in agricultural landscapes, Lamb (2000b) suggests two requirements:

(1) There are suitable differences in spectral reflectance or texture between weeds and their background soil or plant canopy; and (2) The remote sensing instruments have appropriate spatial and spectral resolution to detect the presence of weed plants. In regards to the spatial resolution, Rew et al. (1997) comment that as a general «rule of thumb» a resolution of less than the minimum expected size of the weed patches is required, and this may be sub-metre.

Paterson's curse (*Echium plantegineum L.*), an annual/biennial herbaceous weed common in agricultural areas of Western Australia, presents a good example where success in weed mapping appears driven by the sensor's spectral resolution and time of data acquisition. This weed presents a very distinctive violet flowers during spring (e.g. September to December), KTRI (1998). We used this special phenological attribute to map its distribution in pastures, using 2-m resolution digital multispectral images (DMSI), and hyperspectral Hyperion imagery. The DMSI remote sensing imagery and field data collected concurrently were analyzed using statistical regression techniques.

Figure 4: A natural colour composite of DMSI (bands 3,2,1) showing 'violet' colouring of a heavy infestation of Paterson's curse. Infestations of this magnitude are unusual in farms with good management practices.

A selection of derived image band ratios and band values were used to determine if there was a statistical relationship between the floral percentage values derived from the field photographs, and the remote sensing data. Results indicate that Patterson's curse flowering density cannot be predicted using solely raw image bands and band ratios. In light of this, more advanced image classification algorithms are being investigated. It has also been found that plant density reaches 100% of canopy coverage, showing a density of flowers lower than that rate (e.g. a 30% of flowers may already correspond to a 100% of plant density in the field). For this reason, it appears misleading to base the remote mapping of this weed's density solely on this phonological attribute (e.g. presence and density of flowers).

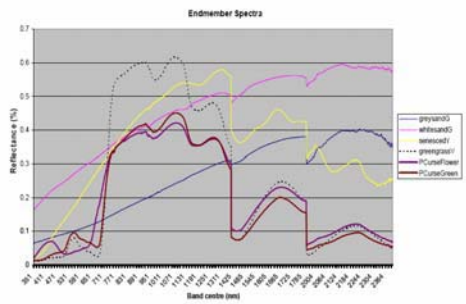

Figure 5: Spectral signature of Paterson's curse flowers and green matter, and other vegetation types, as collected using a hand-held spectrometer (350 to 2500 nm)

A FieldSpec Pro hand-held spectrometer was used to collect field spectra of Patterson's curse and associated cover types (Figure 4). Vertical field photos were taken concurrently with the spectrometer samples. Though in figure 4 Paterson's curse flowers appear to show distinctive spectral absorption features (reflection in the blue region around 450 nm and absorption in the 590 nm of the green), digital image processing of DMSI airborne data suggest that the 'translation' of pure end members spectra collected with field sensors, to air- or satellite-borne imagery may not be as straightforward. The spectral signature of the green component of the weed appears to mix with pastures. In most farms of the agricultural belt of Western Australia, farmers conduct good weed management practices (e.g. spraying, scouting), thus the percentage of flowering Paterson's curse tends to be small (e.g. well below 50%). In light of this finding, it appears that farm management practice is another factor to be included amongst the causes determining successful discrimination of weeds in agricultural landscapes.

The fact mentioned above is further corroborated by previous work of Drysdale and Metternicht (2003) who used one meter resolution DMSI data to map weeds within canola and wheat sown paddocks. From the correlations performed there was only one negative significant correlation between the total weed density m^{-2} and the red DMSI band (-0.38). This was attributed to the fact that the dominant weed present was self sown wheat while other weeds, such as clover, were only present under the leaf canopy of the canola. These results were very poor compared to other research findings of Lamb et al. (1999) who achieved correlations of up to 71% between the NDVI and SAVI with the density of wild oats (*Avena spp*.) in a cropped field. Lamb's work used image resolution from 0.5 to 2m with six differing L factor values used within the SAVI equation, ranging from 0.1 to 1. When analysing their NDVI results from an image resolution of 1m (i.e. same as this research) the correlation coefficient was 0.687. The SAVI correlations, using an L factor of 0.5 (i.e. same as this research) resulted in 0.602 and 0.702 for 2 and 0.5m resolution respectively. These results are significantly higher than the correlations with NDVI and SAVI achieved by Warren and Metternicht (2003). A non-significant positive correlation of 0.267 was calculated for both the NDVI and SAVI. It is thus important to analyse why such a difference in correlation coefficients was achieved between the two studies. One reason is the high variability in crop growth and weed infestations within the paddock. In Drysdale and Metternicht's study, the total weed density ranged from 0 to 180 plants m-2 in conjunction with the canola density ranging from 16 to 96 plants m-2. Furthermore, their study area showed a significant difference in the average leaf area for a canola plant ($74cm^2$) to that of the dominant weed self sown wheat ($12cm^2$). Within Lamb et al. (1999) research, the crop and predominant weed had a similar leaf shape (thin) and were at similar growth stage (two- to five-leaf stage). The mean crop density was 36 plants m-2 and the weed density ranged from 0 - 1750 plants m-2 (e.g. the upper limit is ten times higher than Drysdale and Metternicht's study site). In this manner, the research by Lamb et al. (1999) has performed correlations with a much higher maximum density of weeds, thus improving the opportunity for better correlations. Variability in weed infestation was not the sole objective of the vegetation sampling strategy performed in Drysdale and Metternicht research. The timing of DMSI capture was based on on-farm herbicide application. Thus, it stands that the influence of other factors, such as the difference between crop and weed leaf area, crop growth variability within the target scene, and the timing of remote sensing data acquisition will affect the success of the correlation between imagery and weed density.

Mapping spatial and temporal weeds' rates and patterns: the example of mesquite

Strategies for weed management also require understanding patterns and rates of weed spread. To this end, Robinson et al (2007) mapped canopies of an exotic mesquite population in Western Australia using temporal series of panchromatic aerial photography (1943, 1970, 2001) over an area of 450 ha. The high density of vegetation and relatively large test area demanded a semi-automated technique for mesquite classification. A two-step procedure was implemented to accomplish this. Firstly, all images were processed using an iterative self-organising clustering procedure (ISODATA). The required parameters of the ISODATA routine were found heuristically (20 iterations, 5 clusters). As expected, discrimination between vegetation types was not achieved during this step, although it did adequately distinguish between woody vegetation and other background landcovers. The cluster(s) representing woody vegetation were extracted to form four new raster layers; one for each of the time steps considered (1943, 1970, 2001 and 2004). A subsequent step was required to remove native vegetation from the 1970, 2001 and 2004 images. This was achieved by deleting all patches of vegetation present in the 1943 image, which were assumed to be native (Meadly, 1962; T. Patterson, pers. comm.) from all subsequent imagery using the editing tools in ArcGIS 9. As all imagery was not perfectly coincident (due to georeferencing errors) much of this editing was done manually (on screen).The accuracy of the semi-automated mesquite extraction technique was corroborated in the field and found to be high ($R2 = 0.98$, $P<0.001$); however, only shrubs with canopies over 3 sqm could be reliably detected with the 1.4 m spatial resolution of the imagery used.

Patch analysis was conducted using two landscape metrics: (i) mean distance to the nearest patch (m); (ii) patch density (ha) with the aim of identifying processes that may influence changes in mesquite cover. In addition, histograms were prepared showing the size-class distribution of mesquite patches in 1970 and 2001 for each land type.

Rates and patterns of invasion were compared to mesquite invasions where it is native. It was determined that:

1) The shift from grass to mesquite domination has been rapid, with rates of increase in canopy cover comparable to invasive populations in its native range;

2) Rate of patch recruitment was high in all land types, including stony flats, but patch expansion and coalescence primarily occurred in the riparian zone and red loamy soils;

3) Sheep and macropods have been the main vectors of spread; and

4) Successional patterns, such as high patch initiation followed by coalescence of existing stands, are similar to those where mesquite is native.

Conclusions

The following main findings can be stated as result of the studies described in this paper, and literature reviewed as part of the researches conducted:

5) Environmental settings play a significant role in the success of detection. The mapping of weeds in cropped paddocks, or paddocks under pastures has proven difficult at low to medium densities of coverage (e.g. for wild oats in canola and wheat paddocks, and Paterson's curse in pastures). This is attributed to the patterns of distribution of the weeds (e.g. patchy irregular patterns, their physiognomy and spectral similarity with other vegetation types occurring in the same setting). Furthermore, for maps of weed distribution to be of use for applications like spraying, detection has to be done at «nascent foci» stage. Detection at this stage requires the availability of very high spatial resolution imagery, UAV type (e.g. 5 cm spatial resolution), or DMSI-like (0.5 m resolution), and the provision that the weed in question has a distinctive spectral signature. Additionally to the cost of data acquistion, such requirements are not always met.

6) Management practices: Despite distinctive spectral signatures of flowers, Paterson's curse has not been successfully mapped with high spatial resolution multispectral imagery (ie. 4 bands in the blue-NIR range) when the density of flowers is less than 30%. Conscious farmers will usually have eradication programmes in place to avoid serious infestations of their crops, and thus, under good management, the detection of this annual herbaceous weed does not appear to be straightforward.

7) Successful detection and mapping of woody weeds like Mesquite, proper of rangelands appears to be driven by the spatial over the spectral resolution of the sensor. Our

studies show similar success rate in mapping of mesquite using multispectral, 4-bands imagery at one meter resolution, against hyperspectral Hymap (126 bands).

8) Geographic scale and the foreseen use of the map to be produced (e.g. planning, priority setting, eradication, containment) play a role in the selection of remote sensing technology. Small scale maps of national/regional coverage could be produced using relatively low cost remote sensing technology, as the purpose is to know 'where' higher infestations occur. Conversely, when eradications programs are in place, high accuracy of detection, even at sparse densities of infestations is needed, and therefore, more costly approaches like high spatial resolution airborne multispectral or hyperspectral imagery, of UAV technology should be attempt.

9) The spatial configuration of the weeds mapped. For instance, scarce research has focussed on the design of new technology (e.g. UAV) for rapid detection and surveillance of invasive aquatic, submerged and riparian weeds. Such weeds often occur over limited areal extent that preclude the use of conventional aerial and satellite imagery (e.g. with typical square acquisition areas), collecting data on established path and rows, at pre-determined repeating cycles (e.g. for satellites). Such image configuration increases the cost of data acquisition, with large areas of the image being redundant, and repetition cycles that may not fit to invasive plant species best time frame for detection.

Hunt et al (2003) established that remote observations in georeferenced formats help to assess the extent of infestations, track changes, develop management strategies, and evaluate control measures on noxious plant populations.

The development of cost-effective mapping and monitoring systems for weeds in agricultural areas and rangelands is an important step towards their long-term management. Knowing the spatial occurrence of weeds is a prerequisite of programs aimed at control, prevention and/or eradication of weeds. Furthermore, the mapping of weeds' spatial distribution over time, in a consistent manner, enables establishment of a monitoring system to assess the degree of success in the implementation of control and eradication measures. In addition, evaluation of land managers' compliance with control treatments as determined by the Department of Agriculture, or other Australian government bodies can be undertaken. This project is aimed at developing cost-effective mapping and monitoring systems for two important, but contrasting weeds in Western Australia. If work on these weeds were successful then we would also expect ready transfer of technologies to the effective mapping of other weeds.

Acknowledgments

This research has been undertaken with the financial support of the Australian Research Council (grants LP0454890 and LP0219752), the Department of Agriculture and Food, Western Australia, and SpecTerra Services Pty Ltd of Perth, Western Australia. The author wishes to acknowledge the work undertaken by doctoral students Todd Robinson, Dan McIntyre and Georgina Warren. Thanks are extended to partner investigators Rieks van Klienken and Greg Beeston.

References

Hutchinson, S., 2000, Weeds cost $3.3 bn a year. The Australian, 2nd September 2000, p. 22.

Bulman, D., 2000. Is the application of remote sensing to weed mapping just 'S-pie in the sky'?. Paper presented to the Weed Science Society of Victoria, KTRI, February 2000.

Drysdale, G. and Metternicht, G. (2003) Remote Sensing for Site-specific Crop Management: Evaluating the potential of Digital Multi-Spectral Imagery (DMSI) for monitoring Crop Variability and Weeds within paddocks. 14TH International Farm Management Association Conference, Perth, WA, August 2003.

Hunt, R., Everitt, J., Ritchie, J., Moran, S., Booth, D., Anderson, G., Clark, P. and Seyfried, M. (2003) Applications and research using remote sensing for rangeland management.) Photog Eng and Rem Sens, 69:675-693.

Keith Turnbull research Institute (KTRI), 1998. Paterson's Curse. Notes Series NoPP0003. [Online]. Available: www.nre.vic.gov.au/web/root/domino/ [2002, November 13]

Fitzpatrick, B.T., Hill, G.J.E. and Kelly, G.D. (1990) Mapping and Monitoring of weed infestations using satellite remote sensing data, The 5th Australasian Remote Sensing Conference, Perth, Australia, 8th - 12th October, pp. 598 - 601.

Lamb, D.W. (2000a) The use of qualitative airborne multispectral imaging for managing agricultural crops-a case study in south-eastern Australia, Australian Journal of Experimental Agriculture, Vol. 40, pp. 725-738.

Lamb, D.W. (2000b) Airborne Multispectral imaging for precision weed mapping in crops, Proceedings of 10th Australasian Remote

Sensing and Photogrammetry Conference, Adelaide, Australia, 21st-25th August, pp. 369-386.

Lamb, D.W., Weedon, M.M., and Rew, L.J. (1999) Evaluating the accuracy of mapping weeds in seedling crops using airborne digital imaging: Avena spp. in seedling triticale, Weed Research, Vol. 39, pp. 481-492.

Laliberte, A. and Rango, A. (2006) Unmanned Aerial Vehicles (UAVs) for Rangeland Remote Sensing. URL: http://www.tucson.ars.ag.gov/rise/Posters/LalibertePoster.pdf (last accessed 15 May 2007)

McGowen, I. (2000) Remote sensing for mapping serrated tussock and scotch thistle in pastures. Proceedings of the 10th Australian Remote Sensing and Photogrammetry Conference, Adelaide, Australia, 21st - 25th August, CDROM paper 60 pp. 395-411.

Meadly, G. R. W., 1962. Weeds of Western Australia – mesquite. J. of Agriculture WA 3, 729-739.

Metternicht, G (2003) Vegetation Indices Derived from High Resolution Airborne Video studWestgraphy for Precision Crop Management. International Journal of Remote Sensing, Vol. 24, pp. 2855-2877.

Robinson, T.P., Metternicht G. and van Klinken R.D. (2006) A Neural Network Approach for Mapping Mesquite (Prosopis spp) in the northwest Pilbara Regiona of Western Australia using one-meter resolution digital multispectral imagery, 13th Australasian Remote Sensing and Photogrammetry Conference, Canberra Australia, November. 2006.

Robinson, T. (2007) personal communication.

Thorpe, J.R. and Lynch, R., 2000, The Determination of Weeds of National Significance. National Weeds Strategy Executive Committee, Launceston.

van Klinken, R., Kolomeitz, S., Robinson, T., Metternicht, G., Pullar, D., Shepherd, D. (2005) ‘Spatial Sciences and the management of rangeland weeds in the Northern Australia. Proc. of the North Australian Remote Sensing and GIS (NARGIS) Conference, 4th - 7th July 2005 Charles Darwin University, Darwin, NT, Australia, unpaginated CDrom.