Using EO-1 Hyperion satellite hyperspectral imagery to detect the pasture weed Paterson's curse (*Echium plantagineum* L.) in southern Western Australia

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Summary This paper investigated the utility of satellite hyperspectral (EO-1 Hyperion) imagery to detect and map the agricultural weed Paterson's curse (*Echium plantagineum* L.) in southern Western Australia. A matched filter classification was produced from image derived end-members and validated using a density independent (logistic regression and receiver operating characteristic analysis) approach. The probability (soft classification) map derived from logistic regression had an area under curve statistic of 0.87 and the threshold (hard classification) map had a user's and producer's accuracy of 81% and 83% respectively. The results demonstrated that Paterson's curse in a non-peak flowering condition can be accurately mapped from EO-1 Hyperion imagery. The most likely contributor to the accuracy was Paterson's curse remaining green into late spring when most pasture species were senescent. Future satellite hyperspectral sensors with a higher signal-to-noise ratio and the ability to image larger areas are likely to result in further improvements to mapping Paterson's curse with remote sensing.

Keywords Remote sensing.

INTRODUCTION

The most recent estimate of the financial impact of agricultural weeds in Australia is $3.4–4.4 billion per year (Sinden *et al.* 2004). The impacts of agricultural weeds include loss of production due to weeds outcompeting desired species, loss of value of products due to contamination (e.g. seeds in cotton), control costs, loss of value of products due to herbicide residue, and new production methods that are required in heavily affected weedy areas (Nordblom *et al.* 2001).

Paterson's curse (*Echium plantagineum* L.) is an annual herbaceous weed of particular concern in agricultural regions of Australia. Plants of the species contain pyrrolizidine alkaloids, which can have deleterious effects on animals and livestock, and infestations can reduce the productivity of pastures by replacing more desirable pasture species (Parsons and Cuthbertson 2001). Paterson's curse has a higher survival rate than other pasture species (e.g. *Trifolium subterraneum*) during periods of moisture stress and remains green in late spring and early summer when those species are senescent (Piggin 1976). In densely infested areas, the purple flowers of Paterson's curse makes it one of the most conspicuous weeds of roadsides, pastures, and disturbed lands during the spring months (September-November) in Western Australia (Dodd *et al.* 1993).

Reliable and cost effective methods for mapping agricultural weeds such as Paterson's curse can play an important role for successfully managing the species. Survey methods for Paterson's curse in Western Australia have been based on on-ground visual assessment of the approximate area of Paterson's curse for a given property, with no information on the spatial distribution. This approach involves a significant investment in time and resources to survey all affected properties in the south-west of Western Australia at a regional scale. Remote sensing offers a potentially good source of data for mapping and monitoring Paterson's curse, given the limitations and cost of other survey methods; in addition, the phenological properties (prominent flowers and delayed senescence) of Paterson's curse make it a potentially amenable species for detection with remote sensing.

The objective of this study was to evaluate the accuracy of satellite hyperspectral (EO-1 Hyperion) imagery for detecting Paterson's curse in southern Western Australia. This study is the first application of satellite hyperspectral imagery for Paterson's curse, and provides an opportunity to foreshadow the performance of planned satellite hyperspectral sensors for mapping Paterson's curse.

The study area is located in the wheatbelt region of Western Australia, approximately 85 km north of Perth. The study focussed on three properties located east of the town of Bindoon in the Chittering Shire. The primary land use around Bindoon is dominated by dry-land agriculture (mainly cropping), with some conservation reserves and natural environments dominated by remnant *Eucalyptus* woodland. The climate is hot-summer Mediterranean, characterised by long warm dry summers and winter dominant rainfall.

MATERIALS AND METHODS

The Hyperion sensor on the Earth Observation 1 (EO-1) satellite has the same 30 m spatial resolution as the Landsat 7 and 8 multispectral satellite sensors, but a hyperspectral resolution of 196 unique bands (Jupp and Datt 2004). The large number of bands allows materials to be mapped with conventional hyperspectral classification approaches such as matched filtering and linear spectral un-mixing. A Hyperion image was acquired on November 2, 2006. Conditions during the time of overpass (02:30 GMT/10:30 Western Australian Standard Time) were clear and cloud free. The dimensions of the image were 45 km in the along-track direction (length) and 7.65 km in the across-track direction (width).

The image was atmospherically corrected and spectrally subset to include 49 bands from the visible and near infrared, from 428 nm to 917 nm. This range reduced the dimensions of the dataset, and focused on the parts of the spectrum that are most relevant to Paterson's curse flowering and growth. The image was rectified to a level 1G (terrain corrected) Landsat 5 image using a second-order polynomial, resulting in an overall root mean square (RMS) error of 9.15 m.

An end-member signature representing dense flowering Paterson's curse was derived directly from the image. Three separate end-member signature were extracted from plots comprised of 3 × 3 pixels (90 × 90 m, or 0.81 ha) and combined as one endmember. This endmember was input into a matched filter classification (Boardman 1998).

Field data for accuracy assessment were collected on October 18, 2006, between the daylight hours of 08:00 and 17:00. A total of 85 randomly generated plots containing Paterson's curse were surveyed. Each plot measured 90 × 90 m (3 × 3 pixels). At the centre of each plot, four oblique digital photos were captured, each orientated towards one of the four cardinal compass directions. The approximate percentage cover of Paterson's curse for each plot was visually estimated post-survey from the oblique photos. A total of 100 plots that didn't contain Paterson's curse were used for accuracy assessment, but were not surveyed in the field.

The accuracy of the matched filter classification was assessed a threshold independent approach, which consisted of logistic regression (Pohar *et al.* 2004) and receiver operating characteristic (ROC) analysis (Zweig and Campbell 1993). The approach provides a quantitative measure of the predictive accuracy of a model by comparing the probability values derived from logistic regression with a corresponding validation dataset, comprised of presence and absence data. The predicted probabilities were also used to produce a hard (binary) image output based on the maximum efficiency method (Lippitt *et al*. 2008): a threshold value was determined at the location on the ROC plot where there was the greatest difference between the false positive rate and true positive rate across all possible threshold values of the validation dataset.

RESULTS

High matched filter scores were generally present in pasture and cropped areas of the image and known areas infested by Paterson's curse. Matched filter scores were generally low for areas of Eucalypt woodland, water bodies and fallow/cleared areas. Other areas of Eucalypt woodland had a 'speckle' effect of matched filter values caused by the spatial and spectral heterogeneity.

The hard binary output from the ROC threshold of the matched filter classification is shown in Figure 1 for the three properties. Small areas of *Eucalyptus* (sclerophyll) woodland are incorrectly classified as Paterson's curse in the northern part of property A (Figure 1a). Some areas of crop were misclassified in the eastern part of the property (A). In the south and south-west area of the property, some areas of pasture (B) were classified as Paterson's curse, where these areas are known not to contain Paterson's curse. The main area of Paterson's curse in the eastern section of property B (Figure 1b) was correctly classified (C). The areas on property C (Figure 1c) classified as Paterson's curse were mostly open areas of pasture, although not all of these areas were surveyed on the ground, and could have contained some Paterson's curse. There were some instances of *Eucalyptus* woodland (D) that were misclassified as Paterson's curse.

The results from the accuracy assessment are shown in Table 1. The logistic regression model showed good agreement with the validation data. The model λ of 86.95 rejects the null hypothesis that the matched filter score is not linearly related to the log-odds of presence/absence of Paterson's curse. The area under curve (AUC) statistic of 0.87 from the ROC analysis also indicated good agreement between the matched filter output and the validation data. The resulting matched filter cut-off value represented the top 43% of the dataset, in which 81% of Paterson's curse records were correctly identified (user's accuracy) and 17% of non-Paterson's curse records were misidentified (83% producer's accuracy).

Table 1. Chi-square and AUC statistics and user's and producer's accuracy.

N	λ	AUC	UA	PA
184	86.95	0.87	81%	83%

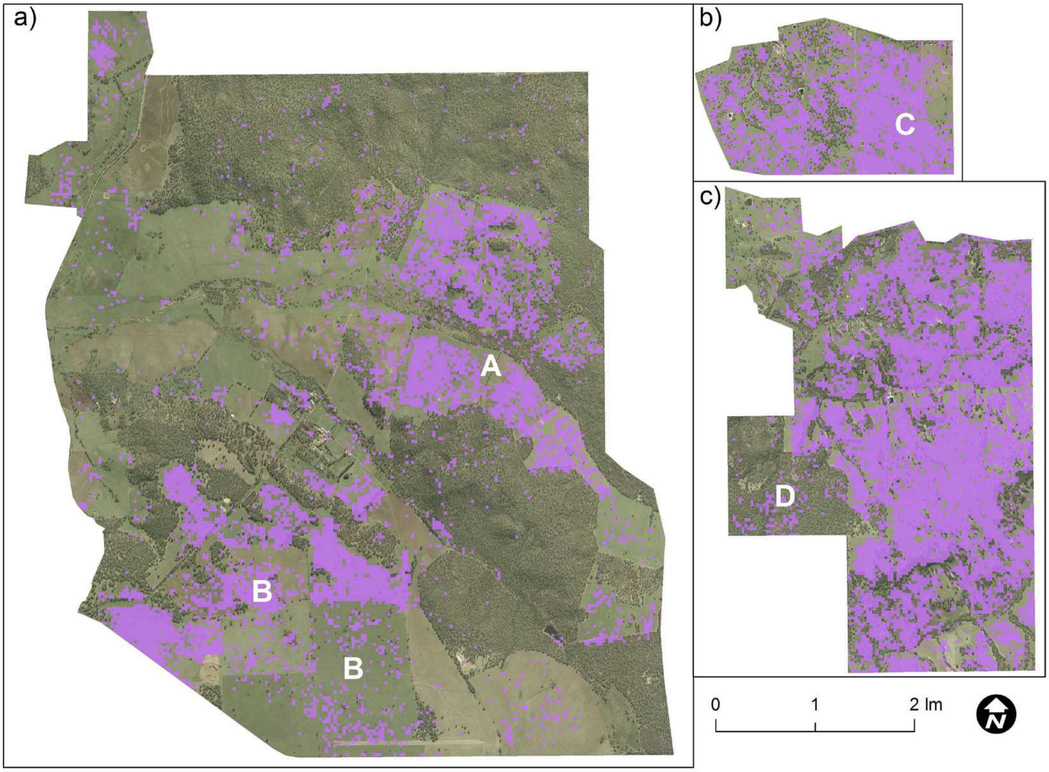

Figure 1. Paterson's curse (purple) mapped on the three properties.

DISCUSSION

The result from the matched filter classification indicates that Paterson's curse in a non-peak flowering condition can be accurately mapped with EO-1 Hyperion data. The most likely contributor to the accuracy was Paterson's curse remaining green into late spring when most pasture species were senescent. The user's and producer's accuracy (81% and 83%) was similar to other non-woody weeds that have been mapped from airborne hyperspectral imagery (e.g. Mundt *et al*. 2005, Mirik *et al*. 2013).

The most likely sources of classification error were from cropped areas and pasture that retrained greenness longer into the season as well as lower density (patchy) areas of Paterson's curse that could not be reliably discriminated from senescent pasture. The Hyperion sensor is limited in its ability to detect weeds at low density due to the coarser spatial resolution and lower signal-to-noise ratio compared to airborne sensors. Within the context of this research, the level of accuracy is acceptable, given that the rationale for using EO-1 Hyperion data was to map the distribution of Paterson's curse over a larger area in a more cost effective manner than airborne sensors, and to highlight areas that can be further investigated in detail (e.g. airborne hyperspectral or field visit).

Despite the limitations of the Hyperion sensor (primarily the low signal-to-noise ratio), the previous limitations on detecting Paterson's curse with medium spatial resolution data (Bulman 2004) were overcome to an acceptable extent by the higher spectral resolution of the Hyperion sensor. This application of Hyperion to Paterson's curse represents an improvement over the previous method of visual estimation on the ground, given that it can map the spatial destruction of Paterson's curse over a large area, with less field time. Next-generation satellite hyperspectral platforms such as EnMAP, with a large swath width (30 km) and a higher signal-to-noise ratio than Hyperion (Segal *et al*. 2010) have the potential to provide greater consistency in image quality and processing, and be more amenable with operational requirements for mapping Paterson's curse over regional scales.

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