The identification and remote detection of alien invasive plants in commercial forests: An Overview

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Abstract

Invasive alien plants are responsible for extensive economic and ecological damage in forest plantations. They have the ability to aggressively manipulate essential ecosystem structural and functional processes. Alterations in these processes can have detrimental effects on the growth and productivity of forest species and ultimately impact on the quality and quantity of forest wood material. Using direct sampling field-based methods or visual estimations have generally expressed moderate success owing to the logistical and timely impracticalities. Alternatively, remote sensing techniques offer a synoptic rapid approach for detecting and mapping weeds affecting plantation forest environments. This paper reviews remote sensing techniques that have been used in detecting the occurrence of weeds and the implications for detecting S. mauritianum (bugweed); one of the most notorious alien plant invaders to affect southern Africa. Gaining early control of these alien plant invasions would reduce the impacts that may permanently alter our forested ecosystems, contributing to its successful eradication and promoting sustainable forest management practices. Furthermore, the review highlights the difficulties and opportunities that are associated with weed identification using remote sensing and future directions of research are also proposed.

1. Background

Invasions by alien plants have extensive economic and ecological effects on their introduced environments and are recognised as one of the most profound causes to biodiversity loss (Richardson and van Wilgen, 2004). The escalating rate of spread of invasive plants is responsible for homogenising biodiversity and may be considered a significant component of species extinction (Joshi *et al.*, 2004). Plant invasions can also contribute significantly to changes in the structure and functioning of ecosystems and have the capability to erode natural capital (van Wilgen *et al.*, 2012). They effectively capture available natural resources, survive and reproduce unaided across landscapes (van Wilgen *et al.*, 2001). Plant invaders indirectly affect native plant communities and invoke ecosystem changes that can alter the quantity and quality of plant substrates, soil properties, the microclimate, water relations, density and height of vegetation (Ehrenfeld *et al.*, 2001). These insidious and resilient qualities of plant invaders are not only responsible for compromising forest health and ecosystem goods and services, but also threaten economic productivity, both in man-made and natural ecosystems (Joshi *et al.*, 2004, Richardson and van Wilgen, 2004, Chornesky *et al.*, 2005).

Alien plant invasions within managed plantations may have detrimental effects on the growth and productivity of commercial forest species (Campbell and van Staden, 1990, Little *et al.*, 1997). These actively managed environments are not immune to plant invasions and have rather become prime invasion sinks for infestation (van Wilgen *et al.*, 2008). Firstly, forestry operations often facilitate invasions through poor weed control measures in nurseries or by transporting invader seeds when utilising field machinery (Le Maitre *et al.*, 2004). Secondly, tree felling, logging and planting are common silvicultural practices that aggravate weed densities and promote weed distribution through disturbances (Mullerova *et al.*, 2005). Finally, roads used to service forest compartments represent pathways that introduce alien species from which some spread from the edges into forest interiors (Pauchard and Alaback, 2004). Given the potential threat alien plants portray, conservationists, scientists and commercial organisations have to develop and adopt mitigation approaches to ensure sustainable forestry management (Chornesky *et al.*, 2005). These include environmental certifications which compel forest companies to limit

the distribution of alien plant invader propagules in support of controlling the spread of alien plant species (Le Maitre *et al.*, 2004).

Despite evidence suggesting that commercial forest ecosystems are prime environments for the establishment of invasive alien plants (IAPs) and the need to protect these valuable and vulnerable resources (Campbell and van Staden, 1990, Little *et al.*, 1997, Chornesky *et al.*, 2005), very little attention has been paid to the detection and mapping of weeds in these complex ecosystems. In this context, one significant alien plant invader commonly occurring within commercial forests as well as provoking serious economic and ecologic concerns is *Solanum mauritianum* (Campbell and van Staden, 1990, Little *et al.*, 1997).

Indigenous to South America, *S. mauritianum,* commonly known as bugweed (Fig. 1), has become one of the most notorious alien invasive plant species to affect southern Africa (Olckers and Borea, 2009). It is recognised as one of the sixth most aggressive, opportunistic and extremely resilient plant invaders in the region. Bugweed is an evergreen, noxious, branched shrub, varying between 2 m to 10 m in height with grey-green oval shaped leaves. The plant has a lifespan of up to thirty years and is a major constituent of agricultural land, forestry plantations, water courses and disturbed environments (Copeland and Wharton, 2006, Olckers and Borea, 2009). Bugweed has earned a classification of a category one 'transformer' weed (Jordaan and Downs, 2012) indicating that extensive stands are able to dominate and replace canopy or sub-canopy layers of forest ecosystems (Witkowski and Garner, 2008, Olckers, 2011). Bugweed invasions may substantially propagate with changes in regional and global climate (van Wilgen *et al.*, 2008). Increased nitrogen deposition, increased levels of atmospheric carbon dioxide, elevated temperatures and variability in rainfall, are all consequences of climate change that favour the establishment of the weed (Huang and Asner, 2009). Frugivorous birds also promote high levels of seedling recruitment across the landscape, making bugweed a successful plant invader (Jordaan and Downs, 2012). The weed has the ability to self-pollinate, with a rapid reproductive output and produces berries throughout the year. Since the berries have a greater nutritional status than many indigenous fruits, its success escalates as many bird species' diets shift with the availability of food resources (Jordaan and Downs, 2012). Each berry contains approximately 150 to 250 seeds of which 98% are viable (van den Bosch *et al.*, 2004) .

Figure 1. The alien invasive plant, *S. mauritianum*, located within the riparian zone of the forest.

From an economic and ecological standpoint, it is absolutely necessary to manage the adverse effects of bugweed in plantation forests. Gaining early control of these alien infestations could reduce the impacts that may permanently alter the structure and function of our forested ecosystems and contribute to the successful prevention and eradication of the weed. With the potential of climate change to significantly exacerbate the problems associated with IAPs, modelling the characteristics, spatial extent and severity of infestations will become unavoidable. While traditional efforts of estimating alien invasive plant cover rely on the generation of costly ground-based survey methods, which are not only technically and logistically impractical (Lawrence *et al.*, 2006), remote sensing technologies offer a rapid alternative by providing a source of obtaining data over broad spatial extents (Kerr and Ostrovsky, 2003, Andrew and Ustin, 2008). Many studies have used remote sensing to detect and monitor noxious alien plant

invasions in natural and semi-natural ecosystems (Everitt *et al.*, 1995, Ustin *et al.*, 2002, Joshi *et al.*, 2004, Everitt *et al.*, 2005, Mundt *et al.*, 2005, Andrew and Ustin, 2009). However, to the best of our knowledge, research has been limited (Atkinson *et al.*, 2014, Peerbhay *et al.*, 2015) with regards to identifying and mapping IAPs in commercial forest ecosystems.

Currently, there are no specific methodologies of detecting or mapping alien plants in commercial forests. Therefore, this review aimed to discuss the potential of identifying and mapping the occurrence of bugweed using remote sensing technologies. Firstly, the difficulties experienced when locating and removing IAPs in commercial forest plantations were assessed. Thereafter, the application of remotely sensed techniques to detect IAP's using direct and indirect approaches were reviewed; whilst generating the necessary knowledge for mapping bugweed within commercial forestry. The utility of aerial, multispectral and hyperspectral remote sensing for this application are also discussed. Finally, the challenges associated with using remotely sensed technologies are considered and possible solutions suggested for guiding the success of future operational interventions for locating and mapping bugweed in commercial forests.

2. Mitigation measures against alien plant invaders

One of the most common management tools used to control alien plant invasions in commercial forests is the use of herbicides. However, weeds are becoming increasingly resistant towards this general execution (Holzmueller and Jose, 2009). The introduction of several chemical and mechanical control methods has also experienced difficulties owing to the expenses associated with such techniques and the spatial extent of infestations. Although biological control programs such as using natural enemies to control the spread of weeds has shown the most potential, to date, their overall impact on controlling IAPs remains insufficient (Olckers and Borea, 2009). Most of the bio-control agents are leaf feeders and usually extend beyond their target plants, becoming pests to cultivated and other plants (Olckers, 2004). Alien plants are often able to persist as invasive despite attempts to eliminate them. Sometimes weed control itself may contribute to the prolific dispersal of seedlings. Most plant invaders also recover rapidly after clearing due to either re-sprouting or germination from dense seed banks within the soil (Witkowski and Garner, 2008). These multiple strategies used to gain dominance in their

introduced habitats have made efforts to control them extremely difficult (Holzmueller and Jose, 2009).

In response to the widespread, fast growing and constant threat which plant invaders may present in forest ecosystems, forest managers require an integrated management system combining detection, mapping and monitoring that is operationally accurate and cost effective (Lawrence *et al.*, 2006). Since weed infestations are not distributed evenly across infected areas, a key requirement for their effective management is to be able to detect and delineate the spatial extent and the severity of infestation (Ustin *et al.*, 2002). Additionally, a precise weed detection system is a prerequisite for a better weed management strategy and effective implementation (Goel *et al.*, 2002). Remote sensing can serve as a viable alternative to traditional field-based methods for obtaining information on weeds in commercial forests. The technology can be used for the accurate and timely detection of weed locations and their distributions and intensities.

3. Assessing the potential of remotely sensed data for alien plant detection

The most common remote sensing approach for detecting weeds is to utilise high spatial resolution imagery such as aerial photography (Huang and Asner, 2009). Everitt *et al.* (1995) for example, conducted studies using aerial photographs to monitor the infestation of one Eurasian (*Euphorbia esula*) and one Asian (*Tamarix chinensis*) plant. Wavelengths in the visible (400 nm – 700 nm) portion of the electromagnetic spectrum and geographic information system (GIS) analysis successfully mapped the infestations. Similarly, Anderson *et al.* (1996) accurately mapped the occurrence of leafy spurge by combining topographical features (aspect, slope and watershed basin) for a more in-depth analysis. Mullerova *et al.* (2005) used time series aerial panchromatic camera (WILD 328) data in conjunction with colour infrared photographs to monitor the *Heracleum mantegazzianum* (giant hogweed) invasion in the Czech Republic. Results were analysed using an analysis of covariance (ANCOVA), multiple regression and path analysis. Multiple photographs showed that the alien plant invader was easily detected due to its flowering and fruiting. Recently, high spatial resolution aerial photographs were also used to identify *Fallopia japonica* (Japanese knotweed) with an object-based classification approach (Jones *et al.*, 2011). While the timing of the acquisition of data is crucial for aerial photographic analysis, these early methodologies to visually observe weeds are limited to small spatial extents (Mundt *et al.*, 2005). Aerial photographs also only work best when the weeds have unique

growth patterns distinct from surrounding vegetation. Therefore, a more robust approach is to use multispectral remote sensing (Huang and Asner, 2009).

Multispectral remote sensing (≤8 bands) improves on aerial photography by recording spectral information in a number of different wavelengths across the electromagnetic spectrum (Mundt *et al.*, 2005; Peerbhay *et al.*, 2014b). For example, Fuller (2005) mapped the invasive *Melaleuca quinquenervia* (paperbark) tree native to Australia using IKONOS imagery with a spatial resolution of 4 m. The study employed a back-propagation neural network (NN) classifier coupled with landscape fragmentation analysis and produced a highly distinctive pattern (overall accuracy >85%) from woody plants. Laba *et al.* (2008) estimated the presence of three alien plants, *Lythrum salicaria* (purple loosestrife), *Phragmites australis* (common reed) and *Trapa natans* (water chestnut) in a diverse wetland environment using high resolution Quickbird imagery (2.4 m). A maximum likelihood classifier demonstrated that the finer spatial resolution was a reliable data source for alien plant detection (overall accuracy ≥65%). Recently, Somodi *et al.* (2012) combined Landsat ETM (30 m), orthophotography (0.5 m and 0.25 m) and GIS layers to detect *Robinia pseudacacia* (black locust). Digital orthophotos taken during the flowering stages provided the best data source for recognising the tree species.

Although multispectral remote sensing has the capability of detecting and mapping alien plants, the weeds are often obscured in a backdrop of natural vegetation making it difficult to detect (Mundt *et al.*, 2005). Multispectral data may therefore only be effective to observe large weed stands and patches whose identification depends heavily on the phenological period during which the images are acquired (Huang and Asner, 2009). For example, Carson *et al.* (1995) were unsuccessful in mapping *Hieracium pratense* (yellow hawkweed) at species level using 30 m Landsat TM and 20 m SPOT data, unless the species stands were large enough (>20% cover). Fuller (2005) was unsuccessful in identifying the invasive paperbark tree at low cover (<50% cover) using 4 m resolution IKONOS multispectral wavelengths. In addition, the spectral similarity in reflectance between weeds and surrounding vegetation create difficulties when using multispectral analysis (Asner *et al.*, 2008a). Alternatively, hyperspectral remote sensing has become more advantageous owing to the improved spectral resolution for mapping IAP's (Glenn *et al.*, 2005).

Hyperspectral data capture information from hundreds of narrow wavebands, providing a full spectral curve for each pixel (Peerbhay *et al.*, 2013). Subsequently, the main advantage associated with hyperspectral data is that they provide detailed spectral profiles that can distinguish native from non-native plants and that the most significant spectral regions in detecting the species of interest can be analysed (Huang and Asner, 2009). Many studies have used hyperspectral remote sensing to detect alien plants (Ustin *et al.*, 2002, Williams and Hunt, 2002, Glenn *et al.*, 2005, Mundt *et al.*, 2005, Asner *et al.*, 2006, Asner *et al.*, 2008a, Asner *et al.*, 2008b, Peerbhay *et al.*, 2014a, Peerbhay *et al.*, 2015). Williams and Hunt (2002) for example, successfully mapped European *Euphorbia esula* (leafy spurge) utilising AVIRIS hyperspectral data. They applied a specialised spectral mixture analysis to improve the spectral recognition of the species. The early stages of leafy spurge were also mapped using high resolution HyMap data (3.5 m) with accuracies greater than 84% (Glenn *et al.*, 2005). Ustin *et al.* (2002) used 4 m AVIRIS data to detect and map several alien invasive plant species including *Carpobrotus edulis* (iceplant), *Cordateria jubata* (jubata grass), *Foeniculum vulgare* (fennel) and *Arundo donax* (giant reed) in mixed chaparral and riparian ecosystems. While several classification methods produced successful results, maximum likelihood classifier methods performed better than unsupervised methods or vegetation indices for mapping the plant invaders. For the mapping of iceplant density, minimum noise fraction (MNF) (55.2%) performance was superior to that of band ratios (44%) or continuum removal analysis (39%).

Mundt *et al.* (2005) discriminated *Cardaria draba* (hoary cress) using different hyperspectral processing parameters and classification algorithms. The most robust approach utilised MNF transformed reflectance data and resulted in producers, users and overall accuracies of 82%, 79% and 86%, respectively. Lass *et al.* (2005) detected spotted *Centaurea maculosa* (knapweed) and *Gypsophila paniculata* (baby's breath) infestations in shrub/grassland using a charged couple device (CCD) sensing in the 415 nm – 953 nm spectral range with a spatial resolution of 2 m. A spectral angel mapper (SAM) classifier was used to classify images over a two year period and produced an overall site detection average of 67% for knapweed and 83.5% for baby's breath. In a previous study utilising a hyperspectral image spectrometer (440 – 2543 nm), Lass *et al.* (2002) showed that knapweed was detectable using a SAM classifier and a spatial resolution of 5 m. Spotted knapweed was also mapped with leafy spurge using the Probe-1 sensor and Breiman

Cutler's random forest algorithm to produce classification accuracies of 84% and 86% respectively (Lawrence *et al.*, 2006).

Recently, in a tree species application using AISA Eagle hyperspectral data (393 nm – 272 nm) and partial least squares discriminant analysis (PLS-DA), Peerbhay *et al.* (2014) demonstrated the capability of separating bugweed from a variety of forest species (67%). Atkinson *et al.* (2014), however, showed impressive classification accuracies when focusing on mapping bugweed occurring only within *Pinus patula* compartments (93%). The study utilized band reduction techniques and support vector machines (SVM). Nonetheless, using a novel unsupervised RF approach and AISA Eagle data, Peerbhay *et al.* (2015) provided a semi-automated mapping accuracy of 88.96% when detecting bugweed as an anomaly within *Pinus Patula* stands.

While the use of hyperspectral sensors have become more advantageous owing to the wealth of spectral information for species level detection (Andrew and Ustin, 2008), the mapping of weeds based on their structural, biochemical and physiological characteristics were also exploited (Asner *et al.*, 2008a, Asner *et al.*, 2008b). In addition, certain studies have also used hyperspectral information in successfully mapping the cover and abundance of IAPs (Table 1).

Table 1. Hyperspectral remote sensing studies related to the structural, physiological and spatial characteristics of invasive plants.

Species	Sensor	Wavelengths	Data analysis	Overall results	Reference
-*Myrica fava* -*Native Metrosideros polymorpha*	Hyperion time series (30 m)	400 – 2500	- Field measurements (LAI, foliar chemistry analysis, leaf physiology) - Hyperspectral indices (LAI, PRI, CRI, NDVI, CWR) - Climate inventory (Temperature, rainfall, relative humidity, canopy vapor pressure deficit)	Myrica growth rates were 16-44% higher than native metrosideros and thrived in bioclimatic stressful periods	**Asner et al. 2006**
- *Falcataria moluccana* - *Fraxinus uhdei* - *Hedychium gardnerianum* - *Morella faya* - *Psidium cattleianum*	Carnegie Airborne Observatory (0.5 m to 2.5 m)	367 – 2510	- Field based transects and plot scale measurements - LAI	Field validation tests yielded <7% error	**Asner et al. 2008a**
- *Ficus microcarpa* - *Grevillea robusta* - *Macaranga mappa* - *Melastoma Candidum* - *Psidium cattleianum* - *Schefflera actinophylla* - *Schinus molle* - *Spathodea campanulata* - *Tibouchina granulosa* - *Trema orientalis* - *Falcataria moluccana* - *Morella faya*	AVIRIS (3 m)	400 – 700 1125 – 2500	- Field leaf samples from tree crowns - Leaf pigment (chlorophyll, carotenoids) - nutrients (N, P) - Structural properties (specific leaf area; SLA) - Partial least squares regression (PLS)	p-values ranged from 0.01 to 0.05 when examining the spectral differences between highly invasive and other native species	**Asner et al. 2008b**
- *Centaurea maculosa*	Image spectrometer (5 m)	440 – 2543	- Field data points - Spectral signature development - Spectral angel mapper (SAM) classification	99% for 1% – 40% cover	**Lass et al. 2002**
- *Gypsophila paniculata* - *Centaurea maculosa*	Charged couple device (2 m)	415 – 953	- Spectral reflectance training curves - Spectral angel mapper (SAM) classification - Field validation	83.5% 67%	**Lass et al. 2005**

Since the capabilities of utilising remote sensing for the detection and mapping of weeds have been documented, the potential to exploit the technology for accurately mapping the unique spectral signatures of bugweed is also recognisable. From an operational perspective, the accurate mapping of weeds in commercial forests requires techniques that are viable and relatively cost effective. Therefore, the limited, yet encouraging results utilising multispectral information provide sufficient evidence to investigate the capability of the new generation of multispectral sensors. These high spatial resolution commercial satellite systems (e.g. WorldView-2, RapidEye and GeoEye) enable detailed observations in the visible to near-infrared range and offer new opportunities for detecting and mapping weeds using space borne platforms.

Furthermore, the potential exists to exploit the effectiveness of readily accessible and available data such as the use of synthetic aperture radar (SAR) for detecting and mapping IAPs. SAR data is captured using an active sensor and can provide information related to the difference in structure and density between vegetation species (Bourgeau-Chavez *et al.*, 2012; Ghulam *et al.,* 2014). Long frequency signals such as the P-band and L-band, have the capability to penetrate the forest canopy to reveal structural information beneath, while short frequency signals such as the C-band is suitable for mapping at the canopy surface. Such information can be complementary when combined with passive optical imagery for mapping IAPs in complex forest environments (Ghulam *et al.,* 2014), while proving access to cost effective remotely sensing data over broader extents. Nonetheless, only a few studies have investigated the potential use of SAR for alien plant detection (Bourgeau-Chavez *et al.*, 2009; Bourgeau-Chavez *et al.*, 2012; Ghulam *et al*., 2014). For instance, using the L-band of the ALOS PALSAR sensor, Bourgeau-Chavez *et al.,* (2009) mapped stands of invasive *Phragmites* (common reed) with better accuracy than airborne hyperspectral AVIRIS data. Subsequently, the effectiveness of multi-season L-band from ALOS POLSAR was demonstrated in accurately mapping the distribution of *Phragmites* over a large area (Bourgeau-Chavez *et al.*, 2012). Finally, Ghulam *et al*., (2014) combined SAR data (PALSAR and Radasat-2) along with spectral information (Hyperion, Landsat, IKONOS) and tree height (GeoEye-1 stereo) to accurately characterize the spatial extent of *Psidium cattleianum* (Guava), *Aframomum angustifolium* (Madagascar cardamom) and *Rubus moluccanus* (Molucca raspberry). The study permits the use of L-band SAR for the detailed mapping of invasive species while the C-band saturating at increased forest height and density.

4. Understory and mixed canopy species

Many IAPs, including bugweed, grow as subtle understory or mid-level canopy vegetation (Joshi *et al.*, 2006). Therefore they do not dominate the canopy making it difficult for direct remote detection (Asner *et al.*, 2008a). Although both spatial and spectral resolutions are primary determinants of the accuracy when mapping IAPs, higher resolutions would not necessarily ensure that weed infestations in forest environments will be measurable (Mundt *et al.*, 2005). Researchers, however, adopt alternate methods such as using conventional image classification techniques and expert systems. Expert systems utilise ancillary data and can infer the most probable characteristics of a target weed species in a specific location (Masocha and Skidmore, 2011). They may be implemented in a GIS environment and often yield better results than using single classification methods. Many studies have been successful in utilising GIS expert systems for mapping understory vegetation (Schmidt *et al.*, 2004, Vaiphasa *et al.*, 2006, Wang *et al.*, 2009). For example, topographical information was combined with hyperspectral imagery to map 19 vegetation types in a salt marsh environment using a hybrid SAM and an expert system (Schmidt *et al.*, 2004). Vaiphasa *et al.* (2006) used soil pH data together with ASTER imagery to discriminate mangrove species using a hybrid maximum likelihood classification algorithm and an expert system. Wang *et al.* (2009) combined an ANN with an expert system and mapped understory bamboo species. Recently, Masocha and Skidmore (2011) combined habitat and terrain position data and mapped the cover of invasive *Lantana camara* (cherrypie) using single and hybrid SVM and NN classification methods. In this regard, GIS expert systems may therefore be used in combination with remotely sensed data to assist in mapping understory IAPs such as bugweed within plantation forestry environments.

Indirect mapping approaches may also assist in mapping the distribution of invasive weeds by using information related to the ecological relationship between species and the environment (Joshi *et al.*, 2004). For example, Joshi *et al.* (2006) estimated canopy gaps to predict understory *Chromolaena odorata* (siam weed) infestations using Landsat ETM+ data. Utilising an ANN, they successfully predicted forest canopy density and light intensity reaching the understory and mapped 64% of variation in *C. odorata* cover. Other studies used the phenological differences between the canopy overstory and understory species. For instance, Resasco *et al.* (2007) and Wilfong *et al.* (2009) successfully detected *Lonicera maackii* (bush honeysuckle)*,* in the understory of deciduous forests stands using Landsat imagery when the overstory trees were leafless. Similarly, Groeneveld and Watson (2008)

used the Landsat TM near-infrared band to map *Tamarix ramosissima* (saltcedar) during winter, when the plant branches were leafless. Landsat imagery was also used to map the distribution of two understory bamboo species by exploiting the phenological difference between overstory trees and understory bamboos (Tuanmu *et al.*, 2010). The success in mapping understory invasive plants from other vegetation covers therefore appears to be dependent on specific acquisition dates of satellite images. This may be further investigated to improve the detection of difficult weed species occurring in South Africa and within complex environments.

5. Limitations of utilising remote sensing for alien plant detection

As mentioned earlier, spatial and spectral information obtained from medium resolution sensors is insufficient when delineating or detecting IAPs. High spatial resolution remote sensing such as aerial photography, although being successful in mapping the distribution of certain plant invaders, may not be capable of distinguishing weeds that are obscured in a backdrop of vegetation. Using even the very high spatial resolution space-borne images may provide a challenge to discriminate such invasive plants at species level (Huang and Asner, 2009). Phenological variations which are significant in detecting plant invasions may not be distinct owing to the coarse spectral resolution of high spatial resolution sensors. On the one hand, utilising high spatial resolution data may be less feasible over large areas and can affect the overall mapping outcome. Utilising the high spectral resolution of hyperspectral remote sensing, on the other hand, may represent an oversampled dataset, which results in high data dimensionality and redundant wavebands that may be irrelevant for detecting the alien invasive plant species of interest. Apart from overwhelming data analysis methods that increase computational demands, spectral variations influenced by background effects such as soil characteristics and non-photosynthetic material could overwrite significant response signals of target invasive plants. It is therefore essential to invest in the development of accurate automated and semi-automated algorithms that are able to fully exploit the huge amount of information linked with remotely sensed datasets so as to address the spectral complexities when detecting IAP species for real-time monitoring and decision making.

6. Summary and discussion

Alien plants present a number of important ecological and economic problems despite attempts to control them. Therefore, the use of remote sensing for the detection of noxious

weeds has become practical in a variety of ecosystem types. Aerial photography, although limited to small spatial extents and dependent on distinct spectral patterns of plant invaders; still provides a reliable method for mapping alien plants. The use of multispectral imagery has demonstrated success in mapping the distribution of plant invaders; however, the low spectral resolution limits the application of this technology. Imagery with higher spectral resolutions such as hyperspectral data therefore provides superior species discriminative capabilities for alien plant detection. In this review, the application of remote sensing techniques for detecting and mapping IAPs were investigated. Overall, remote sensing technologies have been successfully introduced to a variety of weed detection applications and in different environments. However, most of the studies using remote sensing were conducted in areas represented by relatively homogenous landscapes that were free from canopy species. Therefore, detecting, mapping and modelling plant invasions in commercial forest environments will still be a major challenge as many invasive plant species grow as understory vegetation. Bugweed, in particular, has the ability to dominate the understory as well as the ability to establish itself as extensive weed stands. This complexity makes it difficult to delineate complete invasions. However, the capability of remote sensing, integrated with expert knowledge and GIS, may enhance the recognition of the weed in commercial forests.

7. Directions of future research

The increase in satellite sensor technology will provide continuous opportunities for the application of remotely sensed data in mapping and modelling the distribution of invasive weeds. The advancement of the new generation of multispectral sensors (e.g., WorldView-2, RapidEye and GeoEye), with their very high spatial resolutions, has the potential to improve on the detection and mapping of alien species. Future research may also focus on utilising remote sensing technology such as light detection and ranging (LiDAR) which measures the distance between the sensor and target surface. LiDAR information can provide structural information on canopies, underlying vegetation and the terrain below (Asner *et al.*, 2008b) and could be instrumental in recognising a greater variety of IAPs than previously detected. Similarly, the integration of spectral information with LiDAR and SAR instrument systems could improve the analysis of plant invader functional and structural properties and provide an accurate framework for mapping alien plants in commercial forest environments. In

addition, it would be interesting to investigate the utility of LiDAR or SAR within an unsupervised remote sensing weed detection application.

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