Mapping Mesquite (*Prosopis*) Distribution and Density Using Visual Aerial Surveys

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Abstract

Mapping the distribution and abundance of invasive plants is a high priority, but establishing cost-effective and practical techniques at appropriate scales remains elusive. Mesquite is a highly invasive shrub that cannot currently be reliably distinguished from other plant species using remote sensing technologies, at least not at accuracies necessary for mapping mesquite at very low densities. This paper describes and tests an alternative method. A visual, aerial technique was used to map a large mesquite (*Leguminosae: Prosopis* spp.) population in Australia; 216 654 ha was surveyed in 18.5-ha grid cells to include the entire population. The objective was to test the ability of this technique to detect and map mesquite at very low densities for surveillance and to assist in prioritizing management effort and, where mesquite was well established, to categorize mesquite into broad canopy cover classes for change detection and to identify habitat associations. The survey technique was very effective at detecting isolated mesquite plants (< 0.6% canopy cover across a grid cell), which is considerably better than existing remote sensing technologies. Detection of low-density mesquite was particularly important, as most occupied grid cells (55%) had isolated mesquite, and their management may offer the best return on investment. The technique was also competitive cost wise (\$0.39 USD per hectare) and required relatively little expertise. Grid cells with moderate (20%–50%) to dense (> 50%) canopy covers were almost all restricted to a 32 500-ha area on the floodplain delta of the Fortescue River, where the original introductions occurred. Cover class estimates appeared to be well calibrated between observers within a survey; however, they were poorly calibrated between independently conducted surveys, suggesting that further methodological refinement is necessary if this technique is to be reliable for change detection.

Resumen

Mapear la distribución y abundancia de plantas invasoras es una prioridad alta, pero establecer técnicas prácticas y efectivas en costos a escala adecuada es aún difícil. El “Mezquite” es un arbusto altamente invasivo, el cual actualmente, con tecnologías de sensores remotos, no puede ser distinguido confiablemente de otras plantas, al menos no con la certeza necesaria para mapearlo en densidades muy bajas. Este artículo describe y prueba un método alternativo. Se usó una técnica aérea visual para mapear un gran población de “Mezquite” (*Leguminosae: Prosopis* spp.) en Australia: 216 654 ha fueron muestreadas en una cuadrícula con celdas de 8.5 ha para incluir la población total. El objetivo fue probar la capacidad de esta técnica para detectar y mapear “Mezquite” en muy bajas densidades con propósitos de reconocimiento y como auxilio en establecer prioridades de manejo, y donde el mezquite esta bien establecido, categorizarlo en amplias clases de cobertura de copa para detectar cambios e identificar las asociaciones de hábitat. La técnica de muestro fue muy efectiva para detectar las plantas aisladas de mezquite (< 0.6% de cobertura de copa en la celda de la malla de muestreo), lo cual es considerablemente mejor que las tecnologías de sensores remotos existentes. La detección de mezquite de baja densidad fue particularmente importante, porque la mayoría de las celdas de la malla ocupadas (55%) tenían plantas aisladas de “Mezquite” y su manejo ofrece el mayor retorno de la inversión. La técnica también fue competitiva en costos (\$0.39 USD/ha) y requiere relativamente poca experiencia. Las celdas con coberturas de copa de moderadas (20%–50%) a densas (> 50%) estuvieron casi todas restringidas a un área de 32 500 ha en el delta inundable del río Fortescue, donde la introducciones originales ocurrieron. Las estimaciones de clases de cobertura parecieron ser bien calibradas entre observadores dentro del muestreo; sin embargo, ellas estuvieron pobremente calibradas entre los muestreos conducidos independientemente, sugiriendo que es necesario un refinamiento metodológico posterior si esta técnica va a ser confiable para la detección de cambios.

Key Words: aerial survey, Australia, invasive plants, mapping, monitoring costs, remote sensing, visual estimation techniques

INTRODUCTION

Data on the distribution and abundance of invasive plants, captured at the correct scale and accuracy, is critical for predicting future spread and devising appropriate management plans (Mack 2005; Mullerova et al. 2005). Continental- or national-scale maps of distribution and abundance, developed through expert opinion, have informed national- and regional-

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scale policy and management strategies (Thorpe and Lynch 2000). However, landscape-scale mapping is generally necessary as a basis for understanding invasion processes, quantifying impacts, and directing on-ground management strategies (Shafii et al. 2003; Panetta and Lawes 2005). Mapping at the landscape-scale also presents the greatest technical challenges (Rew et al. 2005).

Landscape-scale mapping of invasive plants on rangelands can be done most cost effectively through expert opinion, but many regions are insufficiently visited for reliable maps to be developed in this fashion, especially where landholdings are large and difficult to traverse (Pitt and Miller 1988). Expert knowledge can also lack the quantitative rigor and comprehensiveness required for some weed mapping applications. Landscape-scale mapping is therefore generally conducted visually from ground-based surveys or through remote sensing (from aircraft or satellites). Ground surveying can be very time consuming, necessitating subsampling, although data can be used to generate probability maps of species occurrence (Shafii et al. 2003; Rew et al. 2005). Remote sensing has the potential to provide the most quantitative and comprehensive method for mapping (Ozesmi and Bauer 2002; Everitt et al. 2004; Mack 2005). Plant distribution and density can be accurately mapped from remotely sensed imagery but relies on the identification of characteristic spectral reflectance and in many cases good coverage of the target species (Everitt et al. 2002, 2004; Brown and Noble 2005; Lass et al. 2005). These criteria are not met for many invasive plants (Mack 2000). Additionally, even if the use of remote sensing is technically feasible, imagery taken at the correct time and with sufficiently high spatial and spectral resolution can be expensive, and the classification of imagery can require considerable expertise (Lass et al. 2005; Hunt and Parker Williams 2006).

An alternative mapping approach is to conduct visual surveys from aircraft. Visual aerial surveying has been used for mapping and censusing across a wide range of environmental applications, often benefiting from the ability of the trained human eye to discriminate at a fine resolution based on color, texture and growth habit, and the low technical requirements (Caughley and Grigg 1982; McConnell et al. 2000). For example, aerial surveying has been routinely used for surveying forest pests for over 50 years, and the technique has reached a high level of sophistication (McConnell et al. 2000). It has also been used to detect low densities of plants during eradication and surveillance programs for a wide range of invasive plants (Lawes et al. 2003; C. Yates, personal communication, March 2004). However, methods and results are rarely published, observations tend to be relatively qualitative and therefore of limited value for change detection, and we could find no example where the accuracy of observations has been independently tested.

We developed a visual, aerial survey technique to map the single largest mesquite (Leguminosae: *Prosopis* spp.) population in Australia. Mesquite is an invasive shrub or tree that is causing serious economic, environmental, and social impacts in many arid and semiarid parts of the world (van Klinken and Campbell 2001; van Klinken et al. 2006). The primary requirements for mapping this population were 2-fold: first, to map extensive areas where mesquite was at very low density, both as a surveillance tool and to identify parts of the

population where management work is likely to yield the best return for effort and, second, to classify the full range of canopy cover levels present, which is important for quantifying impacts, identifying habitat preferences, and for change detection (including for evaluating ongoing management efforts). Past attempts to classify mesquite using panchromatic aerial photographs have not been successful because of poor discrimination from other woody vegetation (Everitt et al. 2001; Nagler et al. 2005) or have required manual photo interpretation (Ansley et al. 2001), which is impractical for mapping large areas. Recent attempts using 1-m-resolution imagery gave encouraging results, but commission and omission error rates when classifying mesquite were still sufficiently high (0.03 and 0.04; conditional kappa = 0.82; Robinson et al. 2006) to limit its ability to detect mesquite at low densities, especially among nonmesquite shrublands. We validated our aerial survey results through expert opinion, ground-truthing, and repeat surveys, and results were used to describe the extent and density of this mesquite population, quantify its habitat associations, and make preliminary predictions as to future spread.

MATERIALS AND METHODS

Survey Area

The hybrid mesquite population in the Pilbara Region within the state of Western Australia, Australia (lat 21°11'S, long 115°58'E), is the result of an introduction made in the 1930s (van Klinken and Campbell 2001). It is a hybrid swarm, consisting of at least 3 component species: *Prosopis pallida* (H.& B. ex Willd.) H.B.K., *Prosopis glandulosa* Torrey, and *Prosopis velutina* Wooton. The extent of this population was fairly well known because of previous ground surveys and ad hoc flyovers, although it had not been mapped or quantified. With the exception of the occasional hybrid mesquite plant recorded on other pastoral properties in the Pilbara region (van Klinken and Campbell 2001; R. Parr, personal communication, May 2006), mesquite is currently restricted to 2 pastoral leases, Mardie Station (a 220 865-ha lease) and Yarraloola Station to the south (223 452 ha; Fig. 1A). The original introduction occurred on the delta of the Fortescue River. Mesquite has since spread southwest onto the delta of the Robe River (including onto Yarraloola Station) and northeast toward the uppermost boundary of Mardie Station (Fig. 1A).

The survey aimed to quantitatively map the full extent of the existing mesquite population (Fig. 1B). With the exception of low ranges (to 185 m above sea level) toward the northeastern and southeastern ends of the mesquite population, the elevation is low (0–30 m) (Mitchell and Wilcox 1994; van Vreeswyk et al. 2004). There is a mosaic of 13 diverse land systems across the surveyed region, including hills or stony plains with acacia (*Acacia* spp.) shrublands or spinifex (*Triodia* spp.) grasslands, alluvial plains with tussock grasslands or grassy shrublands, river plains with grassy woodlands and shrublands and tussock grasslands, and coastal plains, dunes, mudflats, and beaches with tussock grasslands, soft spinifex grasslands, and halophytic shrublands (Leighton et al. 2004; van Vreeswyk et al. 2004). Vegetation is highly heterogeneous, even at fine scales

Figure 1. The extent of the surveys and 4 zones in which the survey area was divided for analysis showing the area covered by each survey, major drainage lines, and the edge of the coastal mudflats (**A**) and the distribution of mesquite by density class (**B**). Grid cells are 18.5 ha in size.

within land systems, varying with microtopographic relief and soil type (Mitchell and Wilcox 1994).

For the purposes of analysis and discussion, we divided the survey region into 4 zones (Eramurra, Fortescue, Robe-Mardie, and Robe-Yaraloola) according to drainage systems and barriers to dispersal (Fig. 1A). The Eramurra catchment is relatively minor but is separated from the Fortescue catchment by a line of spinifex-dominated basalt hills. The Fortescue and

Robe River deltas are separated by several independent but minor drainage lines. The Robe River delta is on the boundary of 2 pastoral leases separated by a cattle fence.

Survey Technique

The survey was undertaken in a R44 4-seater helicopter (Raven 1, Robinson Helicopter Company, Torrance, CA) for work at low speed and altitude. The survey team consisted of a pilot, a navigator, and 2 observers who assessed mesquite density or cover in fixed survey grid cells on each side of the helicopter. A total of 11 different observers conducted surveys on 2-hour rotations. All were from the local area and were familiar with mesquite and the local native vegetation, but only 1 had prior experience in aerial survey work.

Survey grid cells were fixed at 620 m long by 300 m wide (about 18.5 ha). Grid cell dimensions were determined largely by the flying height (60 m), flying speed (~110 kph), observation frequencies (~20 seconds, depending on conditions), and viewing width (300 m), which were determined as optimal for identifying and quantifying mesquite while still allowing large areas to be surveyed. These survey parameters were established by tests conducted in a light aircraft prior to the main survey. The survey grid was prepared in a Geographic Information System (GIS)—Intergraph Geomedia™ (Version 6.0, Intergraph Corporation, Huntsville, AL)—and transferred to an HP 5150 Personal Data Assistant (PDA; iPAQ 5150, Hewlett Packard Company, Palo Alto, CA) using Intergraph On Demand for Geomedia™ mobile GIS software. Navigation and data capture were undertaken on the PDA using the mobile GIS software linked to a Holux CF270 Non-Differential Global Positioning System (accurate to 5 m; GM-270-Ultra, Holux Company, Taipei, Taiwan) integrated with the PDA. The entire survey grid and all station infrastructure were available on the PDA to the navigator, and the position of the helicopter was displayed over these features and tracked in real time. This allowed the survey team to know where they were in relation to the survey grid. More important, it allowed flight speeds and therefore observation frequencies to be varied with flying and observational conditions. A track log was programmed prior to the survey to cover the entire survey area. However, it was sometimes varied on the fly by manipulating and annotating the digital data directly on the PDA, for example, when the edge of the mesquite infestation was not reached in the preprogrammed flight path. A track log of the actual flight path was also recorded and subsequently used to cross-check with the compiled survey data as an independent audit of coverage. The track log was not differentially corrected. However, data recorded during the survey were matched to mapped topographic features to verify position data.

Surveys were conducted over 2 periods, 6–12 June 2004 (23 flying hours) and 7–12 November 2004 (25 flying hours). The June survey concentrated primarily on the densest part of the population, which was located on the Fortescue delta, and the November survey on sparser mesquite to the northeast and southwest (Fig. 1A).

Data Recording/Density Categories

Mesquite could be distinguished from other shrub species by its characteristic untidy appearance caused by zigzagged branches

protruding beyond the main canopy, leaf color (dark green), and frequently high level of leaf senescence or defoliation caused by a biological control agent (Gelechiidae: *Evippe* sp.) that was released in 1998 (van Klinken et al. 2003). Mesquite in the Pilbara region is evergreen, but foliage cover varies depending on the cycle between flushing and herbivory. Foliage cover (healthy leaflets only) averaged 45% (recently flushed and low levels of herbivory) and 22% (little new foliage and relatively high levels of herbivory) in the 2 surveys, respectively, as a percentage of total expected foliage on individual trees (L. Anderson and R. van Klinken, unpublished data). Individual mesquite plants could be recognized down to about 1.5 m in size ("small adults"; van Klinken et al. 2006). Overstory (mostly *Eucalyptus* spp.) that could potentially obscure mesquite plants was generally sparse (van Vreeswyk et al. 2004).

Observers recorded mesquite density or canopy cover for each grid cell. Mesquite counts were made up to 70 plants per grid cell (and categorized as isolated mesquite), which was the maximum number that could reasonably be located and counted in 20 seconds. This is equivalent to a summed canopy cover over the grid cell of < 0.6%, assuming an average canopy diameter of 4.5 m (van Klinken et al. 2006). Where mesquite density was too high to count in a grid cell during the survey (i.e., greater than 70 plants per grid cell), canopy cover standards were classified as sparse (< 20% cover), moderate (20%–50%, crowns separated), and dense (50%–100%, crowns slightly separated, touching, or overlapping). A set of representative cover maps were used by observers to assist in estimating covers.

Validation

Three methods were applied to help assess the accuracy of the survey technique. Particular emphasis was placed on testing the ability of the survey method to detect mesquite at low densities.

Any unexpected outliers in the survey results were identified by pastoralists on the affected properties and a state department biosecurity officer with intimate knowledge of the local area (Rob Parr), and suspicious records were subsequently ground-truthed by traversing the grid cells in a vehicle.

The ability of visual aerial surveys to detect low mesquite densities was compared with results from quantitative ground surveys. Eight paired sites were selected to compare groups of adjacent grid cells that were categorized during the June 2004 aerial survey as either "no mesquite" or "isolated mesquite." Possible interactions with vegetation type were tested by placing 2 pairs in grasslands and 2 in native shrublands. Each site was traversed in a vehicle (1.3–6.4 km long), and the total number of small mesquite adults (1.5–3.0 m tall) and large adults (> 3.0 m tall) present within a band (50- or 100-m wide, depending on visibility) on either side of the vehicle was recorded.

The repeatability of density assessments was tested by overflying a cluster of 94 grid cells at the end of the June survey and the beginning of the November survey. Different observers were used in each flyover.

Data Analysis

Data were imported from the PDA used for the survey into a GIS (Intergraph GeomediaTM) and summarized by survey

zone (Fig. 1A). Grid data were converted to centroids for data synthesis. Habitat associations were quantified for the Fortescue survey zone (where mesquite had the longest opportunity to spread throughout) by determining the proportion of each land system that contained grid cells with mesquite in each cover class. Land systems are a synthesis of soil type, topography, and vegetation type and represent the most accurate and highest-resolution land data available for the Pilbara region (Leighton et al. 2004). These data were subsequently used to estimate the total canopy cover of mesquite in each land system by using average percent covers for each cover class (sparse, moderate, and dense only).

RESULTS

A total of 216 654 ha were surveyed (6367 grid cells in June and 5438 in November, including 94 overlapping grid cells that were surveyed both times). The total cost of data acquisition (calculated at an exchange rate of \$0.78 USD/AUS) was \$87 612 USD, or \$0.39 USD per hectare. Costs consisted primarily of labor (819 hours, at \$46.8 USD per hour) and helicopter hire (68 hours at an average of \$517 USD per hour plus fuel).

Validation of Data

The distribution and density of mesquite mapped during the aerial survey matched closely with the local knowledge of pastoralists and weed managers, including the extent of the sparse to dense mesquite on the Fortescue Basin and the location and extent of incipient sparse populations in the Robe Catchment within Mardie Station. Two outlying grid cells that were categorized as sparse were questioned and subsequently identified during ground-truthing as *Acacia victoriae* Benth. In addition, a few outlying records of isolated mesquite were misidentified *Acacia farnesiana* L. and *A. victoriae*, both of which are similar to mesquite in both size and structure. At least some of these misidentifications were made by relatively inexperienced observers. Comprehensive accuracy assessment was not undertaken on the ground, and the extent of isolated mesquite on Yarraloola Station, on which *A. victoriae* and other shrubs are common, may be an overestimate.

Aerial surveys also agreed closely with results from quantitative ground surveys conducted where mesquite was classified during the aerial surveys as either absent or isolated, even in native shrublands (including *Hakea suberea* S. Moore, *A. farnesiana*, and *A. xiphophylla* E. Pritz; Table 1). Only 15 mesquite plants (6 small adults and 9 large adults), or 0.06 adults per hectare, were recorded in the 268 ha of ground surveyed at sites classified from the air as "no mesquite." This compared with an average of 1.5 adult plants per hectare (or a canopy cover of 0.13%) across the 143 ha classified as "isolated mesquite."

There was strong agreement between the 2 aerial surveys on the presence of mesquite within a grid cell (98.9%). However, overall agreement in cover classifications between surveys were very poor (32%), mainly because most grid cells assessed as moderate or dense in June were assessed as sparse in November (Table 2).

Table 1. A comparison of mesquite canopy covers estimated from the air (as either no mesquite or isolated mesquite) and from the ground located within native shrublands and grasslands.

		Ground survey			
		Area subsampled (ha)	Cover ¹	Plant density (per ha)	
Vegetation type	Rep			Small adults (1.5–3 m)	Large adults (> 3 m)
Aerial survey cover					
Native shrublands					
No mesquite (0% cover)	1	34	0.00%	0.00	0.00
	2	26	0.01%	0.04	0.08
Isolated ($\leq 0.6\%$ cover) ²	1	32	0.22%	2.25	0.70
	2	20	0.21%	1.16	1.00
Grasslands					
No mesquite (0% cover)	3	80	0.00%	0.00	0.00
	4	128	0.01%	0.04	0.05
Isolated ($\leq 0.6\%$ cover) ²	3	30	0.05%	0.27	0.23
	4	61	0.09%	0.97	0.28
All vegetation types					
No mesquite (0% cover)	1–4	268	0.01%	0.02	0.03
Isolated ($\leq 0.6\%$ cover)	1–4	143	0.13%	1.04	0.49

¹Cover estimates are based on average diameters of 2.5 (small adults) and 4.5 m (large adults; van Klinken et al. 2006).

²Cover estimates assume that all adults surveyed from the air were large (average diameter = 4.5 m), and are therefore likely to be overestimates.

Extent of Population and Habitat Associations

A total of 70 909 ha, or 29.3% of surveyed grid cells, contained mesquite, most of which were categorized as isolated (55.3%) (Table 3). Mesquite occurred within an area of 200 800 ha, with almost all the moderate and dense mesquite restricted to the Fortescue survey zone, occurring within an area of approximately 32 500 ha. Mesquite was relatively isolated toward the eastern part of the Fortescue zone, and there was very little in the Eramurra catchment. Mesquite was very widespread on the Mardie Station side of the Robe delta, although it was mostly isolated. There was very little mesquite south of the Mardie Station boundary, and any occurrences were isolated plants.

Within the Fortescue survey zone, mesquite was widespread and dense on the floodplains and delta deposits (Table 4). Extent and density was intermediate in the active floodplain, clay plains, sandy dunes, and samphire flats (low shrublands occasionally inundated by salt water). Mesquite was relatively rare on stony and gravelly plains and in the hills and ranges, especially in the higher basalt hills.

DISCUSSION

Visual Aerial Surveying as a Mapping Technique

Visual aerial surveying was an effective technique for detecting low numbers of individual mesquite plants and therefore very low mesquite cover levels (much less than 0.6% canopy cover across grid cells) even among mixed stands of similar shrubs and trees. This reflects the ability of the human eye to reliably differentiate individual mesquite canopies from background shrubland and grassland vegetation under the flying conditions of the aerial survey. Individual mesquite canopies can also be detected using existing remote sensing techniques, including automated extraction from aerial photographs and Digital Multispectral imagery (Robinson et al. 2006). However, it is not yet possible to discriminate mesquite from background vegetation with errors of omission and commission that are sufficiently small to reliably map it at low densities. However, if technically possible, the detection of mesquite at low densities is likely to require multispectral or hyperspectral imagery with a pixel size of less than half the object's diameter,

Table 2. Comparison of observations on grid cells categorized independently during the aerial surveys.

June survey	November survey						Disagreement (with June survey)
	No mesquite	Isolated	Sparse	Moderate	Dense	Total	
No mesquite	0	1	0	0	0	1	—
Isolated ($< 0.6\%$ cover)	0	1	0	0	0	1	—
Sparse (0.6%–20%)	0	3	27	1	0	31	13%
Moderate (20%–50%)	0	3	22	1	0	26	96%
Dense ($> 50\%$)	0	0	28	6	1	35	97%
Total	0	8	77	8	1	94	
Disagreement (with November survey)	—	88%	65%	88%	—	—	
Overall agreement							32%

Table 3. The total area of mesquite, by cover class, in the 4 survey zones (Fig. 1A).¹

Survey zone	Cover class					Total
	No mesquite	Isolated	Sparse	Moderate	Dense	Surveyed (ha)
Fortescue	60.9%	14.5%	11.5%	7.5%	5.6%	110 649
Eramurra	98.4%	1.6%	0.0%	0.0%	0.0%	31 469
Robe: Mardie	63.7%	34.0%	2.2%	0.1%	0.0%	51 208
Robe: Yarraloola	94.9%	5.1%	0.0%	0.0%	0.0%	23 329
Total area (ha)	153 680	34 577	13 838	8 325	6 235	216 654

¹Data acquired in June and November 2004 (see Figure 1).

or 2 m (Lass et al. 2005; Robinson et al. 2006; Weber 2006). Vast areas of isolated mesquite (at least 35 000 ha, or 55% of the invaded area) are therefore not currently detectable using remote sensing. However, their detection is critical to the development, implementation, and evaluation of management strategies.

Mesquite canopies could be readily identified visually from the air. However, our technique was less effective when it came to synthesizing those observations into broad canopy cover classes within each grid cell, limiting its value for change detection. Results suggest that density assessments were internally consistent within surveys. For example, there were no discontinuities between assessments made on each side of the helicopter by paired observers, and there was no evidence of anomalies within a particular survey. However, there was poor calibration between the 2 surveys, mainly because grid cells recorded with diverse cover levels in the June survey were mostly classified as sparse in November. Differences may have partly been a reflection of the difficulty in visually estimating cover where the target plant can be highly clumped within grid cells and where there is a wide range of canopy covers (0.6%–50%). Also, the perception of cover by surveyors in each survey may have been affected by the fact that the June survey was predominantly over relatively dense mesquite, while the November survey was over sparse and isolated mesquite. Further effort is clearly required to better calibrate cover assessments between observers, between surveys, and between observers and reference sites, as has been the case for analogous ground-based visual assessment techniques (Tothill et al. 1992) and aerial surveys of vertebrates (Caughley and Grigg 1982; Pople et al. 1998) and forest pests (McConnell et al. 2000). Possible improvements include the training (e.g., through “backseat apprenticeships”) and testing of spotters in their ability to distinguish plant species and to estimate cover levels (Pople et al. 1998; McConnell et al. 2000), to calibrate cover estimates by each observer against grid cells of known cover classes prior to each survey, and to structure surveys such that areas with high and low canopy covers are done separately.

Acquisition costs for visual aerial surveys are high because of the high labor component. There will be considerable local variation in cost estimation, especially in the availability and expense of an aircraft and of labor. However, at \$0.39 USD per hectare, it was comparable with 1-m-resolution video multi-spectral imagery (\$0.21–\$0.44 USD per hectare) and considerably cheaper than airborne hyperspectral imagery (e.g., CASI, \$1.50 USD per hectare; Lass et al. 2005). Furthermore, visual aerial surveying relies on the ability of observers to detect and discriminate mesquite and to rapidly synthesise large amounts

of information into counts and cover estimates. Data-processing requirements, with respect to both skill and time, are therefore negligible when compared with remotely sensed data (Yang et al. 2003; Lass et al. 2005). Additionally, mesquite can be detected at much lower densities than with existing remote sensing technologies. Nonetheless, in cases where spectral discrimination from background vegetation is possible, remote sensing should offer much greater spatial resolution (e.g., presence within 1-m² grid cells as compared with the cover classes within the 185 000-m² grid cells we used) and provide data at the accuracy required for change detection.

Mesquite Invasion in the Pilbara

Results from the aerial surveys proved useful in quantifying habitat associations of mesquite. Mesquite showed a particularly strong habitat association with land systems that had high pasture potential (Payne and Mitchell 2002) and therefore results in the greatest economic impact. Higher propagule pressure is likely to be a factor underlying these associations, as most mesquite seeds in the Pilbara region are dispersed through the dung of vertebrate herbivores, including livestock such as sheep and cattle, emus (*Dromaius novaehollandiae* Latham), and wallaroos (*Macropus robustus* [Gould]; van Klinken and Campbell 2001; R. van Klinken, unpublished data, 2006), and dispersal is therefore likely to be greatest in land systems with greatest pasture potential. However, habitat suitability also appears to be important, as even within high pasture potential land systems, mesquite showed a very strong association with some (especially floodplains and river deltas) but not others (e.g., clay plain gilgai).

Strong habitat associations provide a useful basis for predicting future spread of the surveyed mesquite population in the absence of further management of mesquite. Results suggest a rapid expansion of mesquite in the Robe River delta, similar to what has been observed on the Fortescue River delta in the past 70 years (T. Robinson, unpublished data, 2006), although invasion rates are likely to be slowed by the presence of an effective biological control agent (van Klinken et al. 2003; Anderson et al. 2006). Approximately 50 plants were recorded on Mardie Station in the Robe survey zone during a ground-based survey in 1983 (Western Australian Department of Agriculture and Food, unpublished data) compared with sparse to moderately dense mesquite being recorded over an 18 000-ha area during our survey (Table 3), suggesting that the population there has already undergone rapid increase. Further spread of mesquite to the southeast and northeast will be impeded as the natural movement of vertebrate herbivores is restricted by basalt and rugged jaspilite hills and ranges dominated by

Table 4. The percent of each land system within the Fortescue survey zone with grid cells in each cover class and the total percent canopy cover for each land system.¹ Poorly represented land systems were excluded (1 443 ha in total).

Land system ²	Carrying capacity ³		Cover class			Total area surveyed		
	No mesquite	Isolated	Sparse	Moderate	Dense	Surveyed (ha)	Canopy cover ⁴	
River plains with grassy woodlands and shrublands and tussock grasslands								
Floodplains and delta deposits	5–30	6.5%	12.4%	33.8%	26.7%	20.6%	28 842	28.2%
Active floodplain and major river	5–30	53.4%	31.7%	13.4%	1.1%	0.4%	4 847	2.0%
Alluvial plains with tussock grasslands or grass shrublands								
Gilgaied clay plains	16–30	69.5%	25.8%	3.0%	1.2%	0.6%	26 122	1.1%
Coastal plains, dunes, mudflats, and beaches								
Sand plains, dunes, and clay plains	51–80	24.6%	65.2%	8.0%	2.1%	0.0%	3 460	1.6%
Mudflats, sandy dunes, and samphire flats	> 120	69.7%	6.9%	18.6%	1.7%	3.0%	4 274	4.7%
Stony plains with acacia shrublands								
Basalt-derived stony plains	51–80	94.0%	3.6%	2.4%	0.0%	0.0%	9 861	0.2%
Stony plains with spinifex grasslands								
Gravelly plains	> 120	89.8%	10.0%	0.2%	0.0%	0.0%	8 510	0.0%
Hills and ranges with spinifex grasslands								
Rugged ridges (jaspalite)	> 120	90.2%	4.5%	4.9%	0.4%	0.0%	4 144	0.6%
Basalt hills	> 120	99.0%	0.9%	0.1%	0.0%	0.0%	19 148	0.0%
Total (ha)							109 206	8.1%

¹Data were obtained primarily during the June 2004 survey (Figure 1).

²Land systems are according to van Vreeswyk et al. (2004).

³Carrying capacity estimated as hectares required to produce 1 cattle unit per year (Payne and Mitchell 2002).

⁴Percent canopy cover was estimated using the mid-point values of each cover class (dense: 75%; medium: 35%; sparse: 10%).

spinifex grasslands, at least in the absence of human-assisted dispersal events.

MANAGEMENT IMPLICATIONS

No mapping approach offers a panacea for assessing plant invasions (Mack 2000). Remote sensing technologies promise much, but currently do not offer solutions for landscape-scale mapping of many invasive plants. This is particularly true when the objective is accurate surveillance or mapping of plants at very low densities (e.g., <0.6% canopy cover), especially where definitive spectral reflectance signatures are lacking, as is the case for mesquite. Even when a high level of spectral discrimination is possible, image acquisition is typically restricted to a very limited window when the target plant is phenologically distinct (Everitt 2002; Hunt and Parker Williams 2006). Systematic, visual aerial surveying techniques therefore offer considerable potential as an intermediate between highly quantitative remote sensing and spatially constrained ground-based surveying, as it has for other applications (McConnell et al. 2000). Acquisition costs compared well with high-resolution images and our technique required considerably less expertise to conduct the survey and to process the data. However, the technique we used requires improvement, such as the development of calibration techniques, if it is also to become a valuable and reliable tool for change detection.

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