Changes in the distribution and density of bitou bush (*Chrysanthemoides monilifera* subsp. *rotundata* (DC.) T.Norl.) in eastern Australia

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Summary

Bitou bush (*Chrysanthemoides monilifera* subsp. *rotundata* (DC.) T.Norl.) is a South African shrub that has invaded large areas of coastal south-eastern Australia. It is widespread along the coast, where it negatively impacts native plants and ecological communities. Detailed spatial information is critical for making informed management decisions, particularly to assist in setting on-ground priorities and allocating resources, and to evaluate the effectiveness of weed management.

The distribution of bitou bush was mapped previously in New South Wales; this paper presents an updated assessment of the distribution and density of bitou bush in Australia for 2008. The data were collated from a range of land managers and community groups, and analysed to determine area, density and spatial changes in bitou bush distribution. Mapping data were also analysed with respect to conservation areas in New South Wales, and national bitou bush containment lines, established to prevent northern and southern spread. The total area of bitou bush in Australia increased by 20% since 2001; 83% of the increase consisted of infestations with less than 10% cover. However, this spread has been offset by a 43% reduction in infestations with greater than 40% cover. Some of the overall increase in area may be attributed to a more comprehensive survey methodology, as this study may have captured sparse infestations that were not recorded in previous surveys.

The distribution of bitou bush was found to be highly coastal, with 90.3% of bitou bush within 2.5 km of the coastline. The area of bitou bush in conservation areas in New South Wales decreased by 21%, including a 56% decrease in infestations with greater than 40% cover. Management in national containment zones has successfully restricted bitou bush spread and significantly reduced its density in these nationally significant areas. Continued support for strategic control programs will ensure the spread of bitou bush in Australia is contained.

Key words: containment zones, conservation areas, impact, maps, spread, Weeds of National Significance, weed surveys

Introduction

History

Bitou bush (*Chrysanthemoides monilifera* subsp. *rotundata* (DC.) T.Norl.) is a highly invasive alien shrub that has colonised large tracts of coastal New South Wales and parts of south-east Queensland and eastern Victoria. Native to south-eastern coastal regions of South Africa (Neser and Morris 1985), bitou bush was first recorded as naturalised in Australia around 1908, near Newcastle in New South Wales. Then known as *Osteospermum moniliferum* L., bitou bush soon became recognised as weedy and was first gazetted as a noxious weed in 1909 at Stockton, New South Wales. It was later removed from the noxious weed list. It was recognised to have value as a dune stabilizing species and deliberately planted along large parts of the New South Wales coastline (Sless 1958, Barr 1965) from 1946 to 1968, to stabilise coastal sand drifts (Mort and Hewitt 1953) and to revegetate sand dunes following mining for rutile, zircon and gold (Barr 1965).

By the mid-1960s, concerns were being raised over its invasive potential, and deliberate plantings ceased in 1968 (Weiss *et al.* 1998). By the mid 1980s concerns were raised about its spread and impacts (Love and Dyason 1985). However, it was not until the late 1990s that it was formally recognised as a serious weed, through: (i) the listing of bitou bush as a noxious weed under the New South Wales *Noxious Weeds Act 1993*; (ii) the listing of the invasion of native plant communities by *Chrysanthemoides monilifera* (bitou bush and boneseed) as a key threatening process (KTP) under the New South Wales *Threatened Species Conservation Act 1995* (TSC Act) (New South Wales SC 1999); (iii) it being declared one of the 20 Weeds of National Significance (WoNS), together with boneseed (*Chrysanthemoides monilifera* subsp. *monilifera* (L.) T.Norl.), the other invasive subspecies in Australia (Thorp and Lynch 2000); and (iv) in response to the KTP listing, the preparation of a New South Wales Threat Abatement Plan (DEC 2006) to reduce, abate or ameliorate the impact of bitou bush. Recognising the scale of the bitou bush problem in New South Wales, bitou bush was declared noxious in Queensland in 1981 and Victoria in 1997. Bitou bush has only invaded limited areas in eastern Victoria and south east Queensland and is under eradication in both states (Cherry *et al.* 2008).

Bitou bush mapping surveys

Accurate mapping is needed to make informed management decisions (Downey 2010). Three statewide bitou bush mapping surveys were conducted in New South Wales prior to 2008. In 1981-82, foredunes and seaward aspects of headlands were aerially surveyed, revealing bitou bush covered 58.7% of the New South Wales coastline (Love 1985, Stanley *et al.* 1989), though bitou bush was not measured in other habitats. Bergs (1986) determined infested coastal dune areas by aerial photo interpretation and recorded bitou bush presence on 92.9% of dunes, equating to 46 937 hectares of bitou bush infestation on sand dunes alone in New South Wales. In 2001, Thomas (2002) mapped bitou bush infestations using aerial photo interpretation followed by extensive ground-truthing. Bitou bush was recorded along 900 km or 80% of the New South Wales coastline, covering 36 767 hectares (Thomas 2002, Thomas and Leys 2002).

Value of mapping

Key objectives of the WoNS Bitou Bush and Boneseed Strategic Plan (ARMCANZ *et al.* 2000) and New South Wales Bitou Bush Threat Abatement Plan (TAP) (DEC 2006) were to re-map the distribution and abundance of bitou bush (i.e. post 2001) and to establish, and ensure control was undertaken in, national bitou bush containment zones in northern and southern New South Wales. The northern and southern bitou bush containment lines were established under the WoNS Strategic Plan to prevent northern and southern spread respectively, and to contract the core bitou bush distribution (i.e. the entire distribution excluding Victorian and Queensland infestations).

In addition to bitou bush containment to reduce spread, bitou bush poses a significant threat to native species and ecological communities (DEC 2006), many listed as threatened under the TSC Act. Reserved conservation areas, and other state and local government lands, as well as private conservation lands are important refuge areas for threatened species and ecological communities. A key action in the Bitou TAP is to reduce the impact of bitou bush at priority sites in New South Wales, many being on lands reserved for conservation. An analysis of the success of bitou bush control efforts on conservation lands is required. In addition to evaluating control programs on conservation lands, an evaluation of where change in bitou bush distribution has occurred requires attention. Weiss *et al*. (2008) reported that the potential distribution of bitou bush covers a much greater area than the actual distribution, and extends to some inland areas. Thus, inland movement of bitou bush needs to be documented early to reduce possible spread.

Aims

The aims of this study are to: 1) report the distribution and density of bitou bush in Australia in 2008 (approximately 100 years after its naturalisation); 2) determine area, density and spatial changes in the core bitou bush distribution (in New South Wales) from 2001 to 2008; and 3) determine bitou bush area and density changes in conservation areas, and in national bitou bush containment zones. To determine distribution and density changes, only the 2001 survey (Thomas 2002) was used because earlier surveys only measured distance of coastline infested or the area of bitou bush on sand dunes. This study identifies the nature and scale of the problem as at 2008 and measures the progress of strategic control programs to assist future planning and management.

Materials and methods

Collecting and collating mapping data

Land managers were the primary source of detailed mapping data for each local area. Relevant weeds officers from coastal councils, New South Wales National Parks and Wildlife Service (NPWS) pest management officers and rangers, as well as community groups, were asked to provide bitou bush distribution and density mapping data for their Local Government Area (LGA) or reserves. In addition, a series of workshops were held along the New South Wales coast where the authors worked with weed officers, other land managers and community groups to collect bitou bush distribution data for 2008.

Land managers were sent 1:25 000 topographic maps (base maps) of their management regions, along with the respective 2001 bitou bush mapping data from the same area. The 2001 maps offered land managers coarse guidance on where infestations were historically located. Land managers were asked to outline the 2008 extent and density of bitou bush infestations by drawing on the base maps using the provided density classes. Ground-truthing was conducted by land managers. Land managers were asked to classify the density of infestations using six density classes: absent, sparse, light, medium, heavy, and very heavy (Table 1). An 'unknown' class was also used for 32 ha of infestations where bitou bush was present but density was unknown. Due to the small area of unknown density this class was excluded from comparisons between 2001 and 2008 data. The density classes correspond to the percentage of live bitou bush foliage projected over the ground when viewed from above. Classes are mostly consistent with national mapping (WoNS) protocols (McNaught *et al*. 2006). Descriptions of density classes, and how they relate to WoNS and Thomas' (2002) density classes, are presented in Table 1.

The majority of mapping data were collected between January and May 2008. Contributors supplied hand-drawn maps or digital GIS shapefiles. The data were supplied as polygons and assigned a density class. Using ArcMap GIS software (ArcGIS 9.2 2007), data were digitised and merged into one common shapefile. The 2001 mapping data were also available to the authors as a GIS shapefile in the same format described above.

The collated 2008 shapefile was viewed and coarsely compared to the 2001 shapefile to identify areas throughout the core bitou bush range that may have been overlooked in the above process. Where possible gaps in the 2008 data were identified, the relevant land managers were contacted to provide mapping data, or, alternatively, to ascertain if other bitou bush mapping surveys had been conducted recently. Mapping data from such surveys were added to this study's statewide dataset if:

Table 1. Bitou bush mapping density classes used and how they compare with other mapping density classes used previously.

Bitou bush density class	Description	Standard WoNS density class [1]	Thomas (2002) density class
Absent	No plants found during survey	Class 1	no plants found during survey
Sparse	One or two plants only	Class 2	
Light	< 10% cover, infrequently dispersed seedlings, small or large plants and small clumps	Class 3	< 10% cover, infrequently dispersed seedlings, small or large plants and small clumps
Medium	10 to 40% cover, plants and small clumps readily located, generally uniformly dispersed throughout the site; occasional clumps	Class 4 equivalent	10 to 40% cover, plants and small clumps readily located, generally uniformly dispersed throughout the site; occasional clumps
Heavy	40 to 70% cover, dense clumps forming continuous infestations in patches, with native flora still present in patches	Class 5 equivalent	> 40% cover, continuous infestations of numerous seedlings, young plants and established plants throughout the site
Very heavy	> 70% cover, bitou bush plants essentially forming monocultures		
Unknown	Bitou bush known to be present but density unknown	Class 6	
Not surveyed	Not surveyed	Class 8	

[1]McNaught *et al*. 2006.

1) similar mapping techniques were used; 2) mapping was conducted over a similar time period, and 3) comparable density classes were used. As a result, an area of 3 002 ha from seven mapping surveys was added. Four of the seven surveys used different density classes to those in this study. Where this occurred, bitou bush polygons were assigned the most appropriate class from this study (Table 1). Mapping data from two further mapping surveys (amounting to 937 ha of bitou bush) were also added to this study's dataset as it was of higher accuracy and/or resolution than the information provided by data contributors. Where two sets of mapping from data contributors overlapped, the highest resolution data were retained.

Spatial analysis

For clarity, the methods and results below are reported in relation to: 1) the core distribution (New South Wales) with respect to i) area and density changes, and ii) changes in location of infestations, 2) conservation areas, and 3) national containment zones. The small remaining populations of bitou bush in Victoria and Queensland are under eradication, hence data from these jurisdictions is not analysed here.

Area and density changes in the core distribution

The total area of bitou bush infestation in New South Wales in 2008 was calculated using ArcMap GIS software (ArcGIS 9.2 2007). The area in each density class (see Table 1) for 2008 was also calculated and compared with 2001 data to analyse change in density.

The above methods closely follow that of Thomas (2002), and were originally defined by Williams and Gerrand (1999). However, this study's methods differed to Thomas' in the following ways: (i) a sparse density class was included in this study to allow for areas with 'one or two plants only' (see Table 1); and (ii) where Thomas (2002) determined distribution and density by interpretation of 1:10 000 or 1:8 000 colour aerial photographs with ground-truthing, this survey provided base maps and the 2001 mapping data to land managers, who were asked to provide bitou bush distribution and density as at 2008. As the 2001 mapping did not use a sparse density class, two approaches were used to compare 2008 to 2001 data. The first method compares 2001 data with all 2008 data, combining the 2008 sparse and light classes for comparison to the 2001 light class. The second method compares the 2001 data with only the equivalent 2008 density classes (light, medium, heavy and very heavy), and excludes the sparse density class, which was not used in 2001. For both methods, the 2008 heavy and very heavy classes were combined to represent infestations with bi-

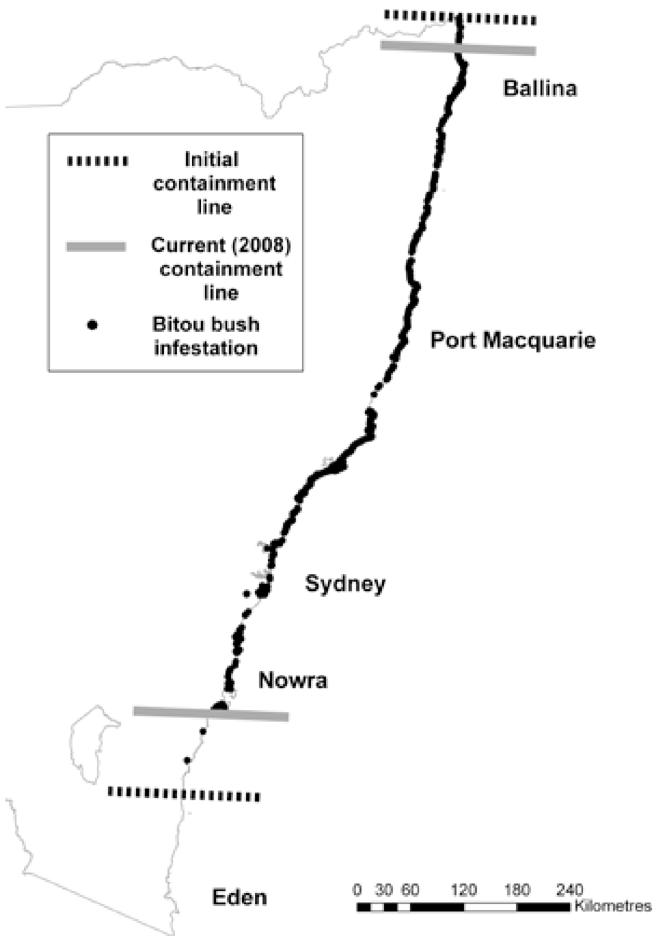

Figure 1. Map showing New South Wales bitou bush infestations in 2008 with cover greater than 10%. Lines represent the location of initial and current national containment lines. Note: infestation polygons are enlarged to increase visibility. New South Wales coastline layer source: © Department of Finance and Services.

tou bush cover greater than 40% (i.e. equivalent to the 2001 heavy class).

Bitou bush contraction and spread was determined from 2001 to 2008. The complete 2008 distribution was overlayed on the 2001 distribution. Areas with bitou bush mapped in 2001 but not 2008 represented bitou bush contraction. Areas with bitou bush in 2008 but not 2001 represented bitou bush spread (with the difference being the net change in area). Bitou bush density in the contraction and spread areas was also calculated.

Spatial change in the core distribution

To determine the change in location of bitou bush infestations, we focused on change in bitou bush area in relation to distance from the coastline.

To measure the distance of the New South Wales coastline infested with bitou bush, a definition of the 'coastline' that included the open coast, major coastal inlets and drowned river valleys was selected, as bitou bush is readily found in these areas. The coastal section of the New South Wales state boundary GIS layer was used for the coastline layer. It incorporated large coastal bays such as Botany Bay and Jervis Bay and drowned river valleys such as Sydney Harbour and Broken Bay. The total coastline length according to this layer amounted to 2 290 km.

To determine bitou bush infestations present on the coastline the GIS analysis required the bitou bush infestation layer to be overlayed on the New South Wales coastline layer. The above described New South Wales coastline layer represents the mean high water mark. Many bitou bush infestations do not grow directly on the mean high water mark, where terrestrial vegetation (including bitou bush) is, mostly, unable to grow. For the purposes of this analysis, a buffer was applied from the edge of the mean high water mark to form a zone that included all land 240 m inland. On the coastline, the first bitou

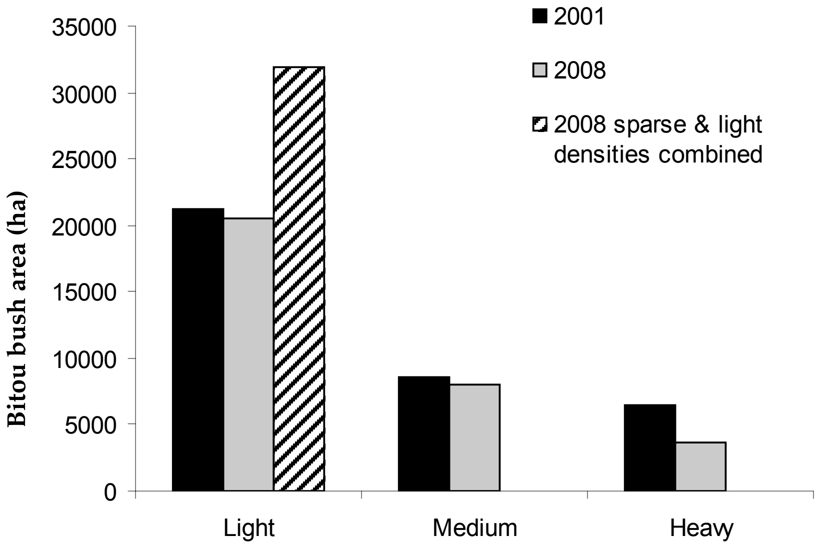

Figure 2. Change in area and density of bitou bush in New South Wales from 2001 to 2008. See Table 1 for explanation of density classes.

bush infestations are primarily found on headlands or on the foredune. The 240 m measure was selected because it spans the majority of the open sand areas (e.g. Stockton Beach, north of Newcastle) between the high water mark and the first record of bitou bush perpendicular to the high water mark. The buffered coastline was intersected where it overlapped with bitou bush polygons and the distance of infested coastline calculated. For comparison, this method was also applied to the 2001 data.

Thomas (2002) reported that 80% of New South Wales coastline was infested with bitou bush. In that study, the coastline length was determined by drawing a simple Euclidean line from the New South Wales/Queensland border to the New South Wales/Victoria border. Infested coastline was determined by projecting all infestation polygons on to a straight (vertical) line from north to south and intersecting these with the parallel Euclidean coastline. Detailed bitou bush mapping and readily available coastline GIS layers allowed a more accurate approach to be taken here.

Lastly, to assess spatial changes in the distribution of bitou bush, bitou bush area was determined at 100 m intervals from the coastline layer using ArcMap (ArcGIS 9.2 2007). The 2008 bitou bush infestation layer was overlayed on each 100 m interval of the coastline layer and the area within each interval calculated. For further analysis, 100 m intervals were grouped into larger 1 km sections. The above method was repeated for 2001 data.

Conservation areas

Lands reserved under the New South Wales *National Parks and Wildlife Act 1974*, hereafter referred to as 'NPWS estate', cover nearly 40% of the New South Wales coastline (DECC 2008). The area and density of bitou bush on NPWS estate was analysed as a proxy for all conservation areas occupied by bitou bush. Other conservation areas outside NPWS estate were not included as the relevant spatial information for these areas was not available to the authors. To analyse bitou bush distribution and density in conservation areas, infestation polygons were split and polygon portions that overlapped with NPWS estate were analysed.

National containment zones

In 1995, a national northern containment line was established along the Tweed River on the New South Wales/Queensland border (James and Wilson 2003, Bushland Restoration Services 2009). Since that time, the line progressed south to Letitia Spit, north of Kingscliff, and, more recently, to the boundary of Tweed and Byron LGAs, 35 km south of the initial line. The southern national containment line was established in 2002 at Tuross Heads, New South Wales (Southern Tablelands and South Coast Noxious Plants Committee 2007, Thompson and Pomery 2008). The line has progressed north 105 km and currently stands south of Sussex Inlet, in the Shoalhaven LGA. To analyse progress of northern and southern containment efforts, we classified the northern containment zone as all coastal areas in New South Wales north of Byron LGA; and the southern containment zone as all coastal areas in New South Wales south of Sussex Inlet. Bitou bush area and density in 2001 and 2008 was compared within the northern and southern containment zones to assess progress towards national containment efforts.

Results

Area and density changes in the core distribution

The 2008 distribution of bitou bush in New South Wales, including the location of the northern and southern containment lines, is illustrated (Figure 1). Bitou bush infestations covered 43 588 ha in New South Wales in 2008. Of this total, 26% of the area was of sparse density, 47% light, 18% medium, 8% heavy, 1% very heavy, and less than 0.1% unknown density (Figure 2).

Bitou bush was recorded as absent from 4 620 ha that were previously occupied by bitou bush in 2001. Although bitou bush no longer occurred in 4 620 ha, the total area of bitou bush infested land in New South Wales increased by approximately 20% from 2001 to 2008 (36 408 ha to 43 588 ha), when the sparse density class was included in the comparison. There was an approximate 43% decrease in the area of heavy density infestations, a 7% decrease in medium density infestations and a 50% increase in light density (including sparse infestations) (Figure 2). When considering only the density classes used in the 2001 survey (i.e. excluding the sparse class), the total area of bitou bush in New South Wales decreased by 11% from 2001 to 2008 (36 408 ha to 32 274 ha), including a 2% decrease in light density infestations (Figure 2).

The area of bitou bush spread amounted to 20 446 ha, including 53% sparse, 30% light and 12% medium density. Conversely, the area of bitou bush contraction amounted to 13 265 ha, including 67% light and 22% medium density. There was a net increase (spread) of 7 180 ha, or 20% since 2001.

Spatial change in the core distribution

The results of plotting bitou bush area against distance from the coastline (at 100 m intervals) are illustrated in Figure 3a (2001) and 3b (2008). For both time periods, the majority of bitou bush is found in close proximity to the coast. In 2001, 91.7% of the area of bitou bush was found within 2.5 km of the coast, and 90.3% in 2008. Throughout the distribution, increases in area are observed at each 1 km interval from the coast from 2001 to 2008. However, the largest percentage increases (in areas approximately 1 000 ha or more) were within the zone 1-4 km from the coast, including a 48% increase in the 1-2 km zone, 77% in the 2-3 km zone, and 50% in the 3-4 km zone. In the zone 1 km immediately adjacent to the coast, where 64% of bitou bush area was in 2008, there was a 9% increase in area from 2001.

In 2001 and 2008, in the core bitou bush distribution, the furthest infestations from the New South Wales coast (high water mark) were 9.5 km and 12.8 km distant from the coast, respectively, on the shores of Lake Macquarie on the Central Coast of

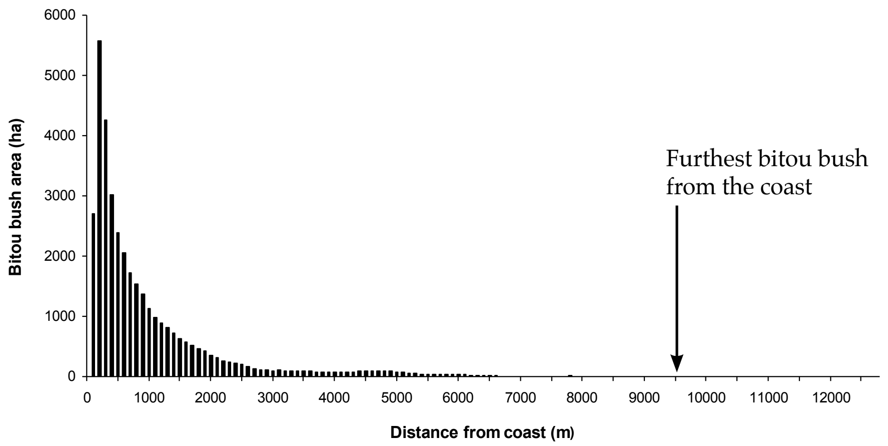

Figure 3a. Area of bitou bush in relation to distance from the open coast (high water mark) in 2001.

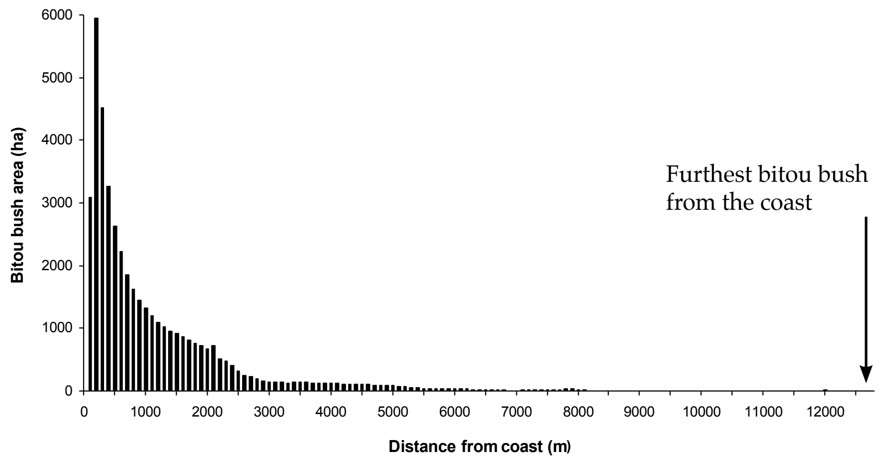

Figure 3b. Area of bitou bush in relation to distance from the open coast (high water mark) in 2008

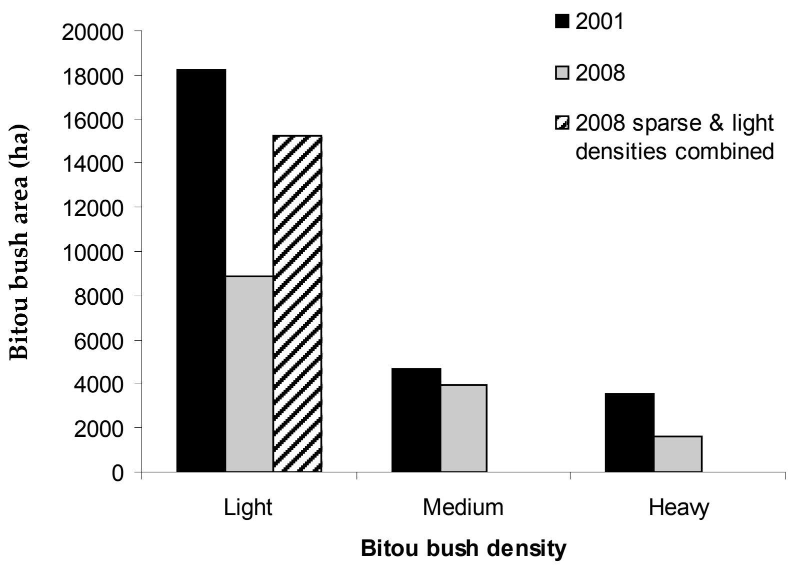

Figure 4. Change in area and density of bitou bush in conservation areas of New South Wales (lands reserved under the New South Wales *National Parks and Wildlife Act 1974***) from 2001 to 2008). See Table 1 for explanation of density classes.**

New South Wales. However, the furthest infestation from a tidal water source (river or lake) was only 5.1 km in 2001 (west of Newcastle) and 7.3 km in 2008 (near Wollongong).

With regard to the distance of coastline infested, in 2008 bitou bush (including the sparse density class) was present along 1 049 km of New South Wales coast, equating to approximately 45.8% of the New South Wales coastline. Applying the same method to the 2001 mapping revealed that 1 033 km or 45% of the New South Wales coast was infested with bitou bush.

Conservation areas

The area of bitou bush infested land on NPWS estate totalled 20 798 ha in 2008. When including the sparse density class in the comparison, the area of bitou bush infestations on NPWS estate decreased by 21% since 2001. More specifically, there was an approximate 56% decrease in heavy density infestations, 14% decrease in medium infestations and a 16% decrease in light density (including sparse) infestations was achieved (Figure 4). When excluding the sparse density class, the area of bitou bush on NPWS estate decreased by 45% (26 432 ha to 14 450 ha) since 2001 (Figure 4), with a 56% decrease in light density infestations.

National containment zones

The movement of national bitou bush containment lines over time is depicted in Figure 1. When including the sparse class in the comparison, in the northern containment zone, the total area of bitou bush declined by approximately 6% (Table 2) since 2001. The most marked reductions in the northern containment zone were observed in the heavy (94%) and medium (89%) density classes. This was offset by an increase of 275% in light density (including sparse). In the southern containment zone, the total area of bitou bush decreased by approximately 34% since 2001 (Table 2). Again, the most marked reductions were in heavy (88%) and medium (97%) density infestations, with a 14% decrease in light density (including sparse).

When excluding the sparse density class, the total area of bitou bush in the northern containment zone declined by approximately 19% since 2001 (Table 2), with a 219% increase in light density. Similarly, the area of bitou bush in the southern containment zone decreased by approximately 79% since 2001 (Table 2), with a 74% decrease in light density.

Discussion

Limitations of analysis

Discussion of how survey methods from this study differ to that of Thomas (2002) is required to interpret the results. This study contained 'sparse' (defined as 'one or two plants only') as the lowest density class, whereas 'light' was the lowest

Table 2. Change in density and area of infestations in the northern and southern bitou bush containment zones in New South Wales from 2001 to 2008.

Bitou bush density[1]	Mapping survey					
	Northern containment zone			Southern containment zone		
	2001 (ha)	2008 (ha)	% change	2001 (ha)	2008 (ha)	% change
Sparse	n/a[2]	129.3	-	n/a[2]	1721.7	-
Light	231.3	737.7	218.9	2877	750.1	-73.9
Medium	371.6	42.7	-88.5	889.2	28.9	-96.7
Heavy[3]	386.8	23.6	-93.9	61.8	7.7	-87.5
Total	989.7	933.3	-5.7	3828	2508.4	-34.5

[1] See Table 1 for definitions of density classes; [2] Not measured in 2001; [3] Includes heavy and very heavy 2008 density classes

density class in the 2001 mapping survey. There is potential for this study to capture a greater area of bitou bush due to the sparse density class being available to data contributors thereby artificially increasing bitou bush distribution in 2008. Further, it is probable that data contributors designated large tracts of land as 'sparse' which consisted of very low density bitou bush unevenly scattered across a large area, thus including many areas without bitou bush. For example, at Nelson Bay an area of approximately 1 400 ha was mapped as sparse density in 2008, but bitou bush-free in 2001. Though it is likely that bitou bush has spread, it is unlikely that it occurs sparsely across the entire area. Such areas may have been excluded in the 2001 mapping due to the lack of a sparse density class.

Other differences in methodology include the increased data capture efficiency of this survey and the method and scale of data collection. Thomas (2002) collected data by aerial photo interpretation of 1:10 000 and 1:8 000 aerial photos, whereas here aerial photo interpretation did not occur and mapping was at a coarser scale (1:25 000). GIS software was also utilised here to compare 2008 and 2001 mapping to identify possible gaps in 2008 data collection. To fill data gaps, several land managers were contacted to verify the current status of bitou bush. Such efforts were not available to Thomas (2002).

Changes in area and density

Despite the varied survey methods, a conservative approach of including sparse infestations in comparisons with 2001 data is taken here. When this approach is used, the data shows that the total area of bitou bush-infested land increased by 20% since 2001, and that most spread consisted of infestations with less than 10% cover. It is likely that this increase in total area is due to a combination of actual bitou bush spread and differences in survey methods. However, this spread has been offset by substantial decreases in the density of bitou bush infestations, by as much as 43% for infestations greater than 40% in cover.

Increases in bitou bush distribution with concurrent decreases in higher density infestations have been observed previously, at a regional scale, on the Tomaree Peninsula on the mid-north coast of New South Wales. Schroder *et al.* (2008) found that, over a ten year period, bitou bush distribution increased by 3.5% but that this increase was accompanied by considerable reductions in density. Infilling in the core infestation coupled with decreases in density, is consistent with management goals for widespread weeds such as bitou bush. Management focus is often on containing spread and protecting important environmental assets (Environmental Weeds Working Group 2007), consistent with the WoNS Bitou Bush and Boneseed Strategic Plan (ARMCANZ *et al.* 2000).

Where have changes occurred?

In addition to analysing change in the area and density of bitou bush, this study aimed to determine where changes in distribution occurred. Weiss *et al*. (2008) showed that the potential distribution of bitou bush in Australia, based on climatic parameters, extends westward along inland waterways. Indeed, inland bitou bush populations have been found in the past persisting near Stroud and Girvan (Winkler *et al.* 2008), up to 34 km from the open coast in the Great Lakes area; near Clarence Town in the Hunter Valley, 30 km from the open coast (R. Armstrong personal communication); and up to 20 km inland along the Nowra River in the Shoalhaven region of New South Wales (Winkler *et al.* 2008). This excludes deliberate plantings and persistence of bitou bush at Menindee Lakes in far west New South Wales. However, after 100 years of bitou bush presence in Australia, bitou bush has not shown significant inland (westward) expansion. In this study, infestations furthest from the coast occurred along the shores of Lake Macquarie, a tidal coastal lake. Bitou bush was found persisting even closer to inland tidal water sources (rivers and lakes). It is probable that if bitou bush were to further increase in distribution it would be in proximity to tidal lakes and rivers. Regular mapping surveys like those presented here are critical for monitoring and management of inland spread of bitou bush, particularly in close proximity to tidal lakes and rivers.

The majority of the increase in bitou bush area since 2001 was within 4 km of the coastline. Increases in bitou bush area were observed from 5 to 13 km from the coastline, but did not comprise large areas, despite being large proportional increases. Figure 3a and 3b reinforce that, in Australia, bitou bush predominantly inhabits coastal areas, including dunes and headlands, as has been observed in the native range in South Africa (Norlindh 1943, Weiss *et al.* 1998). Inland expansion of bitou bush has not occurred on a large scale. Limitations to the species' spread may include extensive control efforts and/or a range of non-climatic variables preventing establishment. Contrary to inland expansion, increases in bitou bush area are the result of infilling of near-coastal areas that were free of bitou bush in 2001. Furthermore, the distance of coastline infested with bitou bush decreased negligibly since 2001, from 45.8% to 45%, suggesting that most of the reported increase in area has not been on the foredune but rather in hind dune and other near-coastal habitats (see Figure 3a and 3b).

Changes in conservation areas and containment zones

Our results indicate that management within conservation areas and the northern and southern bitou bush containment zones is successfully reducing the distribution and density of bitou bush in these areas. Containment lines are being effectively used to restrict the spread and contract the core bitou bush distribution. This has been accompanied by reductions in heavy and medium density infestations (Table 2), which may reduce the spread potential of bitou bush and potential impacts on biodiversity. While areas of light and sparse infestations remain in 2008, these locations are under intense surveillance and management. In addition, recent efforts in the northern containment zone have succeeded in progressing the containment line to the Tweed/Byron LGA border and further works to contain bitou bush are underway (Strehling *et al*. 2011). These substantial efforts to contain bitou bush spread in New South Wales have occurred in concert with eradication and surveillance programs in south-east Queensland, which have resulted in the elimination of all major bitou bush infestations, and management efforts being reduced to annual removal of individual plants (Cherry *et al.* 2008). Similar efforts to eradicate remaining infestations in the east Gippsland area of Victoria are also underway (Adair and Butler 2010).

Factors contributing to change

Determining the factors contributing to changes in bitou bush distribution and density was beyond the scope of this study. However, a variety of integrated management efforts are likely responsible for: i) significant decreases in the density of bitou bush infestations, and ii) removal of 4 620 ha of bitou bush between 2001 and 2008. Since 2001, coordinated efforts to strategically manage bitou bush have been undertaken through implementation of the WoNS Bitou Bush and Boneseed Strategic Plan (ARMCANZ *et al.* 2000) and the New South Wales Bitou Bush TAP (DEC 2006). Control of bitou bush to protect biodiversity is occurring at 114 TAP sites across New South Wales. The TAP advocates control of bitou bush infestations to protect biodiversity at risk (DEC 2006) and recommends repeated follow-up control. Large reductions in bitou bush density have been documented across TAP sites (Hamilton *et al*. 2010; Hamilton *et al*. 2011). These strategic control efforts are assisted by, and coupled with, intense and enduring community effort. In addition, three bitou bush biological control agents, the bitou seed fly (*Mesoclanis polana* Munro), the bitou tip moth (*Comostolopsis germana* Prout) and the bitou leaf roller moth (*Tortrix* sp.) are reducing the reproductive ability of bitou bush (Edwards *et al.* 2009, Adair *et al.* 2012). However, this may not contribute significantly to density reductions (Adair *et al.* 2012).

Finally, refined management techniques, including opportunistic use of fire (Vranjic and Groves 1999, Thomas *et al*. 2006), targeted aerial spraying of herbicide (Toth and Winkler 2008) and other herbicide and mechanical control advancements (Winkler *et al.* 2008) have enabled land managers to more effectively control bitou bush and may contribute significantly to density reductions. In particular, the aerial application of low doses of herbicide (Toth *et al.* 1993; Toth *et al.* 1996) has enabled cost-efficient and effective control of bitou bush, particularly in otherwise inaccessible areas, with little off-target damage (Broese van Groenou and Downey 2006, Toth and Winkler 2008).

Conclusions

This survey provides comprehensive distribution and density data for the core bitou bush distribution in Australia in 2008, one of the few weeds for which such high quality national mapping exists. This data is critical to evaluate the effectiveness of control and containment efforts and validate the efficacy of best practice control techniques undertaken by land managers and community groups. This detailed mapping has many possible uses, including: assisting in setting on-ground priorities and allocating resources; providing baseline data for mapping and modelling; measuring the outcomes of weed control, and providing information to support funding applications and reporting (McNaught *et al*. 2006). Distribution and density data from this study was distributed to stakeholders for use at local and regional levels. It is recommended that future surveys of the distribution and density of bitou bush use the methods outlined in this study (i.e. standard density classes and data collection methods) to enable long-term comparisons with this and the 2001 survey (Thomas 2002). This study presents evidence to show that long-term control efforts are reducing the density of bitou bush in Australia. These significant reductions in infestation density must be sustained through continued strategic control to prevent reinvasion and further spread, and reduce the impact of bitou bush on native ecosystems.

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