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The creation of a New Zealand weed atlas

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Cover: *Morella faya* (fire tree) a very rare weed that has only been recorded from three hectads. *Photo: Clayson Howell.*

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Abstract

In this report, we describe the procedure used to compile an atlas of 181 environmental weeds in New Zealand. The distribution of each species has been depicted as a presence or absence in 100-km^2 (hectad) cells over the entire New Zealand political area. Data were initially obtained from herbaria and electronic databases, and the resultant distributions were then verified through a series of expert meetings (or 'office-truthing'). We found that although weeds are found almost everywhere in New Zealand, few weeds are widespread—and those species that are widespread have been naturalised for a very long time. Of the species we investigated, weed species richness is also clearly higher in urban areas, but unfortunately we are unable to separate any causal relationship from the probable bias in observer effort. The office-truthing process on average doubled the number of hectads in which each species was recorded, demonstrating its immense value in the creation of such maps. We recommend that this process is repeated on a 10-year basis to improve detection of significant range expansions, and to provide up-to-date information for the development of regional and national strategies for managing environmental weeds.

Keywords: environmental weeds, atlas, presence, absence, hectad, office-truthing, verification, New Zealand

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1. Introduction

Robust distribution data for environmental weeds are a fundamental requirement for planning, executing and reviewing weed management programmes. During the planning or initiation phase, the management response for a particular incursion should be based on an assessment of the stage of the invasion process (Hulme 2006) and the uncertainty around estimates of the occupied range (Moore et al. 2011). Quantified assessments of weed ranges can also be used to monitor changes in plant distributions over long time periods (Rich & Woodruff 1996; Preston et al. 2002) or compared with predictions made through climatic modelling (Rouget et al. 2004).

In New Zealand, distribution data for environmental weeds are often incomplete. Although range descriptions have been published for all naturalised plants in the flora volumes (e.g. Webb et al. 1988) or as updates in the *New Zealand Journal of Botany* (e.g. Heenan et al. 2008), these are based on selected herbarium specimens grouped by political district and are updated on an ad-hoc basis.

The simplest form of method for spatially representing distributions is to display known localities using dot-distribution maps. This approach has been used to produce a small number of national maps for a small number of weed species (e.g. Partridge 1987) and atlases depicting multiple weeds at a regional level (Howell et al. 2000; McAlpine & Sawyer 2003). However, although dot-distribution maps can be useful for depicting all known localities for newly naturalised weeds and can be used to predict the distribution of species (Pearce & Boyce 2006; Elith & Leathwick 2007; Phillips et al. 2009), they have limited value for quantitative analysis because there is often inconsistent search effort between species, and across spatial and temporal scales (Rich 1998), making it difficult to be confident that they accurately reflect the current species range. Ecological modelling studies have also shown that such presence-only techniques are most accurate for species with exacting habitat requirements (Guisan et al. 2007; Tsoar et al. 2007).

An alternative approach is to describe species distributions in terms of presence or absence within a series of equally sized cells. Such grid-based systems have been used in long-term repeat assessments of all plants in the British Isles since the 1950s (Preston et al. 2002) and for invasive plants in South Africa since the early 1980s (Henderson 1998). Eight New Zealand native tree species were nationally mapped on 10,000 yard grid squares between 1966 and 1982 using a methodology proposed by Wardle and MacRae (1966). This was followed by a recommendation (Molloy 1967) to use the same grid for selected weeds, but the work was never published.

The aim of this study was to produce the first national atlas of environmental weeds in New Zealand. Since weeds often have a broad range of environmental tolerances (Parker et al. 2003), it seems likely that it would be useful to record both presences and absences for these species. We investigated whether a grid system could be used to describe the presence and absence of a selection of environmental weeds using existing data.

2. Methods

2.1 Species selection

We primarily focused this investigation on the species listed in the National Pest Plant Accord (NPPA) (MAF Biosecurity 2008), as these weeds are nationally banned from sale, propagation and distribution, making it critical that we understand their current distribution. All species in the genera *Cenchrus*, *Equisetum*, *Hieracium*, *Nassella* and *Pilosella* are prohibited in New Zealand but are not individually listed in the Accord; therefore, we also included all species within these genera that have been recorded as naturalised within New Zealand (Howell &

Sawyer 2006) on our list. Hybrid taxa that have at least one parent as an NPPA species are also known from three genera (*Carpobrotus*, *Myoporum* and *Fallopia*); however, these were not included as they are usually found close to the parents and have not been consistently identified. This resulted in a list of 139 weed species.

In addition to the above, we also included 36 environmental weeds that are listed in two or more Regional Pest Management Strategies (RPMS) and six additional weeds that we suspect are having a large impact (*Agapanthus praecox*, *Caesalpinia decapetala*, *Ficus macrophylla*, *Phoenix canariensis*, *Pinus nigra* and *Pseudotsuga menziesii*).

The final list of 181 environmental weeds can be found in Appendix 1. We used accepted current names in New Zealand at the time of writing, some of which differ from those on the NPPA list. The majority of changes can be found in Champion et al. (2010), except for the grass species formerly included in the genus *Pennisetum*, where *Cenchrus* is now preferred (Simon 2010). For each species, the year of the first record of it having established outside cultivation was used to calculate the number of years that it had been naturalised prior to 2009.

2.2 Defining a new grid

We created a grid of 100-km^2 (hectad) cells that covered the entire New Zealand land area, including offshore islands, based on the New Zealand Transverse Mercator Projection (NZTM). This grid contained a total of 3235 cells, ranging from 97 (Taranaki) to 520 (Canterbury) cells per region (based on regional council boundaries). All hectads were classified as belonging to one of six island groups: Kermadec; North Island, including near-shore islands and the Manawatāwhi/Three Kings; South Island, including near-shore islands; Stewart Island/Rakiura, including Foveaux Strait islands and Solander Island (Hatuere); Chatham Islands; and subantarctic islands, including all islands in the Snares, Auckland, Campbell, Bounty and Antipodes groups.

2.3 Collating electronic data

We identified herbarium records and electronic datasets containing records of the selected environmental weeds and their curators were approached to request that distribution data be included in this investigation. All known synonyms and misapplied names were included in data requests to minimise the chances of valuable records unintentionally being overlooked. This resulted in data being obtained from six herbaria: Auckland War Memorial Museum Herbarium (AK), Landcare Research Allan Herbarium (CHR), New Zealand Forest Research Institute Herbarium (NZFRI), University of Otago Herbarium (OTA), Museum of New Zealand Te Papa Tongarewa Herbarium (WELT) and University of Waikato Herbarium (WAIK). In addition, records of weed observations that were not linked to specimens were sourced from three central government agencies (Department of Conservation (DOC)—BioWeb database and subantarctic islands weed database, Landcare Research—National Vegetation Survey Databank (NVS) and the National Institute of Water and Atmospheric Research (NIWA)—Freshwater Biota Information System (FBIS)) and eight local government agencies (Bay of Plenty Regional Council, Canterbury Regional Council, Greater Wellington Regional Council, Horizons Regional Council, Marlborough District Council, Northland Regional Council, Southland Regional Council and Taranaki Regional Council).

Extensive work was required to standardise plant names, reduce dates to year only and transform spatial references into the NZTM projection. All point data were overlaid with the grid of hectad cells in ESRI ArcMap 10.0. Draft maps were then created for each weed species, with cells shaded to indicate the presence of any records for the species within the boundaries of each hectad cell. These maps were used for data validation prior to creation of the final maps.

2.4 Testing data accuracy

The accuracy of a species' distribution when described as presence or absence within a series of cells can be tested in several ways. The most reliable method is to conduct field surveys to ground-truth the status of each weed (e.g. Hamilton et al. 2005). However, the positive identification of a plant can only confirm the species' presence and refute its absence—confirming its absence and refuting its presence can really only be given a probability based on the effort expended and the anticipated likelihood of finding the species if it was present. Therefore, we anticipated that large-scale field surveys to validate both presence and absence with high confidence would be very expensive. Instead, we aimed to validate presence records derived from available electronic datasets and to add strength to implied absences through consultation with regional weed experts. Although this expert meeting (or 'office-truthing') approach naturally carries less confidence than field surveys, it has previously been used to refine distribution models (Pearce et al. 2001) and may offer an efficient method of deriving cell-based data from point-locations.

2.4.1 Office-truthing

To office-truth the draft maps, we ran a series of 20 regional meetings between December 2009 and June 2010. We sent invitations to each local authority, regional DOC staff and other private individuals known to be knowledgeable about weeds (based on recommendations from DOC staff). This resulted in over 100 weed experts being interviewed. Using the draft maps, weed experts were asked to mark additional hectads within their region where they believed each weed was present between 2000 and 2009—this included records for cultivated plants outside containment facilities. We realised this would be contentious, but because definitions of what is established can vary considerably between authors (Gardner & de Lange 1996), and the plants are all recognised weeds, we believe that omitting cultivated plants would be a more serious error. Cultivated plants can clearly contribute to spread by providing pollen, seeds or vegetative material to wild populations. Weed experts were also asked to help identify any errors in the draft maps during the meetings, which were then referred back to the curators of the source data for verification. New records generated during these meetings were assigned coordinates corresponding to the centre of the relevant hectad—establishing a precise location for each new record would have been far too time consuming and was considered an unnecessary level of precision.

2.5 Creating maps

We used ESRI ArcMap 10.0 to create all maps. A map depicting the presence and absence of each weed species was created that also indicated the source of the most reliable record per hectad. Instances of presence qualified by herbarium specimens were ranked above those qualified by datasets and expert opinion. A hotspot map was then created illustrating the number of weeds from our list recorded as present in each hectad.

2.6 Statistical analyses

For each species, we compared the total number of hectads in the draft maps with those generated by the experts during the office-truthing meetings. We also calculated an average spread rate by dividing the total number of hectads occupied in 2009 by the length of time naturalised. To investigate how the number of hectads occupied changes with length of time naturalised we three models (linear, von Bertalanffy and exponential) and analysed residuals for goodness of fit.

To investigate the representativeness of herbarium specimens for presence or absence at the hectad scale, we calculated the proportion of hectad-presence records qualified by one or more herbarium specimens for each species. To characterise range, the number of island groups that each weed was recorded on was calculated, as well as the total number of weeds found on each island group and the subset of those that were not detected anywhere else.

All analyses were performed in R version 2.15.3 (R Core Team 2013). Data manipulation was performed using the packages 'plyr' and 'reshape2', and all graphs were created using the package 'ggplot2'.

3. Results

3.1 Number of herbarium and electronic records

The six herbaria provided 9131 weed distribution records, which are particularly valuable because the species identifications were verified by trained botanists and the specimens can be re-examined. The additional 12 datasets contributed a further 98 435 records. The number of electronic records varied widely between organisations, but every dataset provided some unique data, i.e. at least one instance of a weed recorded within a hectad that was not duplicated by any of the other 17 sources. The total number of records was not necessarily a good predictor of the number of relevant records, however; for example, 80 000 NVS plots captured observations of only 22 of the 181 weeds in this study.

3.2 Data validation

The series of 20 regional meetings collectively generated 20 673 additional records of an environmental weed being present within a hectad between 2000 and 2009. The number of hectads for which presence was confirmed through these meetings varied widely between species, with more than 1000 hectads being added for two weeds but no new hectads being added for 24 weeds. On average, however, the number of hectads added was equivalent to the number of hectads confirmed from electronic data, i.e. the meetings approximately doubled the number of records for a particular species (Fig. 1). Several of the presence records indicated on the draft maps were challenged during the meetings, 51 of which proved to be errors. These were most commonly a result of species misidentifications caused by observers using common names that were later ascribed to incorrect species, rather than incorrect locations being ascribed. However, occasionally the locations derived from the electronic datasets did not match the text description of the location and an incorrect hectad had been highlighted.

Across all weeds, only one-third of all presence records were supported by one or more herbarium specimens. However, weeds that had been detected in only a small number of hectads had a much greater proportion of their presences confirmed from herbarium specimens than more widespread species (Fig. 2).

3.3 Distribution of weeds

The maps depicting the presence/absence of each species as qualified by herbarium records, electronic datasets and/or expert opinion can be viewed at http://auricht.servebbs.com/SquareEyes/index.php1.

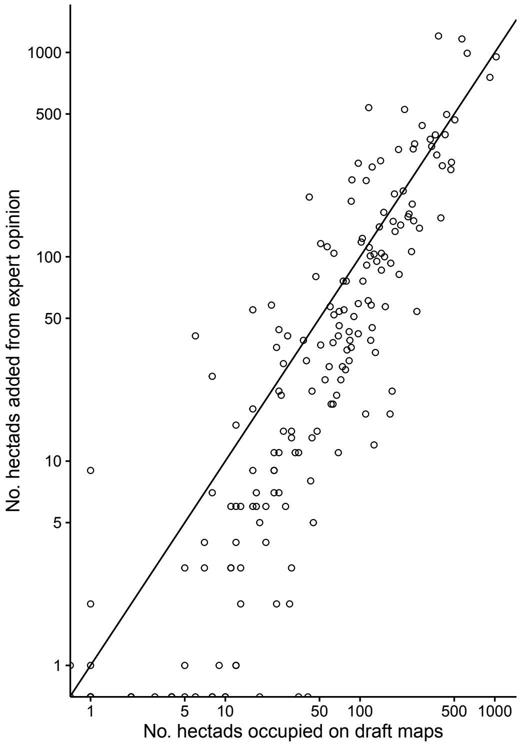

Figure 1. Relationship between the number of hectads confirmed from herbaria and electronic datasets and the number of hectads added during expert meetings. The linear regression line ($y = 1.05x - 9.0$, adj. $r^2 = 0.68$, $P < 0.001$) is shown.

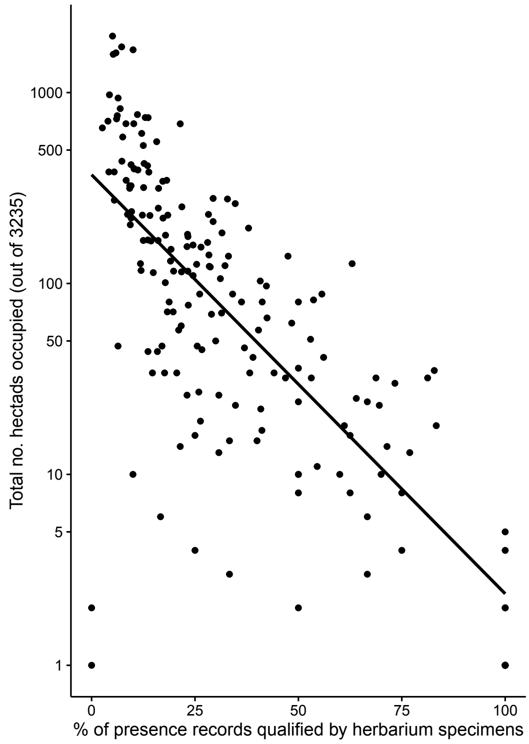

Figure 2. The relationship between the proportion of records of geographically restricted weeds that are qualified by herbarium specimens and the range of weeds. The linear regression line ($y = -0.054x + 6.11$, adj. $r^2 = 0.65$, $P < 0.001$) is shown.

We found that at least one environmental weed is currently present in 91% of the 3235 hectads across New Zealand (Fig. 3). Many of the remaining 290 hectads that completely lack any of the weeds on our list have a very small total land area, i.e. have limited ability to support any terrestrial plants. There appears to be a positive correlation between the number of weeds within individual hectads and the presence of urban areas, with the highest numbers of weeds being found in hectads that contain the main population centres of Auckland, Wellington and Christchurch, and to a lesser extent the provincial centres of Whangarei, Hamilton, Tauranga, Rotorua, Napier, Whanganui, Palmerston North and Nelson. Whanganui contains the hectad with the greatest species richness in New Zealand, with 102 weeds present.

The number of hectads in which each weed has been detected is included in Appendix 1. We found that most weeds are not widespread, with 143 (79%) of the 181 weeds we assessed currently being confined to less than 10% of all hectads. The most widely distributed weed is *Ulex europaeus* (gorse), which is present in 1976 (61%) of the hectads. Seven additional weeds are present in more than 25% of all hectads: *Jacobaea vulgaris* (54%), *Rubus fruticosus* (52%), *Cytisus scoparius* (50%), *Cirsium arvense* (49%), *Salix fragilis* (30%), *Cortaderia selloana* (29%) and *Tradescantia fluminensis* (25%). *Clematis vitalba*, which is arguably New Zealand's best-known environmental weed, is present in 23% of all cells.

None of the 181 weeds investigated here are currently present on all six island groups. Four species have been recorded from five groups, however: *Cytisus scoparius*, *Hypericum androsaemum* and *Ulex europaeus* are present on all except the Kermadec group, and *Cortaderia selloana* has been recorded as present on all except the subantarctic group (although it should be noted that this species is now considered eradicated from the Kermadec Islands; Carol West, DOC, pers. comm.). The North Island has greater weed richness (171 species) than the South Island (143 species) and also has the greatest number of weeds that are not found anywhere else (Fig. 4). All species recorded from Stewart Island/Rakiura (36 species), the Chatham Islands

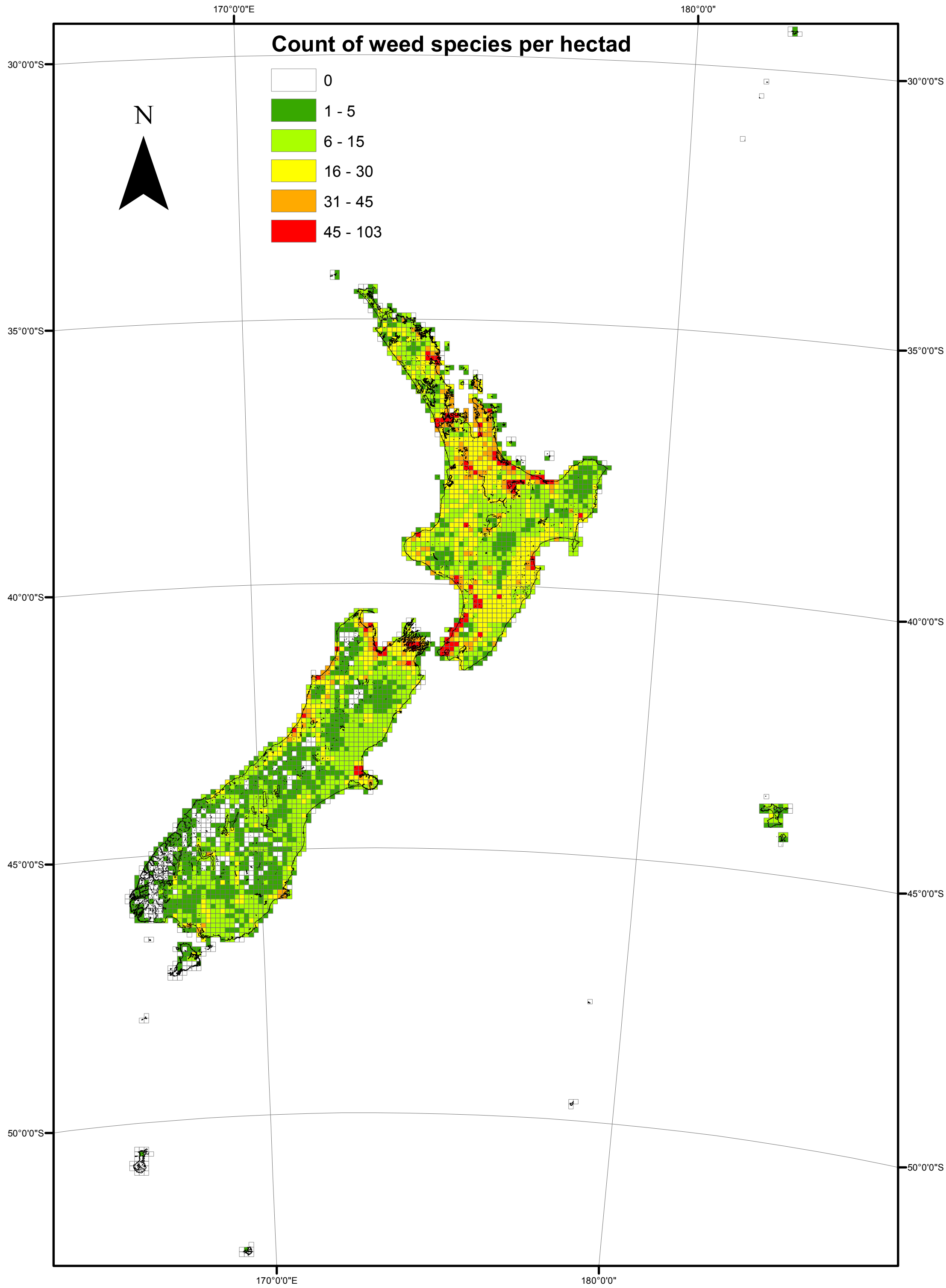

Figure 3. Hotspot analysis of the weed species richness detected in each hectad, based on records from herbaria, electronic datasets and expert opinion. 91% of all hectads have at least one weed present.

(39 species) or the subantarctic islands (3 species) are also present on both the North and South Islands. During this investigation, we found no records for *Cardiospermum halicacabum*. This weed is included on the NPPA, and was listed as being widely cultivated (MAF Biosecurity 2006) but we found no herbarium specimens and none of the experts were able to contribute any sightings. There were no New Zealand herbarium specimens for two further species (*Typha latifolia* and *Sagittaria sagittifolia*) but the experts were able to identify known occurrences.

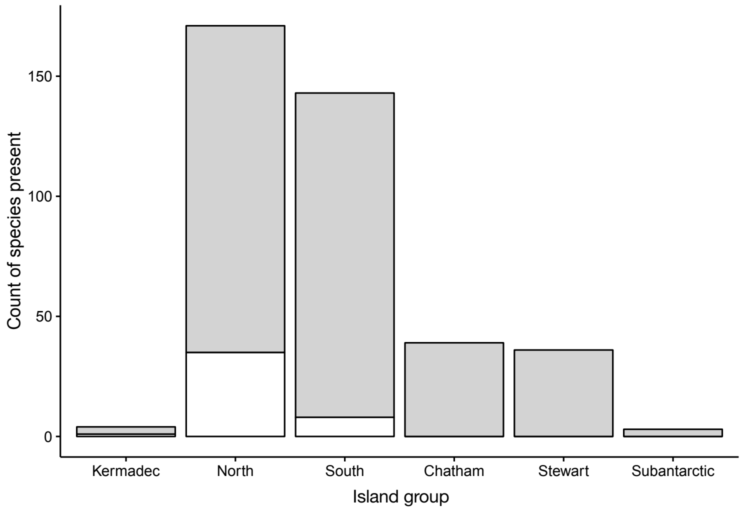

Figure 4. Species richness of selected weeds on six New Zealand island groups (presented in approximate north to south order). White bars denote weeds that are unique to the island group.

The list of fastest spreading species has considerable overlap with the most widely established. In declining spread rate (hectads colonised per year naturalised) the five fastest are *Jacobaea vulgaris* (14.9), *Ulex europaeus* (13.8), *Lamium galaeobdolon* (12.4), *Cirsium arvense* (12.0) and *Erica lusitanica* (12.0). In contrast, *Hieracium sabaudum* has not been recorded in any new hectads since it was first collected in 1904. There is a strong relationship between the length of time naturalised and the number of hectads occupied. Of the models tested, the most favoured model was the exponential model which had an R^2 of 0.31 (Fig. 5). This model indicates annual growth of 2.4% in the number of hectads occupied. In real terms, this model predicts that a species established for 107 years would on average be present in four times as many hectads as a species established for 50. There is little support in the current data for an asymptote, but logically the maximum number of hectads occupied cannot exceed 3235. If the modelled rate of expansion continues, 2000 hectads would be occupied after 300 years naturalisation.

4. Discussion

This study represents the first attempt to produce a national atlas of environmental weeds in New Zealand. In the following sections, we discuss what these maps can tell us about the distribution of weeds, what we have learned from the process of developing these maps and the potential applications of such an atlas.

4.1 Distribution of weeds in New Zealand

Almost every corner of New Zealand is occupied by at least one weed species. However, the suite of weeds present in any one area varies considerably across the country.

Very few of the weeds studied here are truly widespread in New Zealand, with only eight weed species having records in more than one-quarter of all hectad cells. Clearly, widespread naturalisation takes a long time, as the most widespread species have been naturalised in New Zealand for more than a century. Long establishment is required for plants to realise their

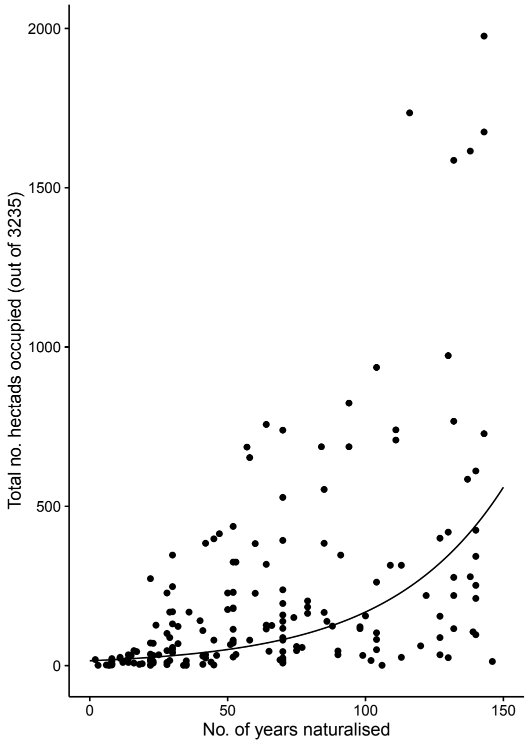

Figure 5. Relationship between the length of time a weed has been naturalised and the number of hectads occupied. The fitted exponential model has R^2 of 0.32 and was the best fitting model of those tested.

full invasive potential, and so many weeds are likely to continue to expand their range within New Zealand. However, even the most widely established weeds appear to remain absent from at least some hectads that contain suitable habitat. For example, *Ulex europaeus* is absent around most of the East Cape and *Cortaderia selloana* is similarly absent from the east coast of the South Island. Therefore, while a century may appear long by human timescales, it does not appear long enough for an invasive plant to establish in all available habitats.

We found that all of the weeds recorded from the Chatham Islands, Stewart Island/Rakiura and the subantarctic islands are also found on both mainland island groups. This probably reflects both the harsh climate of these islands and an introduction path via mainland New Zealand. By contrast, the subtropical climate of the Kermadec Islands has resulted in this group supporting some weeds that do not grow well at more southern latitudes (e.g. *Ficus rubiginosa*) and others that were introduced directly to the Kermadec Islands without a New Zealand intermediary (e.g. *Caesalpinia decapetala*, which was probably taken to Raoul Island from Norfolk Island late in the 19th century (Sykes & Campbell 1977).

Many major range expansions have been reported in datasets and by the experts that have yet to be supported by herbarium specimens. For example, *Hedychium flavescens* has now been reported to occur on the West Coast, which is the first record for this species in the South Island. Similarly, despite many dataset records, we could find no specimens of *Hedera helix* from Southland, or of *Gymnocoronis spilanthoides* from the Taranaki, Wellington or Canterbury regions. Therefore, electronic capture of existing specimens, or the collection of new specimens of these species from the newly reported locations should be made a priority.

4.1.1 Recorder bias

The distribution of plants has been said to reflect the distribution of botanists (Rich & Woodruff 1992). Unfortunately, we are unable to separate underlying ecological patterns from the probable bias in observer effort. For example, from an ecological perspective, it is difficult to explain why the relatively small provincial centre of Whanganui should contain the hectad with the highest number of weeds recorded; however, one botanist (Colin Ogle, who lives in Whanganui) has been a meticulous collector of new records, all of which are accessible. Similarly, councils with large ratepayer bases tend to complete more surveys for environmental weeds than smaller councils. We do not believe that the general trend of hotspots of weeds reflecting population centres is entirely an artefact of the location of botanists and irregular sampling as suggested by Aikio et al. (2010a), however. Around two-thirds of all environmental weeds were originally introduced as ornamental plants (Howell 2008) and many people still consider a number of the ‘weeds’ included here as harmless garden plants—thus, it would be expected that more of these species would be found close to built-up areas (Sullivan et al. 2004) and human population density has been reported as a good predictor of aquatic weed occurrence (Compton et al. 2012).

There has also been an overall decline in the collection of plant distribution records in recent years. The number of herbarium specimen accessions has decreased since the 1970s (Aikio et al. 2010b) and the number of DOC weed observation records peaked in 1997, with a steady reduction of around 15% per year to 2010 (unpubl. data). Data accessibility is also an issue. When the data were collated, not all historic herbarium records were available electronically (Jane Cruickshank, Landcare Research, pers. comm.).

4.1.2 Spread rate

The best fitting model included an increase by 2.4% in the number of hectads colonised with each additional year established. But it is clear that there is wide variation in the species. While there was little support for an asymptote of hectads occupied on the current data, it is clear that the exponential trend cannot continue past 300 years, and would likely start to decline long before this. The cases of the comparatively slow colonisation of hectads by more recently established weeds can only be speculated upon. Lag phases have been identified in collection of herbarium specimens of New Zealand weeds (e.g. Aikio et al. 2010b) and are not discussed further here, but there are a number of other possible explanations for the observed trends of these data.

Firstly the number of years between naturalisation and detection of naturalisation was almost certainly greatest for the earliest established weeds. This difference would cause the calculated spread rate to appear faster in long-established weeds. A catch-up period between 1866 and 1875 where numerous earlier naturalisations were first recognised was identified in an earlier investigation (Howell 2008) and one of the fastest spreading weeds in the current investigation (*Ulex europaeus*) was first recognised in this period.

Secondly, it may be that the species that escaped cultivation earliest are better suited to the New Zealand climate than later escapees and are spreading faster, but their spread is not actually increasing in speed. A possible example is *Clematis vitalba* compared with its congener *C. flammula*. In 1940, *C. vitalba* was restricted to a few sites in the North Island (Allan 1940) but by 1984 was very widespread throughout both islands (West 1992). However, it has not spread appreciably since. In contrast, *C. flammula* has been naturalised for at least 50 years (Webb et al. 1988) but this species rarely thrives in New Zealand and has remained quite rare. Similarly, recent naturalisations of weeds that are capable of spreading widely, may show slower spread due to effective internal biosecurity and targeted control. Because the extent of their infestations is small, recent naturalisations make better candidates for eradication programmes; examples from the current list include *Bryonia cretica* and *Ehrharta villosa*.

Finally, it may simply be that because they are better known, widely established weeds are recognised and recorded more frequently. We consider it likely that all of these scenarios contribute to the increase in calculated spread rate with increased length of naturalisation that we report here.

4.2 Development of a New Zealand weed atlas

4.2.1 Data sources

All data sources used in this investigation contributed unique information, i.e. recorded at least one instance of a weed presence within a hectad that no other dataset provided. This means that the exclusion of any of these datasets would have resulted in false absences, highlighting the need for investigations of this nature to use all reliable sources of distribution data (Crall et al. 2010).

It is also clear that all of the individual sources of data were collected for different reasons, however, giving each their own underlying biases. For example, herbarium weed specimens are often collected close to major cities (Aikio et al. 2010a), while DOC surveys are predominantly conducted in protected areas with high indigenous biodiversity values. We did not attempt to control any bias in individual datasets. However, since the biases will have differed between datasets and the influence of bias in any one dataset will diminish as the number of records accumulates (Rich & Woodruff 1992, 1996), we believe that the collation of all available data at a relatively coarse scale prior to expert review is a pragmatic approach to controlling for bias.

4.2.2 Inclusion of cultivated weeds

The decision to include cultivated specimens was contentious among the experts we consulted during office-truthing. However, we believe our decision to include cultivated plants is important for several reasons. Firstly, different people have different working definitions of what constitutes naturalised (de Lange et al. 2005), so the line between cultivated and 'wild' is often blurred. For example, the first wild record of *Houttuynia cordata* was officially collected in 2006 (Heenan et al. 2008), many years after it was banned due to its weedy tendencies. Secondly, all except five of the species included in this study are banned from sale and propagation because they can spread from cultivated plants. Even male individuals of dioecious plants (e.g. *Bryonia cretica* or *Phoenix canariensis*) can contribute pollen to distant females and potential seedlings. Thirdly, some weed species are still regularly cultivated despite being listed in the NPPA, such as the spectacular flowering *Bomarea multiflora*, the uniquely shaped *Equisetum hyemale* or the unusually coloured aroid lily *Zantedeschia aethiopica* cv. Green Goddess and *Pinus contorta* as windbreaks. Omitting the most visible and obvious weeds will exaggerate future spread if not included now, and in the case of *Morella faya*, the only known specimens are cultivated. Finally, because of the aggressive nature of the species involved, we believe that cultivated plants will almost always share a hectad with seedlings and would thus meet the criteria of 'casual' (Heenan et al. 1998) or 'naturalised' (Gardner & de Lange 1996). We acknowledge that this qualification may not work well for some species (e.g. vegetatively reproducing aquatic species), that are somewhat contained in gardens. However, we strongly suggest that knowledge of the locations of cultivated plants outside approved containment facilities is critical in appreciating the full distribution of weeds in general.

4.2.3 Data validation

The findings from this study showed that the use of existing weed observations in accessible datasets is not sufficient to create accurate distribution maps across hectad cells (or at a finer scale). On average, the expert meetings doubled the number of hectads in which each weed was recorded. There was variability in the extent to which meetings increased the records for the number of hectads occupied, but few clear trends were evident. For instance, although the 24 weeds for which no new records were added through expert meetings were all quite restricted (25 hectads or less), some other weeds with restricted distributions from electronic records had many hectads added during the meetings. Therefore, we can only conclude that the extent to which weeds are under-recorded in accessible datasets is probably due to a lack of historical interest in these particular species or a lack of perception of them as weeds.

During the course of the study, the expert meetings became known as 'office-truthing'. We could find no other references to any similar investigations that have used experts to identify known infestations that were not captured by point data garnered from accessible datasets. While the reliability of such records could be questioned, we believe that this has been a very worthwhile process—and since participants were very confident about the locations they reported, we see little difference between these records and many of the observations recorded in other datasets. Although the precision was not required for this investigation, it would have been desirable to have a method of electronically capturing these casual observations efficiently during the meeting. It also seems likely that increasing the number of experts present would result in some new records, as some weeds on the list were unknown to some participants.

Ground-truthing can be used to validate mapped distributions created from accumulated datasets (e.g. (Maheu-Giroux & de Blois 2005)) and it seems likely that many weeds could be quickly added for many hectads by sampling vegetation. However, absence is very difficult to prove (Mackenzie 2005), with the probability that a weed is detected being dependent on whether the weed is actually present, and being influenced by how detectable the weed is in surrounding vegetation, the ease with which the area can be effectively searched, and the amount of search effort. Therefore, even with considerable ground-truthing, absence cannot be guaranteed. We did not have the resources to compare ground-truthing with office-truthing in this investigation, but this remains an interesting avenue for future research.

4.2.4 The question of scale

Previous studies have used a wide range of grid sizes to produce distribution maps, from a scale of 1 km^2 for a single species (*Calluna vulgaris*) in Tongariro National Park (Chapman & Bannister 1990) to 10 000 km^2 for multiple species of lianes in Australia (Harris et al. 2007). In this study, we separated New Zealand into 100-km^2 cells (hectads) to assess the presence or absence of weed species. This scale is directly comparable to what has been used by the Botanical Society of the British Isles (BSBI) in the United Kingdom, which is a similar-sized landmass (Preston et al. 2002), and is increasingly being used for national surveys around the world (Niamir et al. 2011).

Some meeting participants expressed a desire to assess weeds using smaller cells. However, while it was desirable to make this assessment at the finest scale possible, we were limited by some practical considerations and so considered hectad cells to be the most appropriate scale for producing the first comprehensive picture of weed distributions across the entire New Zealand land area in a timely and cost-effective fashion—indeed, it allowed us to assess 181 weed species over approximately 24 million hectares within a year, with 1.5 full time staff and a modest travel budget. However, it may be practical to use a smaller scale in some regions, especially if experts are willing to spend longer validating draft maps drawn from electronic records. Recording species distributions using a cell size of 1 km^2 is generally only recommended for very rare weeds or new incursions (Walker et al. 2010). However, a grid based on 64-km^2 cells has been developed by the New Zealand Ministry for the Environment for a land use carbon accounting system (LUCAS) (Payton et al. 2004), and so reporting nationally on weed presence or absence at the same scale may provide some useful synergies.

While it is inevitable that some detail cannot be re-created (Araújo et al. 2005), it may also be possible to use modelling techniques to downscale presence or absence data collated at the hectad scale for analysis at a finer scale (Kunin 1998; Kunin et al. 2000; McPherson et al. 2006). For example, techniques have recently been developed that allow cell occupancy to be predicted based on detection probabilities (Niamir et al. 2011; Groom 2013).

Conversely, it may sometimes be useful to aggregate data to an even coarser scale. For example, distributions from SAPIA data (630–710 km^2 cell size) have been overlaid with CLIMEX models of species envelopes (Rouget et al. 2004; Mgidi et al. 2007) to demonstrate the extent to which species occupy their potential habitat. Similarly, any change in range size over time is easily quantified using comparatively coarse atlas data (Telfer et al. 2002). It should be noted that different management conclusions can be reached by analysing presence data at different scales (e.g. Rouget 2003).

4.3 Applications of a New Zealand weed atlas

In this study, we have created an atlas of 181 of New Zealand's most widely recognised weeds, using selection criteria to keep the list in moderate proportions. Similarly, the South African Plant Invaders Atlas database, which records approximately 500 species (Rouget et al. 2004), has been subsampled to 126 widespread or locally abundant species (Nel et al. 2004). By contrast, the long-established BSBI Atlas contains records for 2660 taxa (Rich & Woodruff 1996)—and a full atlas of all New Zealand naturalised vascular plant taxa would be a similar size, containing around 2436 taxa (Howell & Sawyer 2006). To create such an atlas, pre-existing electronic records could simply be collated for all species. However, since office-truthing on average doubled the known range of well known weed species in this study, we believe that using experts to review a shorter list of species is the most pragmatic approach at this time.

There is potential to use the distribution maps created here for a number of purposes. We believe that one of the most important uses will be to support the inclusion or exclusion of particular weed species from Regional or National Pest Management Strategies. These maps could also be used to plan delimitation surveys for proposed regional eradication programmes—for example, they show that *Ageratina adenophora* is absent from the South Island, and *Chrysanthemoides monilifera* is completely absent from the West Coast of the South Island and Stewart Island/Rakiura. Weed eradication is often attempted in New Zealand at both regional and national scales, can be successful against aquatic weeds (Champion et al. 2014) but it is rarely completed when targeting terrestrial weeds (Howell 2012), possibly due to poor delimitation, which is a fundamental requirement for eradication programmes (Panetta & Lawes 2005).

These data may also allow the further analysis of hotspots (e.g. Catford et al. 2011) or be used in the creation of spread models (e.g. Merow et al. 2011). We believe that there is strong potential to use hectad occupancy data to analyse the spread of weeds through time, as other studies have used data at a similarly coarse scale to demonstrate range expansion (e.g. Telfer et al. 2002; Henderson 2007). For example, it would be possible to create a map depicting the decade in which the weed was last recorded in each hectad, which would be particularly useful for the small number of very rare weeds for which there are national eradication programmes. Such an approach is likely to be inaccurate for more common species, however, because we have added so many records to the most recent decade (through office-truthing) that the spread between decades is likely to be biased.

There is also an opportunity to use some of the distribution maps produced during this investigation to improve awareness of domestic biosecurity borders. For example, the records produced show that five weed species (*Egeria densa*, *Erigeron karvinskianus*, *Hedychium gardnerianum*, *Tradescantia fluminensis* and *Tropaeolum speciosum*) that were previously not recorded on the Chatham Islands (Walls 2002) have been detected as new incursions since 2002—and with only 39 of the 181 weeds currently being recorded there, many more species could potentially invade in the future. It is also worth considering those species that are only present on one of the main islands. Seven species are present in the South Island but absent from the North Island (e.g. *Myricaria germanica*) and 35 species are present in the North Island but still absent from the South Island (e.g. *Spartina alterniflora*). Raising awareness of new incursions may allow significant range extensions to be prevented. As has recently been achieved with South Island populations of *Ceratophyllum demersum* (Champion et al. 2014).

Finally, we believe that atlases allow a large number of people to see their knowledge in context and critique distribution maps. An extreme example is the two species (*Sagittaria sagittifolia* and *Typha latifolia*) for which there were no records prior to office-truthing. However, more often, one expert at a meeting knew of local range extensions that were geographically isolated and were of great interest to other participants. These discoveries highlight the important role of atlases in publicising knowledge gaps and also demonstrate how difficult it is to be sure of absences.

5. Conclusions

The process of aggregating distribution data into cells is a good approach to creating species distribution maps because, by combining all available datasets and not excluding any known locations, it resolves some of the problems associated with only using 'found' data. The scale we selected of 100 km^2 was nationally appropriate, in line with other initiatives and, ultimately, fit for purpose. Although finer scales may be desirable for some purposes, there are techniques available to predict the occupancy of subdivided cells or, alternatively, the exercise could be replicated with fewer species or over a smaller range. We consider that validating the resultant distributions was an important step, as it allowed gaps in knowledge to be highlighted and people with detailed knowledge of weed distributions to be actively engaged in qualifying implied absences.

We recommend that the procedure of collating all electronic data, aggregating on hectad cells and conducting validation meetings with weed experts should be repeated on a 10-yearly basis to quantify changes in the extent of naturalisation. This timeframe would allow recorded distributions to be recent enough to provide meaningful data for planning Regional and National Pest Management Strategies. A previous recommendation to capture weed information for New Zealand using grid squares (Molloy 1967) went unheeded for almost five decades, and our knowledge of the spread and distribution of weeds is much poorer as a result. Repeating the procedure described here would also provide a mechanism to record eradications, although absence from previously occupied hectads could be caused by eradication, failure to detect, or a previous false positive. It may also be worth extending the list of species, particularly to include any new species that are added to the NPPA. Species that appear on any single RPMS could also be considered for inclusion, but not at the expense of any of the species listed here. The use of a simple electronic interface during the meetings may make the capture of casual observations more efficient and it is possible that incorporation of the results of any validation meetings could be refined using Bayesian techniques (e.g. (Bierman et al. 2010).

Ideally, specimens supporting further range expansions should be lodged in recognised herbaria, as we agree with the sentiments of Feeley & Silman (2011) that it is impossible to understate the importance of herbaria. Where numerous observations are made without specimens, new records should continue to be created in existing datasets. There are ongoing initiatives to make incremental improvements to data capture and provide greater access to existing data by federating existing datasets, which will greatly assist investigations such as this in the future.

The accuracy of the distribution maps we created is dependent on the confidence of weed experts that these maps were not misleading and accurately reflected the extent of naturalisations. During the course of this investigation, we effectively made more than half a million decisions regarding the status of 181 species in 3235 hectads. It is most unlikely that all of these decisions will have been correct, but we are confident that there are very few instances where weeds have been recorded as being present in areas where they have never existed. We encourage people to critique the distribution maps produced here and to contact us with any concerns, however, so that we can check the data—it is likely that readers will know of yet more unrecorded weed locations.

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Appendix 1

Environmental weeds included in this investigation

The following table includes the scientific and common names of all environmental weeds included in this study. It also indicates whether they are listed in the National Pest Plant Accord (NPPA; MAF Biosecurity 2008) and provides the number of hectads in which they have been recorded.

Table A1.1 Environmental weeds included in this investigation.

SCIENTIFIC NAME	COMMON NAME	NPPA 2008	COUNT OF CELLS
Ferns and allies			
Cyathea cooperi	lacy tree fern	Y	8
Equisetum arvense	field horsetail	Y	124
Equisetum fluviatile	water horsetail	Y	1
Equisetum hyemale	rough horsetail	Y	47
Nephrolepis cordifolia	tuber ladder fern	Y	168
Osmunda regalis	royal fern	Y	62
Salvinia molesta	kariba weed	Y	32
Selaginella kraussiana	African club moss	Y	347
Conifers			
Pinus contorta	contorta pine	Y	325
Pinus mugo	mountain pine	N	71
Pinus nigra	Corsican pine	N	167
Pseudotsuga menziesii	Douglas fir	N	384
Dicotyledons			
Acer pseudoplatanus	sycamore	N	419
Ageratina adenophora	Mexican devil	N	184
Ageratina riparia	mist flower	N	164
Ailanthus altissima	tree of heaven	Y	47
Akebia quinata	chocolate vine	Y	117
Alternanthera philoxeroides	alligator weed	Y	103
Anredera cordifolia	Madeira vine	Y	159
Araujia hortorum	moth plant	Y	220
Berberis darwinii	Darwin's barberry	T	318
Berberis glaucocarpa	barberry	N	687
Bryonia cretica	white bryony	Y	4
Buddleja davidii	common buddleja	Y	757
Caesalpinia decapetala	Mysore thorn	N	2
Calluna vulgaris	heather	Y	156
Cardiospermum grandiflorum	balloon vine	Y	5
Cardiospermum halicacabum	small balloon vine	Y	0
Carduus nutans	nodding thistle	N	740
Carpobrotus edulis	iceplant	Y	155
Celastrus orbiculatus	climbing spindleberry	Y	168
Ceratophyllum demersum	hornwort	Y	110
Cestrum parqui	green cestrum	Y	16
Chrysanthemoides monilifera	boneseed	Y	211
Cirsium arvense	Californian thistle	N	1586
Clematis flammula	plume clematis	Y	24
Clematis vitalba	old man's beard	Y	739

Continued on next page

Table A1.1 continued

SCIENTIFIC NAME	COMMON NAME	NPPA 2008	COUNT OF CELLS
Cobaea scandens	cathedral bells	Y	115
Cotoneaster franchetii	Franchet cotoneaster	N	179
Cotoneaster glaucophyllus	large-leaved cotoneaster	N	414
Cotoneaster simonsii	Khasia berry	Y	325
Cotyledon orbiculata	pig's ear	Y	80
Crassula multicava	fairy crassula	Y	66
Crataegus monogyna	hawthorn	N	708
Cytisus scoparius	Scotch broom	N	1615
Delairea odorata	German ivy	N	252
Dipogon lignosus	mile-a-minute	Y	106
Drosera capensis	Cape sundew	Y	2
Eccremocarpus scaber	Chilean glory creeper	Y	17
Elaeagnus × *reflexa*	elaeagnus	N	238
Eomecon chionantha	snow poppy	Y	22
Erica lusitanica	Spanish heath	N	686
Erigeron karvinskianus	Mexican daisy	Y	528
Euonymus japonicus	Japanese spindle tree	Y	131
Fallopia japonica	Asiatic knotweed	Y	60
Fallopia sachalinensis	giant knotweed	Y	47
Ficus macrophylla	Moreton Bay fig	N	23
Ficus rubiginosa	Port Jackson fig	Y	16
Fuchsia boliviana	Bolivian fuchsia	Y	36
Genista monspessulana	Montpellier broom	N	279
Gunnera tinctoria	Chilean rhubarb	Y	384
Gymnocoronis spilanthoides	Senegal tea	Y	44
Hedera helix	English ivy	N	585
Heracleum mantegazzianum	giant hogweed	Y	34
Hieracium argillaceum	yellow hawkweed	Y	10
Hieracium lepidulum	tussock hawkweed	Y	127
Hieracium murorum	wall hawkweed	Y	8
Hieracium pollichiae	spotted hawkweed	Y	277
Hieracium sabaudum	New England hawkweed	Y	1
Homalanthus populifolius	Queensland poplar	Y	51
Houttuynia cordata	chameleon plant	Y	19
Hypericum androsaemum	tutsan	Y	425
Ilex aquifolium	holly	N	315
Ipomoea indica	blue morning glory	Y	227
Jacobaea vulgaris	ragwort	N	1735
Jasminum humile	Italian jasmine	Y	27
Jasminum polyanthum	jasmine	N	347
Juglans ailantifolia	Japanese walnut	N	228
Lamium galeobdolon	aluminium plant	Y	273
Lantana camara	large-leaved lantana	Y	122
Leycesteria formosa	Himalayan honeysuckle	N	767
Ligustrum lucidum	tree privet	Y	437
Ligustrum sinense	Chinese privet	N	383
Lonicera japonica	Japanese honeysuckle	Y	687
Ludwigia peploides	primrose willow	Y	57
Lycium ferocissimum	boxthorn	N	315
Lythrum salicaria	purple loosestrife	Y	114
Macfadyena unguis-cati	cat's claw creeper	Y	11

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Table A1.1 continued

SCIENTIFIC NAME	COMMON NAME	NPPA 2008	COUNT OF CELLS
Melianthus major	Cape honey flower	N	116
Menyanthes trifoliata	bogbean	Y	1
Morella faya	fire tree	Y	3
Myoporum insulare	Tasmanian ngaio	Y	69
Myricaria germanica	false tamarisk	Y	26
Myriophyllum aquaticum	parrot's feather	Y	141
Nuphar lutea	yellow water lily	Y	1
Nymphaea mexicana	Mexican water lily	Y	3104
Nymphoides geminata	marshwort	Y	34
Nymphoides peltata	fringed water lily	Y	2
Ochna serrulata	Mickey Mouse plant	Y	23
Paraserianthes lophantha	brush wattle	N	343
Passiflora caerulea	blue passion flower	Y	80
Passiflora tarminiana	banana passionfruit	Y	126
Passiflora tripartita	banana passionfruit	Y	230
Pilosella × stoloniflora	hawkweed	Y	13
Pilosella aurantiaca	orange hawkweed	Y	32
Pilosella caespitosa	field hawkweed	Y	35
Pilosella officinarum	mouse-ear hawkweed	Y	227
Pilosella piloselloides subsp. *praealta*	king devil hawkweed	Y	139
Pittosporum undulatum	sweet pittosporum	Y	14
Plectranthus ciliatus	blue spur flower	Y	123
Polygala myrtifolia	sweet pea shrub	Y	97
Prunus serotina	rum cherry	Y	18
Pyracantha angustifolia	orange firethorn	Y	77
Rhamnus alaternus	evergreen buckthorn	Y	80
Rhododendron ponticum	rhododendron	Y	71
Rosa rubiginosa	sweet brier	N	728
Rubus fruticosus agg.	blackberry	N	1675
Salix cinerea	grey willow	Y	553
Salix fragilis	crack willow	Y	973
Schinus terebinthifolius	Christmas berry	Y	32
Senecio angulatus	Cape ivy	N	139
Solanum linnaeanum	apple of Sodom	N	88
Solanum marginatum	white-edged nightshade	Y	34
Solanum mauritianum	woolly nightshade	Y	400
Syzygium smithii	monkey apple	Y	101
Tropaeolum speciosum	Chilean flame creeper	Y	181
Tussilago farfara	coltsfoot	T	15
Ulex europaeus	gorse	N	1976
Utricularia arenaria	bladderwort	Y	1
Utricularia gibba	floating bladderwort	Y	41
Utricularia livida	humped bladderwort	Y	3
Utricularia sandersonii	bladderwort	Y	1
Vinca major	blue periwinkle	N	611
Monocotyledons—not including grasses			
Agapanthus praecox	agapanthus	N	653
Aristea ecklonii	aristea	Y	88
Asparagus aethiopicus	bushy asparagus	Y	70
Asparagus asparagoides	smilax	Y	230
Asparagus scandens	climbing asparagus	Y	248

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Table A1.1 continued

SCIENTIFIC NAME	COMMON NAME	NPPA 2008	COUNT OF CELLS
Bomarea multiflora	climbing alstromeria	Y	57
Carex longebrachiata	Australian sedge	N	82
Egeria densa	egeria	Y	176
Eichhornia crassipes	water hyacinth	Y	46
Hedychium flavescens	yellow ginger	Y	116
Hedychium gardnerianum	wild ginger	Y	393
Hydrilla verticillata	hydrilla	Y	4
Hydrocleys nymphoides	water poppy	Y	34
Iris pseudacorus	yellow flag iris	Y	220
Lagarosiphon major	lagarosiphon	Y	228
Lilium formosanum	formosan lily	Y	41
Moraea flaccida	Cape tulip	Y	45
Phoenix canariensis	phoenix palm	N	169
Pistia stratiotes	water lettuce	Y	4
Potamogeton perfoliatus	clasped pondweed	Y	6
Sagittaria montevidensis	Californian arrowhead	Y	15
Sagittaria platyphylla	delta arrowhead	Y	14
Sagittaria sagittifolia	old world arrowhead	Y	2
Schoenoplectus californicus	Californian bulrush	Y	10
Tradescantia fluminensis	wandering Jew	Y	824
Typha latifolia	great reedmace	Y	1
Vallisneria australis	eelgrass	Y	26
Zantedeschia aethiopica cv. Green Goddess	green goddess arum	Y	127
Monocotyledons—grasses			
Arundo donax	giant reed	Y	151
Cenchrus latifolius	Uruguay pennisetum	Y	18
Cenchrus longisetus	feathertop	Y	25
Cenchrus macrourus	African feather grass	Y	195
Cenchrus purpurascens	Chinese pennisetum	Y	24
Cenchrus purpureus	elephant grass	Y	10
Cenchrus setaceus	African fountain grass	Y	32
Cortaderia jubata	purple pampas grass	Y	398
Cortaderia selloana	white pampas grass	Y	936
Ehrharta villosa	pyp grass	Y	6
Eragrostis curvula	African love grass	Y	30
Glyceria maxima	floating sweetgrass	N	262
Megathyrsus maximus	Guinea grass	Y	10
Nassella neesiana	Chilean needle grass	Y	44
Nassella tenuissima	fine stem needlegrass	Y	34
Nassella trichotoma	nassella tussock	Y	203
Phragmites australis	phragmites	Y	13
Spartina alterniflora	American cord-grass	N	80
Spartina anglica	common cord-grass	N	88
Zizania latifolia	Manchurian wild rice	Y	50