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WRASP: A spatial strategic weed risk analysis tool reveals important subnational variations in weed risks

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Summary

The number and diversity of introduced invasive plants, coupled with limited weed management budgets, require biosecurity managers to employ systems to prioritise weeds for management attention. To assist this process, an analytical protocol and spreadsheet tool were previously developed for post-border weed risk management (PBWRM). The popular PBWRM tool utilises a framework that ignores any spatial variation in risk factors within the geographical area of risk concern. However, invasive plants vary in risk factors such as invasiveness, potential impacts and feasibility of control as a function of spatially variable factors. Logically, the assessment of weed risks should also be spatially explicit, in order to best understand them and to target management appropriately. To address these concerns, we took the PBRWM logic and spatialised it, to allow weed managers to assess weed risks and management across geographical space. We illustrate this new spatial system using a case study of *Senecio glastifolius* in New Zealand, comparing the results of a spatial and an aspatial analysis of the risks it poses and the logical management options. The spatial view of risks revealed locations of higher and lower risk and suitability for management attention that were hidden by blanket, aspatial weed risk scores of the current PBWRM system. The national level risk was also significantly higher when considered in the light of the results from the spatial tool. The spatial tool, WRASP, takes its name from Weed Risk Assessment SPatial.

Keywords: invasive plants, prioritisation tool, strategic weed management, weed risk assessment, weed risk management.

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Introduction

Post-border weed risk management poses a set of costly and challenging problems to both public and private land managers. The spread of exotic plants has been so thorough that many, perhaps most, national flora are taxonomically dominated by exotics. For example, some 26 000 of the 46 000 known vascular plants present in Australia are exotic [pers. Comm. J Scott]. Of these species present, a little over 10% (2700) are naturalised, and of these, 30% (798) are considered a significant threat to the environment or agriculture. In New Zealand, the situation is similar, with the number of naturalised exotic plant species being similar to the number of indigenous species (~2500), and these being approximately 10% of the total number of introduced species (Howell, 2008). Clearly, in any given jurisdiction, there is a need to assess the threat posed by weeds as a step towards ensuring that management strategies are prepared for species posing the most significant threats.

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Weed Risk	Feasibility of Containment					
	Negligible >113	Low >56	Medium >31	High >14	Very High <14	
Negligible <13	Limited Action	Limited Action	Limited Action	Limited Action	Monitor	
Low <39	Limited Action	Limited Action	Limited Action	Monitor	Monitor	
Medium <101	Manage Sites	Manage Sites	Manage Sites	Protect Sites	Contain Spread	Alert
High <192	Manage Weed	Manage Weed	Protect Sites	Contain Spread	Destroy Infestations	Alert
Very High >192	Manage Weed	Protect Sites & Manage Weed	Contain Spread	Destroy Infestations	Eradicate	Alert

Fig. 1 Weed risk and management matrix for the post-border weed risk management protocol (Virtue, 2008).

The risks posed by an invasive plant depend *inter alia* on the *nature* of the plant, its *per capita impacts* on *desirable habitat values,* its *abundance*, its *potential distribution*, the *technical and economic feasibility of control*, the *costs of control* and the *scale* of interest. Considering all of these factors simultaneously is challenging. Since the late 1990s, there has been a considerable interest in risk assessment tools for invasive plants (Pheloung *et al*., 1999; Groves *et al*., 2001; Gordon *et al*., 2008). These tools provide a systematic method for considering the weed risk factors. The patterns of weed characteristics that are associated with weediness and invasiveness (Reichard, 2001) form the basis for a spreadsheet-based point-scoring system to assess the likely weed risks plants might pose under different circumstances.

The Australian and New Zealand National Post-Border Weed Risk Management Protocol HB 294:2006 was developed on the back of a pre-border weed risk assessment system (Pheloung *et al*., 1999). It was developed into a standard protocol for use in Australia and New Zealand (PBWRM, Standards Australia, 2006). Since that time, the Food and Agriculture Organization has adopted it, and it has become an important tool in the management of weeds, being applied in Australia, New Zealand, Latin America, South America and North Africa (FAO, 2011, Auld, 2012).

The PBWRM system was developed as a means of assessing the relative risks posed by different weeds, and a means of prioritising and characterising desirable weed management strategies for each weed (Fig. 1). The logic of the system is clear, and the responses can be reviewed and critiqued, attributes that have doubtless contributed to it becoming popular throughout Australia, New Zealand and elsewhere. This system was updated recently to reflect developments in: '…risk management practice and in indicating the reliability of predictions; the management of contentious plants; and the translation of WRM results into policy and management responses' (Auld *et al*., 2012:317).

One of the inherent difficulties with using this type of aspatial scoring system is the need to cope with the heterogeneous nature of the weed threats and the production or natural resource assets at risk. With the present PBWRM tool, the risk assessment is implicitly conducted for a single point, which has to represent the risks faced across the entire jurisdiction being considered. For example, a question relating to the 'Suitability of the species for [Australian] climates' (Q2.01) will necessarily require a broad estimate considering the potentially enormous range in climatic conditions across the jurisdiction of interest. Similarly, the response to a question relating to 'Prolific seed production' (Q8.01) will be unable to account for variation in seed production resulting from localised climatic or management contexts. In the current aspatial PBWRM system, the risk analyst is required to provide single ratings to each question in the system. This introduces a significant source of instability into the risk assessment method, in terms of the operator-specific or subjective nature of the factors taken into consideration when making their broad estimate. In the worst case, they may simply apply a score transposed from a previous assessment in another region without considering the context-specific factors. The risk assessment results are highly sensitive to how the individual risk analyst transforms the heterogeneous risk factors into a single response (e.g. averaging or taking the extreme case) (see Discussion and references in Barry & Lin, 2010). A second consequence of the point-based nature of the PBWRM tool is that each jurisdiction is required to complete the assessment *de novo*, resulting in wasted effort and inconsistent assessments.

Several authors have recognised that weed risks are inherently spatial, and some effort has been expended on developing spatial decision support systems for identifying weed management actions for invasive species (Crossman, 2004; Crossman & Bass, 2008; Januchowski-Hartley *et al*., 2011; Skurka Darin *et al*., 2011). The analytical frameworks of Januchowski-Hartley *et al*. (2011) and Skurka Darin *et al*. (2011) are each designed to optimise the allocation of resources to tactical weed management, rather than a broader assessment of relative risks. As observed by Auld (2012), they also require detailed information that may not be readily available for newly invading species, thereby limiting their utility for prioritising the management of weed communities that include invasive plants that are newly arrived, through to those that are well-established.

In this article, we describe the development of a spatialised version of the PBWRM tool to provide an analytical framework for identifying strategic weed management priorities. We compare the results of applying the spatial and aspatial versions of the PBWRM tool to assess the risks posed by *Senecio glastifolius* and the management options for it in New Zealand. New Zealand represents a particularly relevant context for such a tool for a number of reasons: (i) high rates of species invasion due to historic biotic isolation but high current levels of trade and tourism, (ii) responsibility for weed risk assessment and resting largely with a number of local government agencies ('Regional Councils') that have at present limited national co-ordination of biosecurity management and (iii) high variability in biogeographic factors that influence invasions and their impacts.

Methods

Case study plant

Senecio glastifolius L.f. (Asteraceae: Pink ragwort, Holly-leaved ragwort) is native to the Cape Region of South Africa (Wells *et al*., 1986). It is an annual or short-lived perennial herb that grows to a height of 1–1.5 m and is presently increasing its distribution in both New Zealand and south-western Western Australia (Hussey *et al*., 1997; Beautrais, 2013). In New Zealand, it was first recorded in 1963 near Gisborne (Williams *et al*., 1999) and has now spread to the northern South Island and the southern east and west coasts of the North Island (Fig. 2). Flowering occurs between September–November, and seeds are small (~0.6 mg, 2 mm) and windborne. The foliage is palatable to livestock, and hence, the plant typically invades ungrazed waste areas, roadside batters and coastal dunes. Its impact is regarded as limited in terms of alteration of natural biota in those ecosystems where it establishes (Williams *et al*., 1999). It has been the subject of localised but considerably labour-intensive management campaigns, commonly using manual removal.

Post-border weed risk management protocol

This Post-Border Weed Risk Management (PBWRM) protocol was published as an Australian and New Zealand Standard (Standards Australia, 2006). It is based on 49 questions covering aspects of the history, biogeography, ecology, biology and impacts of a given species. The scoring system requires either ratings (0, 1 or 2) or yes/no answers to questions and is constructed such that equal weight is given to most questions. This aspatial system is implemented as an Excel spreadsheet. The PBWRM system was used to assess the risks and management options for *S. glastifolius* in the context of New Zealand (Annex 1).

Spatial weed risk management system (WRASP)

The logic of the PBWRM system was translated directly into ArcGIS (10.3) using model builder. Where questions had answers that concerned the biology of the species and were spatially uniform, their non-spatial form was retained as in the current spreadsheet model. Where a question could be answered spatially, the system prompts for a spatial dataset in raster form.

To demonstrate the spatialisation process, let us consider Question 1 in the PBWRM system: 'What is the weed's ability to establish amongst existing plants?'. Establishment is strongly dependent on existing vegetation, and vegetation type varies enormously across space. *Senecio glastifolius* establishes in open-canopy coastal vegetation, for example, but is totally excluded by dense, closed canopy conifer–broad-leaved forest that covers large areas of New Zealand. Spatial data layers for vegetation type are readily available for New Zealand in the form of the Land Cover Database (LCDB, Landcare Research, https://lris.scinfo.org.nz/). The vegetation cover data layer in v 4.1 of the LCDB was reclassified (Fig. 3A) as follows:

- Open-canopy coastal vegetation, grasses and herbs = 3 (very high)
- Artificial surfaces = 2 (high)
- Crops and orchards, scrub and shrubs = 1 (medium)
- Closed canopy forest, water = 0 (low)

The potential distribution of *S. glastifolius* was defined using CLIMEX (Sutherst & Maywald, 1985; Kriticos *et al*., 2015). The model developed by Scott *et al*. (2008) was applied to the CliMond 10' data CM10_1975H (Kriticos *et al*., 2012) for New Zealand (Fig. 3B). An Ecoclimatic Index value of 1 or above was taken as sufficient for establishment. The potential impacts were largely restricted to coastal dunes (Fig. 3C). The Land Cover DataBase layer (Fig. 3D) was reclassified into several different ways to address different questions.

Results

Table 1 shows the structure of the assessment, the responses of the authors, and indicates those

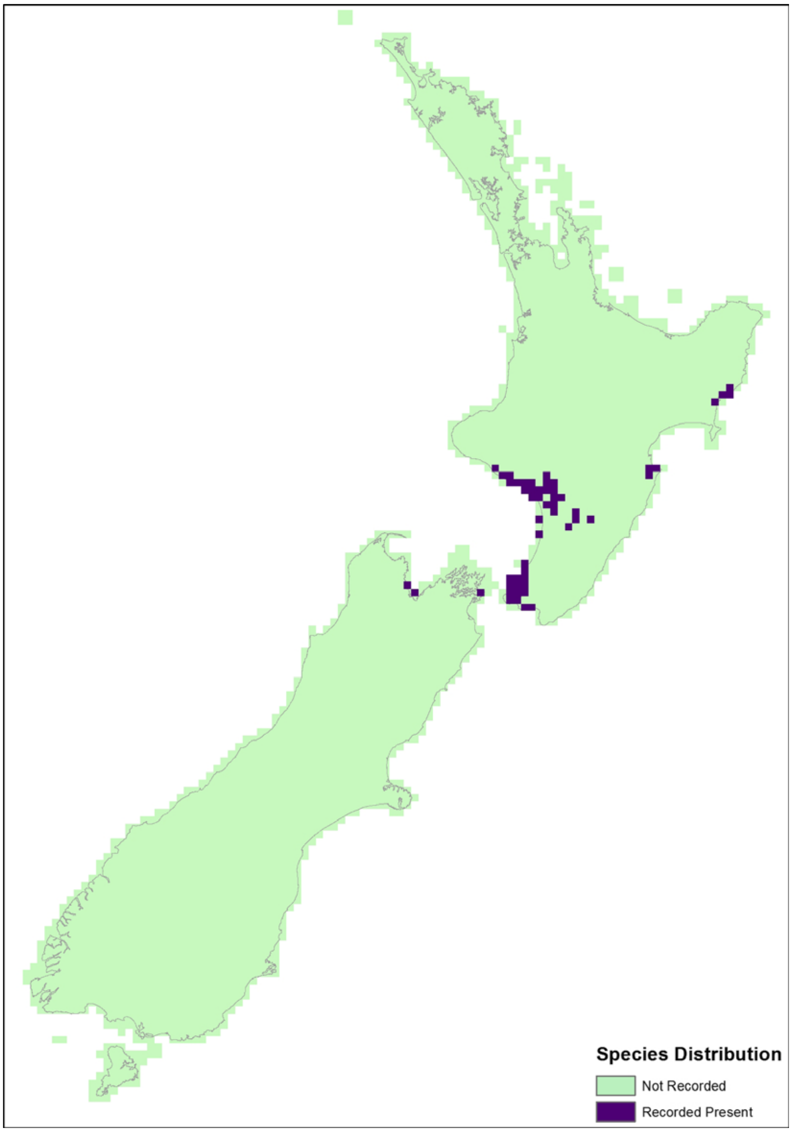

Fig. 2 Current known distribution of *Senecio glastifolius* in New Zealand (source: herbarium records, Regional Council databases, Department of Conservation databases and the observations of the authors).

questions deemed to be amenable to spatially explicit responses. A comparison of the spatialised responses with the corresponding PBWRM responses highlights the struggle that analysts face when applying the PBWRM system to areas that include heterogeneous environments.

The aspatial PBWRM system resulted in a risk score of 6, indicating that *S. glastifolius* posed a negligible risk to New Zealand as a whole. Combined with a feasibility of containment score of 27, the weed risk category was low and the corresponding recommended action was *limited action*. The risk score for *S. glastifolius* was substantially lowered because its potential distribution in New Zealand is limited.

In contrast, the spatial WRASP system provided maps indicating that whilst most of New Zealand was under negligible threat, some areas were under low, medium and even high threat (Figs 4A, 5). The risk maps indicate that the greatest threats lie in the southern half of the North Island apart from the central highlands and in the peri-coastal arc across the northern quarter of the South Island (Fig. 4A). The corresponding management actions range from *monitor populations* through most of the country through to *destroy infestations*, *protect sites* and *contain spread* (Fig. 4B).

Discussion

The WRASP tool revealed significant subnational spatial variation in weed risk and the technically prudent management strategy for the case study weed. Given New Zealand's legislative mandate for Regional Councils to manage pests, the WRASP system provides an economical and effective means for Regional Councils to identify risks and technically appropriate

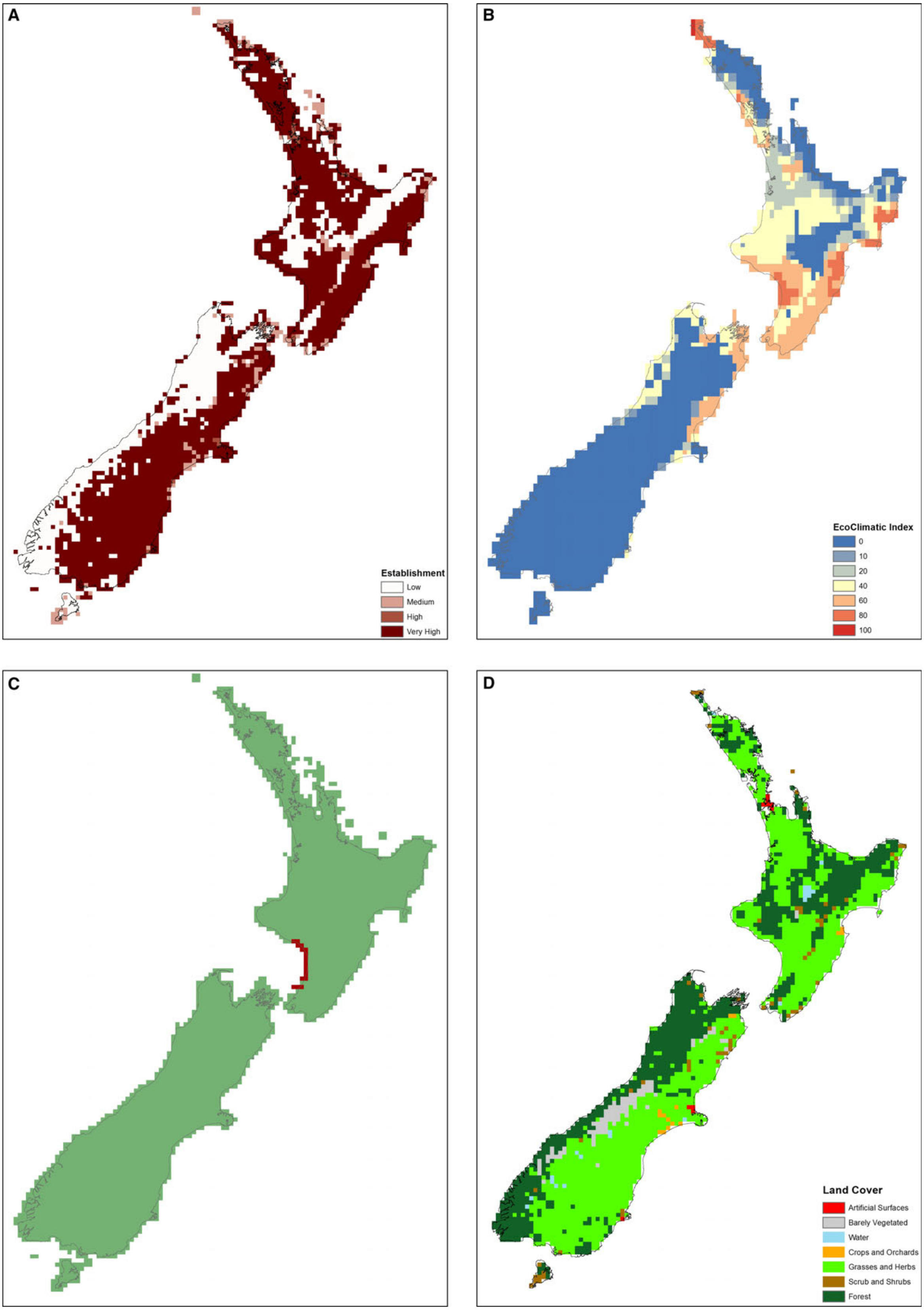

Fig. 3 Spatial data layers used to answer risk factor questions in the spatial version of WRASP. A, Land cover database for New Zealand, reclassified for establishment potential for *Senecio glastifolius*. Open-canopy coastal vegetation, grasses and herbs = 3 (very high), artificial surfaces = 2 (high), crops and orchards, scrub and shrubs = 1 (medium), closed canopy forest, water = 0 (low), B, potential distribution, CLIMEX EI ≥ 1, C, potential impacts (red <10%, green unknown), D, land cover suitability based on first order classes from the LCDB database. This data layer is reclassified in a number of ways to provide answers to relevant questions.

Table 1 Comparison between post border weed risk management system and WRASP

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
INVASIVENESS				
Answer all questions with the land use in mind, except for question 5(a)				Formula: 1/State biology/ ecology consideration (preferably referenced), 2/Data source 3/Transformation process for each data element
1. What is the weed's ability to establish amongst existing plants?	3 = very high 2 = high 1 = medium 0 = low ? = don't know (=0)	Medium	Likely to be influenced by vegetation structure, though possibly affected by climatic suitability.	*Senecio glastifolius* occurs in disturbed bare areas, and is strongly associated with sparsely vegetated sites, though it also invades low nutrient woodlands in Australia and South Africa (Williams *et al.*, 1999). The New Zealand Land Cover Data base (LCDB Version 3) Assign scores for each LCDB class
2. What is the weed's tolerance to average weed management practices in the land use	3 = very high 2 = high 1 = medium 0 = low ? = don't know (=0)	Medium	Average weed management practices vary spatially.	Assign scores 0–3 for LCDB classes (e.g. coastal = medium; low-producing grassland = low)
3. What is the reproductive ability of the weed:			Can grow from cuttings, but not a significant part of invasion biology	
(a) Time to seeding?	2 = 1 year 1 = 2–3 years 0 = >3 years/never ? = don't know (=0)	2–3 years	Aspatial: Can depend on annual heat sum of growing degree days (could use CLIMEX number of generations).	1 (2–3 years)
(b) Seed set?	2 = high 1 = low 0 = none ? = don't know (=0)	High	Spatial: Depends on climate. Variation within range, and cut-off if the annual heat sum is insufficient. Could use CLIMEX generations variable results.	Aspatial

Table 1. (Continued)

Question		PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
(c)	Vegetative spread?	2 = fast 1 = slow 0 = none ? = don't know (=0)	None	Significance of vegetative spread varies spatially, for example river systems, but ability to grow asexually is probably aspatial. Can grow from cuttings, but not a significant part of invasion biology	Aspatial
4.	How likely is long-distance dispersal by natural means:				
(a)	Flying birds?	2 = common 1 = occasional 0 = unlikely ? = don't know (=0)	Unlikely	Aspatial. Depends on factors that are probably too complex for this exercise	Aspatial: not dispersed by birds
(b)	Other wild animals?		Unlikely	Aspatial. Depends on factors probably too complex for this exercise	Aspatial: not dispersed by animals
(c)	Water?		Unlikely	Could use spatial. Use proximity to spatial water body layer	Aspatial: not dispersed by water
(d)	Wind?		Common	Highly wind dispersed, but no evidence for spatial variation	Aspatial. Potentially use a spatial wind run layer
5.	How likely is long-distance dispersal by human means:				
(a)	Deliberate by people? (ignore land use)	2 = common 1 = occasional 0 = unlikely ? = don't know (=0)	Occasional	Use density of human development grouped into 3–4 sensible classes (e.g. Gilbert *et al.*, 2005).	Unlikely to be spatial
(b)	Accidently by people?		Occasional	Use density of human development grouped into 3–4 sensible classes (e.g. Gilbert *et al.*, 2005)	Unlikely to be spatial
(c)	Contaminated produce?		Unlikely	Use a spatial data layer of the relevant produce.	Aspatial: not spread by contaminated produce
(d)	Domestic/farm animals?		Unlikely	Use a spatial data layer on distribution of animal production.	Aspatial: not spread by farm animals

Table 1. (Continued)

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
IMPACTS				
Assume the average weed management practices have not changed to specifically target the weed, and it has spread across/along a whole paddock, orchard, plantation, nature reserve or water body. If the weed is well-controlled by these average practices, then it will occur at a low density and will have minimal impacts.				
What density would the weed achieve?	L = LOW M = MEDIUM H = HIGH	Medium		What is this based on?
1. Does the weed reduce the establishment of desired plants?	3 = >50% reduction 2 = 10–50% reduction 1 = <10% reduction 0 = none ? = don't know (=0)	<10% reduction	Depends on land cover and environmental suitability	Spatial: LCDB reclassified as 1 for coastal dunes, 0 otherwise. We are unsure for elsewhere
2. Does the weed reduce the mature yield or amount of desired vegetation?	4 = >50% reduction 3 = 25–50% reduction 2 = 10–25% reduction 1 = <10% reduction 0 = none ? = don't know (=0)	<10% reduction	Depends on land cover and environmental fitness	Spatial: 2 in sand and gravel, 3 if climate also favourable. 1–2 for pasture in rare instances, but this is beyond the resolution limitations of this exercise
3. Does the weed reduce the quality of products or services obtained from the land use?	3 = high 2 = medium 1 = low 0 = none ? = don't know (=0)	Low	Depends on land cover and environmental fitness	Spatial: Locally *High* along the Whanganui–Manawatu coast, *Medium* in Whitiau etc. (i.e. Horizons region), *low* elsewhere in sand and gravel
4. Does the weed restrict the physical movement of people, animals, vehicles and/or water?	3 = high 2 = medium 1 = low 0 = none ? = don't know (=0)	None	Depends on the geography of these restricted things, plus local species density.	Aspatial: None
5. Does the weed affect the health of animals and/or people?	3 = high 2 = medium 1 = low 0 = none ? = don't know (=0)	None	Depends on geography of people and animals (too complex?) and perhaps species density/fitness (CLIMEX)	Aspatial: None

Table 1. (Continued)

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
6. Does the weed have major, positive or negative effects on environmental health:				
(a) Food/shelter?	−1 = major positive effect 1 = major negative effect	Minor or no effect	Depends on geography of affected community	Minor or no effect
(b) Fire regime?	0 = minor or no effect ? = don't know (=0)	Minor or no effect	Could depend on climate (spatial)	Minor or no effect
(c) Increase nutrient levels?		Minor or no effect	This will be negative in some areas (oligotrophic ecosystems), but could be seen as positive in other areas (e.g. gorse's N-fixing often viewed as positive where it is a nursery cover)	Minor or no effect
(d) Soil salinity?		Minor or no effect	Could use spatial data on soil salinity	Minor or no effect
(e) Soil stability?		Minor or no effect	Could use spatial data on soil stability. Local governments often keep this data for restriction of civil engineering restrictions	Minor or no effect
(f) soil water table?		Minor or no effect	Spatial data likely to be associated with salinity extent.	Minor or no effect
POTENTIAL DISTRIBUTION				
In the assessment area, what area of the land use is suitable for the weed?	10 = >80% of land use 8 = 60–80% of land use 6 = 40–60% of land use 4 = 20–40% of land use 2 = 10–20% of land use 1 = 5–10% of land use 0.5 = <5% of land use 0 = unsuited to land use ? = don't know (=0)	5–10% of land use	Use a model of the species potential distribution. A more granular answer may be sought considering factors such as irrigation in extending the apparent climatic range.	The area is calculated using a CLIMEX Ecoclimatic Index data layer, where suitability is gauged as climates where the EI value is ≥1
COMPARATIVE WEED RISK				
Feasibility Of Containment				
Control Costs				

Table 1. (Continued)

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
1. How detectable is the weed?				
(a) Height at maturity	2 = <0.5 m 1 = 0.5–2 m 0 = >2 m ? = don't know =(2)	0.5–2 m	Could be genetically controlled or be phenotypically plastic. If sufficient data are available, attempt to fit a regression of reported height at maturity to a model of climate suitability and soil fertility. If satisfactory, apply the regression to the climate suitability model and soil fertility data layers	Aspatial: 0.5–2 m. Could depend on environment, But unlikely to exceed the size class boundary
(b) Shoot growth present	2 = <4 months 1 = 4–8 months 0 = >8 months ? = don't know =(2)	>8 months	The annual duration during which the shoot is present may depend on climatic suitability. The CLIMEX Weekly Growth Index (GI_W) variable could provide a suitable estimate	Aspatial: >8 months
(c) Distinguishing features	2 = non-descript 1 = sometimes distinct 0 = always distinct ? = don't know =(2)	Sometimes distinct	Aspatial. Distinctiveness can depend on other vegetation present. Possibly impractical to define variation	Aspatial: sometimes distinct
(a) Pre-reproductive height in relation to other vegetation (in land use)	2 = below canopy 1 = similar height 0 = above canopy ? = don't know =(2)	Similar height	Aspatial. Could depend on other vegetation present. Possibly impractical in most cases	Spatial: 1 for land cover = gorse, 0 for elsewhere
2. What is the general accessibility of known infestations?	2 = low 1 = medium 0 = high ? = don't know =(2)	Medium	Likely to be based on topography. This may be difficult to capture in spatial form	Spatial. Based on topography. 1. Varies hugely (e.g. 2 for seaward Kapiti cliffs, 0 for roadside patches)

Table 1. (Continued)

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
3. Control costs in 1st year for maximum weed density in land use				
(a) Operating costs COST CATEGORY (A, B or C): C	4 = very high 3 = high 2 = medium 1 = low 0 = not applicable ? = don't know =(4)	Medium	Spatial: difficult to map Medium costs in most places	Aspatial: Medium everywhere
(b) Labour costs COST CATEGORY (A, B or C): C	4 = very high 3 = high 2 = medium 1 = low 0 = not applicable ? = don't know =(4)	Medium	May be difficult to map	Aspatial: Medium everywhere
4. Expected level of co-operation from landholders within the land use	2 = low 1 = medium 0 = high ? = don't know =(2)	High	Spatial but political. Could overlay Department of Conservation land here. (Possibly council land, if it can be obtained)	Aspatial: High
CURRENT DISTRIBUTION				
1. What percentage area of the land use is currently infested by the weed?	Refer to the Weed Risk Management Guide for scoring	0.5	Depends on land use. Use current distribution to calculate. Need to identify occupied cells	Spatial. Depends on land use, use current distribution
2. What is the pattern of the weeds distribution across the assessment area?	2 = widespread 1 = evenly scattered 0 = restricted ? = don't know =(2)	Evenly scattered	Weeds might be widespread in some regions but restricted in others. Weeds might be widespread in some regions but restricted in others.	Classify by region: Wellington = 2, Hawkes Bay = 1, Taranaki = 0
PERSISTENCE				
1. Effectiveness of targeted control treatments	3 = low 2 = medium 1 = high 0 = very high ? = don't know =(3)	Medium	Probably aspatial.	
2. Minimum time period for reproduction	3 = <1 month 2 = <1 year 1 = 1–2 years 0 = >2 years ? = don't know =(2)	1–2 years	Could potentially use CLIMEX generations index in combination with knowledge of the plants' reproductive phenology.	Aspatial: 1-2 years

Table 1. (Continued)

Question	PBWRM Options	PBWRM Answers	Spatialisation considerations	WRASP Spatialisation process
3. Maximum propagule longevity	2 = >5 years 1 = 2–5 years 0 = <2 years ? = don't know =(2)	2–5 years	Probably aspatial, but could be modelled spatially using temperature, aridity and possibly soil data	Aspatial: 2-5 years
2. Likelihood of reinfestation				
(a) Natural long-distance dispersal	2 = frequent 1 = occasional 0 = rare ? = don't know =(2)	frequent	Spatial, but probably too complex. Depends on how far 'long-distance' is, and how frequent 'frequent' is	Aspatial: frequent. Most controlled sites are re-invaded every year from neighbouring uncontrolled sites
(b) Grown/planted	2 = commonly grown 1 = occasionally grown 0 = not planted	occasionally grown	Population density/Distance to populated areas	Aspatial: occasionally grown

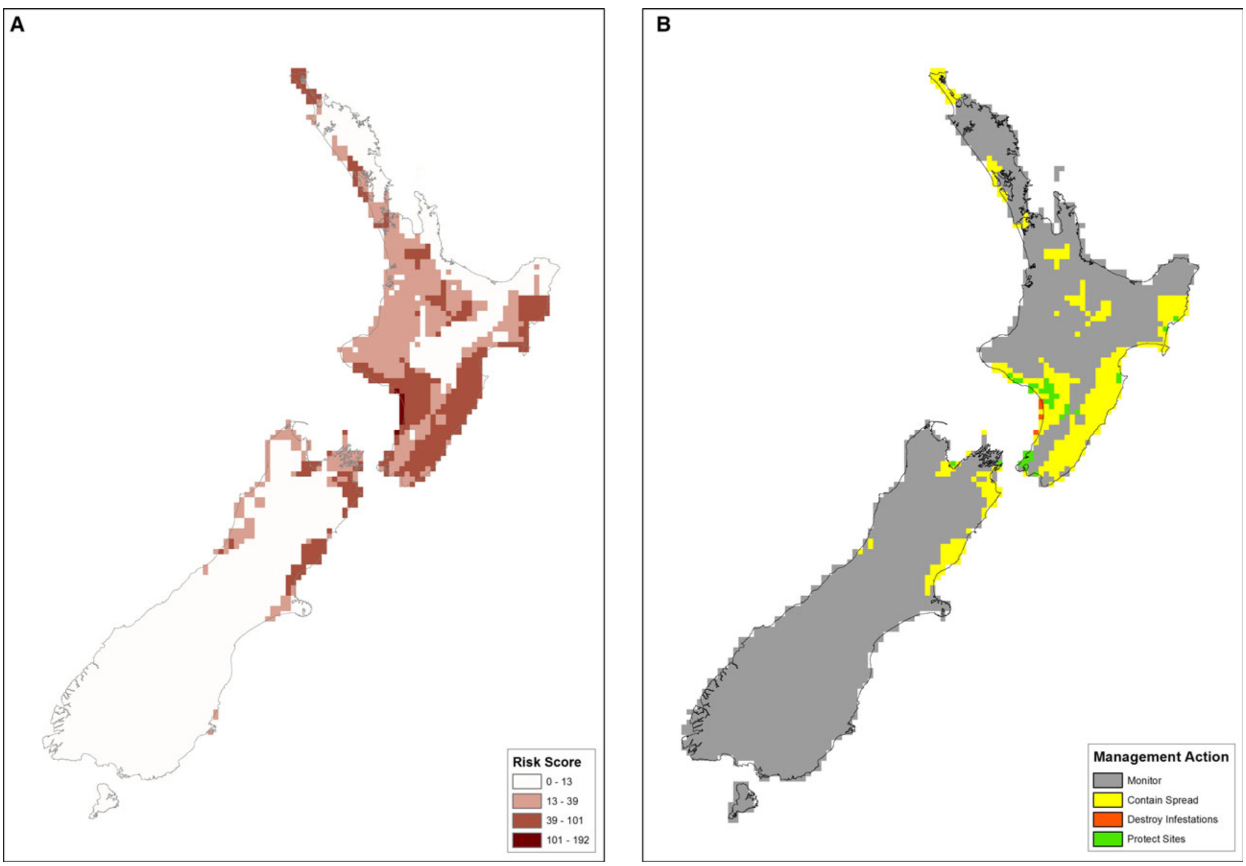

Fig. 4 Spatialised weed risk (A) and management options (B) for *Senecio glastifolius* in New Zealand.

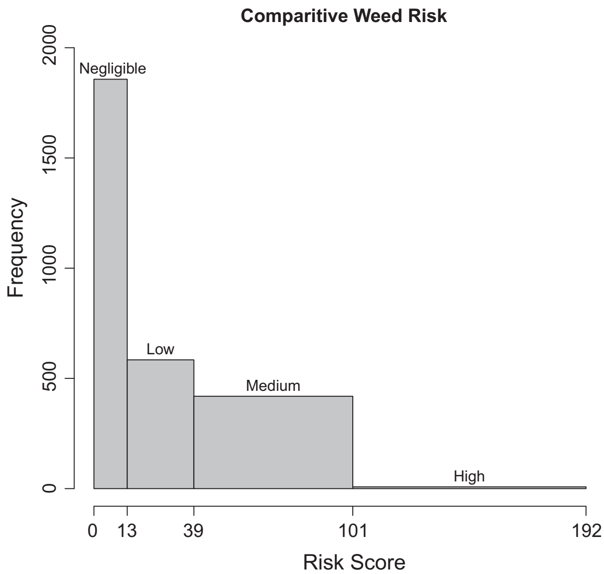

Fig. 5 Frequency distribution of analysed risk for *Senecio glastifolius* in 10 km^2 cells in New Zealand.

Table 2 Comparison of attributes for the aspatial and spatial weed risk management systems

Aspatial	Spatial
Point-based	Map-based
Obscured challenge with framing responses to questions involving spatially variable phenomena	Framing responses to spatially variable phenomena is less challenging
Assessments have to be completed for each separate jurisdiction	Assessments can be completed for multiple jurisdictions simultaneously
Need specific training to frame answers consistently	Need training in basic GIS techniques
Simple risk and management answers	Spatially nuanced risk assessment
Simple prioritisation	More complicated prioritisation

management strategies, perhaps as an input into a further economic screening process (Bourdôt *et al.*, 2015). New Zealand presently has sixteen regional councils. The single spatial analysis conducted here for *S. glastifolius* can be overlain by the council boundaries to highlight the specific risks to each region and the range of management options that should be considered (Fig. 4B). At a glance, the biosecurity managers can immediately see the threat patterns within their individual areas of responsibility. Further, such a picture can highlight opportunities for transboundary co-ordinated efforts for weed management. For example, efforts to contain the spread of a weed in one region may stop or slow the spread to another region where it could generate significant impacts.

The fact that the single analysis can provide answers for all of the councils in New Zealand suggests that there is an economy to be gained by undertaking the analyses in a centralised, or at least co-ordinated manner. The heterogeneity of the resulting risks also highlights the importance of considering how the risk factors vary across the country and the folly of applying the results of the aspatial WRM system throughout the country.

The comparison of attributes of the aspatial and spatial variants of the WRM system make a compelling case for the spatial system (Table 2). The challenge now would seem to be to develop a system that can allow the results of the spatial system to be included into a prioritisation scheme for each jurisdiction. A weighted averaging score is an obvious method to explore.

The spatial tool could theoretically be extended to include consideration of climate change scenarios as a means of future-proofing analyses and guarding against regretful policies. Because this would typically involve the application of a potential distribution model to a novel set of climates, a process-based niche model such as CLIMEX should be preferred to a correlative species distribution model. However, a critical challenge is to find a suitable method for simulating the spatial distribution of vegetation cover types under the future climate scenario. It is unlikely that a digital vegetation model would yield results that are sufficiently granular for the WRASP analysis.

In some cases, an inherently spatial variable phenomenon may not be able to be defined spatially due to the lack of suitable knowledge of the distribution of the phenomenon itself or suitable proxies. In such cases, the analyst will have to make a judgement as to the best course of action, perhaps choosing an aspatial answer to the question. It is possible using this system to test the sensitivity of the results to changes in answers to each question, and the resulting uncertainty can be factored into strategic management plans.

The spatial WRM system is highly scalable. The appropriate raster cell size depends on the size of the modelling universe and the granularity of the jurisdictions: 100 km^2 was a suitable cell size for New Zealand. Whilst Europe is much larger in size than New Zealand, because of its climatic and topographic relief and its high population density, 100 km^2 may still be a desirable level of scale. In contrast, assessing weed risks across Australia may be more suitably analysed at a coarser scale, say 625 km^2.

It is possible to hierarchically nest WRASP analyses across different levels of jurisdiction. For example, a local government authority may wish to prioritise its weed management, in which case, the WRASP system can be applied with finer scale data. In such a case, climate suitability for example may play a less important role than non-climatic habitat factors in defining or influencing weed risk and management.

The spatial WRM system requires an investment in GIS training, niche modelling and the collation of suitable spatial data layers to support the habitat suitability layers. However, once these layers have been collated, and the analyst becomes experienced in translating the knowledge gained from the literature reviews regarding each weed, the speed of applying the analyses should become comparable to the aspatial version of the analysis. The process of assessing risks and management options using this system suggests that it would be most economically applied at a national or regional scale, with data products made available to subnational or subregional jurisdictions. It lends itself to a centralised or bureau service conducting the analyses, with input and review from affected jurisdictions. The interactive nature of the model means that each jurisdiction can challenge the assumptions and the results can be tested in real time. This cost-effective delivery model lends itself to deployment in both developed and developing regions alike.

The stark contrast in results between the PBWRM and WRASP highlights the value of considering how weed risks differ across landscapes and regions. Given that biological invasions and their negative impacts are usually persistent, it is generally preferable to overestimate risks, rather than to downplay them. The comparison we present here reveals a significant bias in the PBWRM system towards underestimating weed risks in heterogeneous environments. In contrast, the WRASP system can reveal hotspots of risk and opportunities for strategic weed management. Because it combines consideration of the risks and the potential for management, WRASP provides a set of information products that can feed into the development of strategic weed management plans for each jurisdiction within the analysis area, complementing economic analyses of costs and benefits of specific management plans for each target species (e.g. Bourdôt *et al.*, 2015).

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References

Auld B (2012) An overview of pre-border weed risk assessment and post-border weed risk management protocols. *Plant Protection Quarterly* **27**, 105–111.

Auld B, Johnson S, Ainsworth N *et al.* (2012) Further development of the National Weed Risk Management Protocol. In: *Developing solutions to evolving weed problems. 18th Australasian Weeds Conference, Melbourne, Victoria, Australia, 8-11 October 2012*, 317–319.

Barry S & Lin X (2010) Point of Truth Calibration: Putting science into scoring systems. Australian Centre of Excellence for Risk Analysis (ACERA).

Beautrais JR (2013) The geographic distribution of *Senecio glastifolius* in New Zealand: past, current and climatic potential. MSc, Victoria University of Wellington, Wellington, New Zealand.

Bourdôt G, Basse B, Kriticos D & Dodd M (2015) Cost-benefit analysis blueprint for regional weed management: *Nassella neesiana* (Chilean needle grass) as a case study. *New Zealand Journal of Agricultural Research* **58**, 325–338.

Crossman ND (2004) The role of spatial analyses in post-border weed risk management. In: *Weed management: balancing people, planet, profit. 14th Australian Weeds Conference, Wagga Wagga, New South Wales, Australia, 6-9 September 2004: papers and proceedings*. (eds BM Sindel &SB Johnson), 450–453.

Crossman ND & Bass DA (2008) Application of common predictive habitat techniques for post-border weed risk management. *Diversity and Distributions* **14**, 213–224.

FAO (2011) *Procedures for post-border weed risk management*, Second edn. Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Rome.

Gilbert M, Guichard S, Freise J *et al.* (2005) Forecasting *Cameraria ohridella* invasion dynamics in recently invaded countries from validation to prediction. *Journal of Applied Ecology* **42**, 805–813.

Gordon DR, Onderdonk DA, Fox AM & Stocker RK (2008) Consistent accuracy of the Australian weed risk assessment system across varied geographies. *Diversity and Distributions* **14**, 234–242.

Groves RH, Panetta FD & Virtue JG (2001) *Weed Risk Assessment*. CSIRO Publishing, Melbourne, Australia.

Howell C (2008) *Consolidated list of environmental weeds in New Zealand*. Science & Technical Pub., Department of Conservation, Wellington, New Zealand.

Hussey BMJ, Keighery GJ, Cousens RD, Dodd J & Lloyd SG (1997) *Western weeds. A Guide to the weeds of Western Australia*. Plant Protection Society of Western Australia, Perth, Australia.

Januchowski-Hartley SR, Visconti P & Pressey RL (2011) A systematic approach for prioritizing multiple management actions for invasive species. *Biological Invasions* **13**, 1241–1253.

Kriticos DJ, Webber BL, Leriche A *et al.* (2012) CliMond: global high resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods in Ecology and Evolution* **3**, 53–64.

Kriticos DJ, Maywald GF, Yonow T, Zurcher EJ, Herrmann NI & Sutherst RW (2015) *CLIMEX Version 4: Exploring the Effects of Climate on Plants, Animals and Diseases*. CSIRO, Canberra, Australia.
Pheloung PC, Williams PA & Halloy SR (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management* **57**, 239–251.
Reichard SH (2001) The search for patterns that enable prediction of invasion. In: *Weed Risk Assessment* (eds RH Groves, FD Panetta & JG Virtue), 10–20. CSIRO Publishing, Melbourne, Australia.
Scott JK, Batchelor KL, Ota N & Yeoh PB (2008) *Modelling Climate Change Impacts on Sleeper and Alert Weeds*. CSIRO, Canberra, Australia.
Skurka Darin GM, Schoenig S, Barney JN, Panetta FD & Di Tomaso JM (2011) WHIPPET: A novel tool for prioritizing invasive plant populations for regional eradication. *Journal of Environmental Management* **92**, 131–139.
Standards Australia (2006) *National Post-Border Weed Risk Management Protocol*. Vol. **HB 294:2006**. CRC Australian Weed Management, Adelaide and Standards Australia International Ltd, Sydney, Australia.
Sutherst RW & Maywald GF (1985) A computerised system for matching climates in ecology. *Agriculture, Ecosystems and Environment* **13**, 281–299.
Virtue J (2008) SA Weed Risk Management Guide. Department of Water Land & Biodiversity Conservation – South Australia.
Wells MJ, Balsinhas AA, Joffe H, Engelbrecht VM, Harding G & Stirton CH (1986) *A catalogue of problem plants in southern Africa*. Memoirs of the Botanical Survey of Southern Africa, Southern Africa 53.
Williams PA, Ogle CC, Timmins SM, La Cock G & Reid V (1999) Biology and Ecology of *Senecio glastifolius* and its spread and impacts in New Zealand. In: *Science for Conservation*, Vol. **112**, 22. Department of Conservation, Wellington, New Zealand

Annex 1
Spatial data sources
New Zealand Land Cover Database (LCDB)

The New Zealand Land Cover Database is a digital map of New Zealand, showing the land cover grouped into the following nine major land cover classes:

1 Exotic forest
2 Exotic shrubland
3 Native forest
4 Native vegetation
5 Other native land cover
6 Primarily horticulture
7 High-producing exotic grassland
8 Low-producing exotic grassland
9 Artificial surfaces

The dataset is derived from classified remotely sensed images. It is available from Landcare Research (www.lris.scinfo.org.nz).