Comparing the outputs of five weed risk assessment models implemented in Australia: are there consistencies across models?

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Summary

Weed Risk Assessment models are increasingly used as decision support tools to prioritize weed species for management. Several models are implemented in Australia, but have not previously been compared for consistency of outputs. This study aims to determine if the outputs of four post-border models are comparable with each other and with the predictive outputs of a Border model. Each post-border model determines weed risk by combining three assessment criteria: Invasiveness, Impacts and Distribution. A common set of 24 species were assessed for weed risk to natural ecosystems through four post-border weed risk assessment models and the Australian Border model. Test species were ranked from highest to lowest weed risk to enable a comparison of model outputs. Pearson's correlation co-efficient and the co-efficient of variation were calculated for all outputs.

Significant positive correlations were observed between the overall outputs of the post-border models. When compared individually, the outputs from the Invasiveness and Impacts criteria also showed significant positive correlations. The distribution criterion was a source of great variability in outputs, producing negative correlations. Outputs from the post-border models also showed significant positive correlations with those from the Border model. The area in greatest need of further development is determining the potential distribution of a species.

Introduction

Decision support tools to assist policy makers and natural resource managers have become integral to developing cost-effective management strategies for invasive pests. New plant species continue to naturalize in areas to which they have been introduced, for example there have been 12 new naturalized species per year in New Zealand in the past 150 years (Lee *et al.* 1999), and a similar number of species naturalized in Australia over the past 25 years (Groves and Hosking 1996). Methods for prioritization of species for control are therefore integral to any successful weed management strategy. Targeted, cost-effective on-ground management is achievable through appropriate risk assessment to identify species that pose the highest threat and have a high likelihood of control success.

The prevention of new incursions of weed species to an area is the most cost-effective means of reducing weed impacts. In Australia, Weed Risk Assessment (WRA) at the Australian border is mandatory for new plant species not already present. This Border WRA model has been developed over 20 years (Pheloung 1996, Pheloung *et al.* 1999), and was adopted as a biosecurity tool in a regulatory framework by the Australian government in 1997. This Border model has since been successfully tested internationally, in New Zealand, Hawaii, the Pacific Islands, Czech Republic, Bonin Islands and Florida. The outputs demonstrated accurate predictive screening of weed potential, and provided economic and environmental benefits (Gordon *et al.* 2008, Keller *et al.* 2007). More recently the model was tested in the Mediterranean basin, where 94% of known invaders were correctly rejected, further demonstrating its effectiveness at identifying true serious invaders (Gasso *et al.* 2010).

Post-border, the need to strategically direct resources for management of invasive pests already present has stimulated the development of several prioritization weed risk management models in Australia (Thorpe and Lynch 2000, Randall 2001, Virtue 2004, Weiss *et al.* 2004, Setterfield *et al.* 2007). A National Post-Border Weed Risk Management Protocol (hereafter referred to as the National Protocol) was published jointly by Standards Australia, Standards New Zealand and the Co-operative Research Centre for Australian Weed Management (2006) to encourage a standardized approach to future post-border model development. These models prioritize plant species already present in a geographic region from highest to lowest weed risk. Post-border models determine weed risk by combining three criteria to assess weed risk: Invasiveness, Impacts and Distribution. In comparison to the Border model, these post-border models are variously implemented and have not undergone rigorous testing or been analysed for accuracy. The general structure of the Border model differs to that of the post-border models in that it divides questions into biogeography/weed history and biology/ecology sections, with three and five subsections, respectively.

Prior to regulatory adoption by Biosecurity Australia, the Border model was initially tested by analysing its performance for 370 plant species (Pheloung *et al.* 1999). Its performance has subsequently been revised using analyses of 111 species (Daehler and Carino 2000), 1183 species (Gordon *et al.* 2008) and 197 species (Gasso *et al.* 2010), and the overall effectiveness of the system in identifying serious weeds was demonstrated, with some improvements to the model suggested. In contrast, only one post-border model developed to determine the 20 Australian Weeds of National Significance (WoNS) (Thorpe and Lynch 2000) has been tested or calibrated (Virtue *et al.* 2001). Performance of the post-border models have not been analysed due to the small number of species assessed through each system, and thus no assessment of consistency between existing post-border models has been undertaken.

An important first step in evaluating the consistency of current models is to assess each model for a common set of species and compare the outputs. The objective of this study is to evaluate the consistency of five different models currently in use in different jurisdictions in Australia. We evaluated the five models by assessing 24 species for weed risk in a particular geographic region and for a specific land use. Specifically we aimed to determine if:

(1) The outputs of four post-border models were consistent, and

(2) The outputs were comparable to the predictive outputs of the Border model.

The information generated through this assessment will contribute to future refinement of the National Protocol by identifying commonalities and inconsistencies among models. The results will also assist land managers and organizations in determining whether a standardized approach can be taken in developing post-border models, and whether models already developed may be adopted in other jurisdictions.

Methods

The outputs of four post-border WRA models, and the Border WRA model were evaluated for a common set of known weed species for risk to natural ecosystems in the south-west of Western Australia. A comparison of the rankings of the test species from highest to lowest weed risk from each model enabled a determination of consistency in outputs.

WRA models

Five WRA models that are implemented or developed in different jurisdictions in Australia were selected for comparison. These include the Border model, three models implemented by different Australian State or Territory governments (Victoria, South Australia, Northern Territory), and a model developed in Western Australia used at regional level in New South Wales (Ash *et al.* 2004) and Western Australia (S. Peltzer personal communication). A summary of the models, their basic structure and scoring method is shown in Table 1. The post-border models have not all been developed independently (Figure 1). This study compares the outputs of the post-border models, and the outputs of the Border model. Feasibility of containment/control, which is included in the SA and NT models and is recommended in the National Protocol, was not considered in this study. This additional section utilizes current distribution and other data to make an assessment on the feasibility of coordinated control of a species and is used in conjunction with weed risk assessment in the overall decision process for allocation of management resources.

To ensure consistency, all assessments were made by the senior author and guided by individual model instructions and definitions. The extent of these instructions and definitions varied between models, as did the use of examples to demonstrate differentiation between answers. For each species, a search of primary and secondary literature sources and consultation with experts was undertaken to source the data required for each assessment.

The weed risk assessments were completed in the context of risk to natural ecosystems, and did not include other land use systems such as agriculture, horticulture, forestry or urban environments.

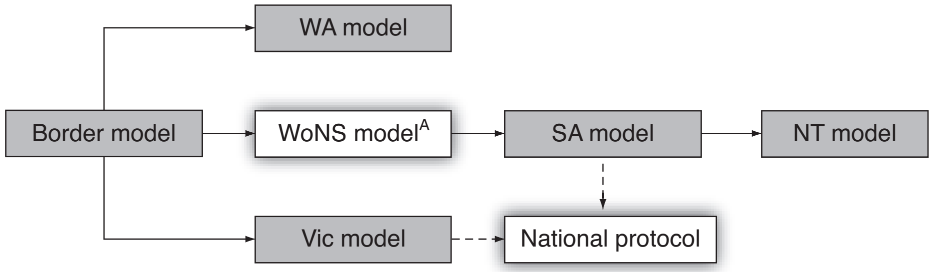

Figure 1. Sequential development of Weed Risk Assessment models compared in this study (shaded boxes). Refer to Table 1 for model references and descriptions. ^A The WoNS (Weeds of National Significance) model was not compared in this study.

Distribution. Distribution can be assessed in different ways in several models, but the National Protocol recommends using potential distribution in weed risk assessment. The Victorian model has two methods for generating a score for this section. One method uses spatial analysis (GIS) of climate match, susceptible land-uses and broad vegetation type (BVT) overlays to determine the ratio of present to potential distribution of a species, which then corresponds to a score for this section. The second method provides descriptive categories based on infestation characteristics in a look-up table to estimate distribution. These correspond to ratios of present to potential distribution generated using the first method. Due to time and resource constraints, the second method was used in this study.

The South Australian method for determining the potential distribution of the species can be done electronically using GIS, or manually using physical map overlays. The electronic method was used in this study. For each species, the climatic and soil preferences were mapped over a land use of native vegetation. Climate preferences were determined using ‘Climatch’ (formerly called CLIMATE) (Brown *et al.* 2006, BRS 2008), a simple software package designed for depicting areas with similar climate characteristics. Global species location data were used to predict the distribution in Australia based on temperature and rainfall parameters. Western Australian location data were excluded from the analysis to ensure the models were not biased with local data. The Euclidean statistical analysis method was used within the program, and any climate match below 70% of the mean was excluded. To map soil preferences in a GIS framework, the Digital Atlas of Australian Soils was used, which enables broad soil preferences to be selected according to the Northcote classification of Australian soils (BRS 1991, Northcote *et al.* 1975). The native vegetation in the study region (Figure 2) was the final layer used in the distribution analysis, using internal GIS datasets from the Western Australian Department of Environment and Conservation (DEC).

The Northern Territory model has three questions that determine the potential distribution of a species. The first question requires Climatch analysis, and the map generated for the South Australia model was used here, excluding the vegetation and soil overlays. The second question describes the 13 broad vegetation types (BVTs) in the Northern Territory. The highest score results if the species could potentially naturalize in up to five of these (38% of total BVTs). The vegetation types in the study region in Western Australia are significantly different to those in the Northern Territory. There are 25 vegetation types that can be described as BVTs in this region, so to retain a similar scoring structure for this analysis, the highest score resulted if the species could potentially naturalize in up to 10 of these (40% of total BVT).

To determine potential distribution the Western Australian model combines an estimate of the current distribution using schematic diagrams describing different types of infestations, with an ‘activity factor’ to determine the potential for spread. Although this section is termed ‘Potential distribution’, in the model, it is really an estimation of current distribution.

The Border model has a default setting for answers to Questions 2.01 and 2.02 relating to climate, where the highest score results if no climate analysis was carried out. The default setting was used for this analysis.

Selection of study geographic region

The geographic location chosen for this study was the Department of Environment and Conservation South West and Warren administrative regions (Figure 2). These regions, totalling approximately 3.46 million ha in size, have a warm to moderate Mediterranean climate, supporting eucalypt forests and woodlands, species-rich shrublands, swamps and Holocene marine dunes. These regions will be referred to collectively as the study region hereafter.

Species selection

A total of 24 test species were selected based on life form, life cycle and current perception of weediness in Western Australia. Species were chosen to ensure a comparison of the models was comprehensive and representative of the range of species that may be assessed in southern Australia. Species with a range of perceived weediness within each life form

Table 1. Summary of Weed Risk Assessment (WRA) models compared in this study.

WRA Model	Model type	Number of questions	Question Sections/Categories	Scoring method	Reference
Border model (Biosecurity Australia)	Border	49	Biogeography/historical Domestication /cultivation Climate and distribution Weed elsewhere Biology/ecology Undesirable traits Plant type Reproduction Dispersal mechanisms Persistence attributes	Additive (some questions weighted)	Pheloung *et al.* 1999
Victorian Pest Plant Prioritization Process (Vic)	Post-border	41	Invasiveness Impacts Present: potential distribution or Current distribution	Additive (Individual questions and sections weighted before adding scores from each section)	Weiss *et al.* 2006
South Australian Weed Risk Management Guide (SA)	Post-border	24	Invasiveness Impacts Potential distribution	Multiplicative (sum scores within each section, then multiply)	Virtue 2004
Northern Territory Weed Risk Management Guide (NT)	Post-border	23	Invasiveness Impacts Potential distribution	Multiplicative (sum scores within each section, then multiply)	Setterfield *et al.* 2007
Which are my worst weeds? (Western Australia) (WA)	Post-border	36	Invasiveness Impacts (Potential) distribution[A]	Additive (final score increased by 10% if species is identified as 'threatening')	Randall 2001

[A] Model assesses current distribution.

Figure 2. Location of the study region: South West and Warren administrative regions of the Western Australian Department of Environment and Conservation (DEC).

and growth habit were deliberately selected to evaluate the capacity of the models to differentiate high weed potential from low weed potential. The perceived weediness of the test species was determined by consultation with selected weed specialists and use of a local weed text (Hussey *et al.* 2007).

Comparing model outputs

For all models, a higher score indicates greater weed risk. To enable a direct comparison of model outputs, the 24 test species were ordered from highest to lowest score for each model and were then given a ranking of 1–24. Species rankings were also compared for individual WRA criteria (Invasiveness, Impacts and Distribution) for post-border models, and compared to the final score ranks of the Border model.

Data analysis

Correlations between final species rankings from the outputs of the five WRA models were analysed using Pearson's correlation co-efficient (Rs) (SAS Publishing 2004). Correlations were also calculated for each of the three individual criteria in the post-border models: Invasiveness, Impacts and Distribution. To determine the spread of scores, the co-efficient of variation (C_v) was calculated for the final scores and scores for each criterion of the post-border models.

Results

Comparison of post-border model outputs

Ranking of the 24 species was variable across models (Table 2). Although each WRA model produced a different ranked list of species based on the final WRA score, there were significant positive correlations between models (Table 3a). The most strongly correlated models were WA and NT (Rs = 0.828) and WA and Vic (Rs = 0.788). The weakest significant correlation was between SA and NT (Rs = 0.415) and SA and WA (Rs = 0.431).

There were ≤5 rank positions difference between models for 14 of the 24 test species, indicating overall consistency in output across models. The spread of final scores within models, reflected in the coefficient of variation (Table 4), was mixed, with SA and NT models producing the largest spread of scores (C_v = 1.32, 1.02 respectively). The smaller spread of scores for the Border model, Vic and WA were similar (C_v = 0.37, 0.31, 0.30 respectively).

Analysis of individual weed risk criteria for each post-border model as opposed to final scores revealed a different pattern of correlation between models. For the Invasiveness criterion (Table 3b), the SA and NT models showed the strongest significant positive correlation (Rs = 0.791). In contrast to the final score rankings, the WA model did not correlate well with any other model for this criterion. Overall, only eight of the 24 test species had ≤5 rank positions difference between all models for this criterion indicating a wide variation in assessment outcomes. The spread of scores for this criterion was similar for all post-border-models, shown by the similar co-efficient of variation values (C_v = 0.77–0.80).

The Impacts criterion produced the most consistent output across post-border models (Table 3c). Significant positive correlations ranged from Rs = 0.925 (SA and NT) to Rs = 0.755 (WA and Vic), and the co-efficient of variation values were also similar across the models (C_v = 0.19–0.26). Overall, 15 species had ≤5 rank positions difference between all models further demonstrating the consistency in output for this criterion.

The results from the Distribution criterion analyses (Table 3d) reflected the differing methods used to calculate a score for this criterion. Correlations between all models were poor, and the only positive and significant correlation was between the WA and Vic models (Rs = 0.587). The co-efficient of variation also varied widely (C_v = 0.26–1.09), reflecting the wide range of scores produced by some models. Only one species was ranked with ≤5 positions difference between all models.

Table 2. Final ranks of test species for all models.

Species	BA	Vic	SA	WA	NT
Chamaecytisus palmensis	7	8	2	6	5
Phalaris aquatica	7	12	9	8	6
Nassella neesiana	1	1	7	1	4
Cichorium intybus	21	13	19	24	21
Trifolium subterraneum	15	18	11	22	12
Lactuca serriola	12	23	19	12	14
Megathyrsus maximus	20	14	19	17	22
Briza maxima	22	24	18	23	15
Pennisetum polystachion	2	11	19	15	23
Lavendula stoechas	7	19	5	14	17
Tribolium uniolae	18	4	6	7	3
Retama raetam	5	2	13	2	1
Gastridium phleoides	24	10	19	19	18
Chloris gayana	15	20	14	17	16
Cenchrus echinatus	7	6	17	13	13
Hyparrhenia hirta	2	5	7	4	10
Eucalyptus cladocalyx	22	16	15	16	19
Oxalis pes-caprae	7	7	16	10	8
Echium plantagineum	13	9	11	9	11
Lathyrus latifolius	15	21	10	21	20
Pennisetum clandestinum	5	15	3	11	7
Digitaria ciliaris	19	22	19	19	24
Chrysanthemoides monilifera ssp *monilifera*	4	3	3	3	2
Acacia pycnantha	13	17	1	5	9

Comparison of post-border and Border model outputs

The outputs of the post-border models were compared to those from the Border model to determine whether the predicted weed risk was similar to the weed risk post-introduction. Two of the test species are not yet present in the study region, but are present elsewhere in Australia. The outputs from all post-border models correlated significantly with the output from the Border model (Table 3a), however the WA model showed the strongest correlation (Rs = 0.677), followed by Vic (Rs = 0.578) and NT (Rs = 0.518) models. Twelve of the 14 species that the post-border WRA models ranked most consistently (≤5 rank positions difference between models), also had outputs with ≤5 rank positions difference for the Border model. Outputs for individual criteria of the post-border models were also compared to the Border output to determine if results from the Border model reflected any of the three criteria more strongly. Overall the Invasiveness and Impacts criteria for all post-border models showed positive, significant correlations with the Border model (Table 3b,c). The Distribution criterion correlated poorly with no significant correlation identified (Table 3d).

Discussion

The proliferation of weed risk assessment models in recent years is evidence that agencies responsible for weed control across various jurisdictions are developing more strategic methods to allocate limited resources. The publication of the National Protocol by Standards Australia in 2006 aimed to provide guidance on how to design a WRA model, and to encourage harmonization and consistency of models across jurisdictions. The recommended structure and content for a WRA model in that publication used many of the principles of the post-border models compared in this study. The results of this study suggest that for the Invasiveness and Impacts criteria, there is already some consistency in outputs. However, there is considerable variation in the determination of species distribution, and this significantly impacts on the final outcome of the weed risk assessment. A standard approach to analysing distribution is urgently required.

Are the outputs of the post-border models consistent?

The post-border models ranked all the test species differently, but closer examination of the results indicates there are consistencies in outputs between some of the models. The results also indicate there is one criterion in the WRA models (distribution) that introduces a significant level of

Table 3. Pearson's correlation coefficients (n = 24) of outputs generated from Weed Risk Assessment models from the Border, Victoria (Vic), South Australia (SA), Western Australia (WA) and Northern Territory (NT). (a) Final rankings, (b) Invasiveness scores, (c) Impacts scores, (d) Distribution scores. Note that for all tables, the correlation with final ranks were used for the Border model, as the model does not explicitly differentiate between Invasiveness, Impacts and Distribution.

(a) Final scores

	Border	Vic	SA	WA	NT
Border	1				
Vic	0.578[A]	1			
SA	0.377[A]	0.108	1		
WA	0.677[A]	0.788[A]	0.431[A]	1	
NT	0.518[A]	0.661[A]	0.415[A]	0.828[A]	1

(b) Invasiveness scores

	Border	Vic	SA	WA	NT
Border	1				
Vic	0.641[A]	1			
SA	0.519[A]	0.672[A]	1		
WA	0.549[A]	0.391	0.236	1	
NT	0.430[A]	0.656[A]	0.791[A]	0.247	1

(c) Impacts scores

	Border	Vic	SA	WA	NT
Border	1				
Vic	0.630[A]	1			
SA	0.590[A]	0.781[A]	1		
WA	0.596[A]	0.755[A]	0.909[A]	1	
NT	0.608[A]	0.816[A]	0.925[A]	0.836[A]	1

(d) Distribution scores

	Border	Vic	SA	WA	NT
Border	1				
Vic	0.097	1			
SA	0.242	−0.323	1		
WA	0.338	0.587[A]	−0.122	1	
NT	0.062	−0.200	0.296	0.070	1

[A] Indicates a significant correlation ($P < 0.05$).

Table 4. Coefficient of variation (C_v) of outputs from the five weed risk assessment models.

Model	Final score	Invasiveness	Impacts	Distribution
Vic	0.31	0.24	0.77	0.37
SA	1.32	0.22	0.77	1.09
WA	0.30	0.19	0.78	0.26
NT	1.02	0.26	0.80	0.39
Border	0.37			

uncertainty into the assessment, and limits the capacity for harmonization across models. This is attributed in part to the different methods used by the models, in particular, whether current or potential distribution is used to generate a weed risk score.

When considering the raw overall rankings of the species, the difference in rank for 58% of the species was ≤5 rank positions, suggesting the models have potential to consistently group species with similar risk. Whether WRA results are presented as a list or grouped in categories depends on the requirements of the end user. The ranked list method is not specifically linked to management outcomes or actions, but does provide guidance on where to place available management resources. By grouping species into categories of weed risk, the management actions can be pre-defined by each category, which may be preferable in a rigid, regulatory framework, because it is more prescriptive for management activity.

The general structure of all post-border models is similar, incorporating three criteria: Invasiveness, Impacts and Distribution. This aligns with the recommendations published in the National Protocol, noting that the National Protocol advocates using potential distribution, not current distribution, to assess weed risk. The ranking of species based solely on the output from the Invasiveness criterion showed some significant, positive correlations. A strong correlation between SA and NT models was expected due to how the models were developed (Figure 1). The output of the WA model correlated poorly with outputs from all other models for this criterion, which is possibly due to the difference in question style. The information gained from the questions in the WA model is similar to that from the other models, however the WA model offers yes/no responses to each question, rather than a scale (multiple choice ratings) of responses. This reduces the ability of the model to distinguish degrees of invasiveness, which is also reflected in the low coefficient of variation for this criterion in the WA model (C_v = 0.19) compared to the other models that are able to suggest degrees of invasiveness.

For the Impacts criterion, the correlation between outputs of all post-border models was consistently high, suggesting each model assesses the impact of a weed species in a similar manner. Reducing linguistic uncertainty in the Impacts criterion questions is probably more crucial than for the other criteria, as for many species the impacts are often not quantified, and the assessor may need to interpret or extrapolate data to decide an answer. The Vic model provides the most detailed instructions for selecting an appropriate answer to each question, with clear boundaries or examples within each classification of low, medium, medium/high or high. The WA model provides the least guidance, with minimal explanation for each question, and only yes/no or don't know options offered. It is possible that the consistency in outputs for this criterion may change if there were multiple assessors. The lead author completed all assessments in this study, and as such, any questions that required interpretation or extrapolation of available data were done consistently across models. Though not tested here, using the responses from multiple assessors to do a similar comparison would provide valuable insights into linguistic uncertainty within model questions. It is likely that greater variation between models would be observed.

The most significant factor impacting on consistency of outputs of the WRA models tested here is determining the distribution of a species. Each of the models assesses distribution using a different method, which is reflected in the results. The Vic and WA models showed the only significant (but weak) correlation (Rs = 0.587) for this criterion, which is likely due to determining distribution by written descriptors, rather than using electronic mapping. The result would likely change for the Vic model if the alternative method using GIS was used. A lack of resources prevented utilization of this method for this study. The methods used for the SA and NT models utilized climate modelling and GIS to predict potential distribution based on climatic parameters, soil and vegetation at risk. The National Protocol advocates using potential distribution to assess weed risk, and current distribution to assess feasibility of control. Estimation of potential distribution is a key driver and is more informative than current distribution data when making long-term management decisions, particularly when management focus is on new and emerging weed species. Spatial modelling utilizing native and naturalized global distribution data is therefore a key component of weed risk assessment, remembering that the objective for any modelling exercise is not to precisely mimic reality, rather to use modelling to assist in decision making (Kriticos and Randall 2001).

Predictive species distribution modelling is a complex process that has received significant attention in recent years as scientists try to understand the effect of climate change scenarios on invasive species (Kriticos *et al.* 2006). Some techniques are prohibitive for many weed risk assessment projects where large numbers of species are assessed, due to their labour intensive and specialist nature. In some circumstances the additional cost may be warranted, but for some weed prioritization projects, a consistent approach that is less sophisticated may meet the end users needs.

The positive correlation between outputs from some models for the Invasiveness and Impacts criteria may be useful in identifying the key questions in a WRA for obtaining an answer that accurately reflects the weed risk of a species. To assess invasiveness, the number of questions in each post-border model ranges from 12 (NT) to 18 (WA). To assess impacts, the variation in number is greater; the SA and NT models ask 11 questions, the WA model 18 questions, and the Vic model 26 questions. To satisfy the criteria suggested by Daehler *et al.* (2002) for an ideal WRA model, a model must have low input costs in terms of time and money. This is more likely to be achieved if questions that do not significantly impact on the outcome are excluded. The National Protocol also states that as few questions as possible should be included without compromising accuracy. Analysis of the Border model has identified key questions that significantly impact on the overall weed risk score (Caley and Kuhnert 2006, Fukuda and Brown 2007, Weber *et al.* 2009), and a similar analysis could be performed on the outputs of post-border models. The danger in reducing the number of questions to only those that significantly impact on the outcome is the ability to differentiate smaller degrees of variation is also reduced.

Are the outputs of the post-border models comparable to the predictive Border model?

The Border model is the most widely tested and analysed WRA model available, and given its proven effectiveness, it is appropriate to compare the outputs of post-border models with the outputs of this model. Several analyses of the Border model have confirmed successful identification of true serious weeds, with an average of 90% accuracy reported by Gordon *et al.* (2008). It is less accurate predicting non-weed species, averaging a 70% success rate, and future improvements are likely to focus on improving the accuracy for this group of plants.

The strongest correlation of the Border model with the WA model could be explained by the similarities in composition and scoring method of the two models. Both models require simple yes/no answers to questions and use an additive scoring method. The Border model has a limited number of questions which are weighted against the responses from other questions. Where the response to a question is 'don't know', the WA model imposes a penalty score, whereas the Border model does not, instead requiring a minimum number of questions to be answered for a result. The Vic model correlated strongly with the Border and WA models overall and also uses an additive scoring method. It differs from the Border and WA models in that scores from each criterion are multiplied by a weighted factor prior to adding them together. Therefore, each criterion does not have an equal influence on the final score.

Quantifying weed risk is a difficult task, due to the inherent uncertainty surrounding the likelihood of species becoming pests. For the models assessed here, the mechanism to do this varies with the aim of the WRA; whether to predict a new weed species, or to rank known weeds by degree of detrimental impact. Regardless, there are several important properties that any WRA model should possess, which Daehler *et al.* (2002) identified as: have a scientific basis, be transparent, minimize subjective opinion, be repeatable, and have low input costs (time, money). The post-border models studied here meet many of these criteria, in that they do have a scientific basis, are transparent and have low input costs. The degree to which subjective opinion and repeatability are achieved was not examined here, but could be examined by comparing results from multiple assessors.

Conclusion

This study showed there are consistencies in the outputs of post-border models implemented across different jurisdictions in Australia, particularly for the Invasiveness and Impacts criteria. The results also suggest that the area in greatest need of further evaluation is the determination of the potential distribution of a species, as this criterion showed the greatest degree of variability and inconsistency between the models. Any improvements to spatial distribution models for post-border weed risk assessment must be balanced with the technical skills of the end user and resources available to complete the weed risk assessments. Investigation of alternative methods of scoring the three criteria in a post-border model to reflect the degree of uncertainty in each section may provide clearer context for the outputs, and differentiate between species where knowledge is a limiting factor. Future analysis of model outputs could also identify the key questions that significantly influence the outcome of a WRA, to reduce the number of questions included, and minimize input costs of completing each assessment. Outputs from the post-border models showed significant positive correlations with those from the predictive Border model, particularly for the Invasiveness and Impacts criteria, indicating that these two criteria form the basis of the Border model predictions.

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