Centre of Excellence for Biosecurity Risk Analysis

Report Cover Page

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Spatial models for marine biofouling and post-border response		
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Summary		
The Australian Department of Agriculture (Aust. DA) and the New Zealand Ministry of Primary Industries (NZ MPI) make various biosecurity decisions that require spatial predictions of the likelihood of pest occurrence or the suitability of potential habitat. A number of modelling tools can inform these decisions, which can be broadly characterised as correlative approaches and process-based approaches. The project used marine and terrestrial case studies to explore their 'defensibility', which focussed on their performance, and their 'usability', which focussed on their ease and cost of use. The project provided no clear consensus that currently available spatial tools will provide adequate solutions for all relevant scenarios. For the marine case it was concluded that a method is required that considers the degree of environmental similarity between source and sink environments, time in donor and recipient ports, and attributes from transit routes of vessels. For terrestrial scenarios it was concluded that process-based models are currently more appropriate for making defensible predictions, but may be more difficult to implement when data are poor and are thus not always suitable for government decision making. Hence, models were proposed that would use a mixture of expert opinion and correlative methods to determine key variables in the native range and the results would be used to make predictions in Australia/New Zealand. New research should explore the relative performance of these approaches and compare the practicalities of implementing them. Developing new methods will also require developing and retaining the expertise to apply them. This project is the basis for two new CEBRA projects that will implement the ideas that emerged: CEBRA projects 1402A: "Development of a marine spatial analysis model for improved biofouling risk assessment"; and 1402B: "Tools and approaches for invasive species distribution modelling for surveillance".		
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Evaluating spatial analysis tools for surveillance and monitoring in marine and terrestrial environments

CEBRA Project No. 1302A

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Final Report

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1. Executive Summary

The Australian Department of Agriculture (Aust. DA) and the New Zealand Ministry of Primary Industries (NZ MPI) make various biosecurity decisions that require spatial estimates of the likelihood of pest occurrence or the suitability of potential habitat. A number of modelling tools can inform these decisions, which can be broadly characterised as either correlative or process-based methods. However, currently there are no systematic approaches in Australian Department of Agriculture for using these methods to address biosecurity questions. In this study, three biosecurity decision scenarios were provided by the Department of Agriculture and the utility of a range of existing methods for addressing them was explored using expert assessments and workshops, both for their 'defensibility', which focussed on their performance, and their 'usability', which focussed on their ease and cost of use.

The three scenarios were:

1. Marine: A requirement to estimate the spatial risk of establishment, that incorporated some estimate of habitat suitability for over 40 marine pest species identified as species of concern.
2. Terrestrial: A requirement to estimate the total potential distribution of a new pest incorporating distribution of its potential hosts.
3. Terrestrial: A requirement to estimate the actual distribution of a newly invaded pest to facilitate emergency response.

The project provided no clear consensus that currently available spatial tools will provide adequate solutions for all these scenarios. For the marine case it was concluded that predicting habitat suitability for 40 species of concern, with limited available knowledge and data, was likely to be difficult and ineffective. Hence, the best way forward was considered to be the development of a method that considered the degree of environmental similarity between source and sink environments, time in donor and recipient ports, and attributes from transit routes of vessels.

For the terrestrial scenarios it was concluded that in some cases process-based models are currently most capable of making defensible estimates of the potential distributions of invasive species and are likely to be most appropriate for high-risk decisions. However, like all models, they include some subjective elements and in some circumstances, these methods may be too time-consuming and difficult to implement for more routine government decision making. Correlative models, which are generally considered more 'user friendly', are inherently less suited to invasive species modelling

problems, which tend to involve projecting models into novel climates. Hence, alternatives were proposed to overcome their shortcomings. At the core of the suggested changes was restriction of outputs to areas not requiring extreme extrapolation, and the use of expert opinion to inform important elements such as defining the best variables to predict into to novel environments. New research should compare the relative performance of these suggested new methods with mechanistic modelling approaches. Research should also consider the practicalities of implementing these types of approaches for biosecurity decision making.

Estimating the potential ranges of invasive species is not straightforward, so whatever methods are adopted, agencies will need to build capability to be able to use the methods appropriately (Elith 2014 accepted). It's clear that without appropriate expertise it's relatively easy to use all methods badly. Agencies such as EPPO, EFSA, CFIA, FERA and USDA APHIS have invested significantly in human modelling capability. Developing new methods will also require developing and retaining the expertise to apply them. It's also clear that standard protocols will need to be developed so that adopted methods generate the level of repeatability and defensibility desired for government decisions.

This project has provided the basis for two new CEBRA projects that will implement the ideas that emerged: CEBRA projects 1402A: "Development of a marine spatial analysis model for improved biofouling risk assessment"; and 1402B: "Tools and approaches for invasive species distribution modelling for surveillance".

2. Introduction

The Australian Department of Agriculture and the New Zealand Ministry of Primary Industries, like other jurisdictions, make biosecurity decisions that require spatial predictions of the likelihood of pest occurrence. Broadly, these decisions can be grouped as: (1) decisions that require some estimate of the total potential distribution of a pest; (2) decisions that require some estimate of where a newly detected pest is likely to be; or (3) decisions that require some estimate of where pests are most likely to invade and establish. Decisions can also be broadly grouped by whether they focus on a specific pest taxon, or whether they require consideration of a range of pests. Finally decisions can be grouped by whether they just require application of some form of species distribution model, or whether they also require some assessment of the likelihood of incursion along pathways.

Currently there are no systematic methods in the Australian Department of Agriculture for addressing many of these types of questions. However, the NEBRA (National Environmental Biosecurity Response Agreement) specifies the Invasive Marine Species Range Mapping Tool Methodology (Invasive Marine Species Range Mapping 2007; Summerson and Lawrence 2007; Richmond et al. 2010) is the preferred method for modelling the potential distribution of marine pests. The model produces maps of the range of pest species in Australia's coastal waters. A number of modelling tools and methods exist which may be appropriate. However, a comprehensive assessment of the various technical and practical benefits and tradeoffs associated with using these for Australian government decisions does not exist. This project involved a preliminary assessment of some of the tools and models available, framed around some case studies (detailed in Appendices 1 and 2) that represent a subset of the broad questions identified above. The three case studies were framed as:

1. Marine: A requirement for an estimate of spatial risk of establishment, that incorporated some estimate of habitat suitability for over 40 marine pest species identified as species of concern.
2. Terrestrial: A requirement for an estimate of the total potential distribution of a new pest incorporating distribution of its potential hosts.
3. Terrestrial: A requirement for an estimate of the actual distribution of a newly invaded pest to facilitate emergency response.

Froese (2012) provides descriptions of some types of biosecurity decisions that require spatial models, with a focus on estimating distributions of individual species. It is not, however, based on detailed knowledge of the different modelling packages. As Froese (2012) points out, the types of models used to predict species distributions (species distribution models – SDMs) can be broadly classified as *correlative models* and *process-based models*. Within these broad types there are several competing methods that make different assumptions and perform differently when applied to invasive species.

The major challenge for all models when estimating potential distributions for invading species is that the species is entering an environment that is likely to differ from the native range (Elith 2014, accepted; Froese 2012; Webber et al. 2012). Physical and biotic conditions will be different and this imposes a fundamental uncertainty in our ability to predict.

In this study the utility of a range of existing methods for addressing the above biosecurity case studies was explored using expert assessments and workshops, both for their 'defensibility', which focussed on their performance, and their 'usability', which focussed on their ease and cost of use.

3. Methodology

3.1. Project Outline

Specialists and expert users of spatial tools for species distribution modelling were identified and invited to participate in the project. These participants met in Canberra in September 2013 and agreed upon spatial methods to be assessed and assessment criteria based around defensibility and operability (human and organisational factors). Department staff provided scenarios to illustrate some of the potential biosecurity questions requiring spatial predictions for both marine and terrestrial systems (Appendices 1 and 2). Subsequently, five method experts independently assessed a broad range of SDM techniques against each of the criteria. These assessment criteria were compiled and distributed to a larger number of participants to frame discussions at a subsequent workshop. This workshop was held at the University of Melbourne in February 2014, where participants met and discussed the expert assessments against the Department's modelling needs.

3.2. Participant Roles

The project included three types of participants, the typology reflecting contributions;

1. *Method experts*: Denys Yemshanov, Jane Elith, Darren Kriticos, Michael Kearney and Rupert Summerson
2. *Technical reviewers*: Simon Barry, Peter Caley, Tony Arthur, Mark Burgman, Heroen Verbruggen, Emma Johnsont and Graeme Inglis
3. *Policy / context specialists*: Paula Brown, Bertie Hennecke, Chris Starkey and José ten Have

3.3. Candidate Modelling Approaches

The following candidate tools were identified during the September workshop:
Maxent, CLIMEX, Climatch, GLM, Bioclim, Niche Mapper, GARP, Hierarchical Bayes, Heat maps, Temperature Tolerance Modelling (TTM), iSDM and Phenofit (see Appendix 3 for descriptions). The analysis excluded SOM (because of the scale of the questions), NAPFAST (because of constraints on data links), MDIG (because it uses a dispersal model), Biomod (an ensemble method) and bespoke models (because these are primarily variants on the selected methods). The selected methods cover approaches including machine learning methods, statistical procedures, climate matching algorithms, and methods that depend to varying degrees on more mechanistic matches between species attributes and the environment.

3.4. Assessment Criteria

An initial literature search identified a number of candidate assessment criteria. Additional potential criteria were brainstormed during the September meeting. After discussions the list was revised and the following criteria were identified (Table 3.1). They fall into two major categories based on: 1) the defensibility of the models; and 2) how feasible they are to implement (operability) given human and organisational requirements.

Table 3.1: ***Assessment criteria for spatial models***

Defensibility	
Mathematical and scientific theories that underlie the approach are well understood and have proven properties. In well-defined contexts, the results of applications of the method should be broadly scientifically accepted. Elements of defensibility are listed below.	
Elements	**Description**
Objectivity	Avoids subjective judgments and biases.
Repeatability	Given the same information and scientific evidence, the method produces the same results each time it is applied, irrespective of the user.
Rigour	• The method uses clearly and unambiguously defines syntax, semantics and algorithms. • The model documentation is thorough and complete.
Correctness	• Calculations are consistent with mathematical logic and statistical theory. • Assumptions for causal processes and dependencies are consistent with ecological theory and accepted scientific facts.
Comprehensiveness	• The method provides for the use of all available, relevant information. • The models outputs can be updated as new information is acquired.
Accuracy	• The method provides accurate and unbiased estimates for species distributions, in circumstances relevant to the applications being contemplated. • If estimates are biased, the direction and magnitude of the biases are known or can be estimated.
Documentation	Assumptions, explicit formal models and precise calculations are documented in manuals, texts, papers or other accessible documents.
Verifiability	The models generate outputs that, if appropriate data were collected, could be used to verify or falsify the models, or to estimate the accuracy and bias of the extrapolations.
Uncertainty	• The method provides a means to incorporate uncertainty arising from variability, incertitude and linguistic uncertainty, and clear representations of uncertainty in model outputs. • The method provides comprehensive and intuitive diagnostics of errors.

Human and Organisational Factors	
Elements	**Description**
Provenness	• The approach has been used to make extrapolations or estimates relevant to the current context. • The methodology, or components of it, are supported or criticised in the research literature.
Transparency	• The methodology is specified and operates in such a way that people external to the process, including non-scientists, can understand what it is doing. • The results and outputs are presented in such a way that users and stakeholders can understand the implications of model outputs and their limitations.
Understandability	The approach can be comprehended by specialists and non-specialists. It can be understood easily by: • The analysts who must apply it • The scientific experts who provide input into it • Decision makers and other stake holders who may be affected by the results of an analysis • Those who must decide if an analysis is defensible.
Robustness	• The model's estimates are sensitive to missing or error-prone data • The model's estimates are sensitive to poorly or inadequately trained operators • The relative risk estimates are susceptible to data errors and inadequately trained operators
Practicality	• The method does not require specialized software or hardware. • The method maps potential distribution. • The method does require specialized inputs (e.g. historical data, presence-absence data, specific environmental layers, physiological models), o If so, are they likely to be available or can they be estimated. • The models are not complex to develop and run, even for trained operators. • Operation does not depend on specialized external support. • The method can be automated.
Cost	The set-up and maintenance costs for the system. • The software is not expensive to purchase and maintain. • The data for a relevant analysis typically are not expensive.
Speed	• The system can be used to develop rapid prototypes, to determine whether outputs are robust, and whether further investment in modelling is likely to clarify critical decisions. • The method has high computational overheads

3.5. Expert Assessments

The five experts with experience in spatial species modelling methods were asked to provide comments and scores for each criterion for the candidate spatial modelling methods identified during the September workshop. The scoring was based on a Likert scale from 1 to 5, representing the range from strong disagreement to strong agreement respectively.

These responses were discussed at the workshop held on February 25th in Melbourne to develop a consensus view of the assessments and develop recommendations for the different scenarios. The results of the expert assessments and workshop deliberations were compiled and are presented below.

4. Results

4.1. Criteria Assessments

Five experts with extensive experience in the development and application of spatial habitat modelling tools, Drs Jane Elith (University of Melbourne), Denys Yemshanov (Canadian Forest Service), Michael Kearney (University of Melbourne), Darren Kriticos (CSIRO) and Rupert Summerson (ABARES) completed the response sheets, assessing the utility of the methods for modelling potential distributions of invasive species. The experts scored the methods against each criterion (Table 3.1) and provided commentary to substantiate their assessments. Their responses are tabulated in the attached Excel spreadsheet (SpatialModelsSpreadsheet_Responses.xls). Extracts of the expert commentary for each method is provided in

Table 4.1

The average Likert score for each method and criterion provided by the experts was scaled categorically as low (0-2.33), medium (2.34-3.66) or high (3.67-5). Score ranges and their scaled categories (represented by cell colour) are provided in Table 4.2 and Table 4.3. The number of experts that scored a method is also provided in the tables. No experts provided scores or commentary for Heat maps. No scores were given for iSDM but commentary provided by Jane Elith indicated it was not a specific method but a name given by two authors (Václavík, T. & Meentemeyer, R.K.) who use various SDM methods under the umbrella name of invasive species distribution modelling and particularly focus on distributions in invaded ranges. For some other methods very few experts provided a response. The main purpose of the scores and responses was to stimulate discussion and shape approaches to solutions in the ensuing workshop.

MCAS (MCAS-S development partnership 2014) only received an assessment from one expert. The main function of this software is to take a species distribution model and combine it with other attributes (for example mapped host distribution). While MCAS has tended to be used with models generated with Climatch, any species distribution model could be included in an MCAS analysis.

Table 4.1: ***Opinions and example statements from the model assessments completed by workshop experts. It is important to note that these comments do not represent consensus positions; some experts disagree with some of the statements.***

Climatch	**CLIMEX**
• Simple climate matching model. • Thresholding of outputs can be arbitrary and there will be subjective choice of variables. • If model options are not repeated results can be very different. • Biased or incomplete samples will affect outcome. • Issues of accuracy in predictions which are ecologically implausible in a large number of cases. • Few publications and often not subjected to peer-review. • Stakeholders can understand the output (usually maps). • Simple, so harder to make major mistakes, but often misunderstood/misinterpreted by users.	• Prediction accuracy may be lower than other predictive models, but may be better linked with species tolerances. • The model alerts the user to problems in input data. The need to satisfy multiple knowledge domains constrains parameter choices. • Repeatability may be limited if hand-fitted, (recommended), but subjectivity is constrained by finite library of biologically-relevant response functions. • Commonly validated with independent data. • Differences in expert opinion over incorporating uncertainty and understandability. • Can take time to parameterize, some knowledge of species ecological and environmental preferences needed. • May be considered a relatively expensive package
GLM	**TTM**
• Subjective selection of covariates can affect objectivity and repeatability; protocols could be implemented to reduce this. • Well established statistical method, though it is pattern-based and like all correlative models, may be inappropriate for invasive species models. • Like all models, it is dependent on quality of input data, which could lead to biased predictions, particularly applying overseas data to an Australian context. • Detailed documentation for GLMs but less so for issues of using correlative methods for predicting invasive species distributions. • It can be applied to a range of response data, though using it with presence-only species records (the most commonly available) requires expertise and interpretation of difficult and potentially misleading literature.	• Provides Python script in ArcGIS to classify suitability for each species in terms of temperature tolerance from grids of sea surface temperature. • Definition of limits can be arbitrary but the syntax is unambiguous. • Calculations follow a logical sequence and are easily understood, but correctness is questioned in the absence of evidence. • There is no manual as it was not considered for external users, but model is described in two reports with good explanatory notes (Richmond et al 2010). • Costs include ArcGIS licence and GIS specialist.
Maxent	**NicheMapper**
• Decisions need to be made about data and model settings, though users often use default settings without justification. • Specifically developed for modelling presence only data. • Selection of “background” points is required and the extent over which these are sampled affects the results. Consequently this needs to be carefully documented • User-options can affect repeatability so need to be documented. • As in all correlative models, physiological and other ecological data can’t be easily incorporated. • Understanding restricted to experts but possibly easiest to use. • Free software	• Parameters will be costly and time-consuming to collect. • High computational overheads and quite a bit of work to get it set up and running. • Very specific data requirements; not much room for subjectivity. • Requires high-level training. • Strongly based on ecological and physiological process but ecological relevance far more complicated. • A number of successful applications but not in widespread use. • Currently would require external support.
Phenofit	
• Package is not expensive, but data acquisition may be expensive and time consuming.	

• May have to guess many of the parameters. • It is well documented and justified biologically. • Comprehensive but for trees only. • No known publications applying this system to invasive species systems where the model can be validated using independent data. • Limited stress mechanism will ensure that many models are incorrectly formulated. • The drive for mechanism disallows the full cross-referencing across knowledge domains.	

There were substantial differences in the experts' opinions of many of the methods. For defensibility, models that include mechanistic functions (CLIMEX, Phenofit and Nichemapper) tended to be more highly rated overall compared with correlative models (Table 4.2). GLM and TTM also received relatively high Likert scores, but only two experts provided assessments for TTM. The one defensibility criterion where many of the methods received low averaged scores was Accuracy; only CLIMEX and GLM methods received an average rating of high, but there was a large range on the accuracy rating for CLIMEX, with one expert giving it a '2'. Accuracy is expected to be especially difficult to achieve for poorly studied species that are new in the Australia environment, such as many marine invasive species. Maxent only received one average score of low (for Accuracy), but there were large ranges for many of the scores – Rigour (2 – 5), Correctness (2 – 5), Verifiability (1 – 5) and Uncertainty (2 – 5). Approaches receiving higher numbers of low averaged scores included GARP (low Understandability, Rigour, Correctness and Accuracy) and Hierarchical Bayes (low Accuracy, Provenness and Understandability), although only 2 assessments were provided for the latter. The variability in the responses arose from entrenched viewpoints, variation in understanding of methods, and, importantly, ambiguity in the questions. While some methods received relatively few assessments, the assessments were used merely as a guide to the attributes of each method, and to prompt subsequent discussions during the workshop (see below).

For criteria based on human and organisational requirements CLIMEX received averaged scores of high for all criteria except Robustness (medium) and cost (low); Understandability had a large range (2 – 5). Most other models (except GARP) received low or medium averaged ratings for Provenness, but there were large ranges on many of these assessments. Climatch, Phenofit and TTM only received an averaged low rating for one criterion each, but only 2 experts provided assessments for each of these methods.

Table 4.2: ***Experts score of each Criteria for Defensibility. Numbers represent the lowest and highest Likert Score given*.**

Defensibility										
Tool	**n***	**Objectivity**	**Repeatability**	**Rigour**	**Correctness**	**Comprehensive-ness**	**Accuracy**	**Documentation**	**Verifiability**	**Uncertainty**
Climatch	2	2-4	2-4	4-5	2-3	1-3	1-3	4-5	4	1
CLIMEX	4	2-4	2-4	3-4	3-5	4	2-5	4-5	3-5	2-4
Maxent	4	2-4	2-3	2-5	2-5	2-3	2-3	3-5	1-5	2-5
Bioclim	3	3-4	4-5	4-5	2-3	1-3	2-3	4-5	4	1-2
GARP	3	3-4	3-4	1-4	1-3	2-4	1-3	1-5	3-4	1-4
Hierarchical Bayes	2	1-3	2-4	2-5	5	4	1-3	3-4	3-4	2-4
NicheMapper™	2	3-5	3-4	3-4	3-5	4-5	2-5	2-4	5	3
GLM	3	2-4	2-4	2-5	2-4	3-4	4	2-5	4-5	2-5
MCAS	1	1	1	3	3	3	3	4	4	3
Phenofit	2	4	3	4	3-4	3	2-3	4	4-5	2-3
TTM	2	3-4	3-5	2-4	2-4	2-4	1-3	2-4	3-4	3

*n = Number of experts which provided comments and/or Likert Score for each tool

***Key for** **Table 4.2** **and** **Table 4.3**;*

Average Likert Score representing the level of support given by experts
High
Medium
Low

Table 4.3: ***Experts score of each Criteria for Human and Organisational Factors***

Human and Organisational Factors								
Tool	**n***	**Provenness**	**Transparency**	**Understandability**	**Robustness**	**Practicality**	**Cost**	**Speed**
Climatch	1	1-3	1-4	2-4	2-3	4	5	5
CLIMEX	4	3-5	4-5	2-5	2-4	3-5	1-2	4
Maxent	4	2-5	1-5	1-4	2-3	4-5	5	4-5
Bioclim	3	2-3	1-4	3-4	2-3	4-5	2-5	4-5
GARP	3	3-5	1-5	1-4	2-3	2-4	4-5	1-3
Hierarchical Bayes	2	1-3	2-4	2	2-3	2	3-4	3
NicheMapper™	2	2-3	3-4	3-4	2-4	1-2	1-5	1
GLM	3	1-5	1-5	2-4	2-3	2-3	4-5	2-3
MCAS	1	2	5	5	1	5	5	3
Phenofit	2	1-4	4	4	2-3	2-3	1-4	1-3
TTM	2	1-3	4	4-5	2-3	4	1-5	4-5

*n = Number of experts which provided comments and/or Likert Score for each tool

Table 4.4: ***Top rated methods based on operability and defensibility***

Top ranked models	
Accuracy/Defensibility of the Methods	**Operability: Human and Organisational Factors**
CLIMEX	Climatch
NicheMapper	CLIMEX
Phenofit	TTM
GLM	Phenofit

4.2. Workshop Summary

The February workshop discussed responses to the assessment criteria to gauge collective opinion on the applicability of the different species distribution modelling methods to the marine and terrestrial biosecurity problems. Workshop attendees included: Paula Brown (Aust. DA); Chris Starkey (Aust. DA); Bertie Hennecke (Aust. DA); Michael Carne (Aust. DA); Belinda Barnes (Aust. DA); Michael Kearney (University of Melbourne); Reid Tingley (University of Melbourne); Denys Yemshanov (Forestry Canada); Simon Barry (CSIRO); Emma Johnston (UNSW); Vira Koshkina (RMIT); Mark Burgman (CEBRA, University of Melbourne); Jane Elith (CEBRA, University of Melbourne); Heroen Verbruggen (University of Melbourne); Tracey Hollings (CEBRA, University of Melbourne). A summary of the workshop outcomes is presented here.

Marine

The general consensus that emerged was that focussing on predicting habitat suitability for over 40 marine pest species identified as species of concern was likely to be difficult and ineffective because:

- The limited spatial data available on the range of environmental attributes likely to influence marine species distributions results in a weak set of predictors that limits the applicability of many methods.
- There is such uncertainty surrounding the biology and the details of the fundamental niches of individual species that species-specific data and models may be largely uninformative.
- The biofouling species of concern list will change over time and therefore methods that avoid the need to modify risk assessments for ports based on these changes will be of more value in the long-term.
- The information available to decision makers typically includes variables such as types and vessel pathways not routinely included in species distribution and niche models.

As an alternative the workshop considered methods that focus on the environmental similarity between source (donor port) and sink (recipient port) environments as a way of capturing risk posed by a range of potentially invasive species. For instance, Euclidean distances in environmental space were discussed as they may provide a useful measure of environmental matching, effectively encapsulating establishment risk. Participants also noted that in addition to environmental matching, the risk model should consider other factors including environmental conditions during transit, transit frequency and typical exposure times in donor and recipient ports. In the overall risk assessment, these would be integrated with the other variables that contribute currently to vessel risk assessments, e.g. vessel biofouling management practices. In the instance where relevant data are available for species on the biofouling species of concern list, applications of correlative or biological models may be beneficial. However, correlative species distribution models are unlikely to be generally useful for modelling invasive marine species potential range across the Australian marine domain because the data are typically unavailable and many species are poorly circumscribed and understood.

Terrestrial

The workshop noted, importantly, that correlative models tend to estimate a species realised niche based on native and introduced ranges, whereas to make projections into novel environments, the models should estimate a species fundamental niche. Models with some biological process basis are better placed to estimate the fundamental niche, providing options to model new environments in biologically realistic ways, but are still impeded by reliance on data from the realised niche.

The workshop discussed options for applying the different methods. Correlative models could be used for invasive species distribution modelling if they were based on the proximal variables. Proximal variables are variables that are closely related to process and are thus more predictive. Proximal variables cannot be determined directly from data but will require some level of expert intervention.

Standard application of correlative models should not be considered where the range of variables in the predicted space lies outside those in which the species has been observed; or if they are, the projections should be confined to the overlapping space and areas outside that space should be mapped as 'unknown' or 'uncertain'.

The workshop also concluded that the extrapolation of probabilities to new environments was fraught with logical problems and more simple environmental matching approaches should be applied.

The meeting discussed process-based models and agreed that with good data and sound biological understanding, they are the preferred method for estimating species potential distributions. The realistic deployment of these tools requires significant experimental data, appropriate software and good model-building skills. For process-based models the meeting agreed that Niche Mapper is probably not yet sufficiently prepared to deal with most of the routine problems that confront regulators.

Experts discussed the candidate methods Maxent, Climatch and CLIMEX. None emerged as serious candidates for all of the tasks of estimating the suitability of habitat for entry and establishment, or the extent of eventual spread of invasive species, while also being suitable for the data and expertise available routinely to DA and MPI. In particular, Maxent and CLIMEX were assessed to be limited currently by access to appropriate 'expertise', Maxent by the inherent assumptions of the method, CLIMEX by the rigidity and subjectivity of its functional forms, and TTM and Climatch by their lack of defensible statistical rigour.

The study originally anticipated assessing the utility of species modelling tools for three questions listed in the introduction above, but it focused on two, namely,

1. Marine: to estimate of spatial risk of establishment, that incorporates estimates of habitat suitability for over 40 marine pest species identified as species of concern.
2. Terrestrial: to estimate of the total potential distribution of a new pest incorporating distribution of its potential hosts.

To reiterate, none of the methods was judged to be ideal for the operational environment and data conditions for either marine or terrestrial invasive species modelling in the Department of Agriculture. Through necessity, the workshop agreed to explore the possibility of developing alternative approaches including alternative implementations of mechanistic models and correlation–based models that use expert-based estimates of proximal variables as input data. These developments should draw on appropriate features in mechanistic models such as CLIMEX and NicheMapper, environment matching models such as Climatch and TTM, and correlation models.

5. Discussion

The project provided no clear consensus that currently available spatial tools will provide adequate solutions for the biosecurity decisions considered. For the marine case, development of a method that considered the degree of environmental similarity between source and sink environments, time in donor and recipient ports, and attributes from transit routes of vessels was considered to be the best way forward. TTM provides a platform for incorporating these features and new work should explore the foundations of this approach and the potential for enhancing models with structured expert judgement. For terrestrial scenarios modified use of correlation models was considered to be worth further investigation. The partly mechanistic CLIMEX was the highest rated model by experts in their assessments on many criteria, but had issues with subjectivity and operability; potentially affecting its applicability for routine use.

Data from the realised niche in the native range is all that is usually available to modellers who make predictions using correlative models. Hence, these types of models have limitations for predicting the fundamental niche. Current consensus is that mechanistic models are best placed to estimate the fundamental niche (Sutherst & Bourne 2009; Webber et al. 2012; Elith 2014, accepted; Froese 2012), a position further supported by the comments and responses of experts during the course of this project. However, even these models are dependent on observations of the realised niche and incomplete understanding of process constraints on distribution.

Two alternative process-based modelling approaches were rated highly by experts in terms of defensibility; CLIMEX and NicheMapper. CLIMEX was also rated highly for operability. CLIMEX, a method specifically designed for invasive species modelling, determines mechanisms by which terrestrial species respond to their environments through the characterisation of growth and stress responses to climate. By combining species locations records from its native range with climate data and other applicable information (e.g. locations of persistent populations in invaded regions, relative abundance, seasonal phenology and laboratory data), infers species climatic requirements (Elith 2014, accepted). NicheMapper uses models that require information on the morphology, physiology and behaviour of species, and a means for "translating" the environment experienced by the animal to the spatial data usually available for mapping. NicheMapper is similar in some ways to CLIMEX, but operates on a finer temporal scale. The models are relatively complex to implement and many of the functions for specific groups, such as plants, have not yet been developed. Hence they are not yet a practical alternative for most routine applications.

A third process-based/mechanistic model considered by experts to be of some value in invasive species modelling was Phenofit. Phenofit quantifies the stress levels and associated impacts on fitness from local climatic data (Morin & Thuiller, 2009). The model rated highly in terms of defensibility, was considered to be easily understood by specialists and non-specialists, and the program itself is inexpensive. However, data acquisition is costly. To varying degrees this is the case with all of the other assessed methods, but can be especially so for mechanistic methods. This notion was supported by Elith (2014, accepted) who considered that while mechanistic models are the subject of much research, they are generally less often attempted than correlative models due to the high cost and time of obtaining data and the complex nature of the models (Elith 2014, accepted). As a result there are few examples of them used in invasive species research and decision-making.

Correlative species distribution models based on regression and machine learning techniques, such as GLMs, Bayesian methods and MaxEnt, considered by experts in this project, were not designed for modelling invasive species. Rather, they were intended to model the relationship of species with their environment within the extent of the sampled geographic area of their current distribution (Elith & Leathwick 2009; Elith 2014, accepted). Despite their limitations for invasive species decisions, because correlative models tend to be easier to use than mechanistic models, experts considered ways of changing how they are used so that they may provide better outcomes when applied to invasive species decisions, by developing new approaches that address the shortcomings of correlative models applied to novel climate situations, and integrating these ideas with ideas from mechanistic and environmental matching approaches.

The marine scenario started with a species-specific focus like the terrestrial scenarios, but moved to a more general focus on environmental matching between donor and recipient ports, because this was considered more appropriate and practical. This move is consistent with recommendations made by Barry et al. (2008) for assessing risks posed by ballast water. There are likely to be terrestrial biosecurity applications that also benefit from this more general approach. Regardless of whether a species-specific or general approach is adopted, estimates of risk posed by transits would also need to consider things like the environmental conditions during the transit, and lengths of visits to donor and recipient ports.

Predicting potential ranges of invasive species is not straightforward, so whatever methods are adopted agencies will need to build capability to be able to use the methods appropriately (Venette et al. 2010; Baker et al. 2011; Elith 2014, accepted) It's clear that without this expertise it's relatively easy to use all the methods considered badly, potentially resulting in highly inaccurate results. It's also clear that standard protocols will need to be developed so that adopted methods generate the level of repeatability desired for government decisions.

Assessments in this project focused on species distribution modelling approaches. MCAS-S is decision support software that allows various data layers to be combined to facilitate decision making (MCAS-S development partnership 2014). A simple example would be to overlay a pest species distribution model generated by one of the methods considered in this project with a GIS layer of the mapped distribution of potential hosts. (e.g. Pardey et al. 2013). This use of MCAS-S has been recommended in a decision support scheme for mapping areas at risk from pests by PRATIQUE (Baker et al. 2011).

This project provides valuable assessments and comparisons of many current SDM approaches, despite not determining a single best approach for the scenarios considered. The project has proposed useful new approaches that may lead to better biosecurity decision making that requires SDMs, and further research in upcoming CEBRA projects 1402A: “Development of a marine spatial analysis model for improved biofouling risk assessment”; and 1402B: “Tools and approaches for invasive species distribution modelling for surveillance”, will provide greater insight and development of some of these approaches for specific applications.

6. Recommendations and future work

- This current project will continue next financial year through CEBRA projects 1402A: Development of a marine spatial analysis model for improved biofouling risk assessment; and 1402B: Tools and approaches for invasive species distribution modelling for surveillance.
- Project 1402A will investigate low, medium and high risk pathways for the arrival and survival/establishment of marine pests of concern, based on compatibility between source and sink environments, and the level of exposure represented by the route of vessels. The project will use expert elicitation, scientific data where they are available, and statistical analyses of the outputs to produce a model based on vessel movement history and characteristics of Australian ports.
- The goal of project 1402B is to partly fill current gaps in strategies and best practise for terrestrial biosecurity applications. The project will explore alternatives to habitat suitability modelling and the implications of grouping various pests and diseases versus focusing on specific species. It will provide protocols for staff to assist them in identifying and using the best method in a given scenario.

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8. Appendix

8.1. Appendix 1: Australian Department of Agriculture Biofouling Scenario

The Australian Government, through DA, is currently enhancing protocols to manage risks from biofouling organisms. The department has proposed biofouling management arrangements for vessels entering Australian waters, and these arrangements would be supported by a risk assessment tool to assess the biofouling risk posed by vessels. This tool currently includes information about vessel biofouling management practices but doesn't include information about the vessel's voyage history, and how that interacts with the biofouling species in the biofouling species of concern list.

DA would like to more accurately distinguish low, medium and high risk vessel pathways based on the following information:

- Environmental compatibility between Australian ports and previous foreign ports of call.
- Temperature tolerances of biofouling species of concern in foreign ports. These tolerances may be based on either physiological or inferred data, so elements from both deductive and correlative mapping models may be useful.
- The biofouling association of the biofouling species of concern (this ranking may vary from low to high based on whether the species has a demonstrated or assumed association with vessel fouling).
- The time spent in the last port of call.
- Seasonal variations in sea temperatures in ports and of seas between ports.

This information could be used to enhance the existing risk assessment tool, by increasing its effectiveness to assess a vessel's risk based on the interaction between its transport history, the distribution of biofouling species of concern and the influence of environmental factors. For example, when a vessel owner completes a risk assessment, they would also provide details about current and previous ports of call. If the vessel pathway is high risk, this is a useful red flag for inspectors during biosecurity interviews, because the vessel should have undertaken an activity to mediate their high inoculation likelihood. The aim of the project is to recommend a tool and an approach that will assist DA to achieve these improvements in risk assessment for vessels entering Australian waters.

The model would need to be able to be updated as new data on biofouling species of concern and port environments become available over time (e.g. influence of climate change shifting species abundance and distribution, or likely changes in species abundance and distribution over time). Other areas of interest include accounting for increasing sea temperatures as a result of global warming, how this could impact on high and low risk pathways, and seasonal variations in water temperatures and how this affects ability to reproduce/spawning behavior.

Documents relevant to this scenario include:
Species biofouling risk assessment:
http://www.daff.gov.au/__data/assets/pdf_file/0008/2059154/species-biofouling-risk-assessment.pdf
Vessel biofouling risk assessment:
http://www.daff.gov.au/__data/assets/pdf_file/0009/2059155/vessel-biofouling-short-version.pdf

8.2. Appendix 2: Terrestrial Plant Biosecurity Scenarios

Scenario 1: Extent of eventual spread in Australia

Huanglongbing, also known as ´citrus greening´, is a bacterial disease that is lethal to citrus. Huanglongbing and the sap sucking insects that transmit the disease are not known to occur in Australia. Long-distance spread of HLB can occur by movement of infected plant material. Both human assisted and natural dispersal through wind (of the vector) can facilitate spread of HLB.

A possible pathway for arrival of Citrus greening (Huanglongbing - HLB) is through escaping detection at the border, it can then persist in infected citrus trees and other hosts in backyards and nurseries in the area. To date HLB and its vectors have not been detected in Australia. One of the potential arrival sites is the port of Melbourne through importation of infected material from Asia. We need to know the likely areas of spread, including identification of sites with a high likelihood of establishment for this species following an initial entry through a port in Melbourne. This information will enable an analysis of the extent of impact of successful establishment of this disease in Australia.

http://www.cabi.org/isc/?compid=5&dsid=16567&loadmodule=datasheet&page=481&site=144

http://www.daff.qld.gov.au/plants/health-pests-diseases/a-z-significant/citrus-greening-huanglongbing

Scenario 2: Species distribution maps for emergency response

Striga asiatica (Red witchweed) is parasitic weed of grass crops such as maize, millet, rice, sorghum and sugarcane, and some broadleaf crops (e.g. sunflower, tomatoes, some legumes). It is primarily associated with agricultural lands, but may also be found in grasslands. *Striga* seeds can be moved along with contaminated soil on the shoes of people and feet of livestock, farm machinery and potentially through soil dispersal by high winds.

Recently, *Striga asiatica* has been found in Mackay and confirmed on a small number of properties in the area. As part of the emergency response, DA needs to know the likely areas of spread, including identification of the most likely areas of establishment, to facilitate the deployment of initial surveillance and quarantine zones and initiate an appropriate response. Initial assessment needs to be available to the decision makers for the implementation of an emergency response within a day, with some opportunity to fine tune analysis in the subsequent week or two.

http://www.issg.org/database/species/ecology.asp?si=968&fr=1&sts=

http://www.cabi.org/isc/?compid=5&dsid=51786&loadmodule=datasheet&page=481&site=144

http://www.ars-grin.gov/cgi-bin/npgs/html/taxon.pl?102305

http://www.invasivespeciesinfo.gov/plants/witchweed.shtml

8.3. Appendix 3: Brief overview of candidate tools

Maxent

Maxent, or maximum entropy modelling, is a machine learning technique which models presence only species data. A species' distribution is estimated by minimizing the relative entropy between two probability distributions, estimated from presence data and a random background sample, in relation to a set of predictor variables within a defined landscape (Elith et al, 2011). Since its release in 2004 Maxent has been used extensively for modelling species distributions and it consistently performs well against competing models (Elith et al, 2006).

CLIMEX

The CLIMEX model is a mechanistic or process based method which estimates the potential distribution of a species based on its tolerance of climatic variables. Stress and growth parameter values are extrapolated for the population from the species' geographic distribution, seasonal phenology and relative abundance. These parameter values are combined into an 'Ecoclimatic Index', which estimates the suitability of the location or year for the species, and can then be used to make predictions at independent locations (Sutherst et al. 2007).

Climatch/CLIMATE

Climatch/CLIMATE is a 'climatic envelope' approach commonly used to assess the establishment potential of invasive species (Bomford et al, 2009). A climate-match score is calculated to compare environmental similarities between the user-defined source population, describing a species native or current range, and the target area. The algorithm uses up to 16 standard BIOCLIM climate variables to calculate the climate-match score, based on minimum Euclidean distances (Bomford et al, 2009).

GLM

Generalised linear models (GLMs) are correlative regression methods that allow for response variables to have non-normally distributed error distributions (e.g. Gaussian, binomial, Poisson, gamma). Models are based on parametric functions, fitted using maximum likelihood with a link function to describe how the response variable relates to the linear predictor. GLMs have been used extensively in species distribution modelling due to their strong statistical underpinning (Elith et al, 2006).

Bioclim

Bioclim is a ‘climatic-envelop’ model using simple environmental matching of presence only records (Elith et al, 2006). The algorithm uses multiple one-tailed percentile distributions of the environmental values at known species locations to estimate an index of similarity at new locations; the closer to the median (50^{th} percentile) the more suitable the location (Hijman and Graham, 2006). Bioclim was the first widely available SDM software, is relatively easy to understand and implement, and consequently has been widely used for species distribution modelling (Booth et al, 2013), but does not always perform as well as other models available (Elith et al, 2006; Hijman and Graham, 2006).

NicheMapper™

NicheMapper is a mechanistic based modelling approach which estimates the fundamental niche of a species based on ecophysiological traits, and without reference to occurrence data (Kearney et al, 2008). The biophysical models comprise both a microclimate model of the environmental conditions at a specific location, and an animal model which computes the effects of the microclimatic conditions on the metabolic and physiological traits of the animal. The effects of environmental conditions on the geographic distribution and physiological output of an animal are then assessed (Porter and Mitchell, 2006).

GARP

Genetic Algorithm for Rule-set Prediction (GARP) is a machine learning technique for modelling presence only data. The technique uses a genetic algorithm to create an ecological niche model which describes the environmental conditions appropriate for a species. GARP does this by selecting a rule set to predict the species distribution from correlations between species occurrences and environmental conditions (Stockwell and Peters 1999).

Hierarchical Bayes

Hierarchical models have the capacity for data structuring of the predictor variables into ‘submodels’ to allow for relationships to be modelled at different scales. Hierarchical models can account for spatial correlation of the observations, detectability of species and ecological processes. The model is fitted to the data within a Bayesian framework.

Temperature Tolerance Modelling (TTM)

TTM is a temperature matching algorithm developed by DA staff. It uses experimental and observational data on target species to define an envelope of temperature tolerances, and then maps available habitat based on the distribution of these temperatures.

ISDM

Not a specific method but a name given by two authors (Václavík, T. & Meentemeyer, R.K.) who use various SDM methods under the umbrella name of invasive species distribution modelling (Jane Elith, pers. comm.).

Phenofit

Phenofit is a process-based modelling technique which estimates the fitness (survival and reproductive success) of an average individual of the species of interest, under different environmental and climatic conditions. Survival probability is estimated by the organism's ability to survive until the following breeding season under potential climatic stress (e.g. frost and drought), and the likelihood that it will produce viable offspring, over an annual time cycle (Gritti et al, 2013; Morin and Thuiller, 2009).

MCAS

MCAS-S is free software that allows different spatial data sets to be displayed and combined using a variety of logical, matrix and arithmetic methods to represent risk (MCAS-S 2014). Results from any SDM modelling approach can be combined with other data layers in a MCAS analysis.