Opening the climate modelling envelope

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Summary
Climate matching identifies geographical ranges that could be colonized by a potential invasive species on the basis of similarity to climates found in the species' native range. In invasive species management, climate matching is used primarily for two purposes: to assess overall invasion risk and prioritize destination-specific management actions. Species-specific factors are not included in climate matching models; however climate matching has been validated as a strong indicator of establishment success. Once distribution records for potentially invasive species have been carefully validated, climate matching is a proven tool to communicate scales of potential distribution within the risk assessment policy framework.

Keywords: climate match, modelling, range limits, risk assessment.

Introduction

Single-species climate match models are used to assess the potential range of an invasive species in a novel environment and define the risk introduced species pose to natural and agricultural systems (Brown *et al*. 2006). Climate matching models compare the climate of a species' current geographical range with the climate of a target site to identify an envelope where the climate is similar and the species could establish if other species-specific factors were present.

The validity of using climate match algorithms has been questioned because many other factors can significantly influence species distributions, e.g. competition, presence of hosts and disturbance regimes. However, it has long been recognized that the ultimate limits of a species distribution are determined by climate (Andrewartha and Birch 1954, Krebs 1978, Hayes and Barry 2008, Bomford *et al*. 2009a,b,c). As such, the output of climate match algorithms should be interpreted as a broad indicator of potential distribution and associated risk rather than a species-specific niche model.

The advantage of using climate matching is that it does not require detailed species-specific information such as that required for niche modelling. Climate matching has been tested against a number of successful and failed species for a range of taxa. Hayes and Barry (2008) examine 24 studies that identify correlates of establishment success across six animal taxa and found only three characteristics consistently associated with establishment success across taxa: climate/habitat match, establishment success elsewhere, and propagule pressure (number of arriving/released individuals and/or number of release events). Hayes and Barry (2008) conclude that risk managers can place faith in risk assessments based on these factors, whilst warning they must be interpreted carefully.

Recent publications by Bomford *et al.* (2008, 2009a,b,c) examined freshwater fish, reptiles and amphibians, and mammals for a total of 2284 successful and 1122 failed introductions. The findings reported in these papers support Hayes and Barry (2008) conclusion on the role of climate match as a primary factor influencing establishment success. Bomford *et al*. (2008, 2009a,b,c) also concur with the conclusions of other authors on a primary role for the abiotic environment in determining establishment success (see for example Moyle and Light 1996, Blackburn and Duncan 2001, Moyle and Marchetti 2006). However, they also noted the difficulty associated with obtaining sufficient reliable species-specific survey and biotic data, highlighting that climate matching can communicate broad levels of risk associated with exotic species where species-specific information is lacking.

Climate match - methodological issues

Climate matching has certain advantages—it offers a tool for undertaking relatively rapid analysis between single species and a key driver for predicting invasiveness—climatic factors. It provides decision makers with insights into bioclimatic range limits or prioritizing destination-specific management actions. However, there are a number of critical methodological issues that need to be addressed to ensure the greatest accuracy of a climate match.

The primary methodological factors that influence the accuracy of a climate match are: error associated with climatic attributes at a location, accuracy and level of resolution of the grid used for matching climates, taxonomic uncertainty in the location records, accuracy of the geocoding, adequacy of points (locations) representing the total distribution and the requirement to check anomalous data points.

There are several algorithms that have been employed in climate matching software. The best known of these are BIOCLIM (http://fennerschool.anu.edu.au/publications/software/anuclim/doc/bioclim.html), the 'match climate' or 'regional match climate' component of CLIMEX (CSIRO/Hearne Scientific, www.climatemodel.com/climFunc.htm) and CLIMATCH (Bureau of Rural Sciences, free web application, www.brs.gov.au/climatch/). This paper uses CLIMATCH to demonstrate some of the key methodological issues that are often overlooked when producing a match between a source and target region.

The reasons for selecting CLIMATCH to demonstrate some of the methodological issues are that access to the software is free, allowing readers to examine such issues themselves, and the Australian target region has been calibrated against a range of taxa to determine the thresholds for the CLIMATCH match scores that are associated with successful establishment (Bomford 2006).

The CLIMATCH algorithm has principally been used to ascertain the risk of a weed or pest animal species establishing (Pheloung 1995, Pheloung 1996b, Bomford 2003, Bomford 2006). More sophisticated algorithms, reviewed in Elith *et al*. (2006), can provide better performance, but CLIMATCH is a simple, repeatable algorithm, and its capacity to predict whether a species will establish has been well demonstrated for a range of taxa using fairly coarse-scale input data (Bomford 2003, Bomford 2006, Bomford 2008, Bomford *et al*. 2009a,b,c).

The Euclidean matching algorithm implemented in CLIMATCH calculates the distance to a location *j* in Australia as:

$$d_j = floor\left\{\left[1 - \min_{i \in sites}\left(\sqrt{\frac{1}{k}\sum_k \frac{(y_{ik} - y_{jk})^2}{\sigma_k^2}}\right)\right] * 10\right\}$$

where the cut function *cut(a,b)* returns the interval, as defined by the break points in the ordered set of *b*, into which *a* falls. A more detailed explanation of the algorithm can be found in the user manual—available from the Bureau of Rural Sciences website http://adl.brs.gov.au:8080/Climatch/docs/climatch_manual.doc#_Toc214942742.

A more simplistic description is that 16 variables derived from temperature and rainfall data—including calculations for hottest and coolest, and wettest and driest quarters are used to compare locations. Meteorological station data from 9460 stations (Pheloung 1996a, Barry 2006) or a subset of interpolated data available from www.worldclim.org (Hijmans *et al*. 2005) are used to derive these variables. Each source location is compared with each target location to derive a score based on Euclidean distance, with a high score indicating a close match with all 16 variables.

The steps in collating information for a climate match apply to any of the algorithms and are: collect overseas (source) and available distribution data for the target region (both validated and anecdotal); validate anecdotal data where possible; undertake a climate match of validated data; check data to ensure it is free from fundamental errors and validate outliers excluding (with explanation) errors and anomalies (e.g. non-viable populations). Using CLIMATCH 'Euclidean score' the sum of all scores above '6' represent scores (climate matches) that discriminate between successful and unsuccessful establishment for birds, mammals, amphibians and reptiles (Bomford 2006, 2008). For weeds, the sum of all scores above '5' represent scores (climate matches) that discriminate between successful and unsuccessful establishment.

Climate match - case study

A climate match was prepared based on all published overseas records for a species originating in South America, now established in North America, South Africa, France, New Zealand and Australia. A subset of species data points are usually withheld from the analysis and used to cross-check predictions and in this case the Australian records were excluded from the records used to estimate a climate match with Australia. After checking the overseas location information to ensure it was free of fundamental errors and validating outliers the distribution data (Figure 1a). A climate match for Australia was run using Worldclim and Australian grid data sets (Figure 1b).

In CLIMATCH a single source location can match with more than one target location and the number of times each point matches to the target climate point is presented as an 'influence map' (Figure 2a). The influence map can be a useful tool to check those locations having significant influence on the target climate match. The example presented here indicates that locations in the most southern parts of North America (Texas and Florida) have the most influence on the Australian climate match. If species expert opinion contraindicates this pattern of influence then these points should be further validated and the climate match re-run if necessary.

For example, after reviewing the climate match for the target region and the influence map, species experts queried the high predicted target climate match for central Australia and suggested that the locations most influencing the target climate match could be anomalies. Discussions with researchers working on the species in revealed that a separate subspecies had been identified in Texas and Florida.

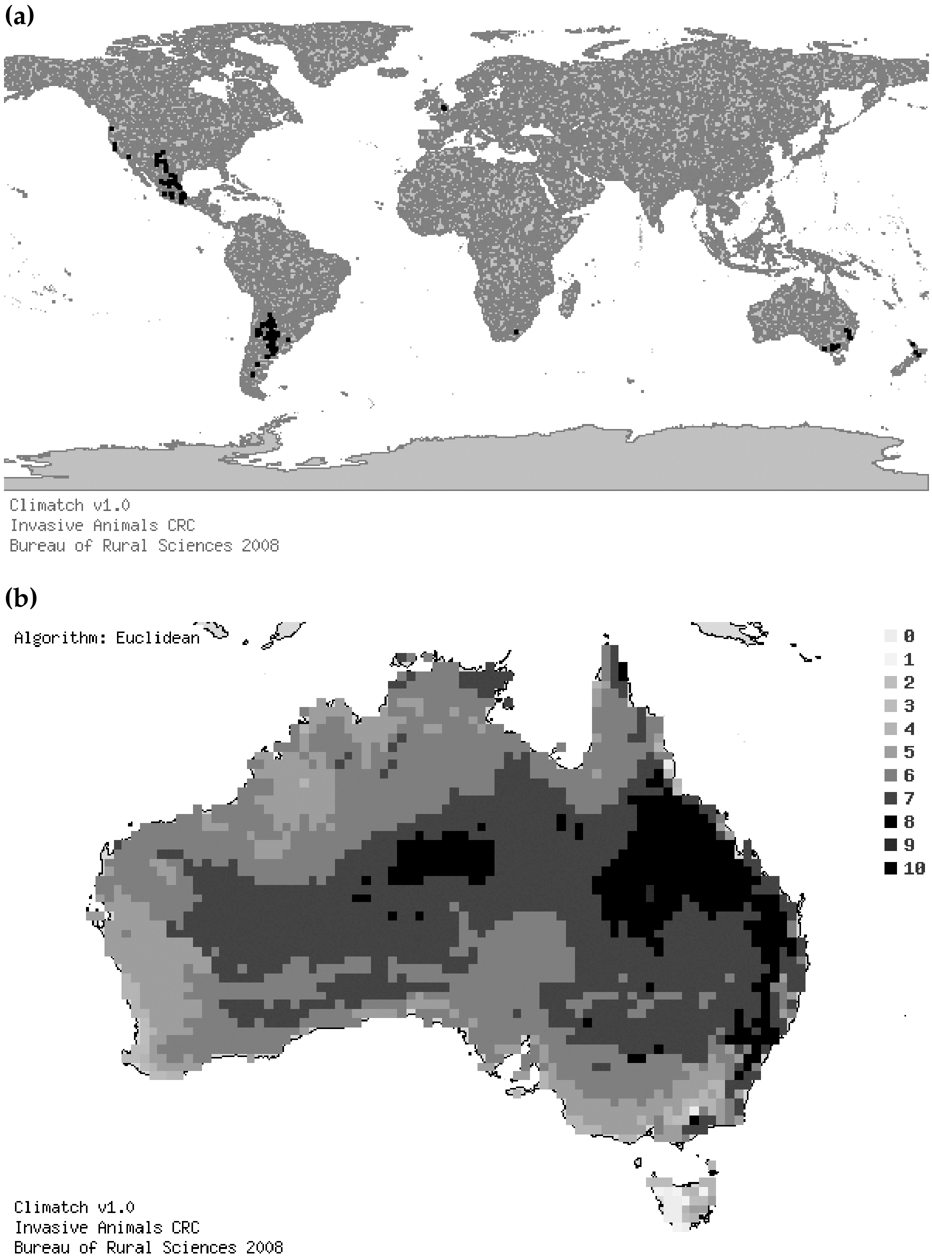


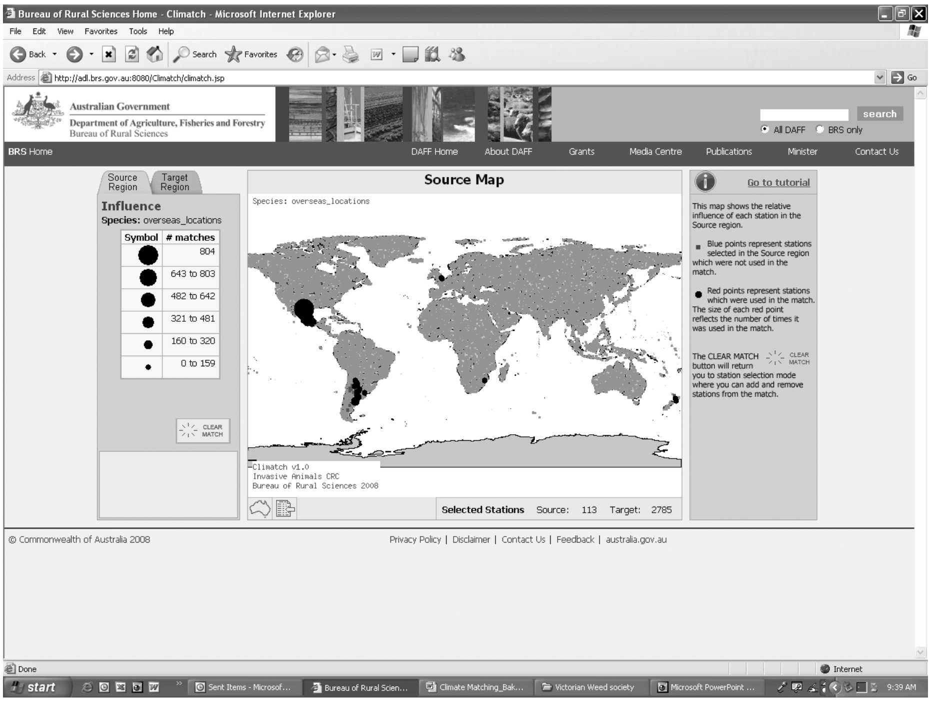
Figure 1. (a) Records for an invasive species originating in South America, now established in North America, South Africa, France, New Zealand and Australia, and (b) climate match for the invasive species shown in (a) based on Worldclim points closest to recorded overseas locations and the Australian grid.

The region this subspecies was growing in covered the locations in the most southern parts of North America. These were also those points having the most influence on the target climate match. The records for the most southern parts of North America were removed from the overseas records and the climate match re-run, producing a target climate match that reflected the experts opinions of the ecology of the species.

The resultant target climate match indicates that species will distribute more widely in the south but is less suited to the arid centre of the continent (Figure 2b). The final 'reality check' was to review this match with the species experts and to overlay the known Australian distribution to confirm that these records are within regions predicted to have a suitable climate match. The removal of a small number of points, or even a single point, can alter a climate match prediction markedly and this highlights the importance of ensuring that only high quality and verified data is used to make climate comparisons.

Thus, climate matching can be used effectively to estimate the potential range of an invasive species or for identifying climatically similar regions for sourcing or releasing biocontrol agents—provided reliable input data are used. Combined with other key drivers, this information can be used to predict successful establishment.

(a)



(b)

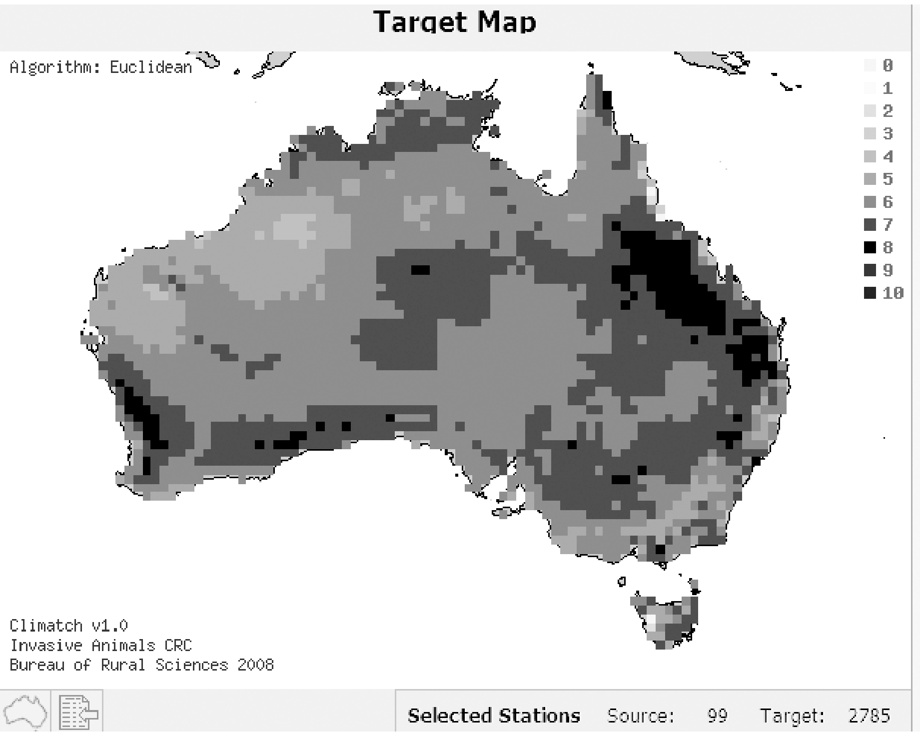


Figure 2. (a) Example of an influence map, larger black circles indicate that these points matched with more target locations. The table shows the number of times each source point matched to a target location. Smaller dark grey circles indicate that other source locations have closer Euclidean matches to target locations, and (b) climate match for a hypothetical invasive species based on Worldclim data points and the Australian grid for published locations, excluding the North American locations believed to be a separate sub-species.

Discussion

Decisions regarding the import of exotic species or prioritizing destination-specific management actions can be controversial so it is desirable to use quantitative methods, where these are feasible and supported by evidence to bring objectivity to the process (Copp *et al*. 2009). There is a pressing need to formulate scientifically sound methods and approaches based on the information available. However, there are times when information is not readily available, but decisions must still be made. Published literature indicates that risk assessments based on climate match and history of establishment success elsewhere will be useful predictors of successful establishment (Moyle and Light 1996, Blackburn and Duncan 2001, Moyle and Marchetti 2006, Hayes and Barry 2008, Bomford *et al*. 2008, 2009a,b,c).

Establishment success does involve complex interactions between the invading species and the physical and biological characteristics of the recipient environment. These may be case-specific and include positive feedback mechanisms (Noble 1989), Allee effects (Drake 2004), genetic variability (Holdgate 1986) and a potential role for biotic resistance from competitors, predators, parasites and disease organisms (Case 1991, Harvey *et al*. 2004, Duncan and Forsyth 2005, Moyle and Marchetti 2006). So, where possible it is desirable to take account of species-level attributes that may influence introduction outcomes, particularly for species that have no history of being introduced elsewhere.

To cope with these complexities a combination of qualitative (e.g. relevant expert opinion) and quantitative methods is useful to provide a framework for predicting successful establishment (Sikder *et al*. 2006, Stohlgren and Schnase 2006). Sikder *et al*. (2006) suggest that this approach is required, because quantitative data alone are insufficient to deal with the complexities and uncertainties inherent in invasive species' interactions with their environment. Thus, climate matching is only one part in predicting establishment success. However, it is a well validated and useful approach to communicate coarse levels of potential distribution and associated risk.

Objective frameworks that predict successful establishment assist the development of decisions based on available evidence, but these decisions cannot be separated from community expectations, environmental and social values and international obligations. However, climate matching is an integral part of the framework when species-specific data is not readily available and remains a useful tool in assisting decision makers.

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