Can spatial data accurately locate optimal sites for assisted colonisation? Identifying suitable habitat for the Western Swamp Tortoise (*Pseudemydura umbrina*) under a changing climate.

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Candidate's Statement

I, Marie Catherine Dade, declare that this thesis submitted for the Master of Science (Environmental Management) by way of Thesis and Coursework degree at the University of Western Australia, is my own work and has not been previously submitted by anyone or me at another University for any degree.

This Master's thesis builds upon my Honours work in 2012 which focused upon using a spatially explicit multiple criteria analysis to identify suitable habitat for the Western Swamp Tortoise (*Pseudemydura umbrina*) under current climatic conditions. This year I expanded on my Honours work by analysing further data and conducting field work to identify suitable habitat for *P. umbrina* under a future climate scenario, and produced a collaborative paper with Natasha Pauli and Nicola Mitchell, based on my Honours work, which has been submitted to Animal Conservation. This Master's thesis refers to this submitted paper as Dade *et al*., 2013 and is included as an appendix in this thesis.

Marie Catherine Dade
October 2013

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Abstract

Declining rainfall under current climatic trends is reducing the suitability of the current habitat of the Critically Endangered Western Swamp Tortoise (*Pseudemydura umbrina*) on the Swan Coastal Plain in Western Australia. Assisted colonisation, a conservation translocation of a species to an area outside its current or historical range, has been proposed for this species. To ensure that suitable sites for assisted colonisation are identified, key habitat criteria must be present and the site must possess a suitable hydrological regime under current and future climatic trends. Therefore the aim of this study was to identify a suitable assisted colonisation site for *P. umbrina* by combining the outputs of hydrological modelling under a median future climate scenario with other habitat criteria, using a multiple criteria analysis.

Habitat and hydrological criteria were mapped using geographical information systems to create a suitability index highlighting potentially suitable areas for *P. umbrina* under a median future climate scenario. Eight potentially suitable wetland sites were then selected to conduct ground-truthing for each of the criteria and to subsequently be ranked based on a weighted summation method, with criterion weights calculated using both pairwise comparisons and expert opinion.

This study shows that sites closest to *P. umbrina*'s current habitat are more suitable than those further away. However, it is recommended that a larger number of criteria and sites are assessed and sampled before a final decision can be made on the optimal assisted colonisation site for *P. umbrina*. Expert opinion was a highly accurate approach for identifying criterion weights for *P. umbrina*, however for other species it is recommended that the pairwise comparisons approach be used to reduce the risk of bias. Overall, this study showed suitable sites for assisted colonisation are likely to be within the same biogeographical region as *P. umbrina*'s current habitat and suggests extensive ground-truthing should be conducted to determine the level of inaccuracy in the spatial data used to identify suitable habitat.

Chapter 1
1. Introduction

1.1 Climate change in south-western Australia

The South Western Botanical Province (SWBP) of Western Australia is widely regarded as vulnerable to climate change (EPA, 2007; Fitzpatrick *et al*., 2008; CSIRO, 2009). Within the past century, this region has experienced a 0.2°C increase in mean temperature and a prolonged rainfall decline, and these trends are expected to continue (CSIRO, 2007; Charles *et al*., 2010). For example, a recent study into future surface and groundwater availability within this region has found that under a median future climate, rainfall will decline by an average of 7% by 2030, relative to historical data (CSIRO, 2009).

Many species within this region are severely threatened by climate change as they will be unable to change their distributions to more climatically suitable areas at fast enough rates (Thomas, 2011; Barron *et al*., 2012). Wetland-dependant species and ecosystems are particularly vulnerable to climate change due to their specific adaptations to particular hydrological regimes, which are determined by temperature, precipitation and evaporation (Barron *et al*., 2012).

1.2 Moving the Western Swamp Tortoise under a changing climate

The Western Swamp Tortoise (*Pseudemydura umbrina*) is one such wetland-dependant species threatened by climate change in the SWBP (Burbidge *et al*., 2010). *P. umbrina* is a small, short necked, freshwater tortoise that is listed as Critically Endangered under the International Union for the Conservation of Nature (IUCN) Redlist (IUCN, 2013). This is due to the decline in the adult population relative to the 1960 population and it currently occurring naturally at only two winter-and-spring wet swamp sites (Ellen Brook Nature Reserve and Twin Swamps Nature Reserve) and two translocation sites (Mogumber Nature Reserve and Moore River Nature Reserve) on the Swan Coastal Plain within the SWBP (Burbidge *et al*., 2010).

The length of time wetlands are inundated with water is known as the hydroperiod. The hydroperiod plays an important role in the viability of *P. umbrina* populations as their growth and reproductive potential is directly linked to hydroperiod length (Mitchell *et al*., 2013; Burbidge, 1981; Mitchell *et al*., 2012).

However, since the 1970's, when the SWBP began to experience declining rainfall, the lengths of the hydroperiods at *P. umbrina*'s current sites have been decreasing, reducing their suitability - a trend which is likely to continue into the future (CSIRO, 2009; Mitchell *et al*., 2013).

An Australian Research Council (ARC) Linkage project was established in 2010 to study the potential for moving *P. umbrina* to wetlands outside its current or historical range that are likely to offer suitable hydroperiods under current and future climatic trends. This type of translocation, known as assisted colonisation, is controversial due to the uncertainty of the impact introduced species may have in a novel environment (Ricciardi & Simberloff, 2009). Due to this uncertainty and the Critically Endangered status of *P. umbrina*, it is particularly imperative that if a number of individuals were to be translocated that their chances of successful establishment are optimised.

Recent reviews on species translocations and suggested guidelines for assisted colonisation emphasise the importance of choosing suitable habitat for the translocation site (Germano & Bishop, 2009; Laws & Kesler, 2012; Harris *et al*., 2013). This suggests that to maximise the chance of a successful assisted colonisation translocation for *P. umbrina*, translocation sites must be identified based on their habitat suitability under current and future climatic trends.

As *P. umbrina* feeds and mates in the water, a suitable hydrological regime at a translocation site is regarded as crucial for a successful establishment (Mitchell *et al*., 2013). Extensive wetland mapping, including the location of ephemeral swamps, has only been carried out within two areas of the SWBP: the Swan Coastal Plain and the area between the towns of Augusta and Walpole on the South Coast (Hill *et al*., 1996a; V. & C. Semenuik Research Group, 1997). Therefore accurate identification of potentially suitable wetlands for *P. umbrina* can only be completed for these two areas. However, to assess the suitability of wetlands within these areas for assisted colonisation, their hydrological regimes under future climate scenarios must be determined. Currently hydrological screening is being conducted to identify wetland habitats with a suitable hydrological regime for *P. umbrina* under a future climate scenario. To do this, a number of factors, including field capacity, hydraulic conductivity, catchment inflow, projected rainfall decline over the next 30 years, wetland geomorphology and whether the wetland is groundwater fed or a basin, were fed into the Wetland Water Balance and Thermodynamic Model (WET-R) to create a screening model identifying areas with suitable hydrological regimes under a future climate scenario (Bin Tareque, 2013) This model than presents areas with a suitable hydroperiod for *P. umbrina* over the next 30 years.

1.3 Assessing habitats based on multiple habitat criteria

The hydrological regime of a wetland is influenced by a range of other habitat factors, such as vegetation and soil types, and these must also be considered when identifying a suitable translocation site (Roe & Georges, 2007).The inclusion of criteria that affect the ecological integrity and security of translocation sites during sites selection is also important, to ensure the site remains suitable into the future (IUCN/SSC, 2013). Attempts to evaluate sites based on such a large number of diverse criteria can become very complicated, increasing inaccuracy and leading to poorly informed management decisions being made (Laws & Kesler, 2012; Tulloch *et al*., 2013).

In a study by Dade *et al*. (2013), a spatially explicit multiple criteria analysis was used to identify potential translocation sites for *P. umbrina* based on remotely sensed data of habitat criteria important to *P. umbrina*. A Multiple Criteria Analysis (MCA) is a decision-making process where options are evaluated based on a variety of criteria important to the overall decision-making goal and the weighting, or importance, of each criterion (Janssen, 2001). This method provided a useful initial screening process for identifying suitable habitat for *P. umbrina*. However, the MCA did not include hydrological criteria, and relied heavily on expert judgements to identify criterion weights, which introduced a degree of uncertainty (Dade *et al*., 2013).

An Analytical Hierarchy Process (AHP) can reduce this uncertainty in a spatially explicit MCA. For example, Kontos *et al*. (2005) found this method to be highly compatible when identifying suitable waste disposal sites on the island of Lemnos, in the Mediterranean Sea. However, as spatial data can include errors it is important that ground-truthing is performed to determine the accuracy of remotely sensed data (Poulin *et al*., 2002; Tulloch *et al*., 2013).

1.4 Aims and objectives

This project expands on the work of Dade *et al*. (2013) by incorporating hydrological criteria with the suitability index constructed in Dade *et al*., (2013) to create a suitability index identifying suitable wetland sites for *P. umbrina* under a future climate scenario, and conducting ground-truthing to determine the accuracy of this spatially explicit method. The specific aim of this project was to identify suitable translocation sites for *P. umbrina* within the Swan Coastal Plain and Augusta to Walpole areas of the SWBP. This was achieved by:

- Combining spatially explicit MCA habitat mapping created in Dade *et al*. (2013) with a hydrological screening study (Bin Tareque, 2013) to identify suitable sites under a future climate scenario
- Ground-truthing a number of potentially suitable translocation sites to determine how accurately the spatially explicit MCA portrayed the actual site conditions
- Using the AHP method and pairwise comparisons to calculate criterion weights and to score and rank sites based on suitability
- Comparing rankings based on the AHP method to those based on the expert opinion method

1.5 Significance and outcomes

As the current habitat of *P. umbrina* continues to become increasingly unsuitable, assisted colonisation may be the only viable management option that ensures wild populations of *P. umbrina* remain into the future. A MCA could provide a robust and transparent decision-making process to identify suitable sites for assisted colonisation that can be easily interpreted by a range of stakeholders (Lahdelma *et al*., 2000).

As the impacts of climate change on biodiversity continue to be manifested globally, it is likely that assisted colonisation will also become a more widespread management option for a variety of endangered species. Spatially explicit MCA methods can easily be adapted for other species to identify suitable habitat under current and future climate trends and helps to reduce the costs of extensive habitat surveying and the risks and uncertainties associated with assisted colonisation (Smith *et al*., 2009).

Chapter 2

2. Literature review

Many conservation biologists believe assisted colonisation will be necessary in the face of climate change because species with very small and fragmented populations are unlikely to be able to adapt or migrate in response to a shifting climate (Hoegh-Guldberg *et al*., 2008; Loss *et al*., 2011; Lunt *et al*., 2013; Thomas, 2011). However, assisted colonisation as a conservation method is regarded as controversial by many within the scientific community, revolving around three main points: ecological risks, costs and uncertainties (Chauvenet *et al*., 2012).

Historically, species introductions have had high ecological costs. Of the 170 species extinctions with known causes that are on the IUCN extinction database, 54% listed invasive species as a cause of extinction (Clavero & García-Berthou, 2005). Introduced species can cause severe damage to communities by introducing pathogens and disrupting ecological processes (Ricciardi & Simberloff, 2009). Ricciardi & Simberloff (2009) argue against assisted colonisation as they believe the level of uncertainty involved in introducing a threatened species into a new environment is too high since we are currently unable to measure the probability of a species harming its new environment (Ricciardi & Simberloff, 2009; Chauvenet *et al*., 2012). For example, translocated phytophagous invertebrates can quickly become invasive if the plants within their translocation site do not have adequate defence mechanisms (Brooker *et al*., 2011).

In contrast, Thomas (2011) argues that the risks of assisted colonisation are predictably low in most situations as long as a species is translocated within the same biogeographical region as the environmental conditions will be similar to that of the species natural range. This was seen in the successful introduction of the tuatara (*Sphenodon punctatus*) to small islands off the mainland islands of New Zealand. These islands had similar environments to the tuatara's natural range but lacked the introduced mammalian predators that were threatening their survival on the mainland (Nelson *et al*., 2002).

Risks posed by assisted colonisation can also be reduced through increased understanding of the habitat requirements and distributions of the target species (Hoegh-Guldberg *et al*. 2008). Habitat type, quality and location play an important role in successful translocations (Germano & Bishop, 2009). Therefore selecting translocation sites that suit the species' habitat requirements allow identification of low-risk situations where the benefits of assisted colonisation can be realised (Hoegh-Guldberg *et al*., 2008).

2.1 Is the Western Swamp Tortoise (*Pseudemydura umbrina*) an ideal candidate for assisted colonisation?; The risks and benefits

Habitat fragmentation, reduced rainfall and reduced groundwater recharge have all contributed to the decreasing suitability of the current habitat of the Critically Endangered Western Swamp Tortoise (*Pseudemydura umbrina*) (Burbidge *et al*., 2010; IUCN, 2013). Hoegth-Guldberg *et al*. (2008) suggests assisted colonisation should be carried out on species likely to become extinct under current climatic trends and/or whose dispersal has been disrupted due to reduced habitat connectivity caused by fragmentation. Therefore, *P. umbrina* has been suggested as a possible candidate for assisted colonisation (Mitchell *et al*., 2013). However, it is important that the risks and uncertainties involved are weighed against the benefits to determine whether this species is a suitable candidate (Carrol *et al*., 2009).

Several aspects of the biology of *P. umbrina* suggest it is a good candidate for assisted colonisation. Tortoises occur within ephemeral swamps and when swamps begin to dry out in November to December they go underground or shelter under vegetation. Here they aestivate for 4-5 months until temperatures cool again in April-May and rainfall resumes (Burbidge *et al*., 2010). Aestivation is a period of inactivity that is both a behavioural and physiological strategy to avoid desiccation and heat stress during the hotter and drier months of the year (Grigg *et al*., 1986). Due to this strategy *P. umbrina* is only active for part of the year, reducing its impact on the environment and competition with other species and its likelihood to become invasive or have a negative impact on the host environment.

P. umbrina also has low fecundity which reduces the likelihood of it becoming invasive in a new environment. Female *P. umbrina* lay one, or rarely two, clutches of eggs per

year. Each clutch usually consists of 3-5 hard-shelled eggs that are laid in underground nests during November/December, just before aestivation begins (Burbidge *et al*., 2010). These eggs usually hatch around April in the following year with the hatchlings leaving the underground nest when the swamps begin to fill again at the beginning of winter. These hatchlings have a high mortality rate and are prone to predation from a range of species including foxes, birds and bandicoots (Burbidge *et al*., 2010).
The growth of these hatchlings is highly dependent on seasonal conditions. For example, in years of low rainfall growth is much slower than that of high rainfall years. On average, juveniles reach sexual maturity between 8-18 years (Burbidge *et al*., 2010). For all these reasons *P. umbrina* populations will not expand rapidly and are unlikely to out-compete other species, reducing pressure on potential food sources and competitors. *P. umbrina* is also adaptable to new environments (Dade *et al*., 2013), making it an ideal candidate for assisted colonisation.

2.2 What does *P. umbrina* require in a translocation site?

Due to the restricted range of *P. umbrina* it is difficult to accurately determine what encompasses a suitable habitat for this species. Since European settlement, this species has only been observed within a limited number of ephemeral swamps on the Swan Coastal Plain (Burbidge *et al*., 2010). However, its adaptation to novel environmental conditions and to captivity suggests that this species is capable of inhabiting a larger range of habitats (Dade *et al*. 2013). It is therefore likely a suitable translocation site may not reflect the environmental conditions present at its current habitat.

There are however several criteria that must be met to ensure a suitable wetland habitat. As *P. umbrina* both feeds and mates when swamps are full, the hydroperiod is extremely important as it influences growth and reproductive potential (Mitchell *et al*., 2010; Mitchell *et al*., 2013; Burbidge *et al*., 1981). Burbidge *et al*. (1981) found that in relatively wet years hatchlings had a mean carapace length of over 57mm, while in the particularly dry year of 1966 the mean carapace length was only 41mm. However wetlands cannot be inundated for the entire year as tortoises will not leave the water to lay eggs and commence aestivation, preventing the production of new hatchlings (G. Kuchling, pers. comm., 2013). A suitable hydroperiod is therefore regarded as being between 5-10 months in length, with 7-10 months being optimal (A. Burbidge, G. Kuchling, pers. comm., 2013).

Water temperature also affects the time that *P. umbrina* remains in the water to feed (Mitchell *et al*., 2013). If the water temperature is below 14°C or above 28°C tortoises generally leave the water (Lucas *et al*., 1963; Burbidge, 1981). Water temperature is influenced by a wide range of environmental factors, including vegetation shading over the wetland, solar heating, long wave radiation, depth of the wetland and the heat conductivity of the soil (Mitchell et al., 2013). There are also many other habitat criteria important in assessing the suitability of a wetland site, as discussed in Dade *et al*. (2013). These include soil type, vegetation type, salinity, macro-invertebrate diversity, land use and the size of a site. It is therefore important that these criteria are all taken into account when prioritising translocation sites, including considering whether criteria could change under future climate scenarios.

2.3 Spatially explicit Multiple Criteria Analysis and species translocations

Assisted colonisation, like all species translocations, requires a broad range of criteria to be considered to increase the likelihood of a successful outcome, including habitat criteria (Burbidge *et al*., 2011). This can be difficult to ensure as it involves assessing a diverse range of criteria, such as soil and vegetation, which are difficult to evaluate relative to one another (Lahdelma *et al*., 2000).
Multiple Criteria Analysis (MCA) has gained much support among environmental decision makers as an ideal method for environmental decision-making. It provides a systematic methodology that ranks or scores the performance of alternative decision options against multiple criteria to determine the alternative with the highest score, and therefore is optimal (Hajkowicz & Collins, 2007; Dade *et al*. 2013).

The use of the MCA method has rapidly increased in the last decade (Huang *et al*., 2011). In Australia it has been used to prioritise management threats to areas of the Great Barrier Reef and to determine regions of highest economic, environmental and social sustainability in the Glenelg Hopkins catchment in Victoria (Hajkowicz, 2008; Graymore *et al*., 2009). However, Dade *et al*., 2013 is the first case of a MCA being used to select potential sites for assisted colonisation. MCA could be an ideal method for identifying assisted colonisation sites as its structured decision-making would ensure that sites are chosen based on the best available knowledge (Chauvenet *et al*., 2012).

Selecting the criteria to use in a MCA to identify suitable assisted colonisation habitats for a species can be difficult. Often there is limited knowledge of the habitat requirements that will be important in selecting a suitable habitat outside the species' current or historical range (Thomas, 2011). As limited knowledge is common in environmental management problems, decisions must often be made using expert opinion (Metcalf & Wallace, 2013). However, Expert opinion can reduce the accuracy of results due to the potential for biasness (Metcalf & Wallace, 2013; Martin *et al*., 2012).

Reliance on expert opinion can be reduced by using the Analytical Hierarchy Process (AHP). The AHP uses a hierarchical model for the decision problem, consisting of an overall goal, a group of alternatives, and a group of criteria linking the alternatives to the goal (Vidal *et al*., 2011). Criterion weights are then calculated using pairwise comparisons, rather than expert opinion (Vidal *et al*., 2011). Pairwise comparisons involve comparing all criteria against one another in all possible combinations, to calculate ratios based on the importance of each criterion over the criteria (Saaty 1990). These ratios are compiled into a matrix and weights are calculated, allowing the decision options to be ranked and scores using weighted summation (Saaty, 1982).

In using a MCA to identify the most suitable assisted colonisation habitat it is important to first determine *where* there is potentially suitable habitat. Surveying an entire biogeographical region for suitable habitat is not feasible due to time, cost and logistical constraints. The most efficient method is to use spatial data and Geographical Information System (GIS) software to first identify suitable habitat. In examining the various applications of MCA in environmental management, Kiker *et al*. (2005) observed that a combined AHP and GIS approach was a common method for site prioritization and land condition evaluation.

2.4 The accuracy of using spatial data to map species habitats

The development, expansion and increasing availability of spatial data and GIS software over the last 20 years has caused a substantial increase in the use of spatial analysis in conservation planning. However, often the spatial datasets used in conservation planning have not been subject to accuracy assessments, leading to poorly informed decisions (Tulloch *et al*., 2013). These errors include incomplete data, processing errors, measurement errors, errors in data collection and out-dated data (Tulloch *et al*., 2013). Data inaccuracies are particularly problematic in habitat species mapping. They can cause conservation features to be under-represented by missing highly suitable areas, or they can over-represent conservation features by including areas that are unsuitable (Tulloch *et al*., 2013). Therefore a decision on suitable species habitat that does not include accuracy assessments could reduce the effectiveness and efficiency of species translocations.

The accuracy of spatial data can easily be assessed through ground-truthing. Ground-truthing involves surveying areas to determine whether the spatial GIS data accurately represents the real current conditions of that area (Poulin *et al*., 2002). This method is widely used in habitat mapping. For example, Smith *et al*. (2007) used ground-truthing to assess the accuracy of habitat suitability maps produced for the Julia Creek Dunnart (*Sminthopsis douglasi*) in Queensland, Australia. A total of 100 sites were surveyed and each was compared to the suitability predicted by the habitat model (Smith *et al*., 2007). This showed that the overall accuracy of the model predictions was 89%, suggesting a moderate-high level of accuracy (Smith *et al*., 2007).

2.5 Summary

Assisted colonisation could be an ideal conservation tool for *P. umbrina*. However to ensure an optimal outcome, translocation sites should be identified based on habitat criteria important to a successful establishment and long term viability of a *P. umbrina* population. This can be done effectively using the multiple criteria analysis method known as AHP. However, inaccurate assessments can arise from using a spatially explicit approach to identifying suitable translocation sites and it is essential that the accuracy of spatial data is assessed. Although the uncertainty involved in identifying a suitable translocation site for *P. umbrina* cannot be completely eliminated, it is possible to reduce uncertainty and risk by using an appropriate decision-making method and ground-truthing.

Chapter 3
3. Materials and methods

3.1 Study areas

3.1.1 Swan Coastal Plain

The Swan Coastal Plain (SCP) is located on the west coast of Western Australia (Figure 1). It extends for approximately 350 km, including the capital city of Perth. Dominate land uses include urban, residential and grazing and pasture (Beeston *et al*., 2002). This region experiences a Mediterranean climate of wet, mild winters and hot dry summers with a Köppen Climate Classification of subtropical in the north and temperate in the south. The annual mean rainfall is 800mm (Stern *et al*., 1999; CSIRO, 2009).

The SCP is within the soil landscape province of Swan and is dominated by pale deep sands, sandy and loamy gravel, and sandy duplexes (Schoknecht *et al*., 2004). The wetlands of the SCP are predominantly seasonal wetlands and commonly found in areas of alluvial and clayey soils (Hill *et al*., 1996b).

The vegetation within this region is dominated by Banksia and sclerophyllous

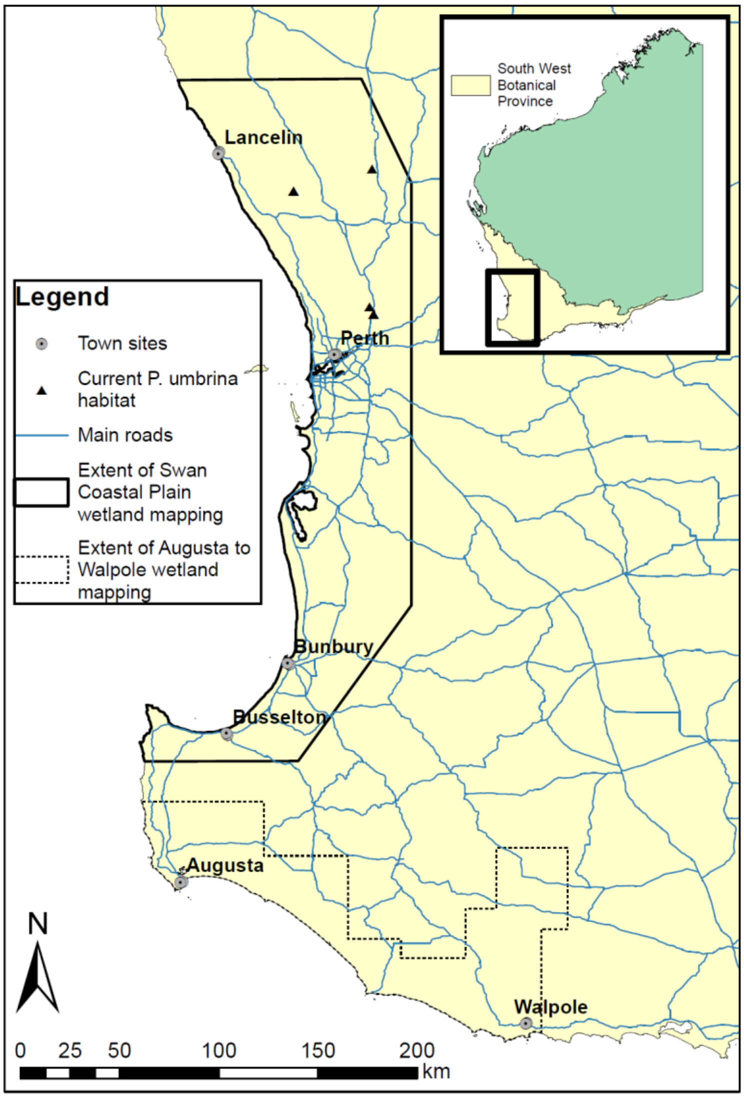

Figure 1. The south West Botanical Province of Western Australia showing the location of the Swan Coastal Plain and Augusta to Walpole area where habitat suitability mapping for *P. umbrina* was performed for this study. Current *P. umbrina* habitat is located in the northern end of the Swan Coastal Plain.

species due to the nutrient deficient soil that dominates this region. Common vegetation communities include; Banksia (*Banksia* sp.) woodland, Jarrah (*Eucalyptus marginata*)-Marri (*Corymbia calophylla*) woodland and mixed shrubland (Beeston *et al*., 2002).

3.1.2 Augusta to Walpole region

The Augusta to Walpole region is located in the south-western corner of Western Australia (Figure 1). It extends for approximately 180 km along the south coast from the town of Augusta in the west, to Walpole in the east. The main land uses within this area include grazing and pastures and natural resource management (Beeston *et al*., 2002). This region is described as temperate by the Köppen Climate Classification system and is the wettest area within the SWBP with an annual mean rainfall of 1200mm (Stern *et al*., 1999; CSIRO, 2009).

The Augusta to Walpole region is divided into two soil landscape provinces; the Swan Province on the western side of the region and the Avon Province on the eastern side. The soils of the Avon Province are predominantly non-calcareous sands, colluvial soils and weathered granite and that enabled the formation of a large number of seasonal wetlands (Schoknecht *et al*., 2004; V. & C. Semenuik Research Group, 1997).
The vegetation of this region is predominantly Karri (*Eucalyptus diversicolor*)-Tingle (*Eucalyptus jacksonii*) forest, Jarrah (*Eucalyptus marginata*)-Marri (*Corymbia calophylla*) forest and woodland, sedgeland, and shrubland (Beeston *et al*., 2002).

3.2 Site selection methodology

Habitat suitability modelling consisted of three main steps: 1) identify the habitat criteria important to a suitable assisted colonisation site for *P. umbrina*, 2) create GIS layers, for each of the criteria with available GIS data, and combine with GIS layers created from hydrological screening (Bin Tareque, 2013) to create a suitability index, and 3), visit individual sites, ranked highly on the suitability index, for ground-truthing and collect data on each habitat criterion.

3.3 Identification of habitat criteria

The criteria used to identify areas with suitable habitat for *P. umbrina* under future climate trends were sourced from Dade *et al*. (2013), Bin Tareque (2013), literature reviews and from consultation with *P. umbrina* experts.

Dade *et al*. (2013) used habitat criteria with data in GIS format to map and identify suitable wetlands for *P. umbrina* under the current climate (full article can be found in Appendix 1). To identify the criteria to be used from habitat mapping performed in Dade *et al*. (2013), a sensitivity analysis was performed to determine which criteria had the greatest influence over determining which wetlands were deemed suitable. Criteria that had little or no effect on distribution and degree of suitability in the suitability index were not used further in this study.

Bin Tareque (2013) developed a hydrological screening model to identify areas with suitable hydroperiods for *P. umbrina* under a future climate scenario projected for the year 2030. This screening model was driven by a 'median future' climate scenario described by CSIRO (2009) where a 1°C increase in air temperature and 7% decrease in rainfall was projected for 2030 based on averages of 16 Global Circulation Models. As *P. umbrina*'s current wetlands sites at Ellen Brook and Twins Swamps Nature Reserves are both claypan basin wetlands with no significant inflows from groundwater, the hydrological characteristics of a claypan basin wetland were fed into the Wetland Water Balance and Thermodynamic Model (WET-R). This models was then run at a number of locations across SWBP to determine the hydroperiod of a claypan basin wetland at that location if air temperature was increased by 1°C and there was 7% decline in rainfall to that of the current climate, which is based on climate data collected from 1990-2009 as part of the Australian Water Availability Project (AWAP) database. This data was then interpolated using the kriging method to provide hydroperiod screening results for the entire SWBP. See Mitchell *et al*., (2013) and White (2012) for further information on the WET-R model and this hydrological screening process.

A literature review and consultations with experts on *P. umbrina* were then conducted to determine remaining criteria important to a successful translocation. Consultations with experts were conducted during June 2013 and consisted of informal group interviews. Experts were presented with a short-list of criteria and asked if they thought each criterion was important and if there any other criteria that should be considered.

The 11 criteria were identified and used in this study to identify suitable assisted colonisation sites for *P. umbrina* and are described below with their suitability grades shown in Table 1.

Table 1. Criteria used in this study to assess wetland habitat suitability for *P. umbrina*, including the grading values used to construct the suitability index and calculate each sites final ranking.

Criteria	Suitability index	References
Soil type	• 1 = Clay, sandy duplex soils • 0.66 = Loamy, loamy duplexes • 0.33 = Sandy • 0 = All other soil types	• Burbidge (1981) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Vegetation composition	• 1 = Banksia shrubland and woodland, melaleuca shrubland, heath and woodland • 0.66 = Shrubland (other than banksia or melaleuca), sedgeland, heath • 0.33 = All woodlands (other than Banksia or Melaleuca) • 0 = All other vegetation communities	• Burbidge et al., (2010) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013) • ESCAVI (2003)
Vegetation cover	• 1 = 0-40% • 0.5 = 40-80% • 0 = 80-100%	• A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Land use	• 1 = Public conservation • 0.66 = Habitat managed area, managed resource protection, private conservation • 0.33 = Remnant native cover, crown land • 0 = All other land uses	• IUCN/SSC (2013) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Food diversity	• 1 = ≥ 1.16 H' • 0.5 = 0.58-1.16 H' • 0 = ≤ 0.58 H'	• Gilbert (2010) • Burbidge (1981)
Site size	• 1 = > 200 ha • 0.66 = 100-200 ha • 0.33 = 50-100 ha • 0 = < 50 ha	• Burbidge et al. (2010) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Salinity	• 1 = 0-800 EC • 0.5 = 800-4800 EC • 0 = ≥ 4800 EC	• ANZECC (2000) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Water temperature	• 1 = 14-28°C • 0 = > 28°C, < 14°C	• A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013) • Mitchell et al. (2013)
Hydroperiod	• 1 = 180-270 days • 0.5 = 270-300 days, 150-180 days • 0 = > 300 days • 0 = < 150 days	• Mitchell et al. (2013) • Burbidge (1981) • A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013)
Water pH	• 1 = 6.5-7.5 • 0.5 = 7.5-8 , 6-6.5 • 0 = > 8, < 6	• A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013) • ANZECC (2000)
Disturbances	• 1 = Nil • 0.66 = Minor • 0.5 = Moderate • 0 = Severe	• A.Burbidge, G. Kuchling, S. Arnall, D. Bradshaw., Pers. comm (2013) • IUCN/SSC (2013)

3.3.1 Soil type

The current habitat of *P. umbrina* consists of predominantly clay soils. At Ellen Brook Nature Reserve, the soil is a claypan and gilgai complex that has high hydraulic conductivity allowing it to retain water for long periods of times, contributing to the length of the hydroperiod (Burbidge, 1981). In contrast, Twin Swamps Nature Reserve consists of a sandy soil complex at the surface with a clay layer approximately 15-30cm underneath (Burbidge *et al*., 1981).

There have been unsubstantiated records of *P.umbrina* at other wetlands in the SWBP that consist of loamy and peaty soils rather than clay (Burbidge *et al*., 2010). This suggests *P. umbrina* is potentially capable of occupying habitats with a variety of soil types providing they are able to hold water to ensure a reasonable hydroperiod. Therefore in this study, clay and sand over clay soils were graded highly suitable, with other soils with high hydraulic conductivity graded as moderately suitable.

3.3.2 Vegetation composition

As previous studies suggest that *P. umbrina* has always had a restricted range, it is difficult to determine what constitutes suitable vegetation at a habitat. The aim of this criterion is to reduce the level of uncertainty by ensuring a translocation site is identified that has a similar vegetation composition and structure to that found at *P. umbrina*'s current sites. Vegetation composition and structure were described using the definitions used by the National Vegetation Information System (NVIS), as defined in ESCAVI (2003). Melaleuca and Banksia woodland and shrubland were graded highly suitable due to these vegetation communities being located within *P. umbrina*'s current habitat. Similar vegetation communities that could provide protection for *P. umbrina* from predators and during aestivation were graded as moderately suitable.

3.3.3 Vegetation cover

P. umbrina is active within wetlands when the water temperature is between 14-28°C (Lucas *et al*., 1963; Mitchell *et al*., 2013). To maximise foraging opportunities for *P. umbrina* this temperature range must be maintained for as long as possible during the hydroperiod. As vegetative shade significantly reduces water temperatures (Mitchell et al., 2013), this criterion was included to ensure that suitable habitat had direct sunlight during the winter months to provide a suitable water temperature.

Habitats with low vegetative cover over the water were graded as highly suitable while areas with high vegetative cover were graded as low suitability.

3.3.4 Land use

As this study aims to identify a translocation sites that will be suitable in the future, it is important that sites are located on secure land that can maintain its ecological integrity (Harris *et al*., 2013; IUCN/SSC, 2013).

Areas already defined as conservation areas and managed by the Government were graded as highly suitable. Areas of conservation that are managed privately and resource management areas, such as state forest, were defined as moderately suitable as there is a possibility their land use may change in the future. Remnant native vegetation cover, including crown land, was graded as least suitable as these areas are unlikely to be secure. All other land uses were classified as unsuitable.

3.3.5 Food diversity

P. umbrina is carnivorous and feeds primarily on aquatic macroinvertebrates (Burbidge, 1981; Gilbert, 2010). A diverse diet is important to *P. umbrina* as it can increase growth rates and reproductive success (G. Kuchling, pers. comm., 2013). This criterion is included to ensure that suitable habitat contains an aquatic macroinvertebrate community that has a similar diversity to that of *P. umbrina*'s current habitat.

Using the Shannon-Weiner diversity index, a diversity value (H') of 1.16 was calculated from samples collected from stomach flushes of individual *P. umbrina* at Ellen Brook and Twin Swamps Nature Reserves (Gilbert, 2010). Hence in this study, habitats with a macroinvertebrate community with a Shannon-Weiner diversity value of 1.16 or more were graded as highly suitable. Habitats with diversity up to 50% lower than this (0.58-1.16) were graded as moderately suitable and any habitat with a lower value was graded as least suitable.

3.3.6 Site size

This criterion was included as a proxy for how robust the habitat is, how large a population of *P. umbrina* it could support and whether it would maintain its ecological integrity while supporting a *P. umbrina* population. Suitable habitat was defined as the combined area of both the wetland and surrounding vegetation.

Habitats with a size of 200ha or more are ideal and were graded as highly suitable (G. Kuchling, pers. comm., 2013). As Ellen Brook and Twin Swamps Nature Reserves are between 100-200ha, habitats within this range were defined as potentially suitable and graded as moderately suitable. Habitats with a size between 50-100ha were classed as least suitable.

3.3.7 Water salinity

As *P.umbrina* is a freshwater species, water salinity is a threat to this species and the freshwater macroinvertebrates it feeds upon. Hence the aim of this criterion is to identify a habitat with minimal water salinity. As limited studies have been conducted to determine the water salinity levels that *P. umbrina* can tolerate (A. Burbidge, pers. comm., 2013), salinity levels were based on the trigger values defined in ANZECC (2000), which determine the health of a freshwater wetland. Wetland habitats with a water salinity level of 0-800 EC were graded as highly suitable, wetlands with a salinity level of 800-4800 EC were graded as moderately suitable and habitats with higher levels of water salinity were graded as unsuitable.

3.3.8 Water temperature

As mentioned previously, it is important that wetlands have an average water temperature between 14-28°C to ensure that *P. umbrina* can be active and forage (Mitchell *et al*., 2012). Under this criterion, wetlands with water temperatures between 14-28°C were graded as highly suitable. Wetlands with an average water temperature below 14°C or above 28°C were graded as unsuitable.

3.3.9 Hydroperiod

The hydroperiod of a wetland is important in defining its suitability for *P. umbrina* as they require water for feeding and breeding purposes but also require an obligatory aestivation period in the hottest months (Burbidge, 1981). Hence permanent water bodies are unsuitable. This criterion aims to ensure that wetlands considered for translocations have a suitable hydroperiod for supporting the life cycle of *P. umbrina*. Habitats with hydroperiods of 6-9 months were graded as highly suitable while habitats with a hydroperiod of 5-6 months or 9-10 months were graded as moderately suitable. Any habitats with a hydroperiod of more than 10 months or less than 5 months were graded as unsuitable.

3.3.10 Water pH

The pH level of freshwater is often used as an indicator of wetland health (ANZECC, 2000). As *P. umbrina*'s current range is restricted it is difficult to determine the water acidity or alkalinity in which this species can survive (Kuchling, G., pers. comm., 2013). The aim of this criterion is to identify wetlands that can support *P. umbrina* while maintaining ecological processes. Suitable pH levels were based on the trigger values defined in ANZECC (2000). Healthy freshwater ecosystems in south-western Australia have a pH of 6.5-7.5 and therefore these habitats were graded as highly suitable in this study. Habitats with a pH of 7.5-8 or 6-6.5 were graded as moderately suitable and habitats with a pH of above 8 or below 6 were graded as unsuitable.

3.3.11 Disturbances

Disturbed habitats are unsuitable for species translocations as they can decrease the vitality of a translocated population and the potential for the habitat to maintain its ecological integrity. Disturbances include the presence of invasive species, eutrophication and fragmented habitats. The aim of this criterion was to ensure that the translocation habitat is robust and able to support *P. umbrina* over a long period into the future. Habitats were graded based on the severity impact index used in DEC (2008). Habitats with no evidence of stress to the environment were graded as highly suitable, habitats with minor signs of stress were graded as moderately suitable and habitats with moderate stress were graded as least suitable. Habitats with severe stress were graded as unsuitable.

3.4 Suitability index for a future climate

The four criteria with data available in GIS format (soil, vegetation composition, land use and hydroperiods) were each converted into a raster layer (30x30m cell size) with each raster cell containing a suitability score for that criterion, as defined in Table 1. These raster layers were overlaid onto the suitability mask constructed in Dade *et al.* (2013), using ArcGIS to show the degree of suitability of potential *P. umbrina* wetlands (Figure 2). The list of data sources for each criterion used in the suitability mask and index is shown in Table 2.

Eight wetlands that scored highly for suitability and accessibility were then selected for sites visits. Here the intention was to collect empirical data on each of the criteria and so to assess the actual condition of these wetland sites and compare this assessment with that generated from the GIS data.

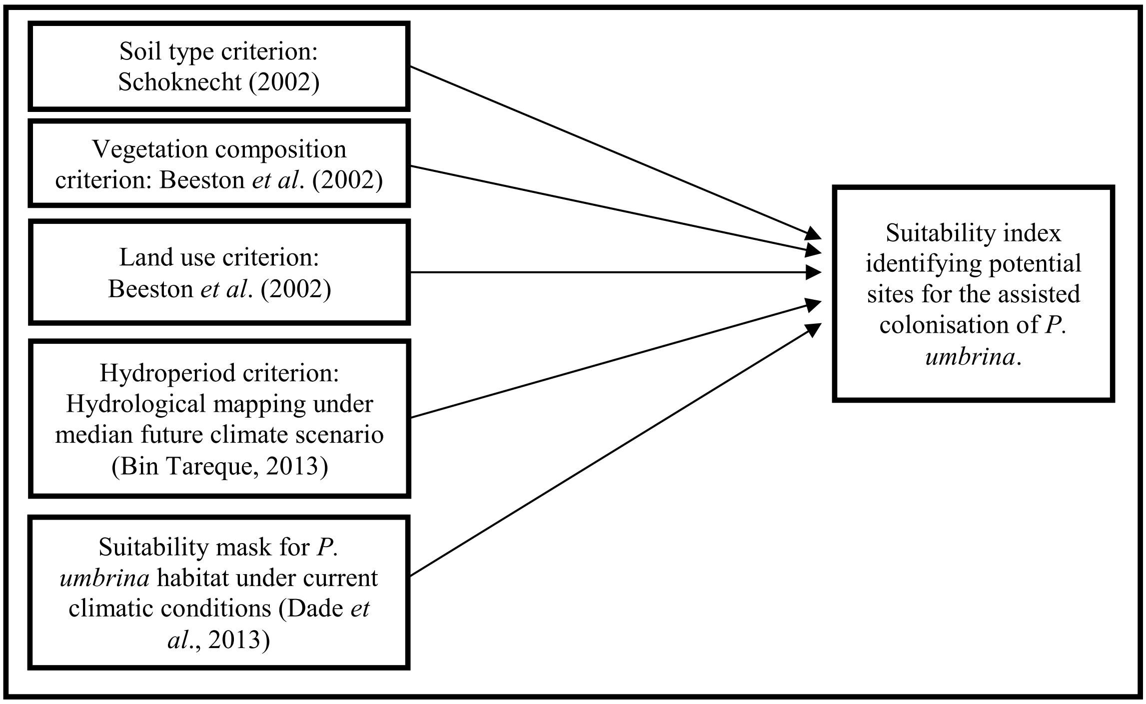

Figure 2. Flowchart outlining the data used to construct the suitability index, including the suitability mask and the four spatially explicit criteria regarded as important to identifying suitable sites for the assisted colonisation habitat of *P. umbrina.*

Table 2. Types and sources of data for the five criteria used to construct a suitability index and limit the number of potentially suitable habitats.

Criterion	GIS data	Data source
Soil type	Soil landscape systems of Western Australia	Schoknecht (2002)
Vegetation composition	Pre-European vegetation Native vegetation extent	Beeston *et al*. (2002)
Land use	Land use in Western Australia, version 5.0	Beeston *et al*. (2002)
Hydroperiod	Surfaces of projected hydroperiods for claypan wetlands	Bin Tareque (2013)
Site size	Geomorphic wetlands, Swan Coastal Plain Geomorphic wetlands, Augusta to Walpole	Hill *et al*. (1996) V. & C. Semenuik Research Group (1997)

3.5 Site sampling methodology

Sites visits were carried out during July and August 2013 to ensure that site conditions were assessed at a time when *P. umbrina* would be active in the wetland. Each criterion was measured at each site, with the exception of the size of the site and the hydroperiod, due to limited time and resources.

A rapid assessment sampling methodology for wetlands was used to assess the sites. This allowed for a "snapshot" of site conditions that is comparable across sites. The methods used to collect data on each criteria are based on the methodologies developed in DEC (2008) and DEC (2012). The sampling methodology for each criterion is listed in Table 3 and the data collection sheets used are shown in Appendix 2.

Table 3. Methodology used to sample and describe the criteria at the eight candidate sites.

Criterion	Indicator	Site sampling method
Soil type	Dominant soil type present at the site	A soil auger was used to collect soil samples at 5, 10, 20 and 40 cm below ground level, or until the water table was reached. Soil texture was determined using the ribbon test, as described in DEC (2012) and soil colour was described using a Munsell soil colour chart.
Vegetation composition	Density and dominant stratum and genus of the vegetation.	A 10x10m quadrat was placed in the fringing vegetation. For each strata level identified, the height, percentage coverage of the quadrat and the dominant plant genus was identified.
Vegetation cover	Percentage of shade over water	Calculated using the point intercept method described in DEC (2012) along a 20m transect within the vegetation on the water's edge.
Land use	Land use and ownership	Assessed based on observations and aerial imagery of the site
Food diversity	Abundance and species richness of aquatic invertebrates	Based on the methods described in DEC (2012), A net was swept through the water once for approximately 5 meters and the contents carefully emptied into sampling trays. Macro-invertebrates were identified using Davis & Christidis (1997), and the Shannon-weiner diversity index (H') was then calculated.
Site size	Area of suitable habitat	This criterion was not assessed during site visits and was instead calculated using GIS.
salinity	Below surface EC value of the water	Water salinity was determined at three points at each site using an EC meter.
Water temperature	Below surface temperature of the water	The temperature of the water was determined using a digital thermometer.
hydroperiod	Length of hydroperiod	This criterion was not assessed during site visits and was instead based on a generalised hydrological model for a claypan wetland driven using 20 year daily climate records (insert years) (Bin Tareque, 2013).
Water pH	Below surface acidity/alkalinity of the	Water pH was determined at three points at each site using a pH meter.
disturbances	Level of environmental stress and ecological integrity of the site	The level of disturbance was identified using methodology developed in DEC (2008) and was based on site observations and consultation with local DPAW staff and landowners.

3.6 Weighted summation and data analysis

3.6.1 Analytical Hierarchy Process (AHP)

The AHP uses pairwise comparisons to calculate priority vectors that are used as criterion weights to calculate the suitability score and ranking of each wetland (Saaty 1990; Kontos *et al*., 2005). To calculate the priority vectors, each criterion was individually compared against all other criteria to determine which criterion was more important. Importance was determined by asking two questions:

- Which criterion is more important to a successful translocation of *P. umbrina*?
- Which criterion cannot be artificially replaced if it is not naturally present at the translocation site?

Based on these questions, the level of importance of one criterion over another was calculated and given a number from an 'intensity of importance' scale created by Saaty (1990) (Table 4). A matrix was then created displaying the importance score designated to each criterion. The weightings for each criterion were then calculated from the pairwise comparisons by estimating the right principle eigenvector of the pairwise comparisons matrix. The right principle eigenvector was estimated using the geometric mean of each row of the matrix, which involved multiplying the elements of each row and then taking the nth root, where n is the number of criteria (described in Saaty, 1982 and Kontos *et al*., 2005).

Criterion weights were also calculated using expert opinion, using the method described in in Dade *et al*. (2013). By comparing the results of both methods, the level of inaccuracy in the expert opinion method can be determined and used to indicate whether this latter method is sufficiently accurate for ranking translocation sites.

Using the data collected during site visits and the criterion weights calculated, an individual suitability score was then given to each wetland using the weighted summation equation, described in Hajkowicz (2008), where the final suitability score is equal to the sum of each criterion score multiplied against their respective weight. These scores were then converted into rankings to identify the most suitable site.

Table 4. The nine-point fundamental scale developed by Saaty (1990) used to rate the importance of each criterion in the pairwise comparisons matrix to calculate criterion weights.

Intensity of importance	definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2 3	Weak Moderate importance	Experience and judgement slightly favour one activity over another
4 5	Moderate plus Strong importance	Experience and judgement strongly favour one activity over another
6 7	Strong plus Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8 9	Very, very strong Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

3.6.2 Analysis of field data

Criterion data collected at each of the sites was both categorical and numerical in form and were therefore analysed separately. Due to the limited number of sites no statistical tests were performed on the categorical criteria. Instead, each criterion was compared across sites to determine if the higher ranked sites had more similar criterion conditions than those ranked as less suitable.

Numerical data were analysed using a regression analysis in Microsoft Excel to determine which criterion had the most influence over site suitability scores, and therefore site rankings.

The R statistics program (http://www.r-project.org/) was used to perform a distance based redundancy analysis (DBRA), known as Adonis, to determine whether there was a relationship between geographical distance and suitability scores. A DBRA analyses variance using distance matrices (McArdle & Anderson, 2001). Depending on how well it is fitted to the linear model it can then be used to determine whether there is a significant relationship between two variables. To perform this test, the Euclidean distance of the longitude and latitude data collected at each site was calculated to create a distance matrix and the Adonis analysis was performed using these euclidean distances and the site suitability scores. The R script used can be viewed in Appendix 3.

Chapter 4

4. Results

4.1 Suitability index for potential sites for the assisted colonisation of *P. umbrina*

The final suitability index based on the GIS criteria shows suitable wetlands on the Swan Coastal Plain (Figure 2) and the Augusta to Walpole area (Figure 4) under a median future climate scenario for *P. umbrina*. Wetland habitats located north of 31° latitude line were unsuitable, which included current *P. umbrina* translocation sites at Moore River and Mogumber Nature Reserves. The dominant criterion contributing to this result was the hydroperiod criterion which identified wetlands in the northern end of the Swan Coastal Plain as having unsuitably short hydroperiods.
Under this index, 95% of the potentially suitable wetland habitats were given a moderate suitability grade of either 2 or 3. Only 3.7% (387) wetland habitats were given a suitability grade of 4 (most suitable).

Within the Augusta to Walpole area, the majority of wetlands with a suitability grade of 4 (most suitable) were located near the town of Walpole (Figure 4). As was the case with the Swan Coastal Plain suitability index, majority of potential wetland habitats (81%) were given a moderate suitability grade of two or three. However a greater proportion of wetland habitats (18%) were graded at 4, relative to wetlands on the Swan Coastal Plain.

4.2 Site sampling and ground-truthing

The eights sites selected for on-ground assessment are shown in Figure 3and Figure 4. Field data collected at each of these sites is summarised in Table 5. Conditions of each of the criteria at each of the sites varied greatly.

Ground-truthing found that not all sites were wetlands with the Frankland National Park site not containing any water though it was identified as a wetland site in the suitability index.Vegetation composition also differed greatly from that displayed in the suitability index. The D'entrecasteaux National Park 1 site consisted of closed Melaleuca forest, a vegetation type graded as unsuitable in the suitability index, and while Benger Swamp Nature Reserve did include Melaleuca shrubland it predominantly consisted of *Typhus* sedgeland, an invasive species.

In contrast, soil conditions and land use were similar between sites and corresponded closely to the criteria conditions displayed in the spatial data used to create the suitability index.

Visually the sites also varied greatly from one another. Of the eight sites, the Donnelley State Forest site looked most similar to the habitat and conditions present at the current wetlands occupied by *P. umbrina* while D'entrecasteaux National Park 1 and Benger Swamp Nature Reserve were most dissimilar (see Appendix 4 for site photos).

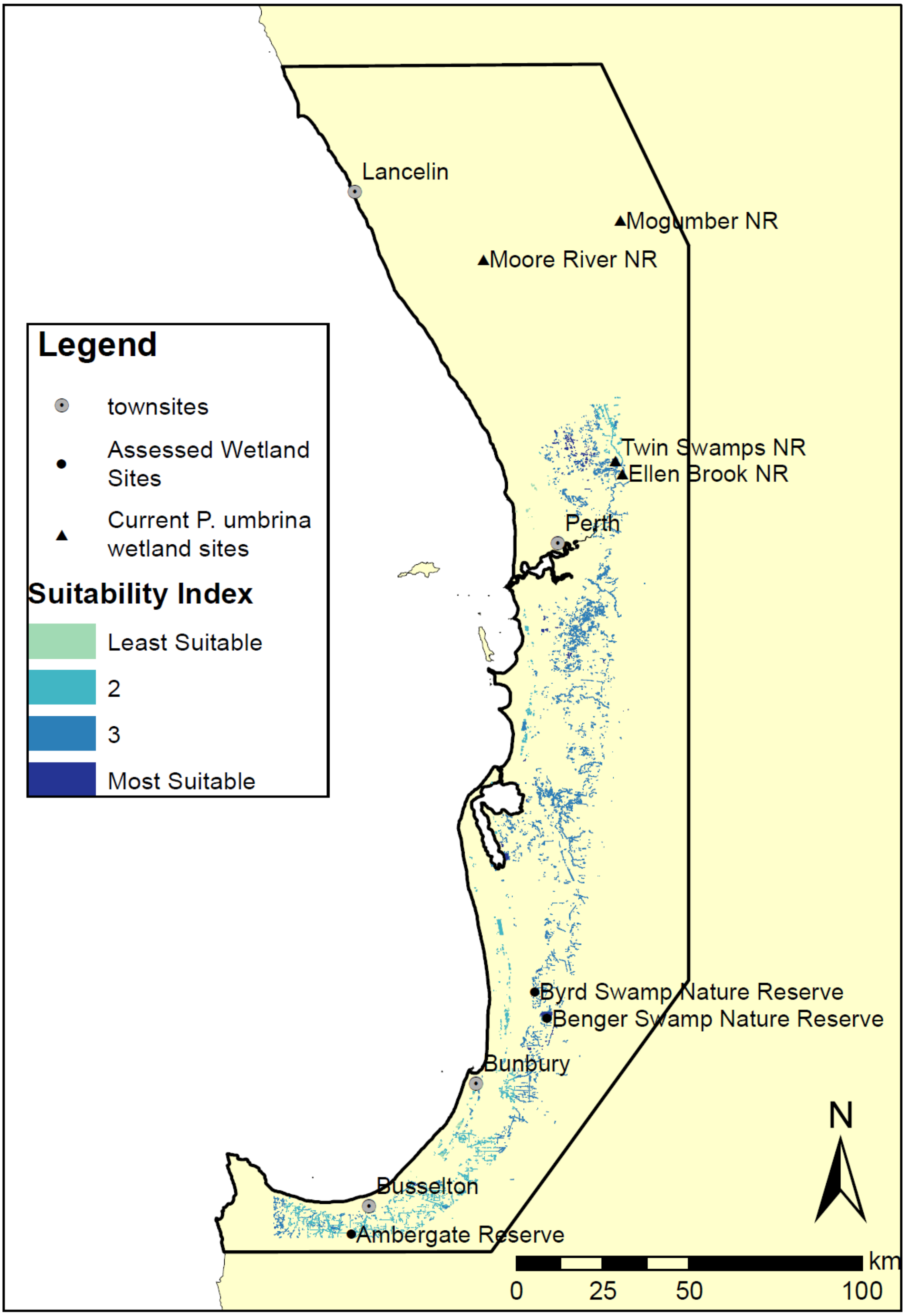

Figure 3. Suitability index for the Swan Coastal Plain showing wetland habitat suitability and potential assisted colonisation sites for *P. umbrina*. Three sites were selected from within this area to ground-truth the criteria and to collect field data on each criterion. NR = Nature Reserve

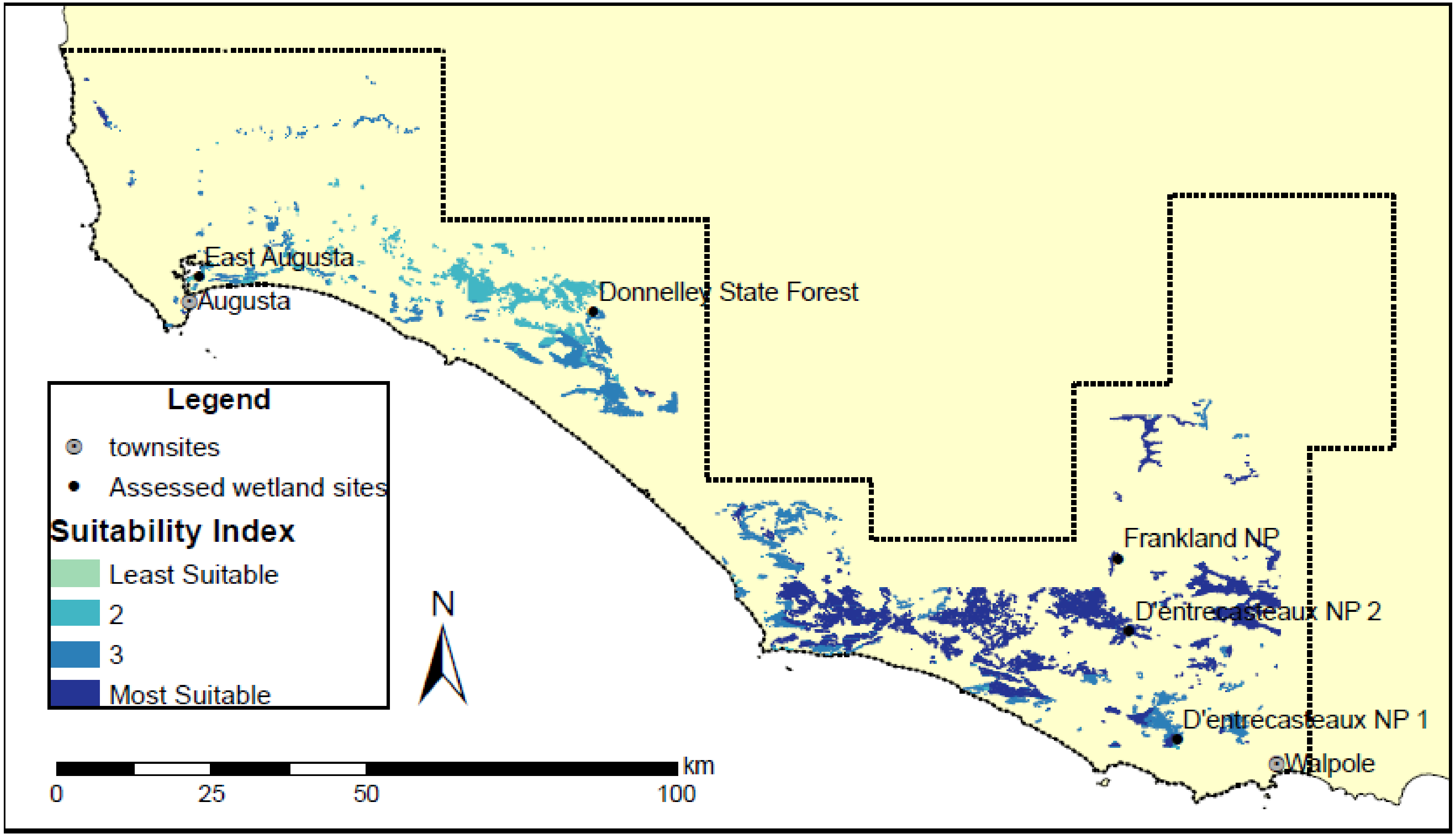

Figure 4. Suitability index for the Augusta to Walpole area showing wetland habitat suitability and potential assisted colonisation sites for *P. umbrina.*Three sites were selected from within this area to ground-truth the criteria and to collect field data on each criterion. NP = National Park.

Table 5. A summary of the field data collected for each criterion and the eight sites assessed in this study. As hydroperiods could not be assessed from single site visits, the data in the hydroperiod column was calculated in Bin Tareque (2013). NR = Nature Reserve and NP = National Park.

Site	Soil type	Vegetation composition	Vegetation cover (%)	Land use	Food diversity (H')	Site size (ha)	Salinity (EC)	Water temperature (°C)	Hydro-period (days)	Water pH	disturbances
East Augusta	sandy	Melaleuca shrubland	74.25	Crown land	1.73	28.1	497	14.33	186	6.72	Nil
Ambergate NR	Loamy sand	Open eucalypt woodland	59.29	Private conservation	0.89	66.6	1555.33	13.20	168	6.82	Moderate
D'entrecasteaux NP 1	sandy	Melaleuca closed forest	96.67	Public conservation	1.28	852.3	107.47	13.27	157	5.40	Nil
D'entrecasteaux NP 2	Loamy sand	Melaleuca shrubland	98.81	Public conservation	1.10	222.1	207.13	13.83	182	4.32	Minor
Frankland NP	Loamy sand	Baumea open sedgeland	25.24	Public conservation	0	114.9	No water present	No water present	188	No water present	Nil
Donnelley State Forest	Clayey sand	Melaleuca shrubland	19.05	State forest	0.51	83.30	111.30	16.57	171	4.26	Minor
Benger Swamp NR	Clay loam	Typhus closed sedgeland	75.00	Public conservation	1.80	313.5	184.10	14.13	199	6.92	Severe
Byrd Swamp NR	sandy	Melaleuca shrubland	22.14	Public conservation	1.60	52.3	45.40	16.70	190	6.44	Minor

4.3 Criteria weighting and site suitability ranking

The pairwise comparison approach identified the hydroperiod as the most important criterion for selecting a *P. umbrina* translocation site (Table 6). Food diversity, soil type and water temperature also had large weights, emphasising their importance. Water pH and disturbances were given the smallest weights and regarded as least important. Overall, the confidence ratio of the pairwise comparisons approach was 0.057. As this value is less than 0.1, the weights calculated using this method can be regarded as robust and a good representation of each of their importance.

When compared to the expert opinion approach, the weights calculated using pairwise comparisons were similar to those calculated using expert opinion (Figure 5). However, weights calculated using expert opinions were more evenly distributed than those calculated using pairwise comparisons. For example, using the pairwise comparisons approach, the hydroperiod criterion was regarded as most important and given a weight of 0.27. Using the expert opinion method the hydroperiod criterion was also regarded as most important but was given a weighting of only 0.14.

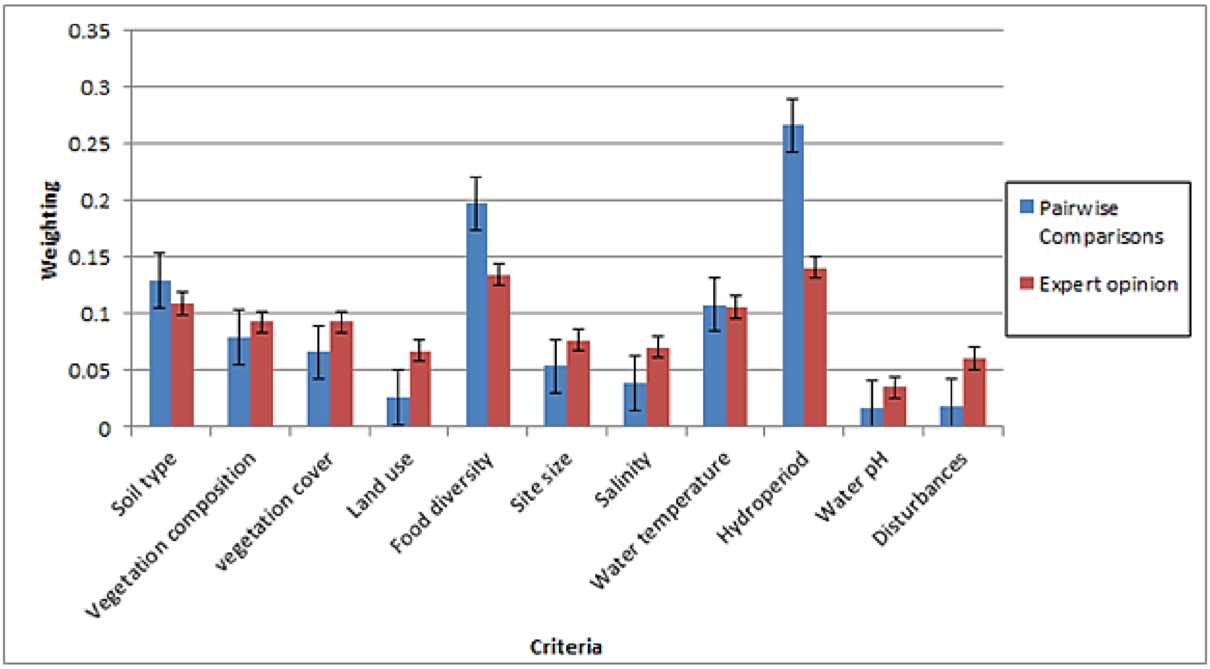

Figure 5. Criteria weights calculated using pairwise comparisons and expert opinion.

Table 6. The pairwise comparisons matrix showing the relative importance of each criterion relative to all other criteria. The priority vectors, calculated from the eigenvalues were used to represent the criteria weights. λmax = principle eigenvalue, CI = Consistency index, CR = Consistency ratio.

	Soil type	**Vegetation composition**	**Vegetation cover**	**Land use**	**Food diversity**	**Site size**	**Water salinity**	**Water temperature**	**Hydro-period**	**Water pH**	**disturbances**	**Priority vector**
Soil type	1.00	3.00	3.00	4.00	0.33	4.00	4.00	2.00	0.25	7.00	6.00	0.13
Vegetation composiiton	0.33	1.00	1.00	4.00	0.25	2.00	3.00	1.00	0.20	6.00	6.00	0.08
Vegetation cover	0.33	1.00	1.00	4.00	0.25	2.00	2.00	0.33	0.17	5.00	5.00	0.07
Land use	0.25	0.25	0.25	1.00	0.17	0.33	0.33	0.20	0.13	3.00	2.00	0.03
Food diversity	3.00	4.00	4.00	6.00	1.00	5.00	5.00	3.00	0.50	7.00	7.00	0.20
Site size	0.25	0.50	0.50	3.00	0.20	1.00	2.00	0.25	0.20	5.00	5.00	0.05
Water salinity	0.25	0.33	0.50	3.00	0.20	0.50	1.00	0.25	0.14	3.00	3.00	0.04
Water temperature	0.50	1.00	3.00	5.00	0.33	4.00	4.00	1.00	0.33	6.00	6.00	0.11
hydroperiod	4.00	5.00	6.00	8.00	2.00	5.00	7.00	3.00	1.00	8.00	7.00	0.27
Water pH	0.14	0.17	0.20	0.33	0.14	0.20	0.33	0.17	0.13	1.00	1.00	0.02
disturbances	0.17	0.17	0.20	0.50	0.14	0.20	0.33	0.17	0.14	1.00	1.00	0.02

λ_{max} = 11.85, CI = 0.09, CR = 0.06 < 0.1

The suitability scores calculated using weighted summation, with the weights obtained from the pairwise comparisons approach, are shown in Table 7. Benger Swamp Nature Reserve was ranked as the most suitable wetland habitat for *P. umbrina*. This was mainly due to high food diversity recorded at this site and the suitable hydroperiod length. The only criteria where this wetland habitat was unsuitable were vegetation composition and disturbances. The Donnelley State Forest site was ranked as the fifth most suitable site, regardless of its visual similarity to *P. umbrina*'s current habitat (see Appendix 4).
The Frankland National Park wetland habitat was ranked as least suitable largely due to the lack of water present at the site.

When weighted summation was conducted using the weights obtained using expert opinion rather than the pairwise comparisons approach, the site rankings changed slightly (Table 7). Benger Swamp Nature Reserve was still ranked the most suitable but Ambergate Nature Reserve dropped down two spots from a ranking of 4 to a ranking of 6. Donnelley state forest however moved up a spot with its ranking moving from 5 to 4.

4.4 Relationship between criteria, location and wetland suitability scores

4.4.1 Categorical criteria

There was little relationship between the categorical criteria data from each of the sites. Benger Swamp Nature Reserve was identified as the most disturbed site but this site was ranked as the most suitable site (Table 8). In contrast, D'Entrecasteaux National Park 1 was one of the least disturbed sites and was ranked as least suitable.
A strong relationship was observed between vegetation composition and soil type, with Melaleuca shrubland most often associated with sandy soils (Table 6).

Table 7. Weighted summation data for the eight assessed sites and final site suitability scores and rankings. Criteria scores are based on field data and spatial data and weights are based on the priority vectors calculated using the pairwise comparisons approach. Sites are ranked from 1 as most suitable, to 8 as least suitable. NR = Nature Reserve and NP = National Park.

	Soil type	**Vegetation composition**	**Vegetation cover**	**Land use**	**Food diversity**	**Site size**	**Water salinity**	**Water temperature**	**Hydro-period**	**Water pH**	**Disturbances**	**Site score**	**ranking**
weighting	0.13	0.08	0.07	0.03	0.20	0.05	0.04	0.11	0.27	0.02	0.02		
East Augusta	0.33	1	0.5	0.33	1	0	0	1	1	1	1	0.81	2
Ambergate NR	0.66	0	0.5	0.66	0.5	0.33	0.33	0.5	1	0	0.5	0.55	4
D'entre-casteaux NP 1	0.33	0	0	1	0.5	1	1	1	0	0	0.5	0.29	8
D'entre-casteaux NP 2	0.66	1	0	1	0.5	1	1	1	0	0	1	0.41	6
Frankland NP	0.66	0.66	1	1	0	0.66	0	0	0	0	1	0.30	7
Donnelley State Forest	1	1	1	0.66	0	0.33	0.33	1	0	1	0.5	0.48	5
Benger Swamp NR	1	0	0.5	1	1	1	1	1	1	1	0	0.87	1
Byrd Swamp NR	0.33	1	1	1	1	0.33	0.33	1	0.5	1	1	0.73	3

Table 8. Site rankings calculated using pairwise comparisons and expert opinion, with 1 as most suitable and 8 as least suitable. NP = National Park and NR = Nature Reserve

	Site Suitability Rankings	
	Pairwise comparisons	Expert opinion
East Augusta	2	2
Ambergate reserve	4	6
D'entrecasteaux NP 1	8	7
D'entrecasteaux NP 2	6	5
Frankland NP	7	8
Donnelley state forest	5	4
Benger Swamp NR	1	1
Byrd Swamp NR	3	3

4.4.2 Numerical criteria

As the Frankland National Park site did not contain any water, data on water temperature, food diversity and pH could not be collected. Hence, this site was omitted from the statistical analysis as it was incomparable to the other sites.

A DBRA of the distributional distances resulted in a significant p value ($p = 0.021$) which signifies there is a significant difference in site scores based on geographical location. Therefore, differences between the site rankings, in terms of the site scores, can partially be explained by the geographical location of the sites. Highly ranked sites were generally clustered together when arranged according to their geographical distribution (Figure 6) with the most highly ranked sites located above -34° latitude and below 116° longitude.

There were also strong correlations between some habitat criteria (Figure 7). There was a strong negative linear relationship between water temperature and vegetation cover ($r = -0.87$), while a positive linear relationship existed between food diversity and hydroperiod ($r = 0.67$) and food diversity and water pH ($r = 0.68$).

Regression analyses conducted between each of the numerical criteria and the site scores showed that water temperature, hydroperiod and water pH each had a p value of less than 0.05, indicating that these criteria have the most influence over the sites scores and rankings.

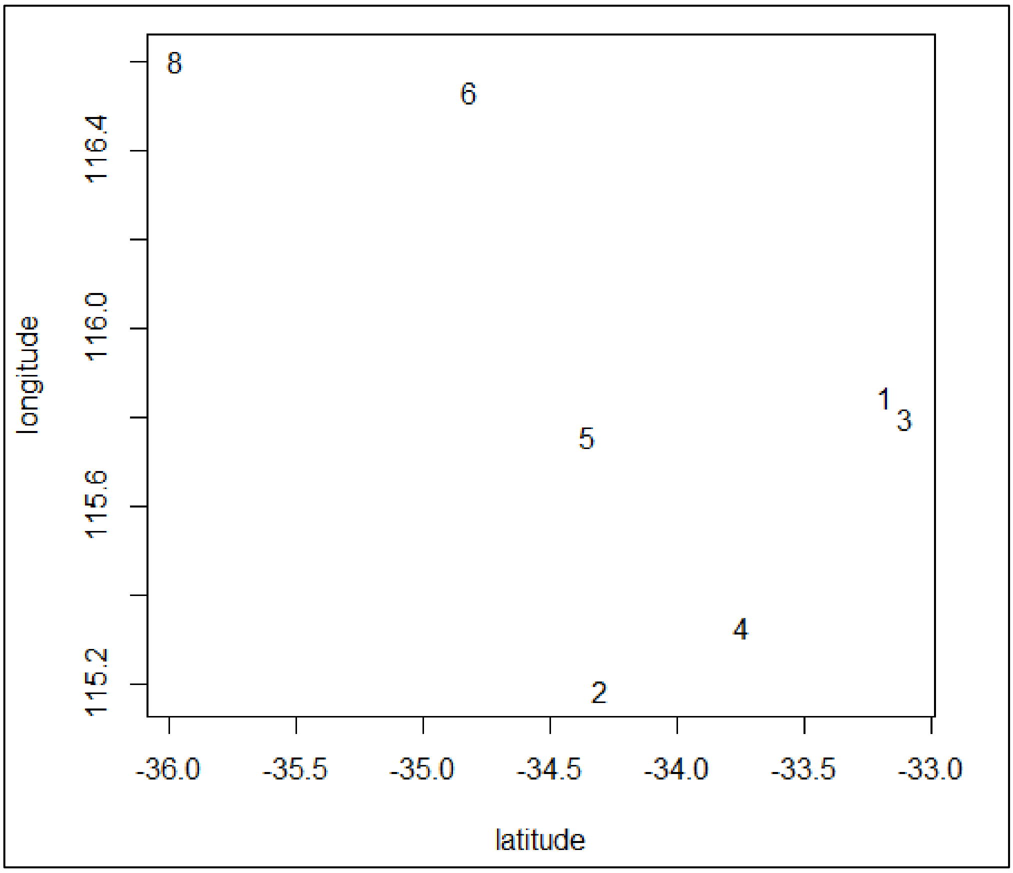

Figure 6. Geographical distribution of each of the sites in terms of their suitability ranking. 1 = Benger Swamp Nature Reserve, 2 = East Augusta, 3 = Byrd Swamp Nature Reserve, 4 =Ambergate Reserve, 5 = Donnelley State Forest, 6 =D'Entrecasteaux National Park 2, 8 = D'Entrecasteaux National Park 1. Frankland National Park (7) was omitted due to limited available data.

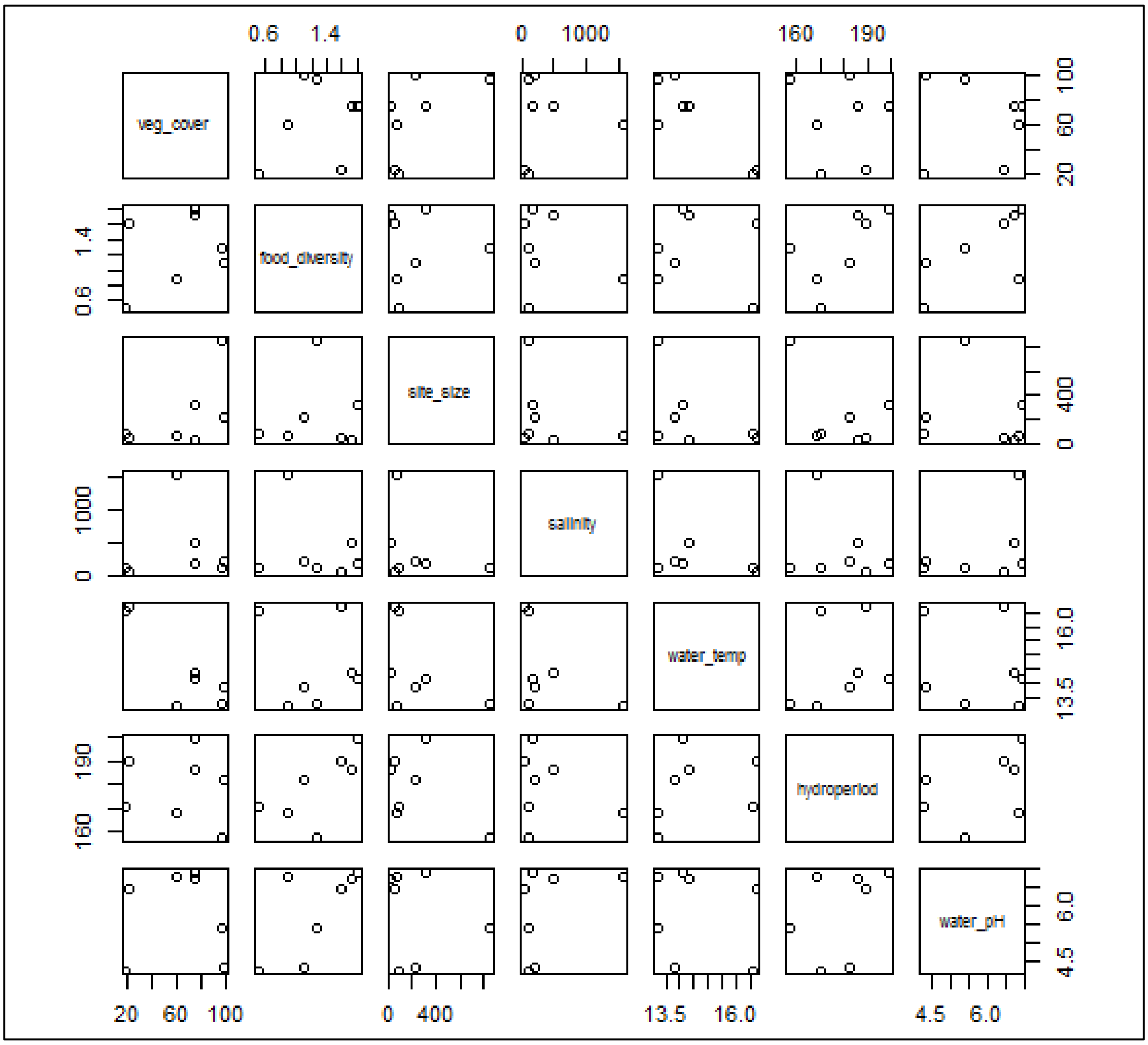

Figure 7. A correlation plot of the data of each numerical criterion. Each criterion is compared against all other criteria to determine if there is a linear relationship between any criteria. Data collected from the Frankland National Park site was omitted due to limited available data.

Chapter 5

5. Discussion

The suitability index and weighted summation methods used in this study suggest that geographical locations affect habitat criteria, and therefore site suitability. Rankings of sites using pairwise comparisons and expert opinion were very similar, suggesting that expert opinion is an accurate and effective method for calculating weights for an MCA for *P. umbrina*. Of the eight sites assessed and ground-truthed, Benger Swamp Nature Reserve, within the Swan Coastal Plain (Figure 3), was ranked as the most suitable site for assisted colonisation for *P. umbrina*. However, Benger Swamp Nature Reserve was visually very different to *P. umbrina*'s current habitat and unsuitable under some criteria that were not considered in this study, such as presence of predators. This suggests that further ground-truthing is needed to determine if the spatial MCA method is able to accurately identify suitable habitat. Alternatively, the rapid wetland assessment method used to collect data at each of the sites may have led to sites being incorrectly evaluated. As sites were only visited once, abnormal environmental conditions on the day that data was collected could strongly influence the final suitability scores calculated.

5.1 Location and suitability of potential assisted colonisation sites for *P. umbrina*.
The suitability index created using GIS revealed that the northern end of the Swan Coastal Plain will be unsuitable under a median future climate scenario projected for 2030. As the suitability index used in Dade *et al*. (2013) did not incorporate hydroperiods and did highlight this area as suitable, it demonstrates that this area is being identified as unsuitable under future climate scenarios due to the length of hydroperiods. The northern end of the Swan Coastal Plain is within the Gingin groundwater area and Gingin surface water basin (CSIRO, 2009). Previous climate change modelling within this area has found that under a median future climate, there will be a -30% change in the mean annual run-off and mean annual rainfall will decrease by 20-40% (CSIRO, 2009). These results agree with the findings of Bin Tareque (2013) that hydroperiods of wetlands in the north of the Swan Coastal Plain will be unsuitable under a median future climate scenario, further supporting the need for assisted colonisation.

The MCA and weighted summation analyses also show that habitat suitability is linked to geographical location. The sites with the highest suitability were located within the Swan Coastal Plain or along the western edge of the Augusta to Walpole area. This is most likely due to spatial relationships between environmental factors or the effects of factors operating primarily in geographic space (Elith & Leathwick, 2009). The habitat mapping performed in this study was formulated on the recommendations of Thomas (2011) and Hoegth-Guldberg *et al*. (2008), which were that assisted colonisation is carried out within areas within the same biogeographic region as a species current range, to ensure habitat and ecological processes are similar. Therefore the criteria were based on the wetlands present at the Ellen Brook and Twin Swamps Nature Reserves on the Swan Coastal Plain.

Soil is linked to vegetation and hydrology, influencing their conditions and characteristics within the landscape (Rodriguez-Iturbe, 2000). The Swan Coastal Plain and the western end of the Augusta to Walpole area are both within the same soil landscape zone of Swan (Schoknect *et al*., 2004) and soil types are similar across this area, including at *P. umbrina*'s current wetland sites. The eastern end of the Augusta to Walpole area, where the lowest ranked sites occurred, was within a different soil landscape zone and the wetlands within this area were very different to those at the current *P. umbrina* wetlands (Schoknecht *et al*., 2004). For example, the two sites located within the D'entrecasteaux National Park had denser vegetation, a higher occurrence of sedges and much colder water than sites on the Swan Coastal Plain or the western end of the Augusta to Walpole area.

The relationship between the criteria and wetland suitability was also seen in the regression analysis with the criteria having a strong influence on site suitability and rankings; in particular water temperature, hydroperiod and water pH. These hydrological criteria are therefore key to identifying a suitable assisted colonisation site for *P. umbrina* as decreasing hydroperiods at the current habitats are one of the major threats to *P. umbrina*'s survival (Mitchell *et al*., 2013). A review by Fischer & Lindenmayer (2000) concluded that the initial threat to the target species must be removed from the translocation site for the translocation to be successful. As water temperature, hydroperiod and water pH characterise the hydrological regime at an assisted colonisation site, these criteria give a strong indication of whether a site is suitable, optimising a successful assisted colonisation attempt. However, they cannot be considered alone as these criteria are linked to other criteria. For example, food diversity, hydroperiods and water pH were closely correlated (Figure 7). Similarly, a study of the macroinvertebrate community of the Three Gorges Reservoir along the Yangtze River in China, found that hydroperiod length had a significant effect on macroinvertebrate diversity (Zhang *et al*., 2010). Water pH also strongly influences macroinvertebrate community structure due to many macroinvertebrate species being highly sensitive to acidity levels (Burgmer *et al*., 2007; Kay *et al*., 2001).

As only eight sites were assessed, it is difficult to determine accurately whether there are any trends occurring between suitability, criteria and geographical location. The most critical parameter of a sampling design is sample size (Hirzel & Guisan, 2002) and it is therefore recommended that more wetland habitats are sampled to identify whether these patterns are occurring within a larger number of wetlands.

5.2 The differences between current *P. umbrina* wetlands and wetlands ranked highly suitable for assisted colonisation

Benger Swamp Nature Reserve was ranked as the most suitable of the eight sites assessed but had little resemblance to that of *P. umbrina*'s current habitat. For example, the majority of Benger Swamp contained sedges and shrubs growing within the water, rather than taller vegetation located predominantly away from the water as occurs at the Twin Swamps and Ellen Brook Nature Reserves. This presence of dense vegetation in the water would make it difficult for *P. umbrina* to move around. There were also a large variety of waterbirds present at Benger Swamp Nature Reserve. Waterbirds prey on *P. umbrina* (Burbidge *et al*., 2010) and would therefore increase *P. umbrina* mortality at an assisted colonisation site.

The Donnelley State Forest site, which most closely resembled *P. umbrina*'s current habitat, was ranked as fifth most suitable suggesting that site suitability cannot be based on the appearance of the habitat. Species are often able to establish successfully in novel habitats that do not resemble their natural habitat. For example, Chapman (2007) found that organisms living on intertidal boulder fields were able to colonize sandstone pavers and persist at approximately the same level of diversity and species richness as that of their natural habitat. Many Mediterranean pine woodlands have also been transformed extensively with new species establishing successfully within these ecosystems as climate change causes shifts in their ranges (Hobbs *et al*., 2006). Species have also successfully established in a variety of human modified environments, such as agroforestry landscapes (Hobbs *et al*., 2006).

It is also possible that the suitability calculated for the Donnelley State Forest and Benger Swamp Nature Reserve may have been influenced by the timing of the field visits. Field visits were conducted during a week of heavy and prolonged rainfall. This can temporarily change the conditions of a habitat. For example, a sudden influx of water can often temporarily reduce the pH of the water and can affect the macroinvertebrate community which is sensitive to hydrological changes (Gasith & Resh, 1999). This is a potentially the reason for the low pH and low food diversity measured at the Donnelley State Forest site, and if so could mean that this wetland is more suitable than was calculated in this study. Therefore to conclude which site can be regarded as the most suitable, ongoing data collection on a wider range of criteria, including the presence of waterbirds, should be conducted at each site at regular intervals to ensure that anomalies can be averaged out.

5.3 Errors and risks involved in using spatial data to map a species habitat under a changing climate

Using spatial data to map a species habitat can introduce errors that reduce the accuracy of the results. This occurred during this study where the spatially mapped suitability index identified a 'wetland' at the Frankland National Park site that contained no standing water when the site was visited.

Errors in spatial data are common in spatially explicit models (Tulloch *et al*., 2013; Barry & Elith, 2006) because spatial models are an attempt to summarize complex environmental patterns with a reduced set of predictor variables which can lead to a mismatch between predictions and actual environmental conditions (Barry & Elith, 2006). For example, errors in maps of coral reefs generated from remote sensing techniques are so common that 50-60% overall map accuracy is regarded as acceptable (Tulloch *et al*., 2013).

These spatial errors are often due to the process used to generate the data. The vegetation, soil and wetland spatial data used in this study were all collected using predominantly remote sensing methods, such as classifying aerial imagery (Hill *et al*., 1996b; V & C Semenuik Research Group, 1997; Beeston *et al*., 2002; Schoknecht *et al*., 2004). Although this has been found to be one of the most accurate methods for classifying land types it is possible for some areas to be incorrectly classified.

As only eight sites were ground-truthed in this study it is difficult to determine the degree of accuracy of spatial mapping used in this study. With a limited number of sites sampled or an incorrect sampling method, anomalies in the data become more significant (Congalton, 1991). Therefore to determine the accuracy of the spatially derived suitability index used in this study, a larger number of sites would need to be assessed via site visits.

The spatial data used may also be inaccurate in identifying suitable assisted colonisation sites as it portrays the hydroperiod under a future current climate projection of lower rainfall, but is otherwise based on present habitat conditions. Climate change can significantly influence the state of a habitat as it can cause changes in vegetation composition, distribution and abundance of species and ecological processes (Parmesan *et al*., 1999; Lenihan *et al*., 2008). A study into the effects of three climate change scenarios on various habitats in California found that even under a mild climate change scenario, the distribution of vegetation shifted significantly with a decline in alpine forest and increase in mixed evergreen forest (Lenihan *et al*., 2008). Fitzpatrick *et al*. (2008) found this was also the case in the SWBP with the range of 66 *Banksia* species declining under three different climate change scenarios (Fitzpatrick *et al*., 2008). Most climate change scenarios project an increase in wildfire frequency which can also alter the landscape (Lenihan *et al*., 2008). Therefore sites presented here as highly suitable may potentially look different and have a different level of suitability by 2030. As it is difficult to determine how a habitat will change under directional climate change, long term monitoring of any potential assisted colonisation sites should occur to gain a better understanding of the potential impacts of climate change on the habitat, and of the effects of such changes on the translocated species (Chauvenet *et al*., 2012).

5.4 Is the Pairwise comparisons approach better for calculating criteria weights than using expert opinion?

The results of this study show that the criterion weights calculated using expert opinion were similar to those calculated using pairwise comparisons. This suggests that expert opinion is an accurate method for identifying habitat criterion weights for *P. umbrina*. Expert opinion is often treated with caution as it can be biased and decrease the accuracy of the final results (Martin *et al*., 2012; Martin *et al*., 2005). However, with many environment management problems it is often the only source of information available (Martin *et al*., 2012).

P. umbrina has a very restricted range and consequently there is limited information on the habitat requirements of this species (A. Burbidge, pers.comm., 2013). Expert opinion is therefore an extremely important source of information and is likely to be one of the most accurate sources of information available. Martin *et al*. (2005) suggests that as long as the views of a large group of experts are used, the influence of bias can be reduced. However, though expert opinion was found to be a relatively good method for calculating criterion weights for *P. umbrina* habitat, the AHP method is more robust as it provides more certain criterion weights for a wider variety of species, regardless of the level of uncertainty (Ho, 2008)

5.5 The future for assisted colonisation: management implications and recommendations

The results of this study suggest that assisted colonisation of *P. umbrina* could be carried out on either the Swan Coastal Plain or the western edge of the Augusta to Walpole area. Translocations often rely heavily on public support for funding and hence translocations conducted with public support more likely to be successful (Parker, 2008). Therefore it is essential that selecting sites for assisted colonisation of *P. umbrina* includes strong communication and collaboration between community members, policy makers and conservation agencies to ensure it is implemented successfully.

As only the hydroperiod was assessed under a future climate projection, it is important that long-term monitoring is conducted at potential assisted colonisation sites to determine the impacts of climate change on other aspects of the hydrological regime, such as water temperature, and other habitat criteria, such as vegetation and food diversity. More sites should be ground-truthed to determine if there are more suitable sites than those already identified. Moreover, a larger sample size will help to better determine if the spatial data used in this particular MCA is accurate, giving a stronger indication as to whether the geographic patterns found in habitat suitability and the relationships between criteria are retained.

The results of this study suggest that if assisted colonisation is to be implemented for a species, decision-makers should focus on areas close to the current range of the species or within a region with similar environmental characteristics, to increase the likelihood of the species surviving and ensuring an optimal outcome.

A MCA is an ideal process to identify these suitable sites for assisted colonisation, and if a spatially explicit method is used then it is important that ground-truthing is conducted on a subset of sites and that errors in data are considered and accounted for. To calculate the criterion weights, the AHP method is the most suitable for an assisted colonisation scenario for most species. However, the expert opinion method is ideal for species that have a restricted range or limited available knowledge, such as applies to *P. umbrina* as expert opinion is often the best source of information for these species. It is also recommended that criteria used in the MCA are modelled under future projected climates to determine the stability of a site over time.

This study shows that by using a spatially explicit decision-making process that accounts for all aspects of the target species habitat, assisted colonisation will be performed under reduced risk and uncertainty. A MCA that takes into account changes in criteria under climate change is therefore an ideal method as it provides a robust and in-depth decision-making process, reducing uncertainty and also costs related to identifying a suitable translocation site.

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Mapping a new future: using spatial multiple criteria analysis to identify novel habitats for endangered species

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Short title: Multiple criteria analysis to guide assisted colonisation

Abstract

Species with restricted ranges or poor dispersal ability may suffer under climate change, and the practice of translocating populations to sites outside the known historical range (assisted colonisation) has been advanced as a solution to reduce the risk of extinction in the wild. Due to the high-risk and bureaucratic complexities of assisted colonisation, it is imperative that a systematic process is used to select release sites that have a reduced likelihood of translocation failure. Here we demonstrate how a spatially explicit, three-stage multiple criteria analysis (MCA) can be used to identify potentially suitable sites for assisted colonisation of an endangered species. We employ this method as an initial screening process, prior to final selection of sites for assisted colonisation of the Critically Endangered Western Swamp Tortoise (*Pseudemydura umbrina*). This species occurs naturally in two small reserves in southwestern Australia, and is currently threatened by a shift to a drier climate and consequent changes to hydrological regimes. A literature review, characteristics of remnant *P. umbrina* habitat, and expert knowledge were used to create a composite index of habitat suitability, mapped across the entire south west bioregion of Australia. The most suitable sites were 150 to 250 km south of the known range of *P. umbrina*, in areas of high landscape connectivity and low human population density. A subset of sites were examined in further detail and ranked using weighted summation. Careful use of MCA, taking into account data uncertainties and differences in expert opinion, can be a valuable tool when evaluating novel habitats for threatened species.

Keywords

multiple criteria analysis, assisted colonisation, translocation, tortoise, *Pseudemydura umbrina*, southwestern Australia

Introduction

The distributions of many species are changing as an adaptive response to altered local and regional climates (Hoegh-Guldberg *et al.*, 2008, Moreno-Rueda *et al.*, 2012, Parmesan *et al.*, 1999, Seddon, 2010). Species that are unable to change their distribution because they are poor dispersers are especially disadvantaged by changing climatic conditions. In such instances, assisted colonisation - the translocation for conservation purposes of a species outside of its known historical range – has been proposed as a means of reducing extinction risk (Hoegh-Guldberg *et al.*, 2008, IUCN/SSC, 2013). Assisted colonisation is controversial, largely due to the risks inherent with introductions of species to novel habitats (Burbidge *et al.*, 2011, Ricciardi & Simberloff, 2009, Seddon, 2010), but has been used successfully as a conservation tool in New Zealand, where threatened birds and reptiles have been translocated to offshore islands to avoid predation by introduced mammals (Clout & Craig, 1995, Thomas, 2011). To date, assisted colonisation has not been widely used as a method to reduce the risk of extinction due to climate change, but is increasingly being considered as a more assertive approach to conservation (Burbidge *et al.*, 2011, Seddon, 2010, Willis *et al.* 2009).

Many past attempts at assisted colonisation were conducted under crisis conditions, and little information has subsequently been available on the reasons behind successful or failed attempts (Towns & Ferreira, 2001). Previous translocations of herpetofauna have shown that without suitable high quality habitat, translocations have a low chance of success (Germano & Bishop, 2009). To ensure that a potential translocation site can support a particular species, habitat evaluation should include characteristics that allow for the survival of the target species, as well as ensuring that the translocation site can maintain ecological integrity (Griffith *et al.*, 1989). Identification of suitable habitat requires understanding of a species' fundamental niche and consideration of management, logistical and socio-economic factors that could influence the likelihood of success (Burbidge *et al.*, 2011, Heaton *et al.*, 2008, Knight *et al.*, 2011, Thomas, 2011). Given the potential risks associated with any species translocation, and particularly with assisted colonisation, systematic and transparent methods for prioritising release sites need to be developed.

Despite habitat evaluation being critical to translocation success, a systematic process for site selection is rarely performed when planning species translocations. Evaluating the suitability of potential habitat involves assessing a range of diverse biophysical and management criteria, which are often expressed in different units of measurement. This can distort assessments, leading to inaccuracy in habitat evaluation and reduce the chance of a successful translocation (Lahdelma, Salminem & Hakkanen, 2000). Multiple criteria analysis (MCA) is a process that provides structured, transparent ranking of decision options, against multiple criteria measured in various units (Hajkowicz, 2008). When applied in the context of site selection, suitable regions can first be identified with geographic information systems (GIS), and alternative sites then assessed using the straightforward and transparent method of weighted summation (Hajkowicz, 2008).

Identifying alternative suitable translocation sites is essentially a spatial prioritisation problem (Knight *et al.*, 2011). A common approach to identification of sites based on multiple spatial criteria involves using GIS to create composite maps with different layers of environmental information for each criterion to be considered (Clifton &

Boruff, 2010, Dermol & Kontić, 2011). Indicators for each criterion are developed, scored and combined to create an overall composite index of site suitability (Graymore, Wallis & Richards, 2009). This approach has been used to identify suitable areas for translocation for species within their current range. For example, Heaton *et al.* (2008) used a spatially explicit MCA model to identify areas for the translocation of the Mojave Desert Tortoise (*Gopherus agassizii*) in California, USA, and a similar method was used by (Smith *et al.*, 2007) to identify habitat for the Julia Creek Dunnart (*Sminthopsis douglasi*) in Northern Australia. Despite its obvious applications in assisted colonisation, spatially-explicit MCA has not previously been used to identify suitable habitat outside of a species' current or historical range.

Here we demonstrate how wetlands that are potentially suitable for the assisted colonisation of a threatened species can be identified using a systematic and transparent MCA approach, combined with expert knowledge. Our example species is the Western Swamp Tortoise (*Pseudemydura umbrina*) – a Critically Endangered reptile from southwestern Australia for which assisted colonisation is planned for the near future (Mitchell *et al.*, 2013). Little is known about the distribution of *P. umbrina* prior to European settlement; for example it is unknown whether current habitats represent a portion or the whole of their fundamental niche. Anecdotal evidence suggest that *P. umbrina* may be a reasonably adaptable species, as captive-bred individuals use artificial aestivation refuges, nest in sand next to holding ponds and eat food that is not part of the diet of wild individuals (S. Arnall, pers. comm. 2012). Hence attempts to replicate the exact habitats found at existing sites may be unnecessarily restrictive when planning assisted colonisation, but factors important to long-term survival of *P. umbrina* and to maintenance of the ecological integrity of the release site should both be considered. Using GIS methodologies, we combine quantitative and qualitative data in a spatially-explicit MCA to produce a mechanism for identifying suitable new habitats for endangered species.

Material and methods

Case study

Reptiles are particularly vulnerable to climate change as many of their physiological processes are dependent on ambient temperature (Huey *et al.*, 2012, Moreno-Rueda *et al.*, 2012). A recent assessment indicated that 19% of the world's reptiles are threatened with extinction, including about 50% of assessed species of tortoises and turtles (Böhm *et al.*, 2013). The Western Swamp Tortoise (*Pseudemydura umbrina*) is Critically Endangered (Burbidge *et al.*, 2010, IUCN, 2012) due to extensive land clearing and a naturally restricted range. This species now occurs in only four wetlands in southwestern Australia; the Ellen Brook and Twin Swamps Nature Reserves, where this species naturally occurs, and the Moore River and Mogumber Nature Reserves, where captive bred individuals have been released (Fig. 1).

Due to long-term declines in rainfall and reduced groundwater recharge, the time during which the wetlands hold water (the hydroperiod) is decreasing in length (Mitchell *et al.*, 2013, Mitchell, Jones & Kuchling, 2012). *Psuedemydura umbrina* feeds and breeds in water, and the viability of wild populations depend on the continuity of suitable hydroperiods. Additionally, the fragmented nature of the current habitat prevents individual *P. umbrina* from seeking out more suitable areas (Burbidge *et al.*, 2010, Mitchell *et al.*, 2013). As the current habitat is unlikely to sustain the species in the wild over the long term, assisted colonisation is being planned for this species (Burbidge *et* *al.*, 2010, Mitchell *et al.*, 2013). Mapping of the thermodynamic niche of *P. umbrina*, under current climates and projected climates for 2030, has recently been completed (Mitchell *et al.*, 2013), and indicates that translocations sites well south of the current range are likely to provide the most climatically suitable habitat in the future.

Study area

The study area encompassed the South West Botanical Province (SWBP) in the southwest of Western Australia (Beard, 1980). The SWBP falls within one of the world's 34 biodiversity 'hotspots', where regions of high endemism are experiencing high rates of habitat loss (Myers *et al.*, 2000). Most of the 7000 plants described from the hotspot (Hopper & Gioia, 2004) have evolved on nutrient-poor, highly-weathered soils and are dominated by sclerophyllous species forming associations including forests, woodlands, mallee and kwongan (heath). The majority of the SWBP is characterised by Mediterranean climates (Köppen classifications Csa and Csb) with warm to hot summers and mild, moist winters (Kottek *et al.*, 2006, Peel, Finlayson & McMahon, 2007).

The SWBP comprises seven bioregions according to the Interim Biogeographic Regionalisation for Australia (IBRA) (DSEWPaC, 2012), covering approximately 298 577 km^2 (Fig. 1). The extant populations of *P. umbrina* are found within the Swan Coastal Plain IBRA bioregion, at the western edge of the SWBP. There are a diverse range of wetlands throughout the SWBP; typologies have been developed to differentiate wetlands according to geomorphic form, hydroperiod, degree of inundation, vegetation type and conservation status (Government of Western Australia, 1997, Semeniuk, 1988, Semeniuk & Semeniuk, 1995, Semeniuk *et al.*, 1990). Detailed mapping of wetlands has only been undertaken in some parts of the SWBP. The initial stages of this study assessed the entire SWBP for habitat suitability for *P. umbrina*, while the final stage focused on two areas where detailed, higher precision wetland mapping was available. These areas were the Swan Coastal Plain (Davis, Townley & Balla, 1996; Hill *et al.* 1996), and the area between the towns of Augusta and Walpole (V&C Semeniuk Research Group, 1997).

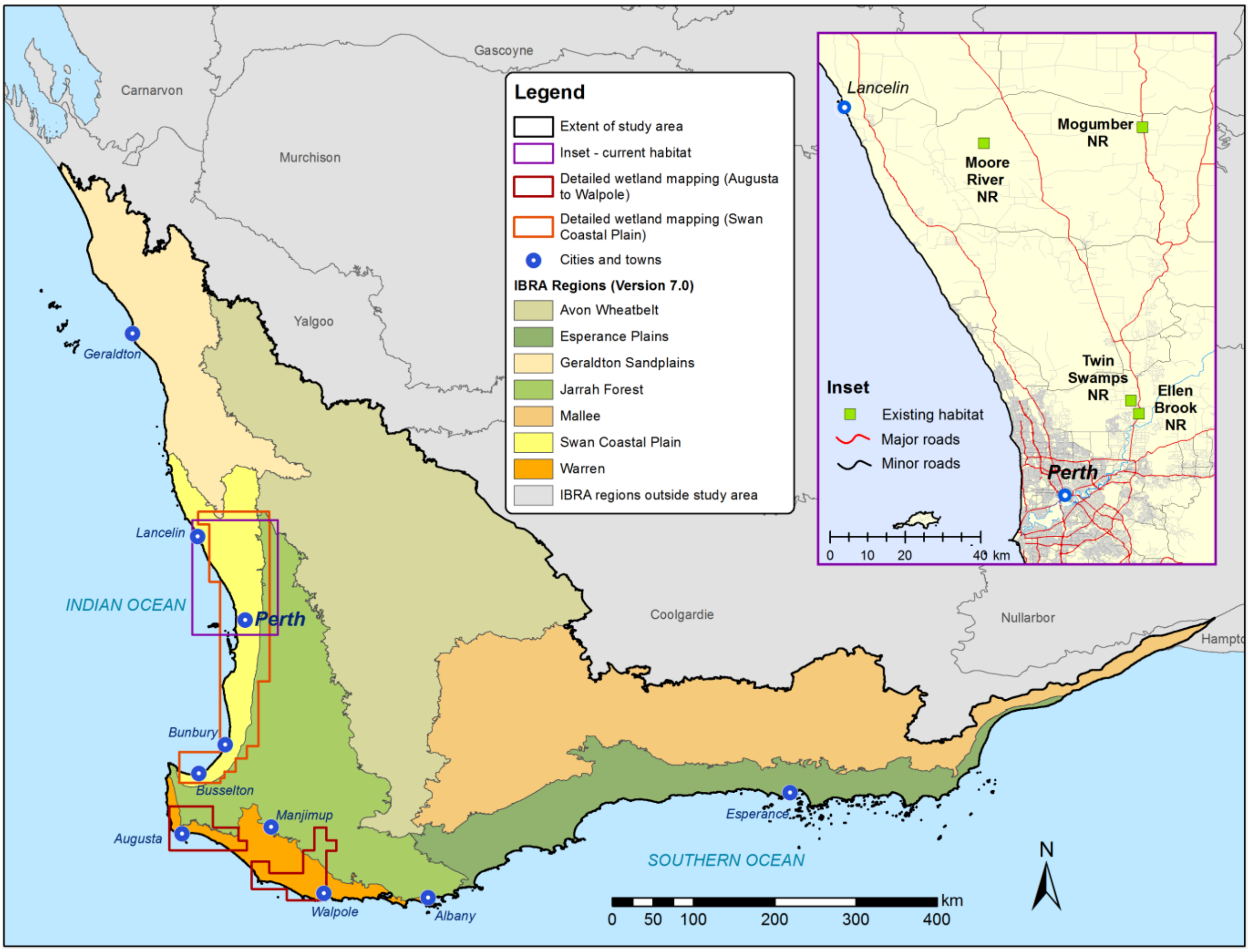

Figure 1 Study area indicating the IBRA boundaries for the South West Botanical Province, together with the extent of detailed wetland mapping available in this region and current habitat for *Pseudemydura umbrina*.

Development of a spatially-explicit MCA model

This research combined spatial analytical tools with multiple criteria analysis (MCA) methods to create a spatially-explicit MCA approach for identifying and ranking potential sites for the assisted colonisation of *P. umbrina*. The development of the spatially-explicit MCA model comprised three stages: 1) identification of habitat criteria and assessment of data availability using a hierarchical decision problem approach; 2) mapping of all potentially suitable habitat in the SWBP and creation of a composite index to determine the degree of suitability; and 3) weighted summation, ranking and sensitivity analysis of a sample of the most suitable sites identified in stage 2 in two high-priority regions: the Swan Coastal Plain and the Scott Coastal Plain. The methods for each stage are described below.

Identification of habitat components, indicators and data availability

To aid in identification and assessment of model criteria, the decision problem was mapped out as a conceptual model using a hierarchical structure (Fig. 2), following the example of Kontos, Komilis & Halvadakis (2005). The first level represents our overall objective to identify suitable translocation sites for *P. umbrina*. The second level represents habitat components that would contribute to the suitability of the host site, either in terms of biophysical characteristics or reduced risk of threatening processes. The third level details attributes of each habitat component that could be used to quantify habitat suitability, based on existing spatial and non-spatial data.

The habitat components and indicators used in the MCA model were identified through a review of relevant literature, observations from a site visit in May 2012 to Ellen Brook Nature Reserve, and through consultation with four experts on the species.

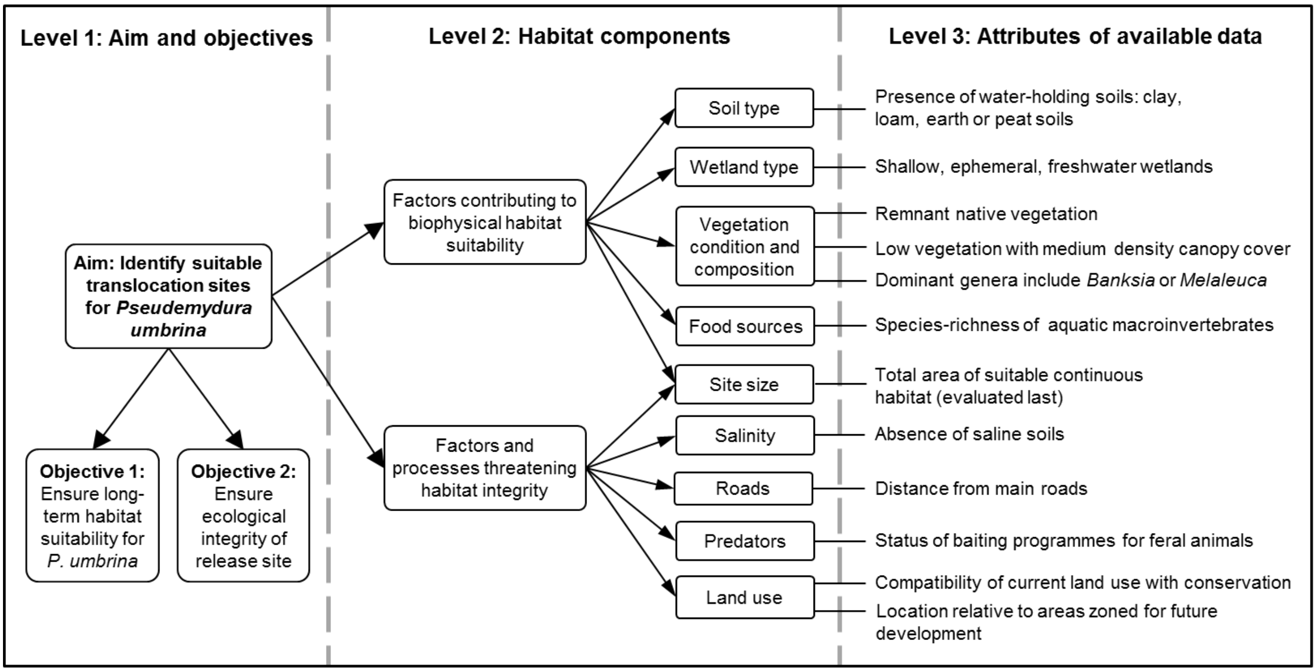

Figure 2 Hierarchical structure of the decision problem for evaluating site suitability of potential translocation sites for *Pseudemydura umbrina.*

Expert consultations were based loosely on the expert elicitation structure described in (Martin *et al.*, 2012). A semi-structured interview was conducted with all individuals to identify the habitat components regarded as important and potential indicators. At a later date, a final list of habitat components was provided to each expert, who was asked to rank the components based on their opinion of how critical each would be to successful translocation of *P. umbrina* to a novel site. The habitat components included soil type, wetland type, vegetation structure and composition, presence of native vegetation, wetland salinity, presence of roads, size of the site, food availability, current land use, land use change, and presence of feral predators (Table 1). As comprehensive spatial data were only available for some of the habitat components, they were divided into two groups: 1) those components that were mapped and used to create a suitability mask and composite index of habitat suitability; and 2) those components that were researched after mapping, using a literature review and online databases, to further assess their suitability (Table 2).

Table 1 Assessed habitat components and their importance to future assisted colonisation of *Pseudemydura umbrina*

Habitat component[a]	Rationale for inclusion
Soil type	*P. umbrina* aestivates underground over summer, requiring water-holding soils. Current habitat occurs on the Gilgai clay complex, or on sandy duplex soils (Burbidge *et al.*, 2010, Schoknecht, 2002). Peat soils may be suitable, due to high water-holding capacity (A. Burbidge, pers. comm., 2012).
Wetland type	The biology of *P. umbrina* is directly linked to wetland hydrological characteristics (Burbidge *et al.*, 2010). *P. umbrina* inhabits freshwater wetlands with a hydroperiod of around seven months, with shallow (< 80 cm) water depth to meet feeding, breeding and temperature requirements (Burbidge, 1981).
Presence of native vegetation	Many wetlands in the South West Botanical Province (SWBP) of Western Australia have been cleared or suffered severe degradation (Davis & Froend, 1999). Intact native vegetation can be used as an indicator of disturbance and potential habitat suitability.
Vegetation structure and composition	*P. umbrina* requires medium density vegetation for aestivation and protection from predators, but will avoid very dense vegetation. Vegetation canopy height must be low enough to prevent excessive shading and reduction in water temperature (A. Burbidge, G. Kuchling, S. Arnall, D. Bradshaw, pers. comm., 2012). Current habitat is characterised by *Banksia* woodland and *Melaleuca* shrubland (G. Kuchling, pers. comm., 2012).
Current land use	Land use is an indicator of disturbance and ease of future management. Urban and industrial areas exert pressure due to dogs, cats and human activity (G. Kuchling, pers. comm., 2012). Agricultural areas can include suitable habitat but have high initial and ongoing costs for land purchase and rehabilitation (A. Burbidge, G. Kuchling, S. Arnall, D. Bradshaw, pers. comm., 2012). Crown land is the most compatible, secure and least costly land use type.

Habitat component[a]	Rationale for inclusion
Land use change	Translocating a species to areas within projected development zones is not a viable long-term strategy if habitat is later developed (Heaton *et al.*, 2008). Note that in special circumstances it is possible for the state Government to purchase and set-aside land for conservation purposes within projected development zones.
Food availability	*P. umbrina* requires abundant, diverse prey in spring and summer. Prey includes aquatic invertebrates, including crustaceans and insect larvae, as well as tadpoles (Burbidge *et al.*, 2010, Gilbert, 2010). Captive-bred individuals can adapt to dietary change (A. Burbidge, G. Kuchling, S. Arnall, D. Bradshaw, pers. comm., 2012).
Site size	Existing reserves for *P. umbrina* are 80 ha and 141 ha (Burbidge *et al.*, 2010). Individuals have been recorded moving outside reserve boundaries, suggesting that larger sites of at least 200 ha are required (G. Kuchling, pers. comm., 2012).
Distance from main roads	Individuals have been killed on roads near existing reserves, regardless of fencing (A. Burbidge, G. Kuchling, S. Arnall, D. Bradshaw, pers. comm., 2012).
Predators	Predators include foxes, cats, pigs, raptors, rats, waterbirds, bandicoots (Burbidge *et al.*, 2010). Baiting for feral animals has reduced deaths through predation (A. Burbidge, G. Kuchling, S. Arnall, D. Bradshaw, pers. comm., 2012).
Salinity	Secondary salinisation threatens the ecological integrity of freshwater wetlands in the SWBP (Burbidge *et al.*, 2010, Wallace *et al.*, 2011)

[a] Habitat components assessed in this study were limited to those for which reliable and/or detailed data were available for either the whole study area, or a significant component of the study area.

Table 2. Criteria and data sources used to define habitat suitability across the study area for *Pseudemydura umbrina*

Habitat component	Criteria type [a]	Data sources	Constraint criteria: Prerequisites for site suitability [b]	Factor criteria: Scores for determining relative suitability of areas satisfying all prerequisites [c]
Habitat components with data in GIS format (used to create composite suitability index)				
Soil type	Both	• Soil-landscape maps at systems level (Schoknecht, 2002)	Presence of wet or waterlogged soil types within soil-landscape unit [d].	• 1 = Soil-landscape unit contains sandy duplex soil types • 0.5 = Soil-landscape unit contains loamy duplexes, clay, sandy or loamy earths, but not sandy duplex soil types
Wetlands	Constraint	Geomorphic wetlands Swan Coastal Plain (Hill *et al*.,1996), Augusta to Walpole (V&C Semeniuk Research Group, 1997) and statewide (GA, 2003.)	Area lies within a mapped dampland, sumpland, palusplain or floodplain wetland type	N/A
Native vegetation	Constraint	• Native vegetation extent dataset (Beeston, Hopkins & Shepherd, 2002)	Native vegetation present	N/A
Vegetation structure and composition	Both	• State Pre-European type vegetation dataset (Beeston *et al.*, 2002)	Area contains vegetation with suitable structure: woodland, shrubland, heathland, sedgeland or grassland	• 1 = Vegetation composition dominated by *Banksia* or *Melaleuca* • 0.66 = Vegetation structure is shrubland, sedgeland or heath dominated by species other than *Banksia* and *Melaleuca* • 0.33 = Vegetation structure is woodland
Current land use	Both	• Land use by Shire dataset (Beeston *et al.*, 2002)	Land use of the area is *not* urban or rural residential, mining, Indigenous uses, manufacturing, industrial, services, transport,	• 1 = Area is designated for conservation • 0.66 = Area designated for natural feature protection, habitat management or natural resource management

Habitat component	Criteria type [a]	Data sources	Constraint criteria: Prerequisites for site suitability [b]	Factor criteria: Scores for determining relative suitability of areas satisfying all prerequisites [c]
			communication, airports, or ports	• 0.33 = Area designated for groundwater or minimum intervention
Distance from main roads	Factor	• Geodata Topographic 1:250 000 dataset (GA, 2006)	N/A	• 1 = >5 km from main roads • 0.5 = 2 to 5 km from main roads
Site size[e]	Factor	• Analysis completed within ArcGIS	N/A	• 1 = site >200 ha [e] • 0.5 = site 50 to 200 ha [e]
Salinity	Both	• Soil-landscape maps at systems level (Schoknecht, 2002)	Soil-landscape unit contains >10% by area of saline soil types.	• 1 = Soil-landscape unit contains <3% by area of saline soil types • 0.5 = Soil-landscape unit contains 3 to 10% of saline soil types
Habitat components without data in GIS format (researched after GIS analysis)				
Land use change[e]	Factor	• Local Town Planning Scheme maps (WAPC, 2011)	N/A	• 1 = Area not within proposed development area [e]
Food availability[e]	Factor	• DEC WetlandBase (DEC, 2012b, Halse *et al.*, 2002, Lane *et al.*, 2010, Storey, 1998)	N/A	• 1 = 10 or more macroinvertebrate species present including 10 or more species recorded as part of *P. umbrina* diet [e] • 0.5 = 10 or more macroinvertebrate species present, but without 10 or more species previously recorded in *P. umbrina* diet [e]
Predators[e]	Factor	• Fox and cat baiting location maps (Western Shield, 2011)	N/A	• 1 = Baiting undertaken for foxes and cats [e]

[a] Criteria for each of the habitat components were classified as 'constraint' (denoting criteria that were regarded as prerequisites for site suitability, and which were used to exclude all unsuitable areas), 'factor' (denoting criteria for which a range of habitat attributes were considered suitable, with some attributes more suitable than others) or 'both' (in these cases some habitat attributes were considered constraints, and others as factors).

[b] During the first stage of spatial analysis, areas that did not satisfy all of the constraint criteria were deemed unsuitable and excluded from further analysis.

[c] For each habitat component, areas that did not satisfy any of the factor criteria received a score of zero for that component.

[d] Each soil landscape unit mapped by (Schoknecht, 2002) represents a mosaic of two or more soil types. The approximate composition of the mosaic is given as percentages for each soil type.

[e] Comprehensive spatial data on land use changes, food availability and baiting for predators were not available for the whole study area. These factor criteria were scored and assessed only for a small selection of wetlands identified as having the highest potential site suitability, which were assessed in the final stage of weighted summation. Similarly, site size was calculated only for the final selection of wetlands included in weighted summation.

Development of a composite index to map habitat suitability

Indicators were developed for each habitat component that could be mapped using GIS (Table 2). The resultant habitat indicators were classified as either ‘constraint’ or ‘factor’ criteria. Constraint criteria were considered necessary to site suitability and were regarded as Boolean criteria, so that potential sites that met the requirements for a particular criterion were given a value of 1, and sites that did not meet the criterion were scored as 0 (Eastman *et al.*, 1995). Factor criteria define some degree of suitability for all areas, giving an area a value ranging between 0 and 1.

The constraint criteria were used to create a suitability mask in ArcGIS 10.1 (ESRI, 2012), following a similar approach to that outlined by (Clifton & Boruff, 2010). Spatial data for each of the six constraint criteria (presence of native vegetation, vegetation structure and composition, soil type, salinity, wetland type, and current land use) were converted into a raster grid with a 30 × 30 m cell size. For each criterion, raster cells were given a value of either 1 (suitable) or 0 (unsuitable). Raster grids for all six constraint criteria were combined using cell statistics in ArcGIS 10.1. The output raster grid was reclassified so that cells with a value of 1 for all six criteria were given a value of 1 and all other cells were given a value of 0. The output grid was used as a suitability mask for the identification of potentially suitable habitat in the SWBP and raster cells that did not return a positive value for all six constraint criteria were eliminated from further consideration.

A composite suitability index was created to show the degree of site suitability for all raster cells not eliminated from the study, using the five factor criteria for which spatial data were available (vegetation structure and composition, soil type, salinity, current land use, and distance from main roads). Comprehensive spatial data were not available for food availability, land use change or predators, and site size was assessed at a later stage (see below). For each of the five factor criteria a raster grid was created with a 30 × 30 m cell size. Each raster cell was assigned a value between 0 and 1, with 0 being least suitable and 1 being most suitable, according to the suitability of the habitat criteria mapped for that cell (see Table 2 for further details of scoring). The five raster grids were combined using cell statistics to create a composite index of site suitability across the masked area within the SWBP, with the highest scoring cells receiving a score of 5 out of a possible 5.

Weighted summation, ranking and sensitivity analysis

The final stage was to assess and rank a selection of the most suitable translocation sites identified through the spatially-explicit GIS model. As 15-30 captive-bred *P. umbrina* individuals are available for release each year (Burbidge *et al.*, 2010), only a small number of sites could ultimately be used for assisted colonisation. In addition, detailed wetland mapping and information on potential food sources for *P. umbrina* was only available for a subset of regions within the SWBP. For these reasons, only wetlands that received the highest possible composite suitability index score, that were located within the boundaries of detailed wetland maps, and that were known to contain suitable food sources for *P. umbrina* (Halse, Scanlon & Cocking, 2002, Lane, Clarke & Winchcombe, 2010, Storey, 1998) were considered for further assessment and ranking.

All nine factor criteria (Table 2) were incorporated into the combined ranking of suitable wetland sites and were weighted according to expert opinion. First, the most suitable wetlands identified through mapping were scored between 0 and 1 for each of the nine criteria in the analysis, with a score of 1 indicating maximum suitability.

Second, the rankings of the nine factor criteria drawn from the four experts were converted into weights using the naïve method of Hajkowicz, McDonald & Smith (2000). Finally, the criteria scores and criteria weights derived from expert rankings were converted into a single score for each site using weighted summation (Heaton *et al.* 2008):

$$u_i = \sum_{j=1}^{m} x_{i,j} \, w_j,$$

with the following constraints:

$$\sum_{j=1}^{m} w_j = 1,$$

$$0 \le w_j \le 1$$

where the overall site score (u_i) equals the sum of all criteria weights (w_j) multiplied by their respective criteria score ($x_{i,j}$), provided that the sum of all weights equals 1 and each weight has a value between 0 and 1.

A sensitivity analysis was conducted to assess the robustness of the criteria weights and the degree of uncertainty in the site scores. Graymore *et al.* (2009) suggest sensitivity analyses for MCA should assess small changes in the weights. In this study, criteria weights were changed, one at a time, by 10% to test whether site rankings were altered. Any change in ranking would suggest a level of uncertainty in the value of the weights (Graymore *et al.*, 2009). The final site scores were used to identify the most suitable wetlands for assisted colonisation of *P. umbrina*, based on the habitat components assessed.

Results

Spatial representation of composite habitat suitability index

Applying the suitability mask and composite habitat index across the SWBP using low-precision wetland data indicated that the greatest concentrations of potentially suitable habitats were located on the Swan Coastal Plain and the south coast of southwestern Australia. For this reason, only detailed maps based on high-precision wetland mapping from the Swan Coastal Plain (Davis *et al.*, 1996) and the Augusta to Walpole region, encompassing much of the south coast (V&C Semeniuk Research Group, 1997) are presented here.

On the Swan Coastal Plain 25 808 ha of potentially suitable habitats were mapped, consisting of 15,682 discrete locations (Fig. 3). Mapping the composite index for the Augusta to Walpole region highlighted 39,727 ha of potentially suitable sites, comprising 6,424 discrete sites (Fig. 4). Wetlands with the maximum composite habitat suitability index of 5 included 2906 discrete sites on the Swan Coastal Plain, 1166 discrete sites in the Augusta to Walpole region, and 689 additional sites outside the boundary of the two areas with detailed wetland mapping, but within the SWBP study area. Three of the four current locations at which *P. umbrina* is found were rated as 5 out of 5 for habitat suitability, while one site scored 4 due to its proximity to a major road (Fig. 3). Many of the most suitable sites identified on the Swan Coastal Plain were small and highly fragmented, with an average size of 1.76 ha compared with 17.01 ha for the most suitable sites in the Augusta to Walpole region.

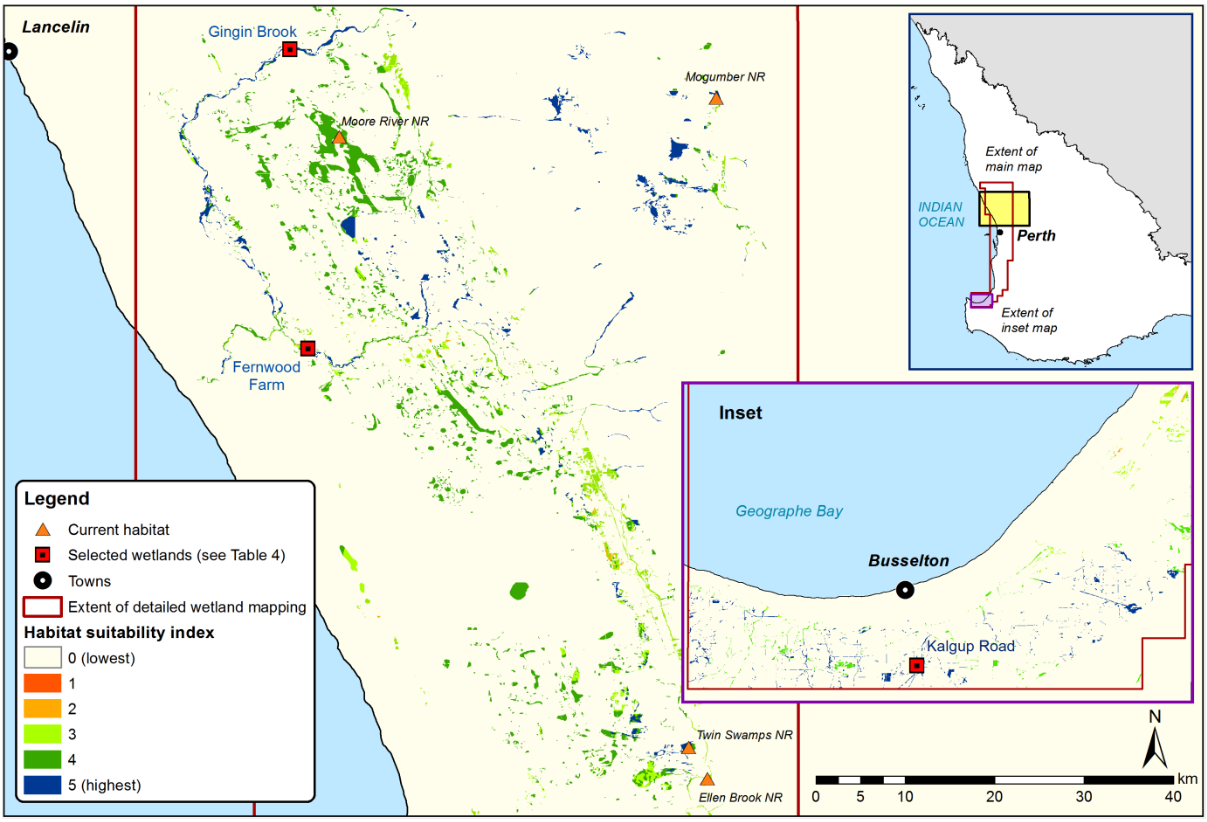

Figure 3 Index of habitat suitability applied to wetlands on the Swan Coastal Plain.

Twelve wetlands with the highest suitability scores and that did not already contain populations of *P. umbrina* were selected for the third stage of the analysis (sites shown on Fig 3. and Fig. 4). These sites were selected based on the total continuous wetland area, and on the availability of data on food resources, feral predators and projected land use change. One site (Owingup Swamp) was outside the boundaries of our detailed wetland mapping but was included because it appeared highly suitable and food, predator and land use data were available.

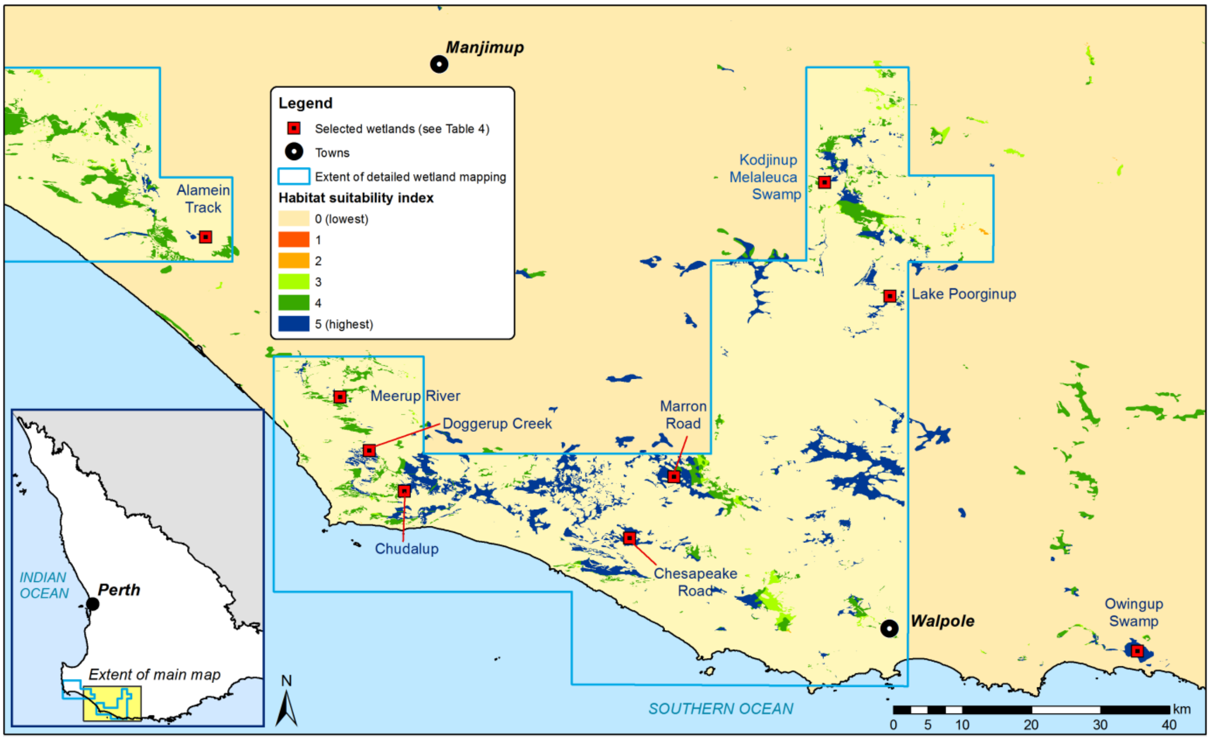

Figure 4 Index of habitat suitability applied to wetlands between Augusta and Walpole.

Criteria weighting, weighted summation and sensitivity analysis

There was appreciable variation in the criteria rankings performed by the *P. umbrina* experts and in the average weight attributed to each criterion (Table 3.) For example, 'distance from main roads' was ranked highest by one expert, but lowest by another. When weightings were averaged across the four experts, 'food availability' was regarded as most important and 'distance to main roads' as least important. There was only a slight difference (5.9%) between the weights of the highest and lowest priority criteria, which made it difficult to identify any particular criterion as most important (Table 3). However, 'land use change', 'soil type' and 'distance from main roads' had the highest variation in weights across the four experts, indicating disagreement on their relative importance.

Table 3 Rankings and weights attributed to habitat components by four experts

Expert number	Rankings attributed to habitat components assessed[a]								
	Soil type	Vegetation composition	Current land use	Land use change	Food availability	Site size	Distance to main roads	Predators	Salinity
1	9	8	4	3	7	6	1	2	5
2	2	4	6	7	1	8	9	5	3
3	2	4	9	1	3	5	8	6	7
4	4	5	6	6	1	6	9	1	1
Average criteria weight [b]	0.126	0.105	0.085	0.129	0.141	0.084	0.082	0.118	0.118

[a] Four experts independently ranked defined habitat components and associated criteria in their perceived order of importance to the survival of *P. umbrina* at a release site. The most important factor(s) received a ranking of 1, and the least important a ranking of 9.

[b] Average criteria weights calculated based on the naïve method outlined in Hajkowicz (2000).

The final suitability scores for the final 12 sites, based on nine factor criteria and calculated using the weighted summation method are shown in Table 4. The Chesapeake Road wetland was ranked as the most suitable translocation site based on the criteria assessed in this study. The three sites on the Swan Coastal Plain (Kalgup Road, Fernwood Farm and Gingin Brook) had the lowest rankings of the 12 selected 'highly suitable' sites. The sensitivity analysis performed on the criteria weights showed that changing the criteria weights by ±10% led to minimal changes in the order of site rankings. A change in the weight of the 'vegetation composition' criterion did result in a difference in the ranked order of sites, as two sites (Alamein Track and Doggerup Creek) switched order. However, as this was the only change in ranking, there was generally high certainty in the ranking outcomes.

Table 4 Results of weighted summation for 12 potential translocation sites

	Habitat criteria scores[a] and **weights** based on expert ranking										
Site name	Soil type	Vegetation composition	Current land use	Land use change	Food availability	Site size	Distance from main roads	Predators	Salinity	Total site score	Site rank
Chesapeake Road	1	1	1	1	1	1	1	1	1	1	1
Kodjinup Melaleuca Swamp	1	1	1	1	1	0.5	1	1	1	0.96	2
Marron Road	1	1	1	1	1	1	0.5	1	0.5	0.90	3
Lake Poorginup	1	0.33	1	1	1	0.5	1	1	1	0.89	4
Owingup Swamp	1	0.66	1	1	0.5	1	0.5	1	1	0.85	5
Chudalup	1	0.33	1	1	0.5	1	0.5	1	1	0.82	6
Alamein Track	0.5	1	0.66	1	1	0	0.5	1	1	0.78	7
Doggerup Creek	1	0.33	1	1	0.5	0.5	0.5	1	1	0.78	8
Meerup River	1	0.33	0.33	1	0.5	0	1	1	1	0.72	9
Fernwood Farm	1	0.33	0.33	1	1	0	0.5	0	1	0.62	10
Kalgup Road	1	0.33	0.33	1	0.5	0	0.5	0	1	0.55	11
Gingin Brook	1	0.33	0	1	1	0	1	0	0	0.51	12
Criteria weights	**0.126**	**0.105**	**0.085**	**0.129**	**0.141**	**0.085**	**0.082**	**0.130**	**0.118**		

[a] Scores for individual habitat criteria range from 0 (least suitable) to 1 (most suitable)

[b] The higher the weight, the more important the criteria to site suitability

Discussion

Assisted colonisation is a recent addition to the conservation toolbox, and instances where it may provide the only means of maintaining wild populations will become increasingly common. Our results show that assisted colonisation is a potential conservation measure for *P. umbrina* as the most suitable wetlands identified were several hundred kilometres south of the species' documented historical range. The few wetlands on the Swan Coastal Plain ranked as highly suitable included existing habitats at Twin Swamps, Mogumber and Moore River Nature Reserves. This cross-validation suggests that our MCA provides a realistic assessment of habitats that would give the greatest chance of a successful translocation.

Ecosystem processes and whether species will persist within ecosystems depend on the characteristics of individual ecosystems and their connectivity (Roe & Georges, 2007). In our case study, regions with high wetland connectivity would allow individual *P. umbrina* to move between wetlands without risking desiccation during transit (Burbidge, 1981). Few interconnected wetlands exist on the Swan Coastal Plain – an area that has experienced significant increases in human density and land clearing in the past century. Translocations of *P. umbrina* within this region may require private or government-owned land to be revegetated and restored to increase connectivity.

In contrast, a number of suitable wetlands are clustered together in the Augusta to Walpole region. This region retains a high proportion of remnant vegetation, including important conservation areas such as the D'Entrecasteaux National Park and the

Ramsar-listed Muir-Byenup wetland system (DEC, 2012b). In this setting, long-term maintenance of hydrological and ecological connectivity is likely. The high conservation significance of many of the potentially suitable wetlands in the Augusta to Walpole region means that final site selection may favour wetland that occurs outside of a National Park or other significant habitat (Harris *et al.*, 2013).

Several habitat components viewed by experts as important to successful translocations were not incorporated in our analyses due to a lack of data at the required spatial scale. These included factors important to ecological integrity, such as the presence of competing species (e.g. the Oblong Tortoise *Chelodina colleri*) or a Threatened Ecological Community (DSEWPaC, 2012). Possibly the most important elements omitted from this study were the hydrological characteristics of the wetlands. Appropriate wetland hydroperiods and water temperatures will be critical to translocation success for *P. umbrina* because they influence tortoise activity and growth (Mitchell *et al.*, 2012, Mitchell *et al.*, 2013). Screening of the ecohydrological suitability of the SWBP under projected climate change scenarios (Mitchell *et al.*, 2013) identified geographical regions that were similar to those we identified here. As more detailed spatial analysis of wetland hydroperiods becomes available, it will be possible to incorporate hydrological characteristics within the composite index of site suitability.

Combining quantitative and qualitative data in multiple criteria analysis to identify translocation sites

The desktop GIS-based analysis demonstrated here can be used as a first step in narrowing down a suite of potentially suitable areas that warrant further investigation. For quantitative data, we relied heavily on low-cost (or free), publicly available spatial data analysed within a GIS framework. The use of GIS to map species habitats can be cost effective relative to conducting extensive field surveys for developing species distribution models (Smith *et al.*, 2007). This is particularly important for species that are specialised to habitats that are difficult to find using broad-scale field surveys (Burbidge, 1981).

To confirm the accuracy of mapped data, some of which may have been derived from remote sensing or inferred from other data sources such as geological mapping, site visits are essential for confirming that an identified site constitutes suitable habitat. Ground-truthing or verification with recent satellite imagery can be used to test the accuracy of a model using an error matrix (Smith *et al.*, 2007). An error matrix can compare suitability identified in the field with that identified in the suitability index, giving an idea of mapping accuracy (Poulin *et al.*, 2002). This is a logical future step for the MCA model used in this study, as it would give a clearer indication of the potential of this method for identifying future translocation sites for *P. umbrina*.

In cases where published or long-term monitoring data are scarce, expert opinion may be an important source of information for environmental management decisions; in some cases, it may be the only available source of information. Using expert opinion in decision-making can increase the inaccuracy of results as opinions may be biased or poorly calibrated (Martin *et al.*, 2012). For example, Hajkowicz (2008) found high levels of disagreement among stakeholders who were asked to rank environmental problems in the Whitsunday Islands in Queensland. In the current study, our sensitivity analysis indicated that the overall rankings of sites were consistent, but there were discrepancies in the weighting allocated to different habitat criteria by the four experts.

One expert ranked proximity to main roads as one of the most important habitat criteria, which may have been related to personal experiences of finding dead tortoises on roads adjacent to an existing reserve. The other experts, having little or no exposure to this experience, ranked this criterion as far less important to species survival.

Martin *et al.* (2012) suggest a mechanism to deal with uncertainty among experts, by allocating different weights to the opinions of different experts, depending on how accurate a decision maker believes an expert's views to be. In the case of identifying translocation sites for *P. umbrina*, experts could be weighted by their years of experience working with the species, or by the nature of the research they have conducted. An additional difficulty with using expert opinion for calibrating criteria weights in studies similar to ours is that for many range-restricted species for which assisted colonisation might be considered, there are likely to be only a small pool of experts available for canvassing, as was the case in this research.

An alternative MCA method, other than weighted summation, could have been applied to our decision problem. The analytical hierarchy process (AHP) is another widely applied method that uses pairwise comparisons and compares criteria and options in every unique pair to produce criteria weights and scores (Hajkowicz & Collins, 2007). However, although weighted summation may produce less accurate results relative to the AHP, the transparency of weighted summation makes it ideal when dealing with a range of stakeholders, such as commonly occurs when making conservation decisions (Hajkowicz, 2008). The tangible benefit of applying weighted summation to the MCA model in this study is not strictly in identifying an optimum site for assisted colonisation, but in providing a transparent process that can be understood by a range of stakeholders who will be affected by the model's results (Hajkowicz, 2008). Indeed, for controversial projects such as translocating species to novel habitats in areas of high conservation value, extensive and transparent stakeholder consultation will be an important step in the selection of final release sites (Burbidge *et al.*, 2011, Harris *et al.*, 2013).

Conclusion

The combination of GIS-based analysis, informed by expert opinion and weighted summation in a spatially explicit MCA can identify potential translocation sites that are well matched to our current understanding of habitat requirements for a species. Our results emphasise the importance of considering multiple criteria in the decision making process. These could include criteria relevant to the anticipated impact of the introduced species to the recipient community, which would be critical to minimising the risks posed by assisted colonisations. Further, when considering the translocation of species, regardless of whether it is within its historical range or to a new area, it is important to consider the suitability of the site based not only biotic factors, but also on socio-economic considerations. Such additional factors are readily incorporated into a MCA framework.

Our results should not be taken as final recommendations for sites for assisted colonisation of *P. umbrina* as they have not been ground-truthed or subjected to logistical considerations such as cost-benefit analysis. However, as sites that provide a good match for existing habitat have been identified, it would be logical to consider these sites for assisted colonisation over any sites within highly novel habitat. Before assisted colonisation can occur it will be important to project the effect of future climate scenarios on ecological and hydrological processes, which are key to the long-term survival of translocated species (Carroll *et al.*, 2009). Fortunately, many habitat components (e.g. soil type, land use) will not be affected by climate change, and the advance of spatially explicit models of the biological impacts of climate change will allow climatically-sensitive criteria to be evaluated and incorporated into MCA models. Rapid improvement in the resolution of GIS data is also likely in many parts of the world. The potential of a method similar to that demonstrated here in planning assisted colonisations is substantial, and when coupled with ground-truthing can allow more strategic deployment of species translocations than has previously been possible.

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Appendix 2. Example of data collection sheets used at the eight wetland sites sampled in this study

Wetland site description

Site name: ______________________________ Site code: ________________

Recorders: ____________________ Time: _________ date: ____________

Coordinates: ____

Location and access description:

____
____
____
____

Wetland type and description (comments on hydrology, size, depth, surrounding vegetation and habitats):

____
____
____
____
____

Land tenure description:

____
____

presence of threatening processes:

____
____
____

Possible presence of threatened ecological communities:

____
____

Notes:

____
____
____
____
____
____
____

Map of site (including site dimensions/boundaries, tracks, roads, location of wetland within site, location of vegetation quadrats, soils samples, macro-invertebrate sampling, photos and other distinguishing features/items of interest etc.)

Vegetation (10x10m quadrat)

Site id	Quadrat id	Dominant stratum	Emergents
Datum	Easting		Bearing
Zone	Northing		Size (m*m)
Reason for quadrat location			Quadrat photos

Strata		Form			Form			Form
Cover %								
height								
Species name (in order of dominance)	GF (tree, shrub etc.)	Id no.	Species name (in order of dominance)	GF	Id no.	Species name (in order of dominance)	GF	Id no.
1								
2								
3								
4								
5								
6								

Strata		Form			Form			Form
Cover %								
height								
Species name (in order of dominance)	GF	Id no.	Species name (in order of dominance)	GF	Id no.	Species name (in order of dominance)	GF	Id no.
1								
2								
3								
4								
5								
6								

Vegetation cover

Point intercept method (determine canopy cover % every 1m)

Site id					date						
Location id					coordinates						
1m interval	0	1	2	3	4	5	6	7	8	9	10
% cover											
1m interval	11	12	13	14	15	16	17	18	19	20	
% cover											

Water sampling

Site id			coordinates	
Location id			date	time
Water property measured	Sample location			
	Location 1	Location 2	Location 3	
Conductivity below surface				
pH below surface				
Temperature below surface				
Salinity (EC)				

Soil sampling

Site id.	date			Soil %								
				Dry		Wet	inundated					
Location 1 coordinates												
depth	0-5cm			5-10cm			10-20cm			20-80cm		
Colour	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma
texture												
consistency												
Location 2 coordinates												
Colour	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma
Texture												
Consistency												
Location 3 coordinates												
Colour	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma	Hue	Value	Chroma
Texture												
Consistency												

Macro invertebrate sampling

Site id.	time	date
Location id	coordinates	

Phylum: Arthropoda- class: Insecta			
Classification (order and/or family)	Common name	present	comments
Phylum: Arthropoda- Class: Crustacea			
Phylum: Arthropoda- Class: Arachnida			
Phylum: Mollusca			
Phylum: Annelida			

Phylum: Nematoda			
Phylum: Platyhelminthes			

Appendix 3. R script used in analysis of numerical data

```
## R script for data analysis on numerical data (2013)

##open environmental data file
ed <-read.csv(file.choose())
ed
## geographic location of the sites
with(ed,plot(latitude,longitude))
## plot again with labels
with(ed,plot(latitude,longitude,type="n"))
with(ed,text(latitude,longitude,rank))

##separate numerical data
envtdata <- ed[,4:10]
envtdata

##plot correlations of numerical data
plot(envtdata)
cor(envtdata)

##separate latitude and longitude data
geogdata <- ed[,11:12]
geogdata

##calculate euclidean distance from longitude and latitude data
geogdists <- dist(geogdata)
geogdists

## distance based redundancy analysis (adonis) on the geographical distances to see
## if the difference between the sites in terms of suitability scores is explained by the
geographical distribution
## load vegan libray to access adonis function
library(vegan)
adonis(geogdists~ed$score)
help(adonis)
```

Appendix 4. Photos taken at the eight wetland sites assessed in this study as compared to the current *P. umbrina* habitat at Ellen Brook Nature Reserve. Photos are arranged in the order the sites were visited during July and August 2013.

Ellen Brook Nature Reserve
(current *P. umbrina* habitat)

East Augusta

Ambergate Nature Reserve

D'entrecasteaux National Park 1

D’entrecasteaux National Park 2

Frankland National Park

Donnelley State Forest

Benger Swamp Nature Reserve

Byrd Swamp Nature Reserve

Appendix 5. Journal reference style: Diversity and Distributions

Diversity and Distributions A Journal of Conservation Biogeography

Diversity and Distributions, (Diversity Distrib.) (2013) **19**, 1106–1113

BIODIVERSITY RESEARCH

Improved spatial estimates of climate predict patchier species distributions

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ABSTRACT

Aim Correlative species distribution models (SDMs) combined with spatial layers of climate and species' localities represent a frequently utilized and rapid method for generating spatial estimates of species distributions. However, an SDM is only as accurate as the inputs upon which it is based. Current best-practice climate layers commonly utilized in SDM (e.g. ANUCLIM) are frequently inaccurate and biased spatially. Here, we statistically downscale 30 years of existing spatial weather estimates against empirical weather data and spatial layers of topography and vegetation to produce highly accurate spatial layers of weather. We proceed to demonstrate the effect of inaccurately quantified spatial data on SDM outcomes.

Location The Australian Wet Tropics.

Methods We use Boosted Regression Trees (BRTs) to generate 30 years of spatial estimates of daily maximum and minimum temperature for the study region and aggregate the resultant weather layers into 'accuCLIM' climate summaries, comparable with those generated by current best-practice climate layers. We proceed to generate for seven species of rainforest skink comparable SDMs within species; one model based on ANUCLIM climate estimates and another based on accuCLIM climate estimates.

Results Boosted Regression Trees weather layers are more accurate with respect to empirically measured temperature, particularly for maximum temperature, when compared to current best-practice weather layers. ANUCLIM climate layers are least accurate in heavily forested upland regions, frequently over-predicting empirical mean maximum temperature by as much as 7°. Distributions of the focal species as predicted by accuCLIM were more fragmented and contained less core distributional area.

Conclusion Combined these results reveal a source of bias in climate-based SDMs and indicate a solution in the form of statistical downscaling. This technique will allow researchers to produce fine-grained, ground-truthed spatial estimates of weather based on existing estimates, which can be aggregated in novel ways, and applied to correlative or process-based modelling techniques.

Keywords
Australia's Wet Tropics, Boosted Regression Trees, climate downscaling, spatial climate layers, spatial weather layers, species distribution model.

INTRODUCTION

How can we know where a species occurs? This question is central to ecological theory and its answer is also of great concern to conservation planners. Increasingly, when faced with uncertainty in species' distributions, we rely on species distribution models (SDMs hereafter) to generate maps describing these distributions. SDMs utilize spatial layers of environmental variables to generate species–environment relationships (SERs) and to predict occurrence in geographic space (Austin, 2007). As such, the quality and resolution of these spatial environmental layers will affect the quality of

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Detailed description of datasets used in BRT downscaling procedure.

Appendix S2 Detailed description of BRT model fitting procedure.

BIOSKETCH

The Centre for Tropical Biodiversity and Climate Change Research at James Cook University is a cross-disciplinary research team focusing on the ecological, environmental and social impacts of global environmental change. Using the data-rich Australian Wet Tropics as a model system, CTBCC researchers hope to gain an understanding of how global environmental change impacts natural systems, and develop toolkits for rapid assessment of vulnerability across spatial scales and diverse ecosystems. Learn more about the research conducted at the CTBCC by visiting https://plone.jcu.edu.au/researchatjcu/research/ctbcc.

Author contributions: C.S. and J.J.V. conceived the ideas for the manuscript. S.E.W., CS and numerous others collected the data. C.S. completed the analyses with technical support from B.P. and J.J.V. C.S. led the manuscript writing with significant contributions by J.J.V. and B.P.

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