Habitat suitability and susceptibility modelling for strategic control of invasive Buffel grass, South Australia

A report intended to inform natural resource managers.

2013

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CONTENTS

1. BACKGROUND AND SCOPE

Invasive plants pose serious threat to ecological, environmental and cultural values of infested regions and can be costly to control. Mapping, monitoring, and understanding invasive species ecology sufficiently to identify habitats prone to invasion are important for management of the invasive plant.

Approaches to invasive species management and biosecurity are moving increasingly towards the spatial explicit predictive modelling of species potential distribution to prioritise mitigation efforts at regional scales.

Empirical models (predictions based on real species presence-absence data) are ideal because they typically produce the most regionally accurate predictions. However often comprehensive species distribution data is lacking. For this reason, the benefits of mechanistic models (predictions based on knowledge of species environmental tolerances) such as Bayesian Belief Networks (BNNs) are gaining recognition and acceptance. Mechanistic models are best applied at course scales, but offer the advantage of requiring no species distribution data.

In a recent publication by Smith et al. (2012) a framework and BNN for estimating weeds invasion potential that utilised expert knowledge of dispersal establishment and persistence was presented. Biosecurity SA (division of PIRSA) is currently exploring the adoption of this framework for risk assessment of invasive species in the state to aid the decision-making process on where to invest limited resources in pursuit of weed control and biodiversity conservation. The framework makes a distinction between habitat suitability and susceptibility: suitability pertains to the ability of the plant to establish and persist in a habitat, whilst susceptibility is the suitability of the habitat combined with likelihood that seed will arrive at the site. This distinction is important throughout this report.

Presently, perhaps the most contentious weed species in the state is Buffel grass *(Cenchrus ciliaris)*. Buffel grass is an African perennial tussock, popular in arid rangeland worldwide, which arguably signifies the greatest threat to biodiversity in arid environments. South Australian natural resource management regions are actively controlling Buffel grass infestations within their jurisdictions in accordance with the South Australian Buffel grass Strategic Plan 2012-2017 (Biosecurity SA 2012). Strong knowledge of the introduction pathways of this grass makes it an ideal test species to trial the development of an invasion risk framework.

In 2010 a comprehensive roadside survey was conducted in regional arid South Australia to fill gaps in the known distribution of the species. This data has been used to construct empirical habitat suitability models (HSMs) for Buffel grass in arid South Australia (Marshall et al. 2013, *In Review*).

Here, the HSM constructed by Marshall et al. (2013, *In Review*) is adapted to become spatially explicit, and restructured to fit within the Theoretical Framework proposed by Smith et al. (2012).

Key outputs of this report are spatially explicit models of habitat suitability, introduction pathways and landscape susceptibility for Buffel grass invasion in the arid zone of South Australia. In this study, habitat suitability maps are not based on expert-defined parameters, but on empirical modelling of 2010 roadside survey data.

We report on the key environmental variables influencing habitat suitability for Buffel grass in arid South Australia, specify the scale at which models can be interpreted and summarise the known limitations of the model and modelling framework.

2. METHODS AND MATERIALS

2.1 Study Area

In South Australia very few pastoralists cultivate Buffel grass, yet it is becoming widespread. Anecdotal evidence suggests that Buffel grass has been transported into the state along public roads and tracks, and spreads out from the roadsides where environmental conditions are appropriate. Buffel grass is considered widespread in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands, and in some pastoral districts of the South Australian Arid Lands (SAAL) Natural Resource Management (NRM) region. Infestations with potential for becoming widespread are present along the Stuart and Eyre Highways, in regional communities such as Oak Valley.

The spatially explicit models are produced for arid South Australia only. Extrapolation beyond this area may invalidate predications, which are based on species occurrence data from within this climatic region. Species occurrence data was obtained from 2010 Buffel grass Roadside Survey (Shepherd et al. 2010). The area surveyed (Figure 1) samples a north-south climate gradient, more arid further north. Elevation ranges from below sea level within salt lakes, such as Lake Eyre, to over 1000m in the Gammon and Flinders Ranges. Vegetation is predominantly low-lying chenopod shrubland, and stony plains, which allow clear views of the land adjacent the roadside. Vegetation on surrounding hills is typically open mallee woodland. The land is predominantly used for sheep and cattle grazing of natural vegetation; few differences can be observed in land cover as a result of management throughout the study area.

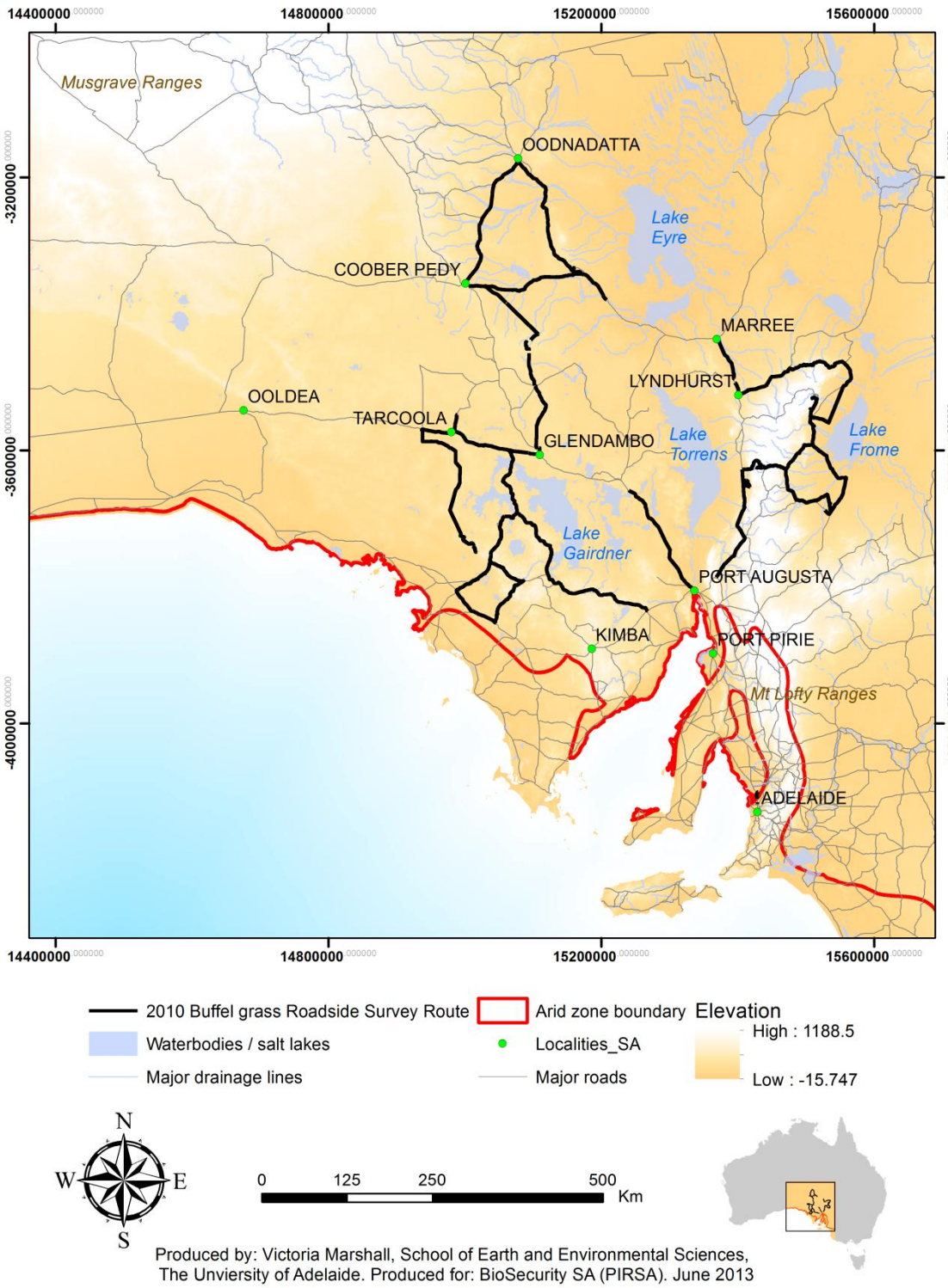

Figure 1 the 2010 Buffel grass Roadside Survey Route (black line), and arid zone boundary (red line) used as predictive modelling extent.

2.2 Theoretical framework for modelling landscape susceptibility to weed invasion

The theoretical framework proposed by (Smith et al. 2012) is based on the three fundamental invasion processes common to all plants: introduction/ dispersal, establishment, and persistence at a site. Establishment and persistence determine a site's suitability for establishment, and this combined with introduction vectors and pathways determines the sites susceptibility to invasion (Figure 2). Unlike Smith et al (2012) who applies BBN (mechanistic) we utilise this theoretical framework to develop a hybrid empirical-mechanistic model. The construction of our hybrid framework for habitat suitability, introduction pathways and susceptibility is described below.

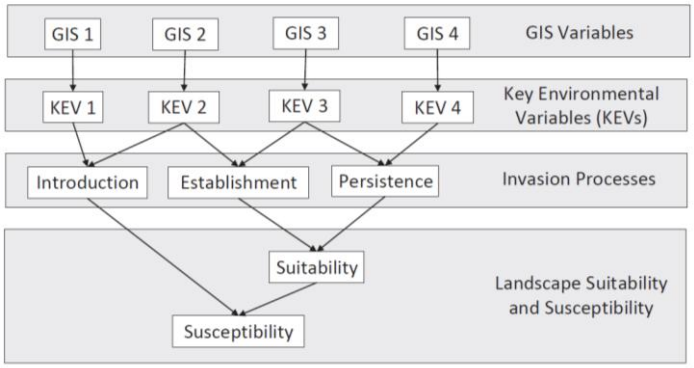

Figure 2 Theoretical framework for modelling landscape susceptibility to weed invasion (Smith et al. 2012)

2.2.1 Suitability

Habitat suitability was modelled using an additive logistic regression analysis[1]; selected environmental variables were regressed against Buffel grass presence-absence data obtained during 2010 Buffel grass Roadside Survey. This model represents habitat suitability for establishment only (persistence is excluded). Inclusion of "persistence" would require either a repeat survey or some surrogate measure of persistence such as patch size/ rate of spread or patch size > 10 ha, in order to quantify persistence. For this reason, "persistence" was excluded from our adapted invasion risk framework.

2.2.2 Introduction Pathways

Introduction pathways were selected based on expert knowledge and we did not utilise any empirical data in our approach to modelling introduction pathways. In this instance, empirical modelling was void because our source of species distribution data was the roadside, which is an

[1] Empirical modelling is based on research undertaken towards Victoria Marshall's doctorate and is temporarily withheld to protect intellectual property until PhD examiners reports are finalised. (APPENDIX)

important pathway for the spread of Buffel grass seed. Consequently, roadsides could not be included as a covariate in an empirical model. Instead, a geographic information systems (GIS)-based model was constructed.

Introduction pathways were identified as water courses, roads, especially major roads, townships, and railroads. The formula for weighting introduction risk was simple: The closer to an introduction pathway, the more likely introduction would occur. So “distance to” each of the introduction layers were calculated. Each “distance to” layer was normalised between 1 and 10. Then the layers were added. So for example, if a habitat was close to a water course, plus a township, plus a major road, it would be more likely to receive propagules than a location only near to a water course. Note that, Buffel grass source populations were identified as an introduction factor but excluded from the model as inclusion would limit the models longevity.

2.2.3 Habitat / landscape susceptibility

In accordance with the theoretical framework, habitat susceptibility is the combined impact of introduction pathways and habitats suitability. We normalise between 1 and 10 both Introduction Pathways and the Habitat Suitability GIS layers then calculate the product (multiply the two GIS layers). The resulting map is a graduated map with values 1 – 100 where landscape susceptibility to invasion increases to a value of up to 100.

2.3 Model inputs and construction

2.3.1 Overview

This section describes the model inputs for each spatially explicit model of Buffel grass Invasion Pathways, Habitat Suitability and Habitat Susceptibility. An overview of out modelling framework and how the input variables fit together is depicted in Figure 2. This demonstrates the hybrid nature of our framework; it also provides a quick view of the key environmental variables used in our empirical habitat suitability model and the input variables used in our GIS-based introduction pathways model.

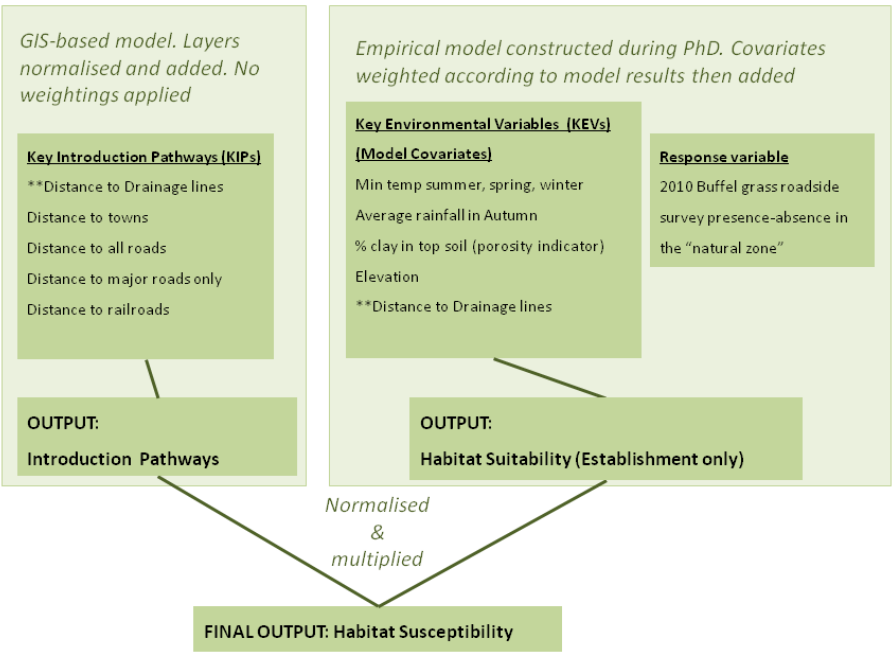

Figure 3 Theoretical framework adapted from Smith et al (2012) for modelling landscape susceptibility to Buffel grass invasion; input variables used for modelling habitat suitability and susceptibility also shown. (**) indicates variable duplication in Final Output.

2.3.2 2010 Buffel grass roadside survey: Response variable for habitat suitability modelling

Roadside survey was carried out from 6th to 14th of May 2010 to map the regional distribution of Buffel grass in arid South Australia (Shepherd et al. 2010). Over 3800km of roads were identified for survey between Oodnadatta, Lake Frome, Port Augusta, and Tarcoola, mostly along major highways; the survey route is depicted in Figure 1.

There were two crucial elements of this survey which made the data usable in habitat suitability modelling: (1) the continuous collection of presence and absence data for the entire survey route and (2) the distinction (at the time of data collection) between roadside and adjacent land (Area beyond the roadside relatively unaffected by anthropogenic disturbances; the dynamic threshold

separating roadside and adjacent land is defined in the Survey Report). This second feature is vital because the roadside is a biased environment that favours seedling establishment and is a pathway/ vector-carrier for the spread of Buffel grass. Full details of the roadside survey methodology (adapted from 2005 Buffel grass Roadside surveys conducted by Rural Solutions SA) can be found in (Shepherd et al. 2010); the benefit of making this roadside-adjacent land distinction is quantified in (Marshall et al. 2013, *In Review*).

Presence-absence on "Adjacent land" (referred to as "Natural Zone" in (Shepherd et al. 2010)) were used as the response variable in our habitat suitability model (HSM).

When viewed in the geographic information system (GIS) environment, each road segment recorded during the survey is a polyline with attributes: presence-absence (roadside), presence-absence (adjacent land), density (roadside), density (adjacent land), and extent (adjacent land). For statistical analysis, we re-sampled the polylines as points. A point was created for every line-segment, and for line-segments greater than 1200 metres an additional point was created every 654 metres (the mean polyline-segment length). The re-sampled data constituted a set of 5535 observations, which after accounting for null-values and missing numbers in the environmental datasets, was reduced to 5107 observations on which to base our model.

2.3.3 Key Environmental Variables (KEVs)

We initially considered approximately 50 environmental variables for inclusion in our Buffel grass habitat suitability model that can be broadly classified as climatic, geological/ landscape, anthropogenic and vegetation. Values at each survey data point were extracted from these environmental layers (Table 1) for further analysis and through a series of statistical test of independence and covariance we selected a subset of KEVs for inclusion in our model. The 12 KEVs initially included in the model were: distance to water, vegetation (growth form in tallest and lowest stratum), elevation, temperature, rainfall, geology (stratigraphic description) and percentage of clay in the topsoil (an indicator of soil porosity).

The 12 selected covariates were regressed against Buffel grass occurrence using the *glm* function ("stats" package, R) (R Development Core Team 2008). A stepwise / step down logistic regression analysis assessed based on the Akaike Information Criterion (AIC) was implemented using the *step-AIC* function (MASS package, R) (Venables et al. 2002) . The AIC is a weighted sum of squares with a penalty for the number of covariates; the step-AIC is used to identify the best performing model based on AIC, and eliminate covariates that do not significantly contribute to each model. During this process, geology was dropped from the model. It's possible that the number of geological unit classifications contributed to this elimination.

Ultimately, KEVs incorporated into the spatially explicit habitat suitability model for Buffel grass were: minimum temperature in spring, summer and winter, average rainfall in autumn, elevation, percentage of clay in the top soil, and vegetation growth form in the lower and upper stratum.

Table 1 Source and specifications of environmental covariate datasets regressed against Buffel grass presence-absence

Key Environmental Variables	Details	Data Source
Climatic variables(temperature, rainfall, humidity)	Continuous; monthly means based on standard 30-years climatology (1961-1990); Humidity is as recorded at 9am. Temperature and Rainfall are mean monthly minimum and maximum; Seasonal averages calculated	Australian Bureau of Meteorology
Surface geology	Categorical; intended for use at scales between 1:5,000,000 and 1:2,500,000 , compiled by different authors, 2010 edition	Geoscience Australia, ID: ANZCW0703013575
Percentage of clay in top soil	Continuous; Surface of predicted % Clay in soil layer 1 (A Horizon - Top-soil) surface for the intensive agricultural areas of Australia, derived from soil mapping by different agencies	Australian Soil Resources Information System (ASIRS) custodian - National Land and Water Resources Audit (NLWRA)
Elevation	Continuous; 9-second (250 m) Digital Elevation Model (DEM-9S, Version 3)	Geoscience Australia, ID: ANZCW0703011541
Vegetation	Categorical; post-European settlement (1988), intended for use at 1:5,000,000 scales, areas over 30,000 hectares are shown; attributes include type, growth form and dominant species in upper and lower stratum	Geoscience Australia, ID: ANZCW0703005426
Land use	Categorical; generalised parcel-based land use	Department of Planning, Transport and Infrastructure, South Australia, Data set no. # 219
Distance to water	Continuous; calculated from Water bodies and detailed drainage line data (cell size =25, 25 m) ; natural log transformed	Department of Primary Industries and Resources of South Australia (PIRSA)

2.3.4 Key Introduction Pathways (KIPs)

Introduction factors selected for inclusion in the Introduction Pathways model were water courses, all roads (major and minor), major roads, townships, and railroads. To make this model spatial explicit and extrapolate over arid SA, "distance to" each of these introduction pathways was used as model input. Source and specifications of KIPs are summarised in Table 2. Regarding data preparation, the natural log of "distance to" variables was applied, raster cells were then 1000m pixels, based on minimum cell value. Minimum was selected to emphasis closer distances.

To calculate a "Sum of Weights" Score akin to "likelihood of introduction" each of the "distance to" layers was normalised from 1 – 10 using the equation:

$$1 + ((\text{KIP} - \text{Minimum KIP value})(10-1)) / (\text{Maximum KIP value} - \text{Minimum KIP value})$$

Normalised "distance to" layers were then added together in the GIS environment.

Table 2 Source and specifications of key introduction pathways datasets used in GIS "sum of weights" model of Buffel grass Introduction Pathways

Key Introduction Pathways	Details	Data Source
Distance to water	Continuous; calculated from Water bodies and detailed drainage line data (cell size =25, 25 m) ; natural log transformed; aggregated cell size = 1000, 1000 m; normalised	Department of Primary Industries and Regions of South Australia (PIRSA)
Distance to roads (major and minor)	Continuous; calculated from Detailed Road network polyline data (cell size =50, 50 m) ; natural log transformed; aggregated cell size = 1000, 1000 m; normalised	Department of Primary Industries and Regions of South Australia (PIRSA)
Distance to towns	Continuous; calculated from Localities dataset (includes major towns and regional centres but does not include regional communities such as Oak Valley and Kalka) (cell size =100,100 m) ; natural log transformed; aggregated cell size = 1000, 1000 m; normalised	Department of Primary Industries and Regions of South Australia (PIRSA)
Distance to major roads	Continuous; calculated from major Road network polyline data (cell size =50, 50 m) ; natural log transformed; aggregated cell size = 1000, 1000 m; normalised	Department of Primary Industries and Regions of South Australia (PIRSA)
Distance to Railroads	Continuous; calculated from major Road network polyline data (cell size =500, 500 m) ; natural log transformed; aggregated cell size = 1000, 1000 m; normalised	Department of Primary Industries and Regions of South Australia (PIRSA)

3. RESULTS

3.1 Habitat Suitability

The statistical model (Table 3) was executed in GIS environment to produce a spatially explicit habitat suitability map (Figure 4). The model indicates that the entire arid region could support the establishment of Buffel grass. Environments highly suited to Buffel grass establishment occur in regions with dense drainage networks at longitudinal coordinate 152000000 also in alignment with the Mt Lofty Ranges. Areas less suited to its establishment occur in the Victoria Desert and towards the South-East.

Table 3 Overall model performance and contribution of environmental covariates on Buffel grass presence-absence in on Adjacent land in arid SA

		Coefficient	Probability	Significance
	(Intercept)	-61.85000	0.00000	***
Vegetation	Tallest stratum, growth form: Shrubs > 2m	4.20700	0.00010	***
	Tallest stratum, growth form: Shrubs < 2m	4.10200	0.00018	***
	Lowest stratum, growth form: Shrubs >2m	4.34300	0.00174	**
	Lowest stratum, growth form: Shrubs <2m	5.60000	0.00000	***
Climate	Rainfall (autumn)	0.62340	0.00000	***
	Minimum temperature (Summer)	4.53500	0.00000	***
	Minimum temperature (Spring)	-4.10800	0.00005	***
	Minimum temperatures (Winter)	2.11200	0.00187	**
Landscape	Percentage of clay in top soil (Porosity indicator)	-0.00004	0.06908	.
	Distance to water (natural log)	-0.43630	0.00000	***
	Elevation	-0.00869	0.00527	**
AIC			**604.65**	

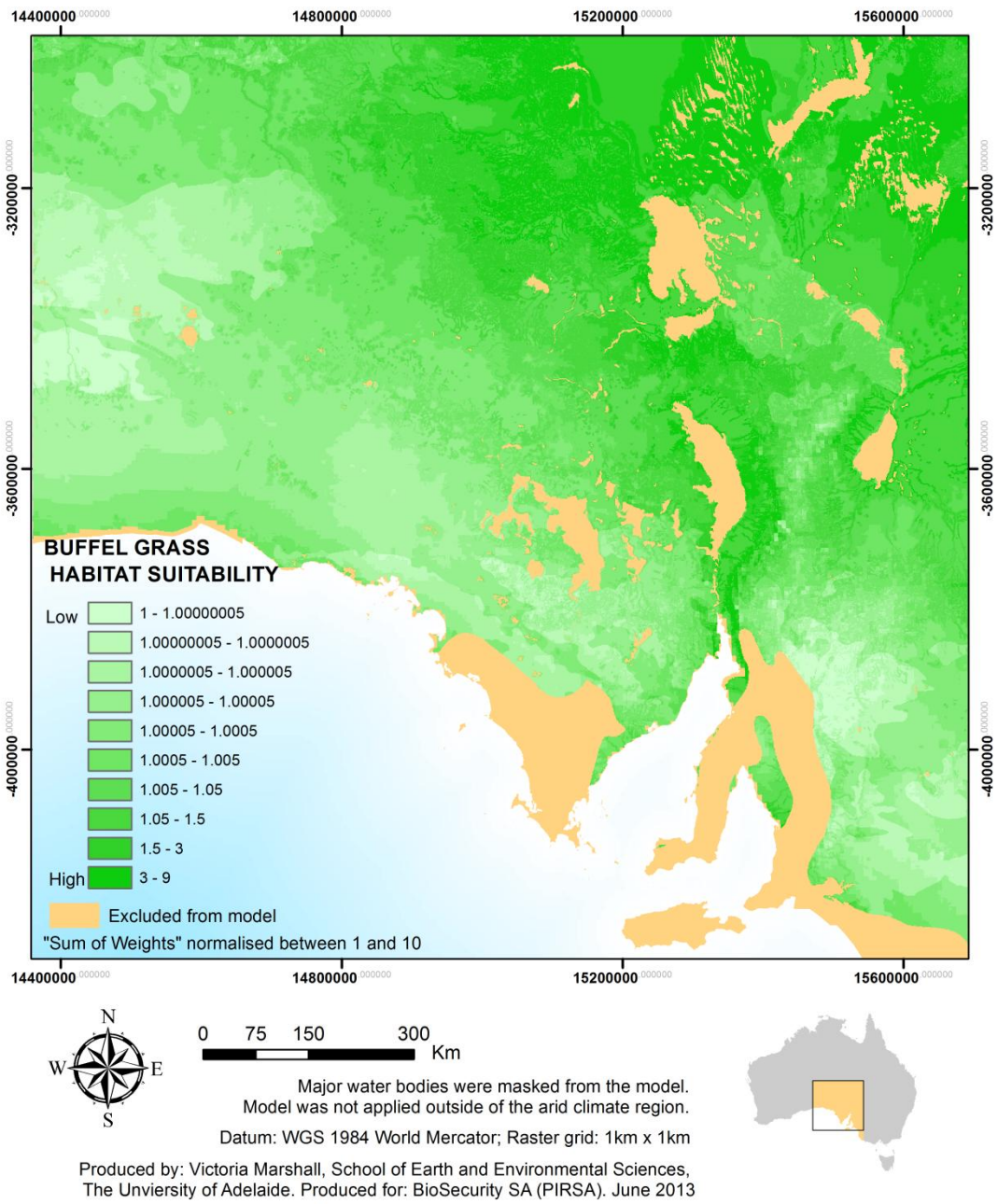

Figure 4 Buffel grass habitat suitability; The probability (normalised from 1-10) that habitat is suitable for Buffel grass establishment.

3.2 Introduction Pathways

The "Sum of Weights" executed in GIS environment to produce a spatially explicit introduction pathways map (Figure 5). The model indicates regions most prone to influx of Buffel grass seed are areas close to major roads, railroads, drainage lines and roads in general (major and minor). Regions where two or more of the model inputs intersect are more likely to see seed arrive, regional centres such as Port Augusta appear particularly prone to seed arrival.

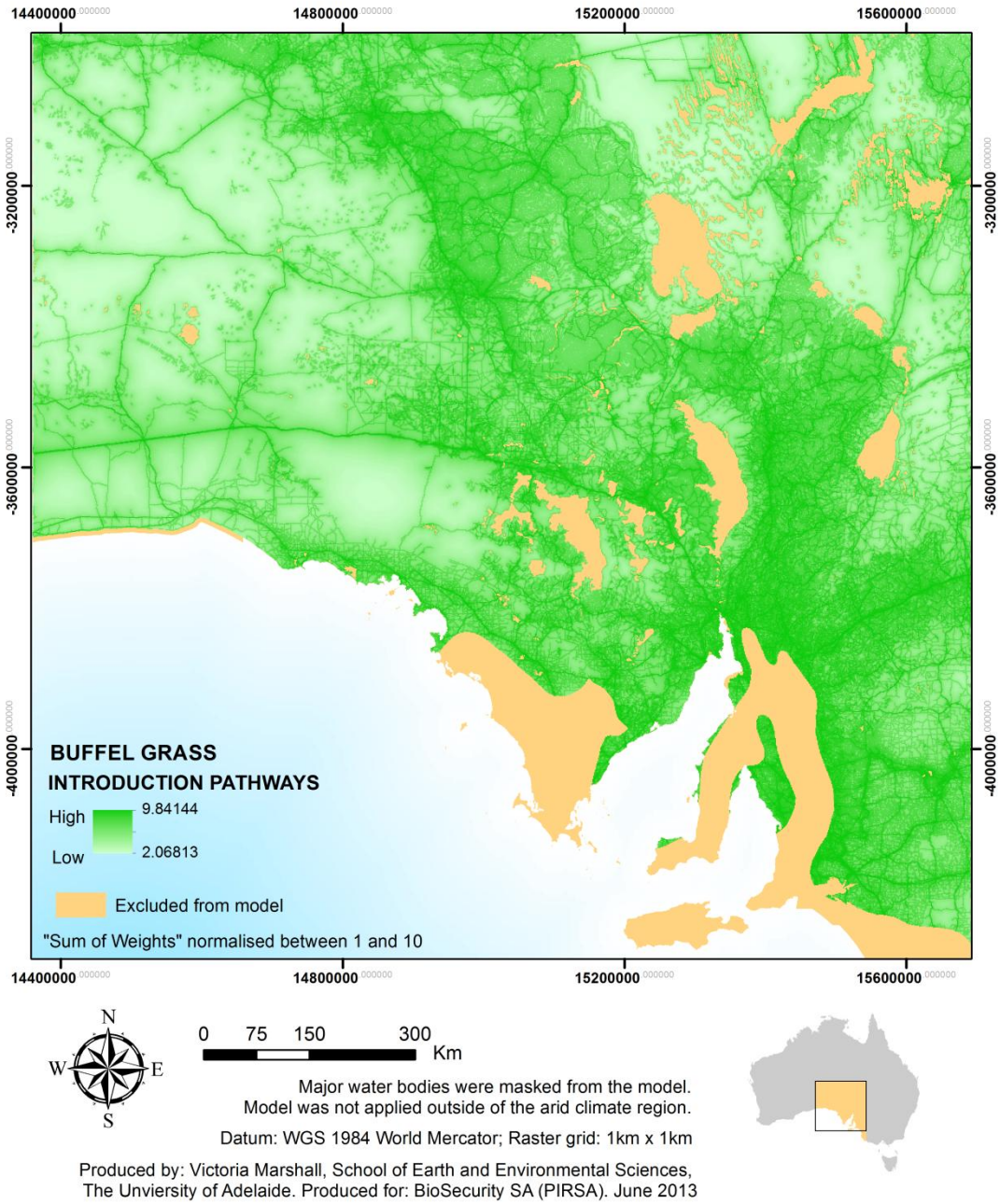

Figure 5 Buffel grass introduction pathways; "Sum of weights" normalised from 1 (low) to 10 (high) representing a likelihood that Buffel grass could be introduced

3.3 Habitat Susceptibility

The product of Introduction pathways (Figure 5) and Habitat Suitability (Figure 4) executed in GIS environment produced a spatially explicit habitat susceptibility map (Figure 6). Intuitively, the product shows that regions where high suitability interact with high level of introduction pathways will be most susceptible to invasion.

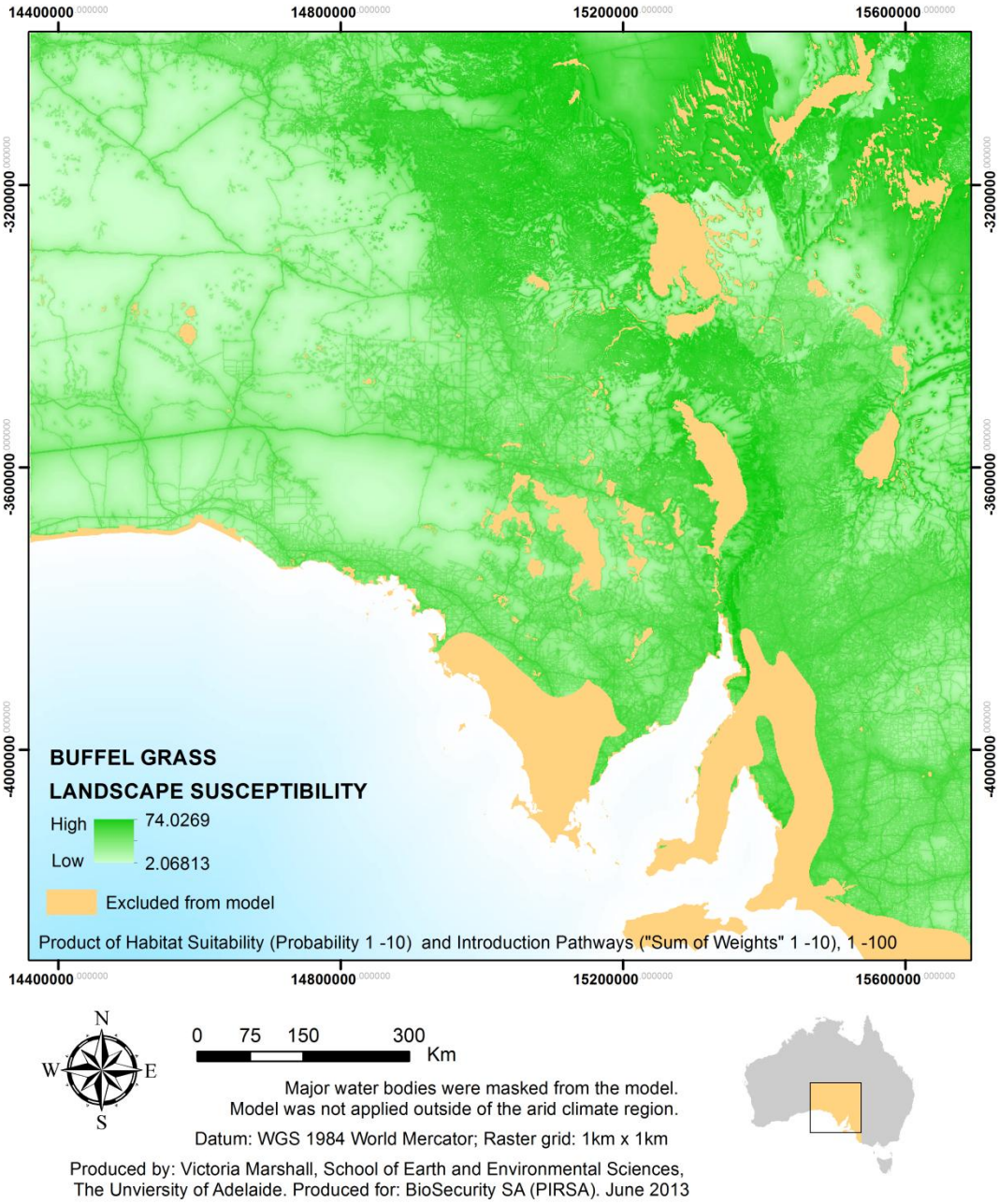

Figure 6 Buffel grass landscape susceptibility "Sum of weights" normalised from 1 (low) to 10 (high) representing a likelihood that the landscape would be susceptible to Buffel grass invasion

4. DISCUSSION

4.1 Limitations to the Theoretical Framework

The theoretical framework presents a useful structure upon which to consider the three fundamental elements of invasion process (introduction, establishment and persistence). However, the segregation of these three processes presents challenges for spatially portraying the end product (the habitat/ landscape susceptibility model). The first challenge which presents is that a vector for spread (and therefore an Introduction input variable) could also be a determinant of establishment and persistence. Specifically, we encounter this issue with Key Environmental Variable (KEV), "Distance to Drainage lines and water bodies". Buffel grass is known to be dispersed along waterways, but also disturbance caused by water and the increased soil moisture, make waterways particularly suited for Buffel grass establishment. In this scenario, we chose to incorporate it in both "introduction" and "suitability" models, thus it is included twice in the final model. Whether a standard procedure should be outlined, or whether this will need to be decided on a species– by-species basis should be considered in the next stages of development for this invasion risk framework.

The next major challenge is that of scale and this is not made plain in the suggested framework. Ecological processes operate at different scales. In this example, we identified five introduction pathways: all linear features in the landscape, which become challenging to interpret at a state-wide scale. The state-wide habitat suitability depicted at 1:1000km scale, is not an acceptable resolution for Introduction pathways, typically in this case less than 50 m wide. This issue is partially addressed by using "distance to" as the measurable input. However, this presents an ecological question of *how far can seed disperse?* Should there be a distance limit, where it is completely unlikely that the seed could spread from that pathway? Perhaps pathways should be considered at an alternative scale to that of suitability.

An additional consideration of scale, although not relevant in this study, is how to capture and document expert observations and opinions which are likely formed at a localised scale, and may not be applicable at state wide scales, which due to limitations of data availability and resolution they are likely to be.

The framework presented is intended for construction of mechanistic models. Here, we attempted to hybridise the model, to include some empirical data. The modelling research that underpins this study and is presented in (Marshall et al. 2013, *In Review*) was constructed using all the KEVs listed for this study, as well as, introduction factors "distance to towns" and "roadside occurrence" ("roadside" populations recorded on 2010 Buffel grass roadside survey). In order to fit the Theoretical Framework for modelling invasion, empirical modelling was rerun for this study to

exclude those introduction pathways. How this change alters the statistical prediction is untested. It may or may not be comparable. However, it is worth noting that there is difference and the overall impact of utilising this framework on the performance of spatially explicit models should be explored more thoroughly prior to adopting this framework for empirical-hybridised models in future.

4.2 Limitations to the Models

The primary limitation to any predictive habitat model is data; availability, spatial resolution, extent and consistency of spatial layers depicting key environmental variables and introduction pathways. In this study, models are produced at a state wide scale. Datasets with a large enough extent to cover this area are only available at course resolutions. The limitation which this imposes is clearly demonstrated in the case of "soils" data. In this study, we use "percentage of clay in the top soil" as the soils variable. In the field, Buffel grass can be observed at high densities on alluvial soils. This might include alluvial fans and creek lines. These landscape features are perhaps 50 – 500m wide. Now, there is no reason that "alluvial soils" throughout the state could not be identified as vulnerable to invasion. However, soils data with state-wide coverage is only available at a 1:250,000 scale. At this scale, small or narrow soils units are swallowed up into larger unit classifications. The implication is that soils are poorly represented in the final state-wide model. It may explain the relatively low weighting that "clay in the top soil" receives in our empirical model (Table 3). Similarly, climate layers (interpolated from weather stations across Australia to a resolution of 5km) can be rescaled to a localised (larger scale) while maintaining the integrity of the model. However, local observations the impact of temperature cannot be reapplied at a state-wide scale.

When viewing and interpreting this habitat susceptibility model it will be important to "zoom in". The maps should be considered as interactive. The reason for this is demonstrated in Figure 7. It shows that those regions with tightly compacted linear features (creeks and roads), when up-scaled to the state-wide map, appear as solid blocks of "highly susceptible" land. In fact, when viewed at a regional scale, those highly susceptible regions are restricted to the linear features. Greater variation can be seen when zoomed in, and this is an especially important consideration when looking at areas which appear less susceptible to invasion. At a regional scale, the scales relevant for on ground managers, the localised variation may be quite significant.

Our suitability model is empirically based and as such the strength of predictions is likely to be lower for environments where no presence-absence data was collected. For example, the roadside survey route does not sample regions of high elevation greater than approximately 600 m. At higher elevations different environmental interactions may be important for Buffel grass growth. For example, aspect is likely to be significant; Buffel grass prefers to grow on north facing slopes.

Another example might be rainfall interacting with soil clay content. High rainfall may have a strong positive effect for Buffel grass growing on sandy soils (low clay content), whereas it may have a negative impact on Buffel growth in heavy clay soils that become water logged easily. The fact that not all interactions are captured by the presence-absence data is a weakness of this model. It is for this reason that we limit the models' spatial extent to the arid region. However, there is likely to be some correlation between model accuracy and distance to the 2010 roadside survey route.

Susceptibility estimates are lower than expected in the Musgrave Ranges (far North West), where Buffel grass is known to be widespread and particularly dominant on the flats between the ranges. There are several likely contributors to this lower than expected susceptibility ranking. Firstly, it's over 600 km from the survey route. Secondly, the Musgrave ranges are an area of high elevation. As explained in the preceding paragraph, high elevations were not sampled on the roadside survey. Thirdly, there are fewer drainage lines in the Musgrave ranges than in for example, the Stony Plains IBRA region. Distance to drainage lines is strongly weighted by the empirical model (Table 3) and also in the final model because it is incorporated twice (suitability and introduction, Figure 2). Therefore, there may be an issue with this variable emphasising areas near to or densely packed with drainage lines.

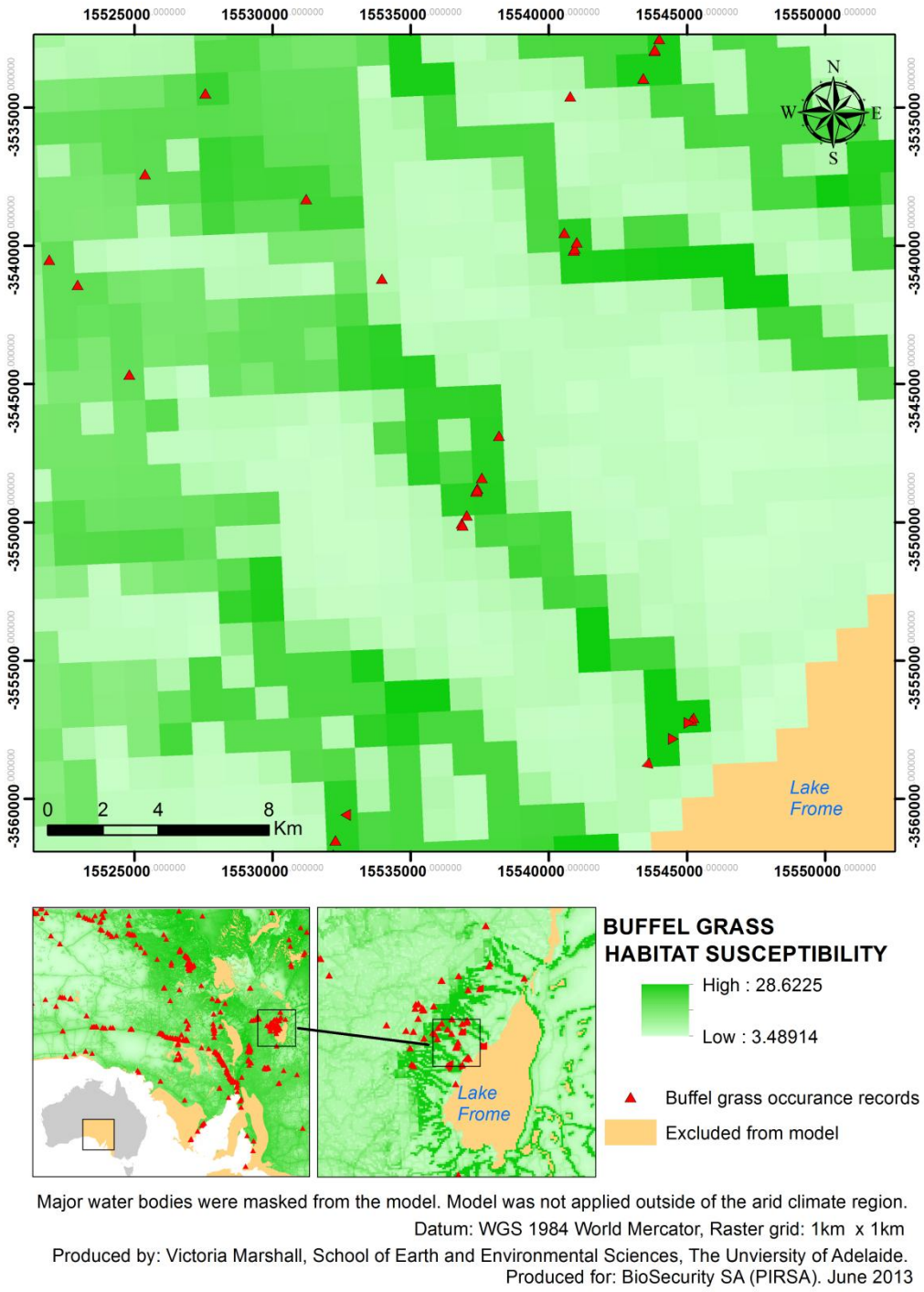

Figure 7 Buffel grass landscape/ habitat susceptibility "Sum of weights" normalised from 1 (low) to 10 (high) representing likelihood that the landscape would be susceptible to Buffel grass invasion. An area of "high susceptibility" near Lake Frome is more closely examined to reveal that high susceptibility area is primarily restricted to creek lines. To indicate accuracy Buffel grass occurrence records collected from various sources (Rural Solutions SA surveys, Biological Survey of South Australia, local government and NRM) are overlayed.

4.3 Conclusions, Recommendations and Future Outlook

Invasive plants such as Buffel grass pose serious threat to ecological, environmental and cultural values of infested regions. Spatially explicit predictive habitat models are desired to prioritise regions for surveillance and control. Non-mathematical invasion risk frameworks that could be implemented by non-experts are preferred. However, these mechanistic-type models are typically less regionally accurate than empirically based models. We present a hybrid mechanistic- empirical model of habitat / landscape susceptibility to Buffel grass incursion. Management recommendations, model limitations and key findings are summarised below.

Buffel grass management

- Modelling shows that the entirety of arid South Australia could support Buffel grass establishment. Sites most susceptible to Buffel grass invasion include the Stony Plains, Arcoona Plateau and the Simpson Desert, particularly drainage lines within these units. Sites least susceptible to invasion include the Eastern Maralinga / Great Victoria Desert, and western portion of the Murray Darling Basin, away from roads and drainage lines.
- Regions where drainage lines intersect rights of way such as rail, and road should be focal points for management
- Maps should be used interactively or reproduced at larger scales for full benefit of predictions at regional scales: “zoom in”. To obtain optimal contrast in graduated display of suitability/ introduction pathways/ susceptibility, when viewed in ArcGIS the recommendation is to set Properties > Symbology> Statistics > From current display extent> Standard deviations (2)

Limitations and future development of the models

- The introduction pathways map is a generic GIS-based model incorporating distance to roads, major roads, water courses, towns and railroads that presents a sort of worst case scenario of areas where Buffel grass could be introduced. This model would have relevance for any invasive weed that spreads in the same method as Buffel grass: along roads and waterways and promoted by disturbance. This model could be significantly improved by inclusion of additional variables such as traffic volume indicators, road surface type, town population sizes, grazing / cattle movement (and for that matter – camels, donkeys, etc), heavy traffic movement and fire. Another consideration may be direction of flow in the drainage lines.
- Distance to Source (current known populations of Buffel grass) is a critical introduction pathway, which should be incorporated in future. Considerations for including distance to source as an introduction factor are that it limits the lifespan of the map; it may need updating

annually. The question also arises of how seed spreads from the source; in that sense, it is a slightly different concept to an introduction pathway.

- This introduction pathways model has unlimited distances associated with seed spread away from introduction pathways. We chose not to limit the distance from pathways because potential for spread by wind is an unknown. However, a distance threshold is worth considering
- The impact of duel inclusion of distance to water ways on the final model is unknown, it may be worth exploring if waterways are being overemphasised in the final model
- Both the suitability and susceptibility models are likely to have lower predictive strength with increasing distance from the presence/absence data source: the 2010 roadside survey.
- In case it is noted that there is opportunistic occurrence data throughout the state, and the question of why this data was not used arises. The reason is that for generalist species (species like Buffel grass that can grow almost everywhere) presence-based models are less effective – effectively because every environment is suitable.
- We used an additive logistic regression analysis to construct our suitability model. It returned strong overall performance figures (AIC ~ 600). However, improvements could be made. For example would be interesting to look at interactions between the variables (multiplicative model)
- Accuracy assessments should be performed on the spatial suitability and susceptibility models
- The greatest limitation to the final model is data availability and resolution. In particular, a higher resolution soils dataset is desired. In the present model, known Buffel grass favoured alluvial soil types are not represented.

Considerations for future application for the modelling framework

- Resulting from our conundrum of whether to include distance to water as an introduction pathway, establishment criteria or both, we suggest developing protocol for scenarios where key environmental variables could be incorporated as any of the three phases of invasion.
- It is worth recognising that ecological processes operate at different scales and as such we recommend that for use in mechanistic modelling, where expert opinion is being used to construct environmental thresholds for invasion risk, that a method be developed for geo-coding / spatially referencing expert opinion. Certainly consideration of the climatic zone where the observation was made should be a consideration for state-wide models
- The introduction pathways model has potential application for risk assessment of numerous species that spread and disperse in the same way as Buffel grass.

- The modelling framework may present challenges for species which spread and disperse via mechanisms which are challenging to quantify and apply spatially, such as wind dispersed species.
- In this study a hybrid empirical – mechanistic model is applied. It will be worth investigating the validity of this methodology via comparative accuracy assessments of spatially explicit models if intended for continued application.

Conclusions

This report delivers three spatially explicit models of introduction pathways, habitat suitability and landscape susceptibility to Buffel grass invasion. The models are best viewed interactively in a GIS environment as regional detail is lost at the state wide scale. Drainage lines appear most susceptible to invasion, and areas where roads intersect drainage lines should be monitored closely. The theoretical framework proposed by Smith et al. (2012) represents a useful structure upon which to model landscape susceptibility, and although intended for mechanistic modelling, functioned for the hybrid empirical model presented here. For future application of this framework it will be useful to develop protocol for spatially referencing expert opinion and handling of duplicate input variables across the three invasion phases.

5. REFERENCES

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6. APPENDIX

"Mapping, modelling and remote sensing Buffel grass infestation in arid Australia"

Ph.D Thesis Abstract of Victoria Marshall submitted March 2013

Invasive plants pose serious threat to ecological, environmental and cultural values of infested regions and can be costly to control. Grass invasions are particularly concerning because they can alter wildfire regimes and change ecosystem function and structure at a global scale. Mapping, monitoring, and understanding invasive species ecology sufficiently to identify habitats prone to invasion are important for containment of the invasive plant. To this effect, remote sensing and spatial information science can be useful.

In arid and semi-arid rangelands worldwide, African perennial Buffel grass has been introduced to improve pasture. However, it has become contentious because it can rapidly invade and transform non-target landscapes. Most research into Buffel grass relates to its agricultural uses, and little is known about the invasive ecology of the species. There is a need to consolidate existing knowledge, as well as, map the current distribution, model the potential distribution and improve efficiency in the detection of new infestations in remote landscapes. This research addresses these needs by developing and applying techniques from the spatial sciences to map and model Buffel grass distribution in remote, arid Australia.

For controversial invasive species, like Buffel grass, raising awareness about the ecological dangers of allowing spread to continue unchecked is important. Here, a new, comprehensive review is presented of the ecology, distribution and biodiversity impacts of Buffel grass when behaving as an invasive species. Importantly, this review also lays foundations for research into localised habitat requirement, setting the scene for subsequent components of this research. Research reveals temperature is a primary limitation to distribution at a global scale, soil texture may be a significant habitat parameter at localised scales and disturbance is required for seedling emergence. It is strongly suspected that Buffel grass fuelled fires are responsible for declining numbers of characteristic arid plants, the Saguaro Cactus (Arizona, USA) and the River Red Gum (Australia) and that worldwide, arid landscapes stand out as requiring urgent control.

The distribution of Buffel grass in invaded landscapes in arid southern Australia is not explicitly known. Over 3800 km of South Australian roads

were surveyed to document current Buffel grass distribution in collaborative work with government. The grass was found to be wide ranging along major highways, but was mostly only sparsely distributed.

Empirical modelling of species distribution helps identify local environments that may be prone to invasion, and is becoming an increasingly important step in effective management planning. Buffel grass roadside survey data was used in an exploratory regression analysis to identify environmental parameters of the species distribution across regional South Australia. “Roadside” populations were recorded separately from “naturalised” populations and considered as separate dependant variables for predictive modelling. Model comparisons show distance to towns and climatic covariates are the strongest contributors to “Roadside” distribution and that occurrence at the roadside is the strongest contributor to the distribution of “Naturalised” populations away from the road.

Remote sensing presents as an ideal mode for mapping and monitoring invasion as it affords a landscape scale view and can be cost effective compared with laborious field work. However, it is challenging to implement because of the overall similarity of the spectra of different grasses and variability of Buffel grass stands, and photosynthetic status within the species stands over space and time. In this thesis, Buffel grass discrimination is trialled using high spatial resolution satellite imagery and aerial photography. Multispectral (8-band) satellite imagery (2 m GSD), Worldview-2 was found to effectively map dense infestations, however for early detection of emerging infestations, it is shown that aerial imagery with no less than 5-6 cm spatial resolution is required.

Presented in this thesis are tools needed to mitigate Buffel grass spread in arid Australia, including maps of present distribution, techniques for mapping and monitoring invasion over time, and an understanding of the species ecology as an invader to predict regions vulnerable to infestation. The methodology for roadside survey which makes the data more applicable to landscape-wide predictive habitat modelling could be adopted for any species where roads are considered a vector for spread. The research has important implications for Buffel grass management in regional arid Australia, and also for understanding the exotic distribution of Buffel grass worldwide. For detection of emerging Buffel grass infestations at a regional scale, aerial survey is recommended. Use of satellite imagery for monitoring of larger infestations is one area for future research.