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SCIENCE DIRECTORATE

Tetratheca erubescens Habitat Study

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Executive summary

Cliffs Asia Pacific Iron Ore Pty Ltd (Cliffs) commissioned Kings Park Science in January 2015 to undertake an investigation into the distribution and habitat of *Tetratheca erubescens* J. P. Bull (Elaeocarpaceae) based on desktop modelling and field survey.

Tetratheca erubescens is a threatened (DRF) plant species restricted to the southern Koolyanobbing Range where approximately 6,300 individuals occur in a single population split into four 'groups' that extend over an area of approximately 1.6 x 0.4 km. The species grows almost exclusively on ironstone 'cliff face' habitat and the extent of cliff habitat occupied by *T. erubescens* totals approximately 1.6 km of cliff line and an area of occupancy of approximately 3.5 ha.

The objectives of this study are to further characterise the habitat in which *T. erubescens* currently occurs; and to develop a "first-pass" model for the purpose of predicting where *T. erubescens* could potentially occur elsewhere across the Koolyanobbing Range.

The study developed models of the environmental parameters associated with the distribution of *T. erubescens* and projected this model across an area of 30 x 30 Km around the Koolyanobbing Range to identify locations where *T. erubescens* could potentially occur. Environmental parameters slope angle and elevation (interpreted as a proxy for ironstone substrate) successfully modelled the distribution of *T. erubescens.*

Almost two thirds of cliff line habitat predicted with the highest likelihood of supporting *T. erubescens* population (model likelihood 0.6 – 0.78) within the 30 x 30 km projection area did support *T. erubescens* plants, and three quarters of *T. erubescens* occurrences were within these most highly predicted areas.

All but 200 m of the 1.9 km of ridge or cliff line habitat that was most highly predicted (model likelihood 0.6 – 0.78) for *T. erubescens* occurrence was located in the vicinity of the existing population. Within the region of the fragmented *T. erubescens* population, 550 m of this most highly predicted habitat is unoccupied.

The study undertook field survey of highly predicted but unoccupied habitat, and of occupied habitat to identify if differences in any easily observed site features might correlate with the difference in occupancy. We surveyed 19 continuous and seven categorical variables relating to geomorphological, substrate, slope soil and vegetation attributes at 372 points on 56 transects.

On average, unoccupied sites had slightly lower slope angles and rock cover and greater soil depth and plant cover than occupied sites. They also were significantly more likely to include hillslope and talus features and less likely to be cliff features, they had more locations with soil, and that soil was more likely to be visually assessed as mineral rather than organic.

The environmental differences observed likely correlate with other plant-relevant soil, biotic or microclimatic interactions that are more likely to be the proximate drivers of species distribution limits. Further research could better characterise substrate structural or hydrological differences, but ultimate testing of these hypotheses is best performed through formal experimentation, including translocation research.

Introduction

Following discussion in December 2014 Cliffs Asia Pacific Iron Ore Pty Ltd (Cliffs) commissioned Kings Park Science (KPS: January 2015) to undertake an investigation into the distribution and habitat of the Rare Flora species *Tetratheca erubescens* J. P. Bull (Elaeocarpaceae) based on desktop modelling and field survey.

Tetratheca erubescens was first discovered in 2002 and formally described five years later (Bull 2007). Its conservation status is Threatened Flora (Declared Rare Flora) under the *Wildlife Conservation Act* (1950). The species is now well surveyed (Maia Consulting 2013). Its distribution is restricted to the southern Koolyanobbing Range where approximately 6,300 individuals occur in a single population split into four 'groups' that extend over an area of approximately 1.6 x 0.4 km. As part of their 2013 census, Maia Consulting recorded the landscape form on which *T. erubescens* individuals were found, reporting that the species grows almost exclusively on ironstone 'cliff face' habitat (89% of individuals), about 8% occur on 'Boulder' habitat and 1% or less in 'Base of Cliff', 'Rocky slope' and 'Rock cavity' habitats (Maia Consulting 2013). The extent of cliff habitat occupied by *T. erubescens* totals approximately 1.6 km of cliff line and an area of occupancy of approximately 3.5 ha.

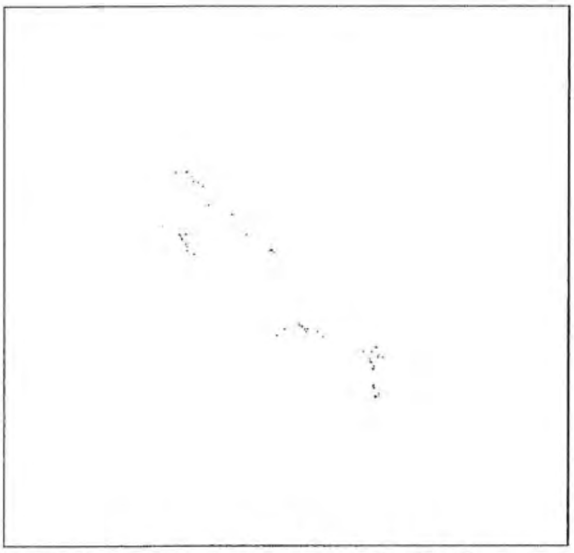
The objectives of this current study are to further characterise the habitat in which *T. erubescens* currently occurs; and to develop a "first-pass" model for the purpose of predicting where *T. erubescens* could potentially occur elsewhere across the Koolyanobbing Range.

Tetratheca erubescens growing in cracks in ironstone substrate on the southern Koolyanobbing Range

Cliff habitat of *Tetratheca erubescens* on the southern Koolyanobbing Range

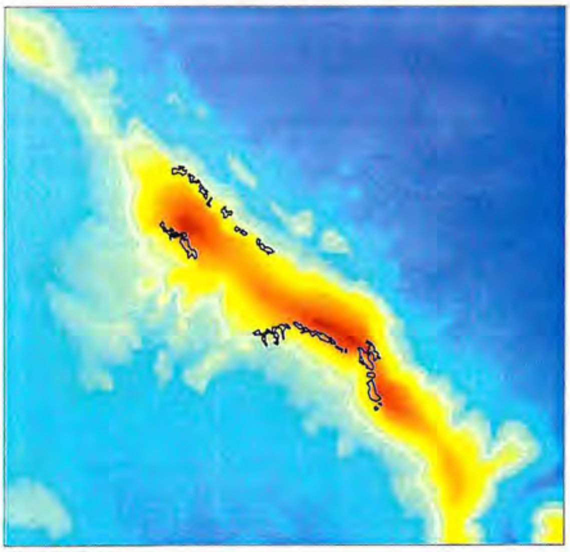
Methods

The study included two phases. The first involved modelling the distribution of *T. erubescens* in relation to derivable mapped environmental variables. This modelling had the following objectives: identifying landscape drivers of the distribution of *T. erubescens*, and, by extrapolating the model across a larger region, identifying locations outside of the current distribution that (according to the model) would be most likely to support translocated populations of *T. erubescens*. The study's second phase involved field survey of habitat attributes of unoccupied locations that were highly predicted by the model as *T. erubescens* habitat, as well as locations where *T. erubescens* does occur, with the aim of identifying local or site factors that might correlate with, and hence potentially explain, the presence and absence of *T. erubescens* within the Koolyanobbing Range.

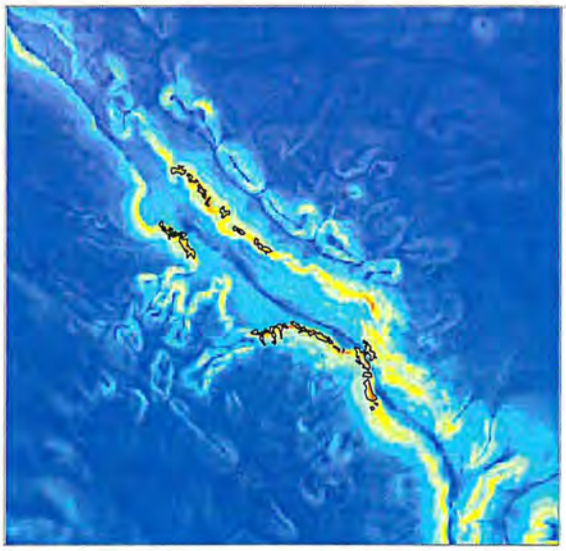


Distribution of *T. erubescens* (area = 3 x 3 km)

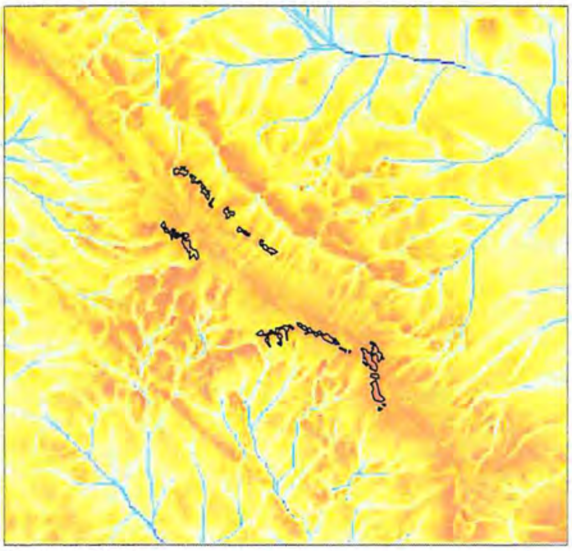
Detail of northern distribution (0.6 x 0.6 km)



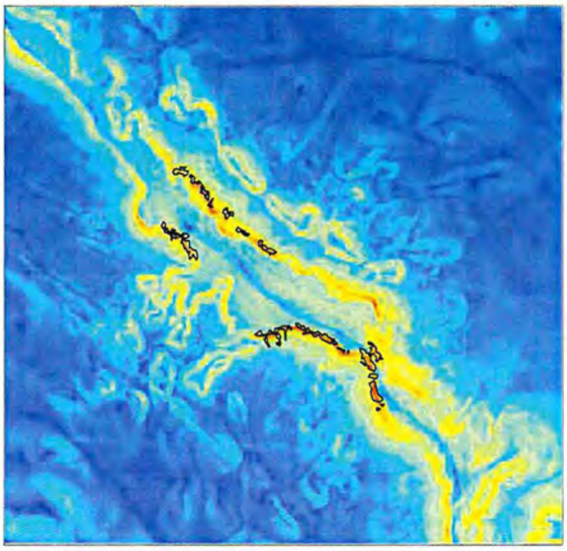
Elevation



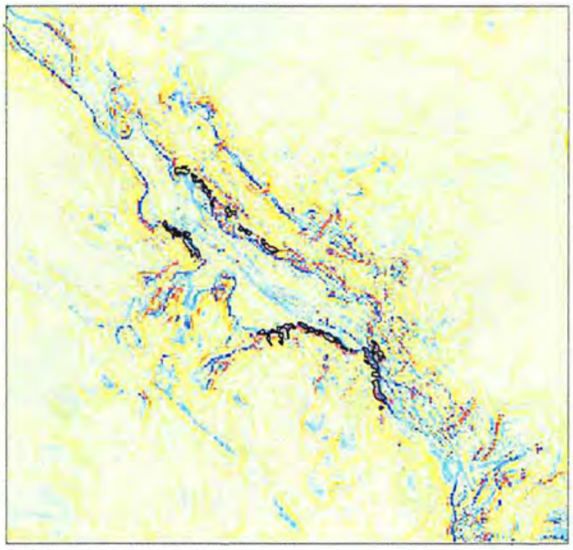
Slope



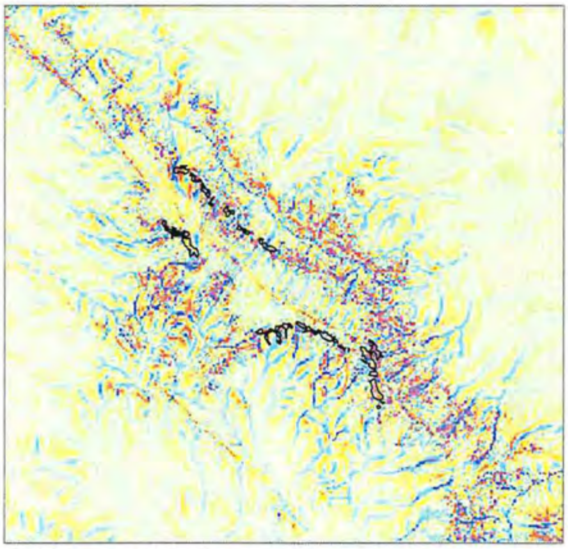
Wetness index



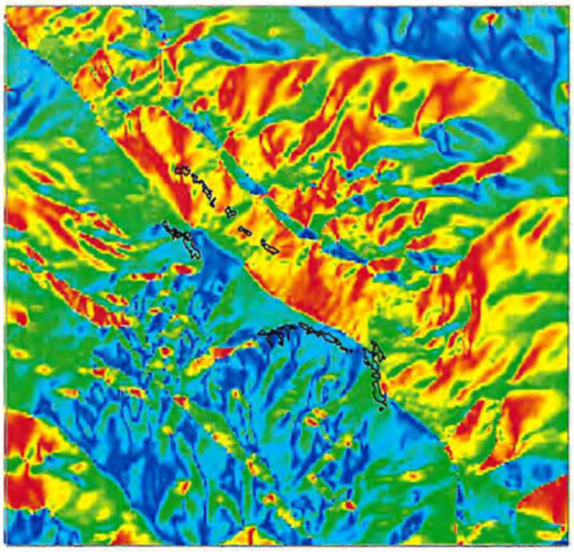
Roughness



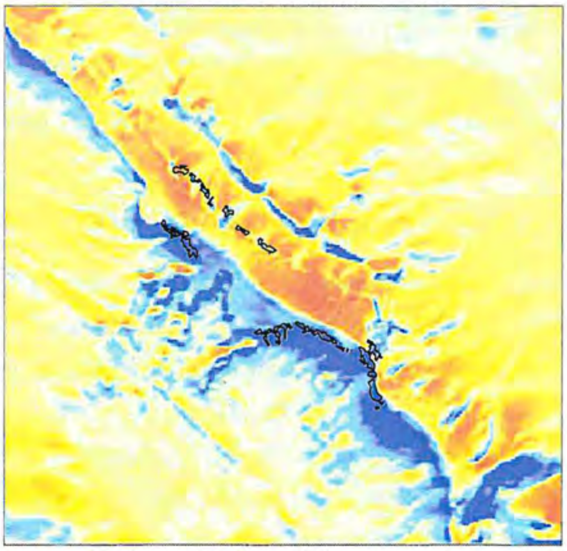
Curvature down slope



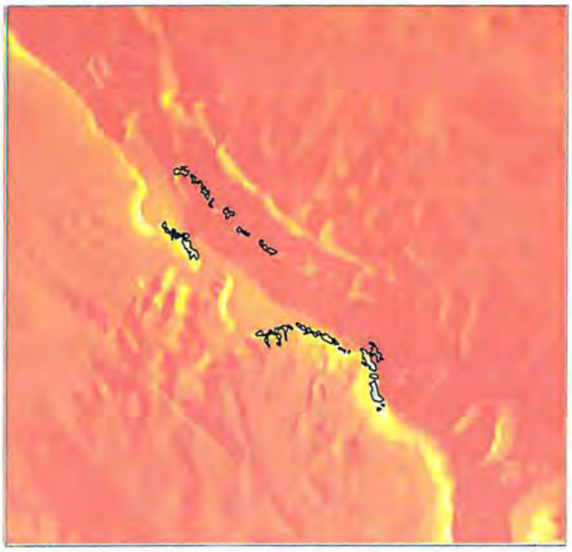
Curvature across slope



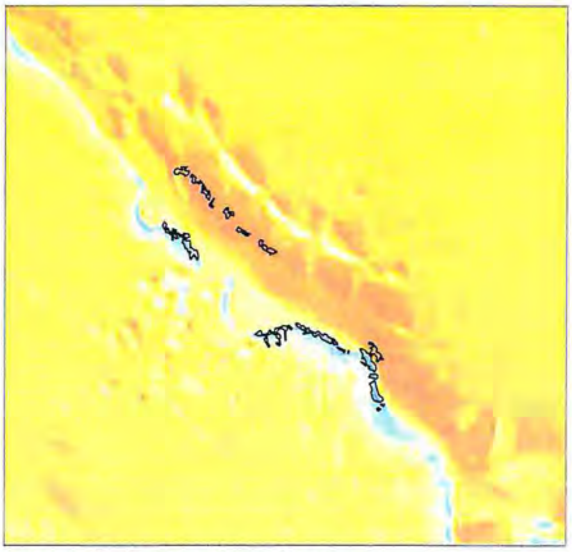
Aspect



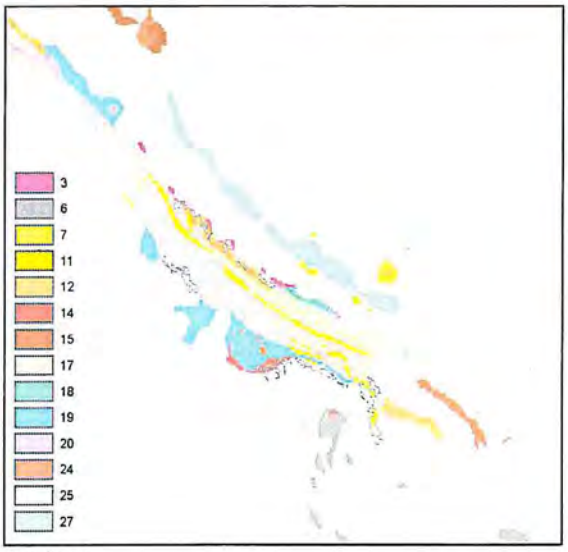
Solar radiation: annual monthly average



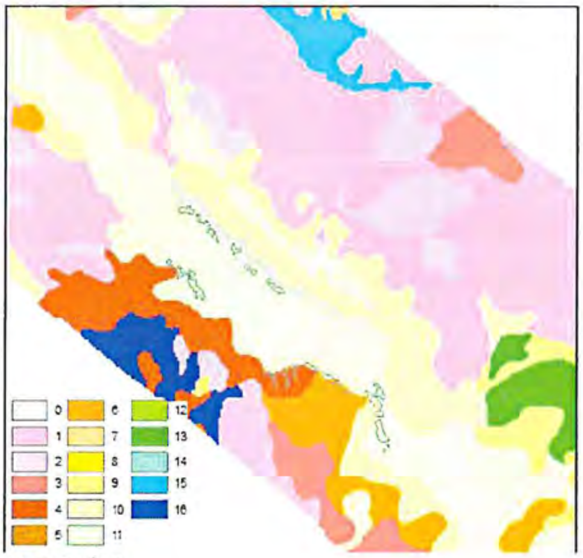
Solar radiation: Summer solstice, 10 am



Solar radiation: Equinox, 10 am



Geology



Vegetation

Figure 1. The data used as model input. Top row: Presence-absence data showing GPS points in a 1 x 1 m grid (pink squares). Grey/black lines visually delineate groups within the population. Other rows: spatially explicit environment data. Note white space in the Geology and Vegetation layers represents no data available (see appendix 1 and appendix 2 for geology and vegetation codes).

Correlative Distribution Modelling and Interpretation

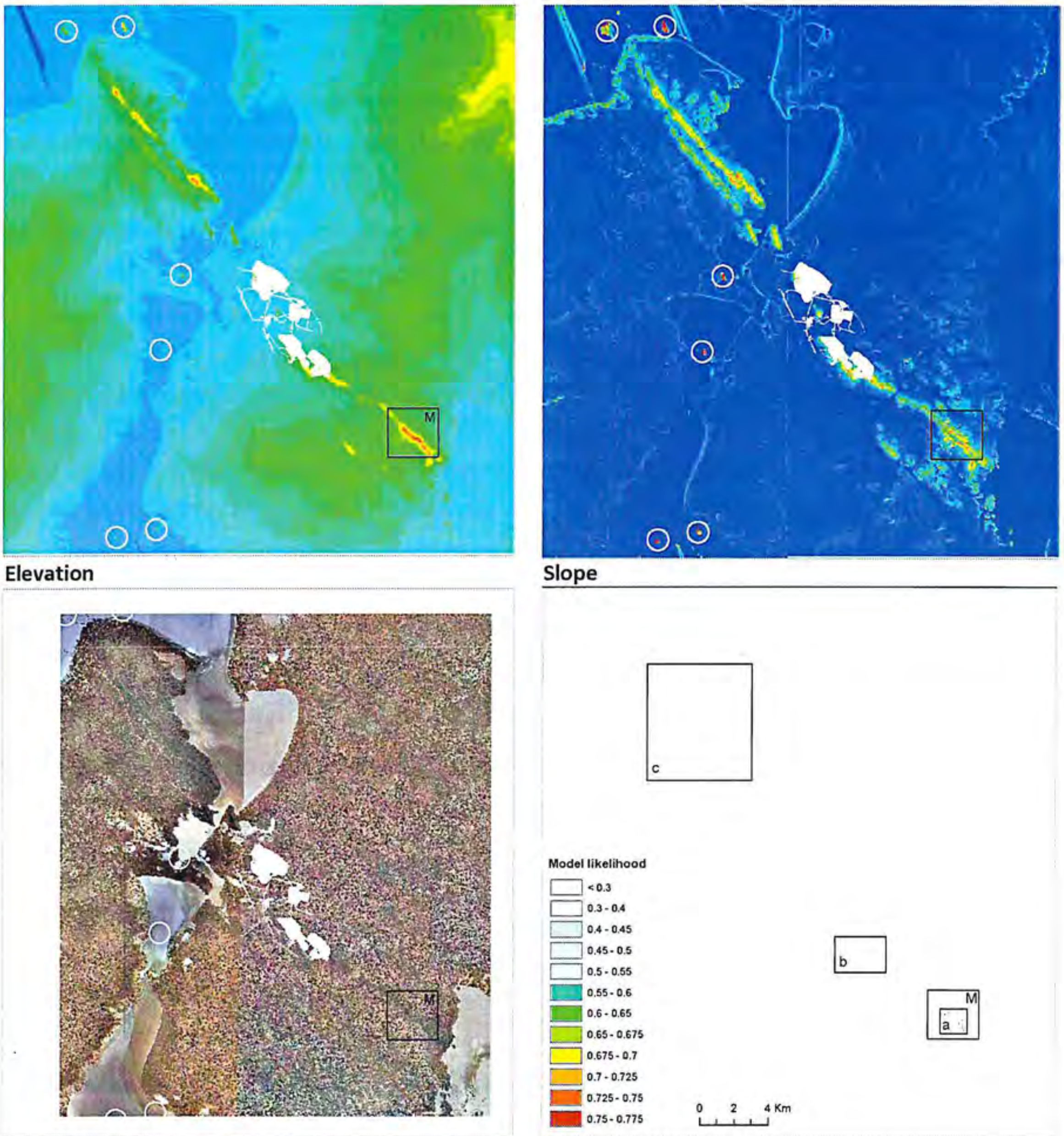
We used the maximum entropy algorithm implemented in MaxEnt version 3.3.3a (Phillips et al., 2006; Phillips and Dudik, 2008) to model the local distribution of *T. erubescens* within the southern Koolyanobbing Range. Site-specific climate and environmental ('background') variables were obtained on a 10m grid scale for a 3 x 3 km area around the mapped species distribution. These included data for slope aspect, downslope curvature, curvature across the slope, total curvature, elevation, geology, slope angle, landscape roughness, topographic wetness index, annual average monthly solar radiation, and solar radiation at both solstices and equinox, measured at 10am and

2pm, and vegetation classification. Maps of most of these variables are shown in Figure 1 for the modelling area. These data were supplied by CAD Resources and the definitions of these variables and their derivation can be found in Appendix 1. Presence-absence data used as model input was based on the GPS records of individual locations from the Maia (2013) survey converted into a binary presence absence value in a 1 x 1 m grid (also shown in Fig 1).

In order to avoid over-fitting in our models (Beaumont et al., 2007), we restricted our backgrounds to variables known to have physiological significance to plant survival, and based upon their representative importance in preliminary models of all environmental variables. Within this restricted set of variables, tests of linear correlation were conducted using the base-level statistical packages in R version 3.0.3, and subsequent linear models of presence constructed using only permutations of uncorrelated variables. These linear models were compared in R version 3.0.3 using the AICcmodavg (Mazerolle, 2013) package. We eliminated geology, despite its importance in the most informative models, on the basis of its incompleteness, being focused on ridgelines and the locally associated formations, and lacking information for other areas, including locations of *Tetratheca erubescens* presence records (Fig 1).

The final selected model was projected (extrapolated) from the 3x3 km modelling area to a 30 x 31 km ('projection') area based on the same environmental data layers mapped at the same resolution (Fig 2). This projection provided a map of modelled likelihood of occurrence across an area that included the entire length of the Koolyanobbing Range (comprising the northern Koolyanobbing Range and the southern Koolyanobbing Range). Some data artefacts are apparent in the projected area data (Fig 2), but appear in locations that do not interfere with output interpretation, i.e. they are either of low intensity or unambiguously intense and distinctly out of place in salt lakes. The ultimate source of these artefacts is unclear, they first arise in the DEM data and suggest the presence of significant topographic features in places that in reality are featureless salt flats. Perhaps salt reflectance creates problems for image sensors that result in features being interpolated where none exist. However, the ultimate cause of these artefacts is not relevant here, but their restriction to salt lakes is, as it facilitates their interpretation and clear recognition as artefacts and permits us to confidently ignore them in model interpretation. All other sites of high elevation and/or slope outside of salt lakes in the projection area are confirmed as real features.

We used the default MaxEnt parameter settings (maximum number of background points 10,000; regularization multiplier 1; auto features; maximum iterations 500; convergence threshold 0.00001 and duplicate records deleted) to develop logistic likelihoods of occurrence, ranging from zero at the lowest likelihood of presence to one at the strongest prediction for presence (Phillips, 2008). We applied the 10th percentile training presence (10%), which omits the 10% most extreme presence observations in order to more accurately represent the 'core of the species present range' (Morueta-Holme et al., 2010), and also placed a 10% test presence. To explore the patterns of extrapolation in the resulting model projection, we measured similarity based on the Mahalanobis distance using the ExDet tool (Mesgaran et al., 2014) to compare the model backgrounds with the projection to the wider project area.



Elevation **Slope**

Satellite image Spring 2001 **Model projection**

Figure 2. The 30 x 31 km projection area in relation to: **(top left)** Elevation data. The highest point of the Koolyanobbing Range is just over 500 m asl, salt lakes are ~350 m; **(top right)** Slope angle; **(bottom left)** 2001 satellite mosaic (the image coverage is incomplete at edges); **(bottom right)** Projected likelihoods of occurrence from Maxent modelling of *Tetratheca erubescens* (likelihoods <0.3 are white: see figure 3 for greater detail of projected areas). The box marked 'M' on each chart is the 3 x 3 km modelling area of the southern Koolyanobbing range, corresponding to Figs 1 and 5. Boxes 'a', 'b' and 'c' on the projection map identify three regions with high predicted likelihoods corresponding to Fig 3a, Fig 3b and Fig 3c. Regions modified by mining activity are indicated with white shading on all figures. White circles indicate the locations of six pure data artefacts within the Lake Deborah East salt flats that derive from the DEM data that underlies all topographic layers. These artefacts indicate steep pinnacles or long troughs within the salt flats which are, in reality very flat and featureless, the artefacts do not represent real features and are ignored in model interpretation.

Habitat Field Survey

The final modelled and projected outputs were examined to identify locations with the highest predicted likelihood for the occurrence of *T. erubescens*. These locations are shown in Figures 2 (overall) and 3 (in detail). The maximum modelled likelihood found in the modelled area was p = 0.78, in the remaining projected area the highest modelled likelihood was p = 0.68. Field survey was then undertaken for three landscape classes with respect to observed and predicted areas:

1. areas that did contain populations of *T. erubescens* ('in' sites: usually, but not necessarily with high predicted likelihoods);
2. areas immediately adjacent to populations, but where no plants occurred ('out' sites, usually, but not necessarily with lower predicted likelihoods), and;
3. sites with high predicted likelihood of occurrence, but away from known populations ('away').

Data on environmental attributes was collected within each of these site types on 2.5 m interval transects of varying length that ran downslope through (or out from) each identified site. In addition,

4. the same data was collected from points associated with the position of the *T. erubescens* plant ('plant') closest to each 'in' transect point.

This approach allowed comparison of the attributes of occupied and unoccupied habitat, to identify: A) if attributes of the points of emergence of *T. erubescens* plants differs from the general habitat in which they occur (comparing types 1 and 4); B) what features correlate with the boundaries of populations (comparing types 1 and 2), and; C) whether predicted but unoccupied habitat differs from occupied habitat (comparing types 1 and 3).

Transects varied according to the size of the feature being measured, from 7.5 to 30 m in length. The number of unique sites (total 8), transects within sites (56) and points within transects (372) surveyed is shown in Table 1 and Figure 3.

Table 1. Number of unique sites, transects within sites and points within transects surveyed in four site types: (**out**) points on transects immediately adjacent to, but outside of the *T. erubescens* population; (**away**) points on transects in localities predicted to contain *T. erubescens*, but outside of the known distribution; (**in**) points on transects within the *T. erubescens* population, and; (**plant**) the locality of plants within the *T. erubescens* population being the closest plant to each point on the 'in' transect. Sites within the southern Koolyanobbing Range contained up to three types of transects, hence Total sites is not equal to the sum of sites for each site types.

	plants	in	out	away	total
Sites	4	4	3	4	8
Transects	16	16	9	15	56
Points	92	99	59	122	372

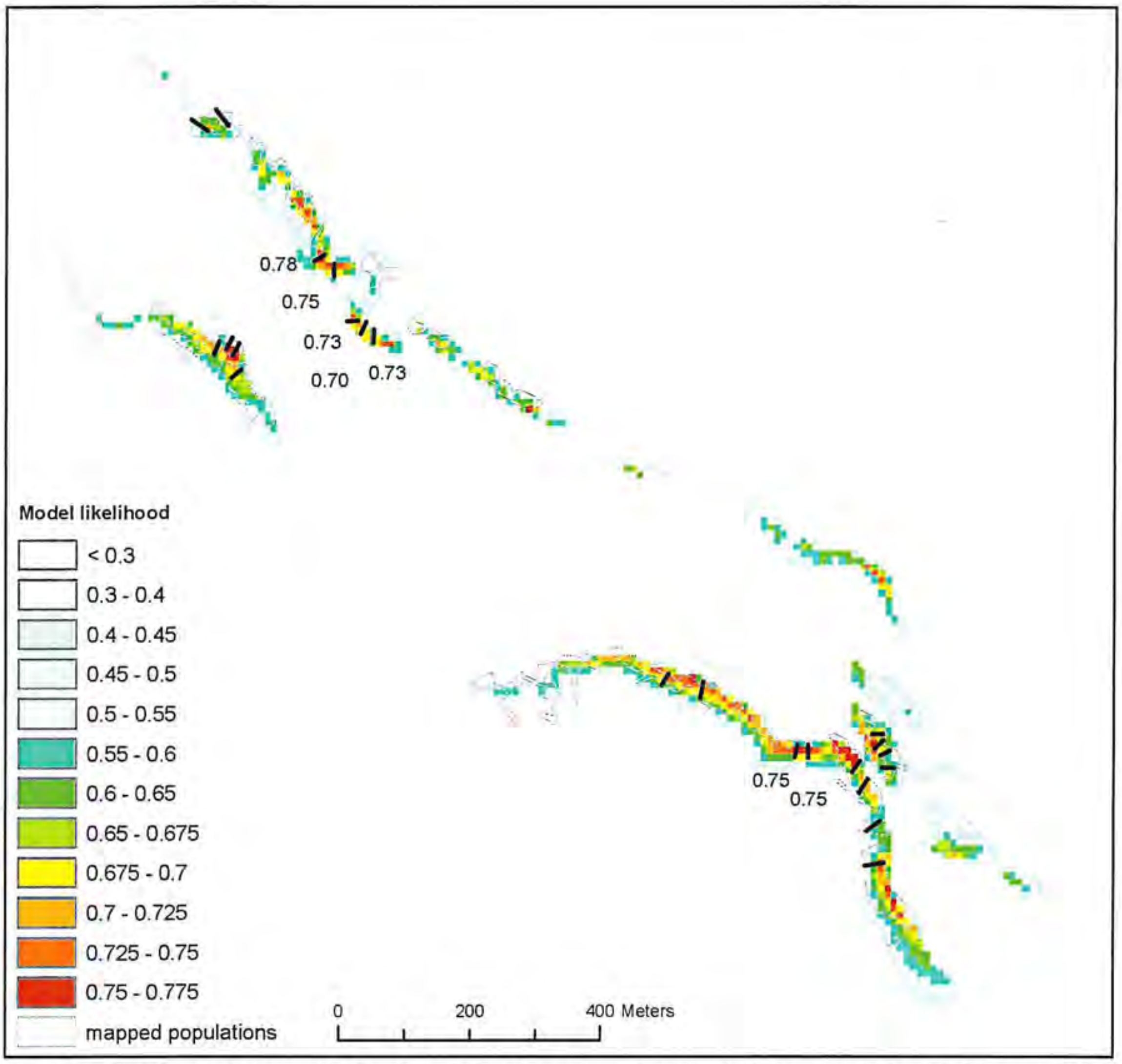
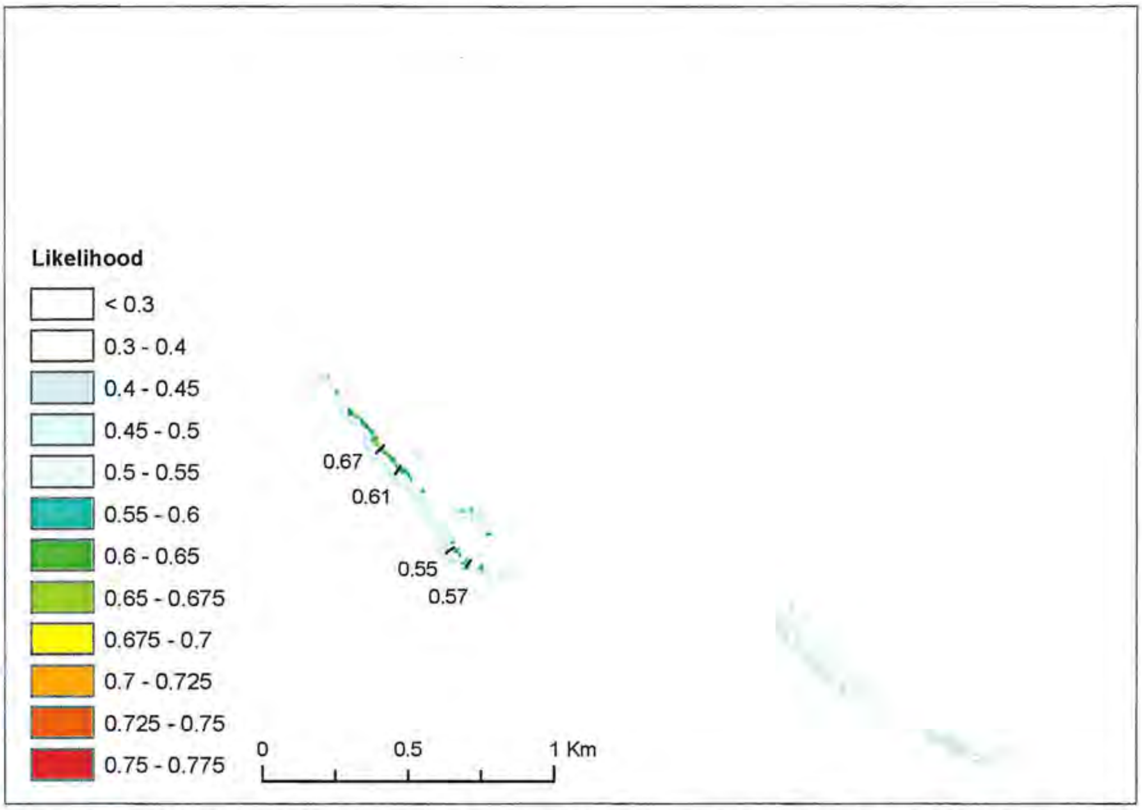


Figure 3a. Locations of transects (short black lines) surveyed in predicted areas and the existing population, both overlaying maxent model projected likelihoods for the region of the southern Koolyanobbing range where *Tetratheca erubescens* populations occur. Figures indicate model predicted likelihood for 'away' transects.



3b. Locations of transects (short black lines) surveyed in predicted areas within the southern Koolyanobbing Range close to Pits A-D. Areas disturbed by mining are shown in grey outline. Figures indicate model predicted likelihood for 'away' transects.

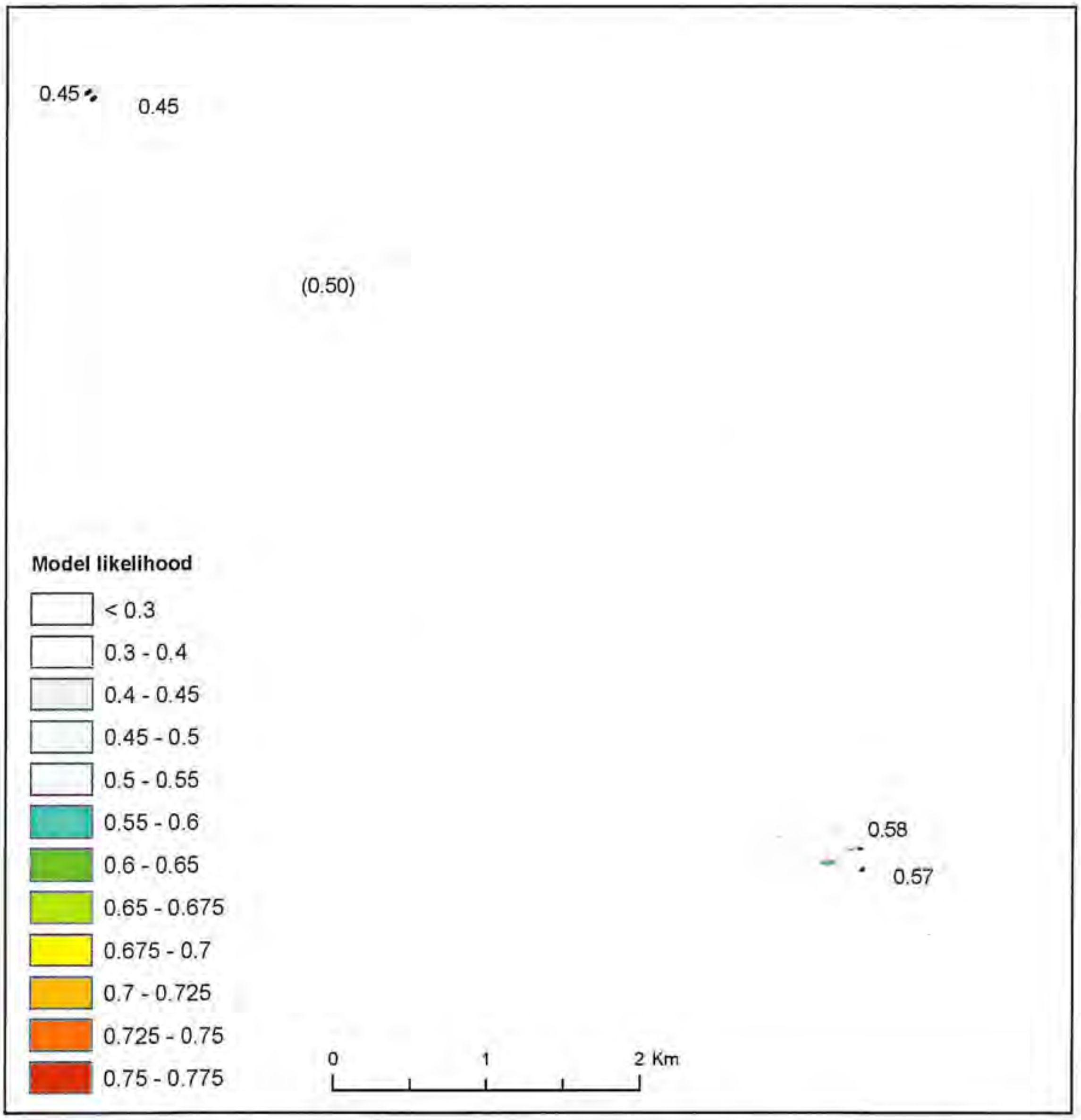


Figure 3c Locations of transects (short black lines) surveyed in predicted areas within the northern Koolyanobbing Range. Figures indicate model predicted likelihood in transects (one region that was not surveyed is shown with the maximum likelihood given in parenthesis).

The characterisation of sites was adapted and expanded from the methodology of Yates *et al.* (2008 Table 2.1) that was used for related *Tetratheca* species. Except for those noted, and where possible (i.e. soil depth not measured where soil was not present), we assessed each of the following parameters at each transect point and plant:

1. Landscape position (crest, upper slope, midslope, lower slope, drainage)
2. Transect slope angle (measured once with a clinometers for the entire transect)
3. Local slope trend (underhang, maximal, waxing, simple, waning, minimal, depression, Fig 4)
4. Local slope angle (measured with a protractor with bob)
5. Slope aspect (measured via compass)
6. Geomorphologic feature (ridge, tor, cliff, cliff foot, talus, hill slope)

7. Position within feature (top, upper, mid, low, base)
8. Substrate type (massive or nonmassive – largely determined by the presence of retained visible ironstone strata
9. Local geomorphologic feature (rock face or projection, slope soil, rock crack, bench in rock or slope)
10. Rock cover (estimated % in 1 m^2 around each point/plant)
11. Soil type (none, mineral, organic)
12. Soil depth (mean of five values - point + 4 cardinal directions @10cm; obtained by pushing a 1.8mm diameter wire rod perpendicularly on the ground surface and measuring depth of penetration)
13. Distance to nearest crack (mm; crack defined subjectively as a fissure or join in rocks where soil or plant roots might lodge)
14. Depth of nearest crack (mm; penetration of 1.8 mm rod)
15. Width of nearest crack (mm)
16. Estimated upslope local catchment area (cm, in 2 dimensions, converted to m^2)
17. Live plant intercepts directly above (counts in 4 classes; <50cm, 0.5-1 m, 1-1.8m, >1.8m)

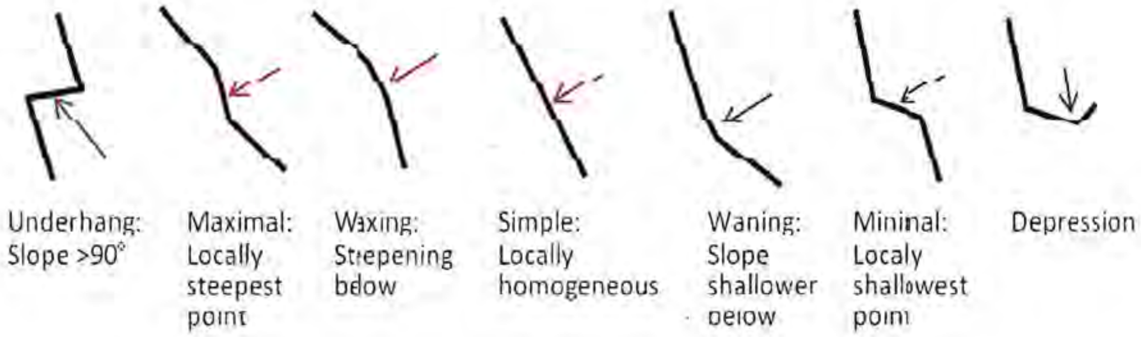


Figure 4 Local slope type. Arrows indicate assessed positions, red arrows indicate locally shedding slope types, blue arrows were considered to be relatively water capturing or receiving slope types

Differences between site types in quantitative variables were assessed via inspection of graphed means and standard errors, while differences in categorical variables were assessed via chi squared tests (G-tests).

Results

Distribution modelling

The final MaxEnt species distribution model obtained a high area under the curve (AUC) for *T. erubescens* (0.970) within the modelled (background) area. In theory, AUC can range between 0 and 1, but can only attain those values under exceptional situations. A value of 0.5 indicates that the model's selection of landscape regions is just as good as a random selection of the landscape in terms of differentiating presence and absence of target features. A very high AUC indicates that the model is very efficient at predicting occupied and unoccupied locations within the modelled environmental parameter space. The model predicted high likelihoods of occupancy for most sites where *T. erubescens* populations occurred (0.6 to 0.78), although individuals also occurred in locations with lower predicted likelihoods (to 0.1) (Fig. 5).

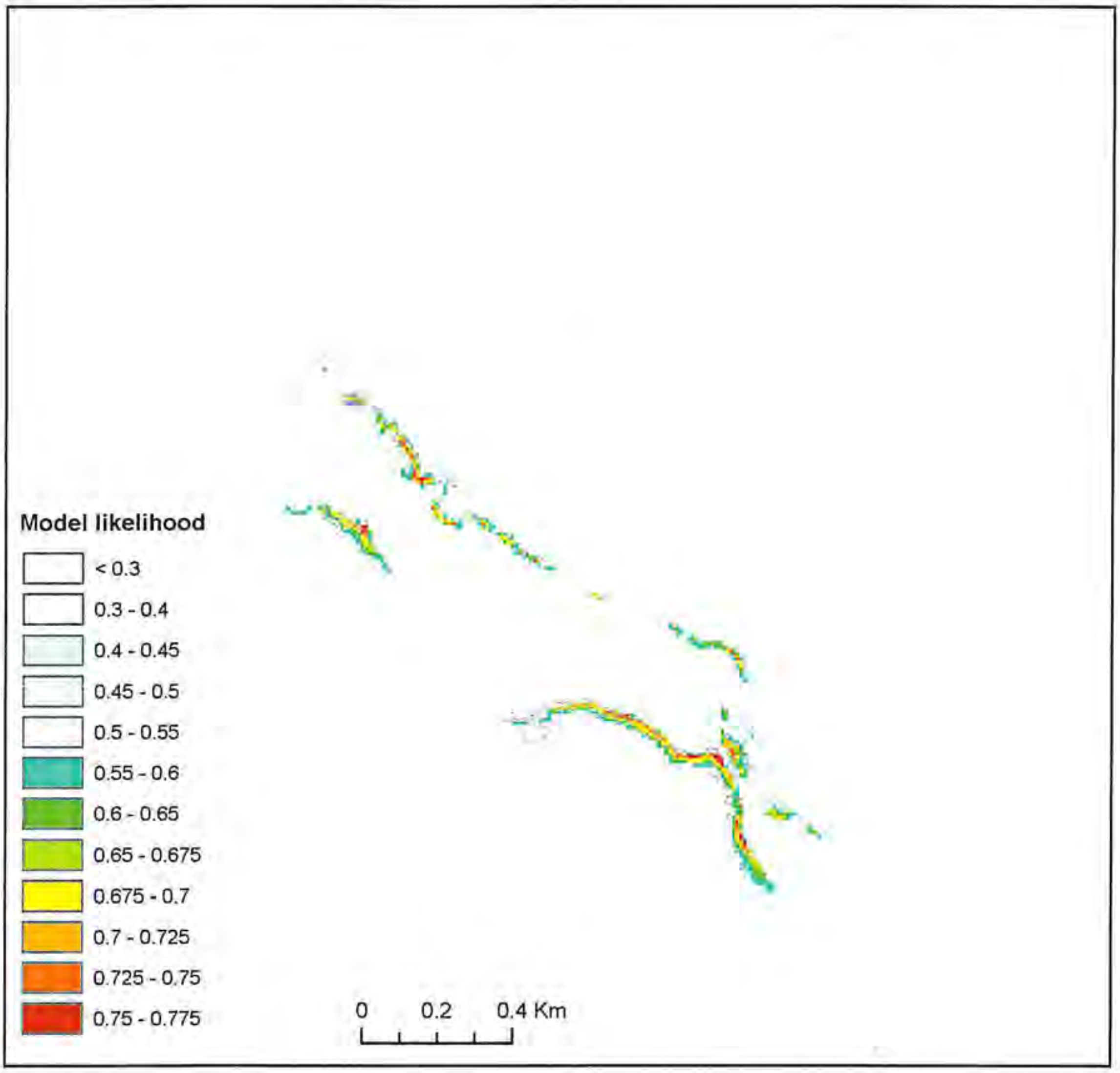


Figure 5. *Tetratheca erubescens* likelihood of occurrence for model 3 × 3 km modelled area, derived from Maxent model, with existing populations extents overlain using black polygons.

The final constrained model employed variables for elevation, slope, wetness index and solar radiation at summer solstice (at both 10am and 2pm). The last three variables accounted for just 6.4% of the model training gain and less than 2% of the training importance (Table 2).

Almost two thirds of cliff line habitat predicted with the highest likelihood of supporting *T. erubescens* population (model likelihood 0.6 – 0.78) within the 30 x 30 km projection area did support *T. erubescens* plants, and three quarters of *T. erubescens* occurrences were within these most highly predicted areas.

All but 200 m of the 1.9 km of ridge or cliff line habitat that was most highly predicted (model likelihood 0.6 – 0.78) for *T. erubescens* occurrence was located in the vicinity of the existing population. Within the region of the fragmented *T. erubescens* population, 550 m of this most highly predicted habitat is unoccupied.

Table 2: Relative contributions of the environmental variables to the final *Tetratheca erubescens* MaxEnt distribution model. Percent contribution is determined by the change in regularisation at each iteration. Permutation importance is determined as the percentage normalised change in the area under the curve as the value is randomly permuted

Variable	Percent contribution	Permutation importance
Elevation	58.1	69.6
Slope	35.8	28.5
Wetness	2.8	0.5
Solar Radiation summer solstice 10am	1.8	0.6
Solar Radiation summer solstice 2pm	1.6	0.7

Species Distribution Projections

When interrogated for patterns of novelty, the majority of the broader projection was found to occur within similar covariate space to that present in the modelled area, suggesting that projections were more reliably based in interpolation rather than extrapolation.

Projection of the final model to the wider project area (Fig 2) indicated the predicted areas for *T. erubescens* habitat fell into three general regions: 1) the northern Koolyanobbing Range where three isolated regions have predicted occurrence probabilities between 0.45 and 0.6 (Fig 3c); 2) localities on the south western face of the southern Koolyanobbing Range in the vicinity of Pits A-D with predicted likelihoods up to 0.675 (Fig 3b), and; 3) areas between known *T. erubescens* occurrences in the southern Koolyanobbing Range (up to 0.78) (Fig 3a). In total, these regions include 250 m of cliffs with highest quality predicted habitat (likelihood 0.7-0.78, all adjacent to the existing *T. erubescens* population at the southern Koolyanobbing Range), 500 m of ridges or cliffs predicted at 0.6-0.7 (including 200 m in the highest and steepest part of the southern Koolyanobbing Range outside of the area of the recorded *T. erubescens* population) and 1,120 m of habitat with 0.5-0.6 likelihood across both the southern and northern Koolyanobbing Range (Table 3).

Table 3 Size of occupied habitat and unoccupied habitat predicted by MaxEnt across projection region classified by prediction likelihoods. Habitat size is expressed in length of ridge (in m). Areas are calculated for different sections of the Koolyanobbing Range shown in Fig 3. The eastern section of the southern Koolyanobbing Range includes highly predicted areas that do and do not contain *T. erubescens* plants.

locality predicted likelihood	<0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8
Northern Koolyanobbing Range (Fig 3c)					
northern section		500			
central section		275			
southern section		600	120		
Southern Koolyanobbing Range					
western section (Fig 3b)		1,350	600	200	
central section (Fig 3b)		850			
eastern section (Fig 3a)		500	400	300	250
Total unoccupied	**na**	**4,075**	**1,120**	**500**	**250**
occupied (Fig 3a)	**40**	**100**	**260**	**500**	**670**
% occupied		**17%**	**39%**	**63%**	**73%**

Habitat attributes analysis

Many of the quantitative parameters surveyed were at least as variable within the four locality types as they were between locality types (Table 5, Figure 6). For these parameters, differences between locality types would not be significant. On the other hand, lower variability in some parameters did enable demonstration of differences between the locality types examined.

Table 5. Mean and Standard error of environmental parameters measured in four site types corresponding to: (**out**) points on transects immediately adjacent to, but outside of the *T. erubescens* population; (**away**) points on transects in localities predicted to contain *T. erubescens*, but outside of the known distribution; (**in**) points on transects within the *T. erubescens* population, and; (**plant**) the locality of plants within the *T. erubescens* population being the closest plant to each point on the 'in' transect.

site type	plant	in	out	away
Local slope (°)	44.9 ± 4.7	42.5 ± 4.4	20.5 ± 2.7	37.5 ± 3.9
Max local slope (°; per transect)	85.2 ± 3.1	75.7 ± 3.0	35.6 ± 1.9	70.6 ± 3.0
Soil depth at point (mm)	13.7 ± 5.3	5.1 ± 6.7	15.2 ± 6.8	8.8 ± 7.2
average soil depth (mm)	4.8 ± 3.2	4.5 ± 5.3	10.2 ± 3.5	5.6 ± 4.2
upslope catchment area (m^2)	0.02 ± 0.48	0.03 ± 0.52	0.02 ± 0.33	0.01 ± 0.31
distance to nearest crack (cm)	0.7 ± 4.3	36.9 ± 10.8	26.8 ± 11.4	23.4 ± 8.9
Crack width (mm)	37.4 ± 17.8	20.4 ± 10.7	17.4 ± 4.5	15.6 ± 4.9
Crack depth (mm)	28.4 ± 15	41.2 ± 16.5	33.0 ± 5.4	31.4 ± 7.5
Crack density (cracks per 50 cm)	3.1 ± 1.2	2.9 ± 1.4	3 ± 1.6	4.1 ± 1.5
% rock cover (in $1m^2$)	89.6 ± 1.3	87.4 ± 1.9	66.6 ± 2.8	79.8 ± 2.2
Plant cover (%cover)	75 ± 51	30 ± 84	39 ± 79	35 ± 81
excluding *T. erubescens*	19 ± 91			
mean live plant intercepts: Grand total	1.38 ± 0.92	0.63 ± 1.63	0.83 ± 1.57	0.81 ± 1.71
excluding *T. erubescens*	0.30 ± 1.26			
total <0.5 m	1.15 ± 0.86	0.24 ± 1.64	0.02 ± 1	0.14 ± 1.35
excluding *T. erubescens*	0.02 ± 1.00			
total 0.5-1 m	0.04 ± 0.98	0.06 ± 1.52	0.15 ± 1.41	0.13 ± 1.33
total 1-1.8 m	0.02 ± 0.99	0.04 ± 1.21	0.29 ± 1.86	0.11 ± 1.35
total >1.8 m	0.19 ± 1.22	0.29 ± 1.50	0.37 ± 1.32	0.43 ± 1.71

Local slope within the *T. erubescens* population averaged 43-45° and did not differ between random (transect) points, and points where plants were observed to be growing. Local slope in predicted but unoccupied localities averaged 37° and slope in transects immediately outside the *T. erubescens* population averaged 21° (Figure 6). Mean rock cover showed a similar pattern, averaging 87-90% in the population (transect points and plants), 80% in predicted localities and 67% in transects adjacent to the population.

Effectively all *T. erubescens* individuals surveyed occurred in cracks, other locality types did not differ substantially from each other in distance to cracks, averaging 23-37 mm. Similarly, live plant cover was always high where *T. erubescens* plants occurred, simply because of the presence of the *T. erubescens* plant itself. Removing this effect shows that plant cover is otherwise lowest where *T. erubescens* occurs (averaging 19%), even relative to random transect points within the *T. erubescens* population (30%). Predicted unoccupied sites and transects adjacent to, but outside of the *T. erubescens* population had 39-35% plant cover.

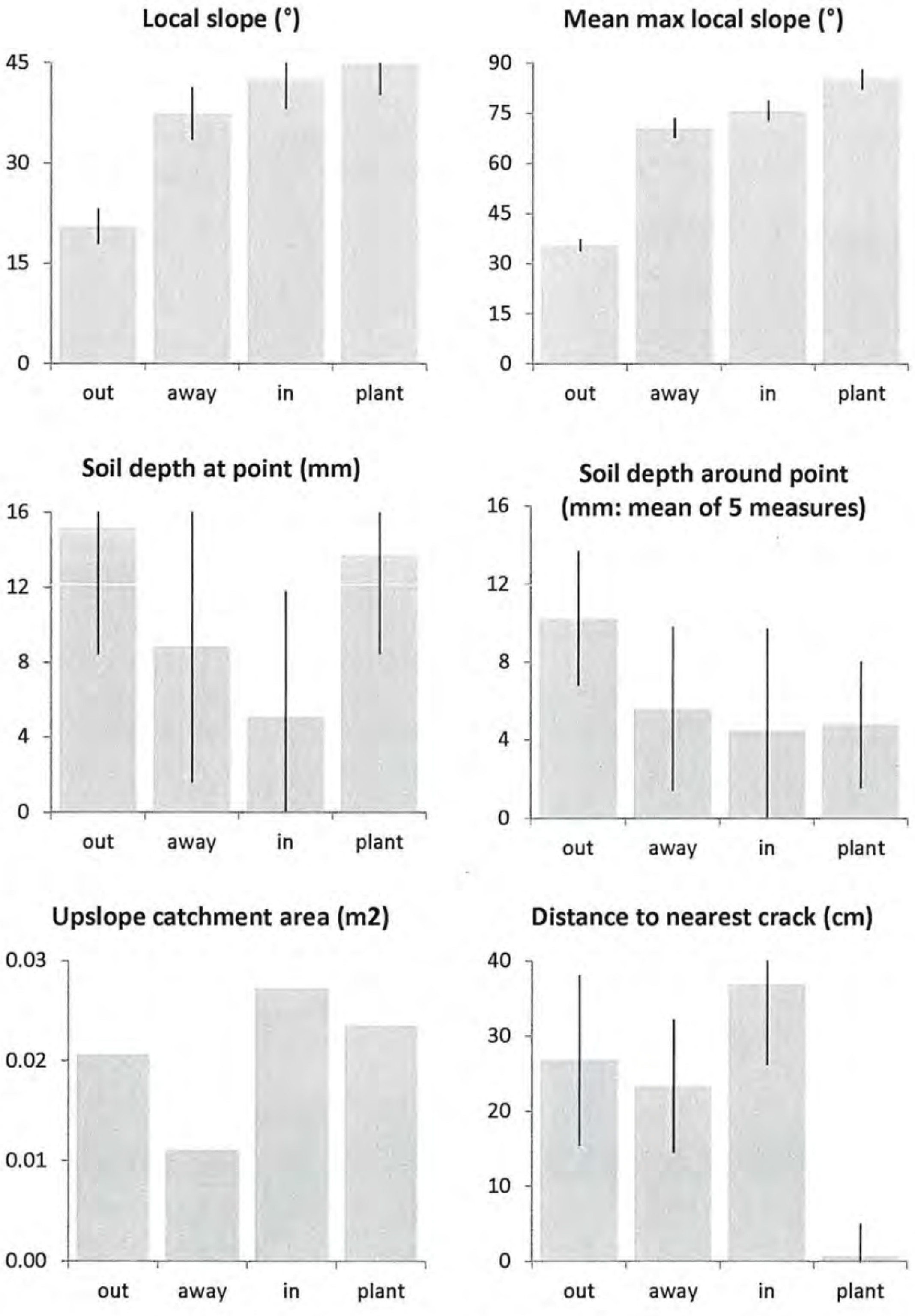


Figure 6a Mean (± standard error, if not excessive) of environmental parameters (slope, soil depth, relative catchment size, crack distance) measured in four site types: (**out**) immediately adjacent to, but outside of the *T. erubescens* population; (**away**) localities predicted to contain *T. erubescens*, outside of the population; (**in**) on transects within the *T. erubescens* population, and; (**plant**) the closest plant to each point in each 'in' transect.

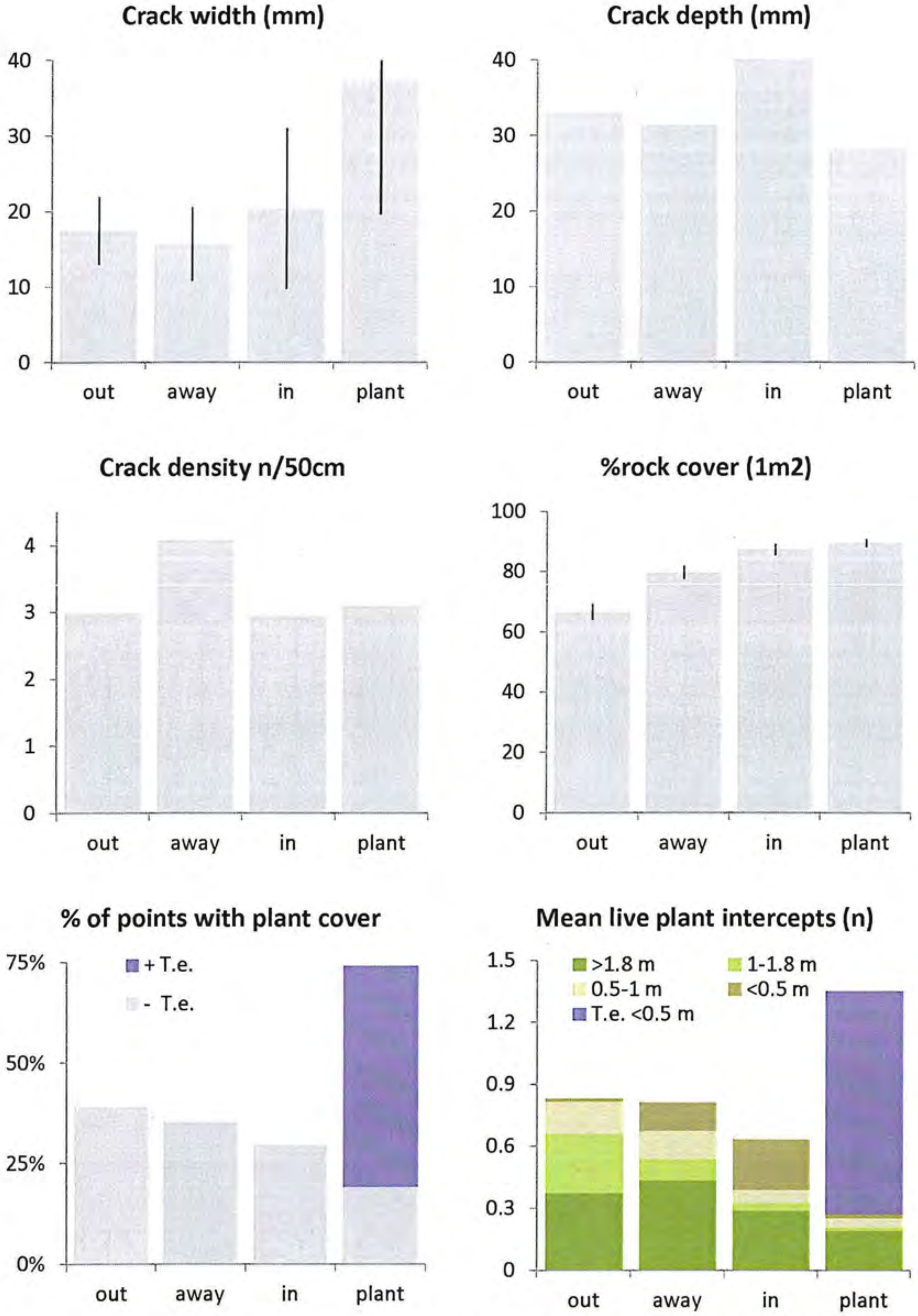


Figure 6b Mean (± standard error, if not excessive) of environmental parameters (crack attributes, rock cover, live plant cover and vegetation structure/intercept counts) measured in four site types: (**out**) immediately adjacent to, but outside of the *Tetratheca erubescens* population; (**away**) localities predicted to contain *T. erubescens*, outside of the population; (**in**) on transects within the *T. erubescens* population, and; (**plant**) the closest plant to each point in each 'in' transect.

The structure of vegetation also varied across site types with almost no small shrub or ground layer but more large shrub cover in sites adjacent to the *T. erubescens* population. Vegetation unit mapping (Figure 1) undertaken by Woodman (2014) indicates the vegetation units in which *T. erubescens* extends across the length of the southern Koolyanobbing Range.

Surveyed categorical environment parameters also revealed some differences between site types (Table 6, Figure 7). Landscape position did not vary between site types: between 7 and 15% of points surveyed across site types were on ridge crests and 27-33% of surveyed points were classed as midslope, the remaining 58-64% being upper slope. Geomorphological features identified in the survey included ridge crests, cliffs, benches on cliffs, talus slopes of fallen rock below cliffs and hillslopes. Almost all points surveyed were associated with cliffs, being cliff faces, tors, benches in cliffs or cliff foot on transects (78%) or at plant locations (84%) within the *T. erubescens* population, the remaining 22-16% were the crests and hillslopes. Cliffs and associated features comprised 57% and 5% of unoccupied sites outside of known populations that were identified by the distribution model with a high likelihood of occupancy and unoccupied sites adjacent to the *T. erubescens* population, respectively. Position on feature was non-informative. Massive substrates more frequently characterised unoccupied predicted sites (occurring in 58% of surveyed points), nonmassive substrates were found at 56-55% of points on transects and at plants within the *T. erubescens* population, and points within sites adjacent to the *T. erubescens* population were most dominated by nonmassive substrates (78%).

Table 6. Tests for differences in frequency of categorical environmental parameters measured in four site types corresponding to: (**out**) points on transects immediately adjacent to, but outside of the *T. erubescens* population; (**away**) points on transects in localities predicted to contain *T. erubescens*, but outside of the known distribution; (**in**) points on transects within the *T. erubescens* population, and; (**plant**) the locality of plants within the *T. erubescens* population being the closest plant to each point on the 'in' transect. Results are χ^2 (adjusted G) scores with P values in parenthesis. Significant results (P<0.01) indicated in bold.

	all types	in v away	plant v in	in v out
Position in landscape crest, upperslope, midslope	3.51 (0.742)	2.17 (0.337)	0.06 (0.969)	0.55 (0.758)
Geomorphological feature crest and slope v cliff	120.4 **(<0.001)**	10.1 **(0.002)**	1.28 (0.256)	8.86 **(<0.001)**
Position on feature top, mid, bottom	14.00 (0.029)	1.28 (0.527)	2.72 (0.257)	4.45 (0.108)
Substrate type massive, non-massive	21.80 **(<0.001)**	3.55 (0.059)	0.00 (0.968)	8.85 **(0.003)**
Local feature bare rock, crack, bench soil	109.38 **(<0.001)**	1.83 (0.607)	63.59 **(<0.001)**	9.42 (0.024)
Slope type shedding, receiving	17.52 **(0.001)**	0.00 (0.984)	12.21 **(<0.001)**	0.42 (0.518)
Soil mineral, organic, none	113.82 **(<0.001)**	5.32 **(0.007)**	29.59 **(<0.001)**	46.46 **(<0.001)**

Slope type, local feature type and soil type differed within the *T. erubescens* population between random transect points and locations where *T. erubescens* plants occurred. Slope categories were analysed as relatively water shedding or relatively water receiving. Most 84% random transect positions within *T. erubescens* populations were water shedding, while points where plants grew were 2.4 times more likely to be relatively water receiving (39%).

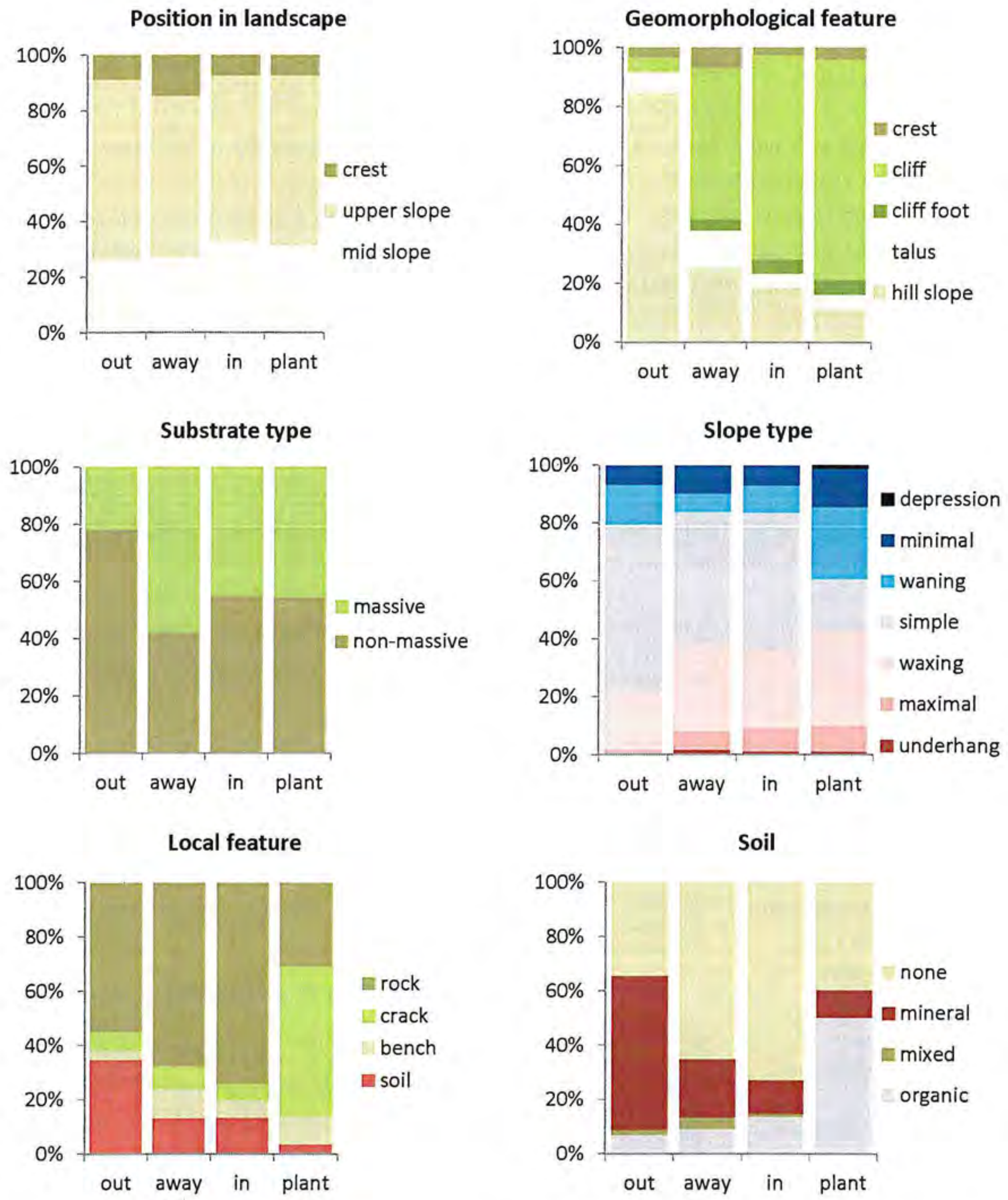


Figure 7 Proportions of surveyed points classified by landscape, geomporphological, slope type and substrate categories across four site types: (**out**) immediately adjacent to, but outside of the *T. erubescens* population; (**away**) localities predicted to contain *T. erubescens*, outside of the population; (**in**) on transects within the *T. erubescens* population, and; (**plant**) the closest plant to each point in each 'in' transect

Three quarters (74%) of random locations within the *T. erubescens* population were open rock and 12% were rock cracks or cliff benches. In contrast, 66% of plants were described as growing in cracks or benches: the 31% of plants described just as growing on 'rock' must also have been growing in cracks too small to be identified as such in regular survey. Sites adjacent to the *T. erubescens* population and highly predicted sites away from the *T. erubescens* population both had a lower proportion of open rock points (55% and 68%) than random sites within the *T. erubescens* population, but even the lowest of these is still more than half rock.

Finally, where soil occurred close to or at transect points, it was more likely to be mineral soil in sites away from the *T. erubescens* population and more likely to be organic in points occupied by plants (soil type assessed crudely via colour, i.e. red *v* grey).

Discussion

This study aimed to identify attributes of the habitat of *T. erubescens*; to identify locations of habitat most suited to but not currently occupied by *T. erubescens* and; to compare the attributes of these locations with those of the *T. erubescens* population.

We were able to effectively model and describe the distribution of *T. erubescens* using available environmental parameters using Maxent. This model principally used slope angle and elevation to distinguish locations of the *T. erubescens* population. Essentially, the model finds that *T. erubescens* occur within the steepest and highest parts of the landscape where it occurs. Slope angle has significant implications for parameters of meaning to plant growth, soil development, solar radiation receipt, surface erodibility and stability, and site hydrology. The inclusion of solar radiation in the model demonstrated that this effect of slope was not critical in limiting the *T. erubescens* population distribution, as slope was still the dominant parameter even when radiation was included. Elevation difference can be an ecological meaningful parameter if its variation is large through its impact on climate. The elevation range of the Koolyanobbing Range is not sufficient to have any effects on precipitation or temperature. The topographic form of the southern Koolyanobbing Range is likely to affect local wind patterns –anabatic winds (uphill wind produced by the effects of local heating) were observed in the afternoon during the field survey – but the frequency and any significance of this effect is unclear. We interpret the importance of elevation in the model as a proxy for geology. Early model iterations identified a significant role of geology in modelling the distribution of *T. erubescens*, however we could not include this data layer as it did not extend across the all of the modelling area; being focussed on the Koolyanobbing Range ridges (with no data on the unmineralised surrounding plains) and arguably sometimes too much detail for ecological interpretation and projection. The Geological Survey of Western Australia (2015) 1:500,000 geology map series indicates that all high elevation areas within the modelled and projected regions are "Youanmi Terrane greenstones: banded iron-formation, jaspilite, chert, and shale with associated mafic rock; metamorphosed" (Figure 8); which provides a very broad overview of the local geology.

If this interpretation is correct then Maxent species distribution modelling simply identifies the habitat of *T. erubescens* as being the steepest slopes and cliffs of various Banded Iron Formation and associated rock types in the Koolyanobbing area. Few areas outside of the existing population were predicted as best quality habitat for *T. erubescens*, although some areas within the southern Koolyanobbing Range seem well suited, but lack individuals. The highest and steepest areas of the southern Koolyanobbing Range – located between the Koolyanobbing mine airstrip and the existing mine pits (at the A, B, C and D Deposits) - are the highest predicted areas outside of the recorded area of the *T. erubescens* population.

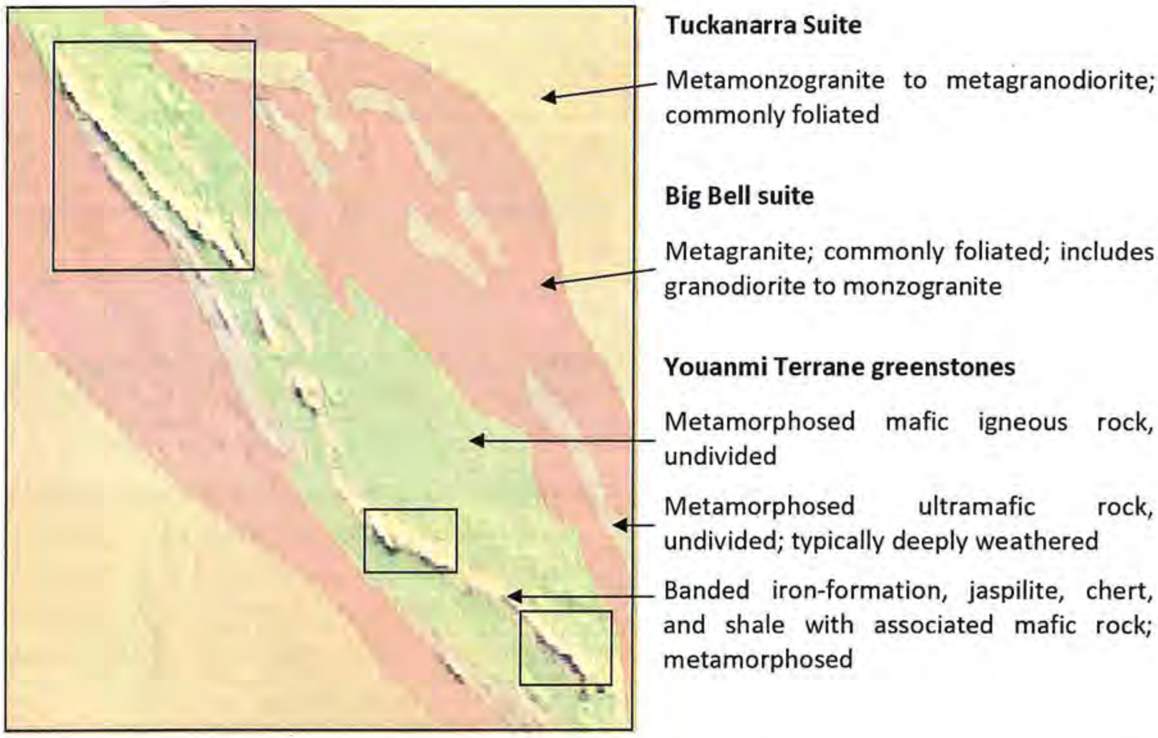


Figure 8 1:500,000 geology excerpt (Geological Survey of Western Australia 2015) showing the geology in relation to relief and the three surveyed areas (boxes).

While the model results appear convincing, it must be noted that maxent is only correlative, it finds environmental correlates of population boundaries, leaving inference of the process to the user. Above we identify how elevation may function on these models as a correlate of a more relevant parameter (i.e. rock type). We must also note that slope and rock type in themselves point to other patterns and processes that might actually be influencing *T. erubescens* distribution. These are likely to include substrate fracture patterns, surficial and subsurface water movement patterns and the capacity to store and provide water in cracks and fissures for appropriate periods. We did not map, model or survey these parameters.

Field survey was designed to identify and describe habitat attributes of the *T. erubescens* population and to compare attributes of locations where *T. erubescens* populations did occur with locations that were identified as the most suitable within the Koolyanobbing Range but *T. erubescens* populations did not occur.

Predicted but unoccupied habits was found to differ slightly from random transect locations within the *T. erubescens* population. On average, these sites had slightly lower slope angles, slightly lower rock cover and greater soil depth and plant cover, they also were significantly more likely to include hillslope and talus features and less likely to be cliff features, they also had more locations with soil, and that soil was more likely to be mineral rather than organic in sites within the *T. erubescens* population.

We additionally tested whether the locations where plants did occur had any specific features at the local scale within their habitat. Because we compared random points within the population to effectively random points within predicted habitats, we needed to know how representative our random sampling within the *T. erubescens* population was of *T. erubescens* habitat. We could not restrict our surveys simply to the specific habitat of *T. erubescens* because, in the predicted habitat transects there were no plants present to identify the locations where they would grow if they did occur there. Our survey showed that while there were differences between predicted unoccupied transects and occupied transects, there were also differences between the random locations within the *T. erubescens* population and the locations of *T. erubescens* plants. The locations where plants grew were more likely to be in a locally water concentrating position in a crack within the steepest regions, on a cliff, with some small amount of local soil that was organic rather than mineral in nature, and with lower plant cover. If required, a more targeted survey could consider assessing the frequency of these locations in habitats that are predicted to be most suitable for *T. erubescens*, rather than the random sampling approach taken here.

Finally, we compared the habitat attributes of locations where the *T. erubescens* population occurred with regions immediately adjacent to the *T. erubescens* population where plants did not occur, i.e. we were looking for correlates with population boundaries as further potential explanations of limits to the distribution of *T. erubescens*. Again we found slope angle, cliff feature and soil depth and type, together with higher likelihood of non-massive (i.e. more weathered) substrates to be the most important differences.

Parameters such as massive or non-massive substrate type, geomorphological feature, slope, rock and crack features are not plant-relevant traits in themselves. However, these traits are highly likely to correlate with features that were not measured, but are relevant to plant persistence, growth and reproduction. These features are likely to include the hydrological, structural and chemical features of the root habitat: the volume of water, its depth and persistence, the ease with which plants can extract it, its period and frequency of availability. Organic soils in ironstone substrates may be highly acidic, which may also potentially influence the form and availability of some nutrients. Finally, cliff habitats might also offer some protection from some types of any grazing animals, if present. If translocation programs were to be developed for *T. erubescens* populations, we would recommend that these statements above be refashioned and tested as hypotheses in appropriately designed studies.

Studies to further refine our understanding of the *T. erubescens* habitat could include geophysics survey of the hydrological and related soil/substrate attributes of locations with and without *T. erubescens*, including within existing populations and in regions remote from the existing population. Study of the physiological and demographic responses of *T. erubescens* to variation in these attributes may also be useful for understanding the parameters that limit the distribution of this species.

Ultimately, the approaches described in this report are correlative and as such simply create hypotheses about the limits to *T. erubescens* distribution. The ultimate testing of these hypothesis is best performed in a formal experimental setting that should include translocation research.

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Appendix 1: methods of environmental data layer extraction.

The following are the methods for generating base data for the Koolyanobbing Range *Tetratheca erubescens* Habitat Modelling project.

The landform data generated has been done so based on the elevation data supplied by Landgate.

- Elevation – source: Landgate. This data is comprised of two projects, the eastern side is the 2007 Bullfinch (2736) DEM and the western side is the 2012 Seabrook (2836) DEM. The data supplied was 10m resolution as an ers (ER Mapper) format. This was converted to a tiff format for processing in ArcGIS (version 10.2).

The landform datasets generated from this elevation data were:

- Slope – Generated using ArcGIS (10.2) 3d Analyst extension, output to a tiff format in Degrees.
- Aspect – Generated using ArcGIS (10.2) 3d Analyst extension, output to a tiff format with a numerical value representing the direction of the slope:
- Curvature – Generated using ArcGIS (10.2) 3d Analyst extension, output to a tiff format with a numerical value representing the curvature on the surface on a cell by cell basis. Additional Curvature rasters, Profile Curve (Down Slope) and Plan Curve (Across Slope) were also generated during this process.
- Roughness – Generated using ArcGIS (10.2), Geomorphology and Gradients metrics toolbox – Roughness script (utilising the Spatial Analyst extension), to apply a 3 x 3 cell rectangular analysis with an output to a tiff format.
- Wetness Index – Generated using SAGA (System for Automated Geoscientific Analysis) Wetness Index with an output to an ascii format (using the default parameters). The result was compared to that generated using ArcGIS (10.2) Spatial Analyst extension, and was comparable and therefore adopted as it was deemed to be a surface that was a better representation of the wetness index.
- Solar Radiation – Generated using ArcGIS (10.2) Spatial Analyst extension, Area Solar Radiation tool. The result was generated for the Spring Equinox (2pm and 10am), Winter Solstice (2pm and 10am), Summer Solstice (2pm and 10am) using the within a day configuration. Annual solar radiation was also calculated by calculating the whole year with a monthly interval and then totaling each of the 12 months (12 individual bands) to give a sum for the year and also an average but dividing this sum by 12.

Other datasets supplied were:

- Geology – Supplied by Cliffs Natural Resources covering the Northern and Southern Koolyanobbing Ranges. The polygon data was converted to a raster (tif) format with a numerical value of 0 to 30 representing the lithology code. Data outside of the survey area was classified as "NoData". The lithology codes are represented as follows:

LITH_CODE_	Lith_No	LITH_CODE_	Lith_No	LITH_CODE_	Lith_No
fbx	1	mgh	11	qvn	21
fsh	2	mgo	12	qz	22
ftf	3	mif	13	scg	23
ggn	4	ocg	14	sct	24
grt	5	oci	15	sif	25
mam	6	ocl	16	sit	26
mbs	7	odt	17	siy	27
mcs	8	ogr	18	sqz	28
mdl	9	olf	19	umu	29
mgb	10	olt	20	utc	30

- Vegetation – Surveyed by Woodman Environmental in 2013 covering the Southern Koolyanobbing Range and supplied by Cliffs Natural Resources. The polygon data was converted to a raster (tif) format with a numerical value of 0 to 16 representing the community code (with the cleared area converted to a value of 0). Data outside of the survey area was classified as "NoData".

- Fire history was considered but there is no data recorded in this area by Cliffs Natural Resources, its previous owner Portman Mining Limited or Landgate. Historic aerial photography was investigated over a number of dates (1983, 1984, 1990, 1997, 2001, and 2006 to 2014) and no evidence of fire was visible from these images.

- *Tetratheca erubescens* data supplied by Cliffs Natural Resources as surveyed by Maia Environmental. The data was supplied as a series of sites with the plant numbers recorded or estimated. The data was converted to a raster (tif) format with a corresponding value of 1 for presence or 0 for absence within the study area defined by the Maia survey tracklogs. Data outside of the survey area was classified as "NoData".

All data was set to the same extents and cell size using the environmental controls in ArcGIS (10.2). Raster snapping was also used to align all cells of the data created.

Each data set was created to the extent of the larger project area covering the Northern and Southern Koolyanobbing Ranges. This became the "Projection" area supplied.

Each dataset was then cropped to the study area (which was defined using the tracklogs from the Maia Tetratheca erubescens Survey and matches that defined with the presence / absence data). These datasets then became the "Modelling" area supplied and maintained the consistent extent, cell size and cell position (using raster snap).

Prior to supplying all datasets were converted to an ascii (asc) format using ArcGIS (10.2). These asc datasets were viewed in ArcGIS (10.2) following their creation to confirm the data was exported as expected.

Once this process was complete the data was supplied to Botanic Gardens and Parks Authority for input into the "Maxent" program for species distribution modelling.

Brian White
CAD Resources
9/2/2015

Appendix 2 Vegetation mapping codes

Woodman Environmental (2013)

0 Cleared

1 Mid woodland of mixed species including Eucalyptus salmonophloia, Eucalyptus corrugata, Eucalyptus salubris, Eucalyptus longicornis and Eucalyptus vittata over tall to mid sparse shrubland dominated by Atriplex nummularia, Exocarpos aphyllus, Eremophila scoparia, Scaevola spinescens and Senna artemisioides subsp. filifolia over low sparse shrubland dominated by Atriplex vesicaria, Maireana trichoptera, Olearia muelleri, Sclerolaena diacantha and Rhagodia drummondii on red, brown, orange or red-brown clay, clay loam and sandy loam with dolerite, quartz and ironstone stones on plains, flats and low rises.

2 Mid to low woodland dominated by Eucalyptus ravida and Eucalyptus celastroides subsp. celastroides over tall to mid sparse shrubland dominated by Atriplex nummularia and Eremophila scoparia over low sparse shrubland dominated by Atriplex vesicaria, Sclerolaena diacantha, Maireana trichoptera, Maireana georgei and Rhagodia drummondii on red, brown, orange or red-brown clay with dolerite, quartz and ironstone stones on plains and flats.

3 Mid woodland dominated by Eucalyptus longicornis and Eucalyptus vittata over low open mallee woodland dominated by Eucalyptus celastroides subsp. celastroides over tall to mid sparse shrubland dominated by Atriplex nummularia, Eremophila scoparia, Exocarpos aphyllus, Eremophila interstans subsp. interstans and Halgania andromedifolia over low sparse shrubland dominated by Atriplex vesicaria and Olearia muelleri on red, brown, orange or red-brown clay with dolerite and quartz stones on low rises.

4 Mid woodland dominated by Eucalyptus capillosa or Eucalyptus salubris over tall to mid sparse shrubland dominated by Eremophila oppositifolia subsp. angustifolia, Alyxia buxifolia, Acacia tetragonophylla and Exocarpos aphyllus over low sparse shrubland of mixed species including Grevillea acuaria, Acacia erinacea, Olearia muelleri, Rhagodia drummondii and Acacia andrewsii on red, brown or red-brown clay with laterised ironstone stones and occasionally with laterised ironstone outcropping on slopes adjacent to lateritic breakaways and cliffs.

5 Mid to low woodland of Eucalyptus vittata over mid sparse shrubland dominated by Atriplex nummularia, Eremophila oppositifolia subsp. angustifolia and Eremophila caperata over low sparse shrubland of mixed species including Olearia muelleri, Acacia erinacea, Maireana georgei and Ptilotus obovatus var. obovatus on red or red-brown clay with ironstone and quartz stones on lower slopes of ranges and low rises.

6 Mid to low mallee woodland of Eucalyptus corrugata and/or Eucalyptus vittata over tall to mid open shrubland dominated by Exocarpos aphyllus, Senna artemisioides subsp. filifolia and Eremophila interstans subsp. interstans over low sparse shrubland dominated by Olearia muelleri, Acacia erinacea, Dodonaea stenozyga, and Ptilotus obovatus var. obovatus on brown or red-brown clay loam with dolerite stones and occasionally dolerite outcropping on lower slopes of ranges and low rises.

7 Low open mallee woodland of Eucalyptus corrugata and Eucalyptus longissima over tall shrubland dominated by Allocasuarina helmsii over mid sparse shrubland dominated by Dodonaea stenozyga and Acacia dissona var. indoloria over low isolated shrubs of mixed species on brown clay loam with dolerite stones and some dolerite outcropping on low rises.

8 Low isolated mallees of Eucalyptus longissima or Eucalyptus loxophleba subsp. lissophloia over tall shrubland dominated by Acacia sp. narrow phyllode (B.R. Maslin 7831) and occasionally Acacia tetragonophylla over mid open shrubland dominated by Dodonaea inaequifolia and Scaevola spinescens over low isolated shrubs of mixed species on red or red-brown clay with ironstone stones on low rises.

9 Low open mallee woodland dominated by Eucalyptus loxophleba subsp. lissophloia over tall open to sparse shrubland of mixed species dominated by Acacia sp. Mt Jackson (B. Ryan 176), Acacia sp. narrow phyllode (B.R. Maslin 7831), Acacia tetragonophylla and Allocasuarina acutivalvis subsp. acutivalvis over mid open shrubland dominated by Scaevola spinescens, Eremophila oppositifolia subsp. angustifolia, Grevillea zygoloba, Dodonaea inaequifolia and Philotheca brucei subsp. brucei over low sparse shrubland dominated by Dodonaea microzyga var. acrolobata, Olearia pimelioides, Prostanthera semiteres subsp. semiteres and Olearia muelleri on red, red-brown, orange-brown or brown clay or clay-loam with ironstone stones, occasionally with banded ironstone outcropping, on mid to lower slopes of ranges and low rises.

10 Tall open shrubland dominated by Acacia sp. Mt Jackson (B. Ryan 176), Acacia tetragonophylla and occasionally Santalum spicatum over mid open shrubland dominated by Dodonaea inaequifolia, Scaevola spinescens, Philotheca brucei subsp. brucei and Eremophila clarkei over low sparse shrubland dominated by Ptilotus obovatus var. obovatus, Olearia pimelioides and Rhagodia drummondii on red, red-brown or brown clay or clay-loam with ironstone stones, often with banded ironstone outcropping, on mid to lower slopes of ranges.

11 Low isolated trees and mallees of Eucalyptus longissima, Banksia arborea and Brachychiton gregorii over tall shrubland to open shrubland dominated by Acacia sp. Mt Jackson (B. Ryan 176) and Allocasuarina eriochlamys subsp. eriochlamys or Allocasuarina acutivalvis subsp. acutivalvis over mid open to sparse shrubland dominated by Philotheca brucei subsp. brucei, Grevillea zygoloba, Eremophila clarkei, Scaevola spinescens and Leucopogon sp. Clyde Hill (M.A. Burgman 1207) over low sparse shrubland of mixed species including Olearia humilis, Prostanthera althoferi subsp. althoferi, Hibbertia exasperata and Dianella revoluta var. divaricata on red, red-brown or brown clay or clay-loam with ironstone stones, usually with banded ironstone outcropping, on the crests and slopes of ranges.