The Population Ecology of *Tetratheca* (Eleaocarpaceae) on the Banded Iron Formation Ranges of the Yilgarn

An integrated research program focussed on practical outcomes for the ex situ and in situ conservation, restoration and translocation of the DRF *Tetratheca paynterae* subsp. *paynterae*.

Final Report to Portman Iron Ore Limited
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Executive summary

Introduction

The banded iron formation (BIF) ranges of the Yilgarn Craton in the Midwest and Goldfields regions of Western Australia are isolated ancient ranges set in a predominantly flat landscape. They form a relatively small proportion of the total land area of the region and provide unique habitat for flora and fauna, due to different geology, soils and landforms compared to the majority of land in the region.

Initial botanical survey and research shows that BIF ranges on the Yilgarn Craton provide unique island-like environments with often high levels of endemism, rare and geographically restricted species and high levels of species turnover among ranges. As a consequence, each BIF range tends to be biologically distinct supporting different plant assemblages and often endemic species. Moreover, initial surveys have discovered a significant number of plant species new to science. As knowledge continues to accumulate the Yilgarn BIF ranges are increasingly recognized as centres of plant endemism and diversity, and for making a significant contribution to regional and global biodiversity. Exemplifying patterns of plant diversity on BIF ranges are five rare and geographically restricted leafless shrub taxa in *Tetratheca* (Elaeocarpaceae), from the Koolyanobbing region of south-western Australia. All of the taxa grow within the rocky and cliff environments, but each taxon is restricted to a single BIF range, with one taxon replacing another across adjacent ranges, within a relatively small geographic area.

The recent growth in the world economy, particularly China, has increased the global demand for iron-ore, and in south-western Australia BIF ranges and their biodiversity are increasingly under pressure from mining (DEC and DOIR 2007). In the Goldfields region of the Yilgarn Craton, three of the BIF ranges where endemic *Tetratheca* taxa grow are currently subjected to open-cut mining with operations directly impacting on one of the taxa, *Tetratheca paynterae* subsp. *paynterae* in the Windarling Range. In 2004 the then Department of Conservation and Land Management (now Department of Environment and Conservation, DEC) and the Botanic Gardens and Parks Authority (BGPA) were engaged by Portman Iron Ore Ltd. to undertake research into the *ex situ* conservation techniques and translocation of *T. paynterae* subsp. *paynterae*, and population genetics and ecology of *T. paynterae* subsp. *paynterae* and three other *Tetratheca* taxa on adjacent BIF ranges. Comparative studies of *T. paynterae* subsp. *paynterae* with the other BIF taxa *T. paynterae* subsp *cremnobata*, *T. aphylla*, and *T. harperi* were included to determine whether they are ecological analogues. The rationale being that if no differences are observed in the ecological characteristics of the four *Tetratheca* taxa, then the relatively undisturbed taxa may provide useful bench-marks for gauging the performance and viability of the *T. paynterae* subsp. *paynterae* population in the mine and post-mine environment.

The objectives of the DEC components of the research programme were to:

- describe and compare the physical environmental domains of the four BIF *Tetratheca* taxa and associated floristic assemblages to assist with identifying sites and techniques for translocation;
- describe and compare the reproductive biology of the four BIF *Tetratheca* taxa and investigate how reproduction is influenced by climate;

- describe and compare the population structures and demography of the four BIF *Tetratheca* taxa and estimate annual rates of demographic parameters;
- construct models of population dynamics for exploratory investigation of the potential impact on population viability of further reducing the number of plants in the *T. paynterae* subsp. *paynterae* population and other disturbances.

Key findings

The environmental domains of *T. paynterae* susbsp. *paynterae*, *T. paynterae* subsp. *cremnobata* and *T. harperi* are more similar to one another than they are to *T. aphylla*. The two *T. paynterae* subspecies and *T. harperi* are almost exclusively restricted to growing from fissures in massive banded ironstone landforms. In the cases of the two *T. paynterae* subspecies on cliffs and tors on the upper slopes of BIF ranges, and in the case *T. harperi* on hillcrests, cliffs and cliff footslopes on the crests and upper-slopes of BIF ranges. In contrast, *T. aphylla* is often found growing in skeletal soils on a wide range of landform elements across almost the whole range of slope morphologies on BIF ranges.

The geographic restriction of the BIF *Tetratheca* to single BIF ranges, and the highly specific habitat, restrict options for translocating the taxa if habitat is destroyed by mining. The common practice of using seedlings grown either from seed or cuttings will not be suitable for three of the BIF *Tetratheca* (*T. harperi*, *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp *paynterae*) which are almost exclusively restricted to growing from fissures less than 1cm wide. Translocation will have to rely on planting seeds into fissures within the massive banded ironstone. Currently there is no way of knowing which fissures will be suitable for germination and seedling establishment.

Although the environmental domains of *T. harperi*, *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp *paynterae* differ in some aspects, they are similar enough to be considered ecological analogues. The relatively undisturbed, *T. harperi*, and *T. paynterae* subsp. *cremnobata* can be used to provide useful bench-marks for gauging the performance and viability of the *T. paynterae* subsp. *paynterae* population in the mine and post-mine environments.

Flowering, fruit and seed production occurred annually in winter and spring in the four BIF *Tetratheca* taxa. Larger plants produced more flowers. After adjusting for plant size there were no significant differences in the number of flowers produced by plants among the four BIF *Tetratheca* or between years. Similarly, there were no significant differences in levels of pollination or the number of developed seeds per fruit among the four BIF *Tetratheca* or between years. The number of seeds per fruit varied substantially among years within the four taxa.

In 2005 three of the BIF *Tetratheca* produced significantly lower numbers of fruit compared to 2004 and 2006. This may be the result of well below average monthly rainfall from May 2004 to May 2005, which resulted in a decline in canopy condition. At flowering in 2005, plants were still recovering from the drought and may not have had the resources to devote to fruit production.

Climate variables, particularly the amount and season of rainfall, are key drivers of population dynamics and plant growth in the four BIF *Tetratheca* taxa. Seedling recruitment occurred each winter but was highest in the wettest winter when rainfall in the months May to September was above the long term average.

Rates of mortality varied among life-stages, and were highest in seedling stages and lowest in adult stages. Mortality in seedlings occurred in each of the three census years, but in adults was restricted to a year when rainfall in the previous 12 month period was well below the long term median. The condition and size of plant canopies were also affected by the drought with plant canopies dieing back, having fewer green shoots and becoming smaller.

The high rates of seedling mortality may be a consequence of both the amount of rainfall in the first 12 months following seedling emergence, and many rock fissures being suitable for germination, but not for subsequent seedling growth and survival. Reasonably high rates of mortality also occur in juveniles, indicating that fissure suitability may still be influential in determining which plants survive. Relative to other life stages the low mortality rates in adult plants indicate that individuals that survive to maturity are quite resilient.

The low frequency of winters in the region when rainfall is sufficient to stimulate high rates of seed germination, coupled with consistently high rates of seedling mortality in most years, and no way of determining which rock fissures will be suitable for plant establishment, contribute to making translocation an extremely high risk strategy for conserving BIF *Tetratheca* affected by mining.

Measurements of demographic parameters are confined to two annual time-steps encompassing a sample of the variation in climate but not the entire range and extremes that are likely to drive population dynamics of the BIF *Tetratheca*. The models therefore should be treated as exploratory and not definitive. The base model parameterized with the demographic census data predicts that the *T. paynterae* subsp. *paynterae* population will decline substantially in the next 50 years. This may be a consequence of the study period not including a “high rainfall” year when there is likely to be a pulse of seedling recruitment.

Pulse recruitment is a common strategy of plants particularly in arid and semi-arid environments with highly variable rainfall. For *T. paynterae* subsp. *paynterae*, we assumed pulse recruitment would be associated with high winter rainfall, stimulating germination, followed by high summer rainfall allowing seedlings to survive the critical first summer and establish an extensive root system. This is particularly important for cliff dwelling plants which require an adequate root system to exploit cracks for water and nutrients and provide stability. Inclusion of pulse recruitment in the model reduced the probability of population decline relative to the base model. Increasing the probability of seedling survival in the models also reduced the probability of population decline relative to the base model.

Reducing the *T. paynterae* subsp. *paynterae* population from 5,000 to 4,000 plants did not result in extinction in the next 50 years under the base model or any of the pulse recruitment scenarios, but did reduce the viability of the population. Because of the uncertainty in estimating recruitment in the PVA, the predictions of the different scenarios should be seen as an ensemble of potential futures which range from decline to population stability.

Further research investigating the influence of rainfall amount, duration and seasonality is needed to confirm whether the infrequent congruence of high winter and summer rainfall is a major driver of pulse recruitment in the BIF *Tetratheca* taxa.

Although seed output and seedling recruitment rates are important in the longer term viability of the population, adult plants will sustain populations through adverse periods. The BIF *Tetratheca* are likely to have developed specific adaptations to variability in climate over millennia and have morphological and physiological adaptations that allow them to persist.

The stochastic sensitivity analysis indicates that the viability of the *T. paynterae* subsp. *paynterae* population may be very sensitive to an increase in the mortality of reproductive adult plants. This is typical of stress tolerators which are able to persist under adverse conditions. Consequently, events which increase the mortality of adult plants may have a significant impact on the viability of the population. There has been a demonstrable impact of mining on the *T. paynterae* subsp. *paynterae* population at Windarling. The mine generates considerable amounts of dust that accumulates on the stems of *T. paynterae* subsp. *paynterae*, especially during prolonged dry periods. In 2004 -2005 when rainfall was well below the long term median, mortality of adult plants was significantly higher in the 10 m “buffer zone” at the edge of the W3 open cut compared with the rest of the population (Yates and Williams 2005, McNee and Cockerton 2006). Plants immediately adjacent to the mine were under more water stress than plants 150 m from the mine (Close et al. 2005).

If the impacts of mining on *T. paynterae* subsp. *paynterae* are cumulative then increased water stress and mortality may occur further from the mine edge as the life of the mine progresses and the stochastic sensitivity analysis indicates that this could have a significant impact on the viability of the *T. paynterae* subsp. *paynterae* population. Monitoring of the whole *T. paynterae* subsp. *paynterae* population should be given a high priority and any increase in adult mortality should be a cause for concern.

1. Introduction

1.1 Background

The banded iron formation (BIF) ranges of the Yilgarn Craton in the Midwest and Goldfields regions of Western Australia are isolated ancient ranges set in a predominantly flat landscape. They form a relatively small proportion of the total land area of the region and provide unique habitat for flora and fauna due to different geology, soils and landforms, compared to the majority of land in the region.

Compared to other outcrop lithologies in south-western Australia, such as granite/gneiss inselberg systems, the floristic and ecological investigation of vegetation on banded ironstone formations is in its infancy (Hopper et al. 1997; Yates et al. 2003). In the Midwest and Goldfields regions of the Yilgarn Craton there are estimated to be 50-100 BIF ranges. For the majority of these ranges there is little detailed biological information. Initial botanical survey and research shows that like granite inselbergs on the Yilgarn Craton, BIF ranges provide unique island-like environments with often high levels of endemism, rare and geographically restricted species and high levels of species turnover among ranges (Gibson et al. 1997; Markey and Dillon 2006 ab; Meissner and Carouso 2006 abc). As a consequence, each BIF range tends to be biologically distinct, supporting different plant assemblages and often endemic species. Moreover, initial surveys have discovered a significant number of plant species new to science (Butcher et al. 2007a; Gibson et al. 2007). As knowledge continues to accumulate, the Yilgarn BIF ranges are increasingly being recognized as centres of plant endemism and diversity, making a significant contribution to regional and global biodiversity. Exemplifying patterns of plant diversity on BIF ranges are five rare and geographically restricted leafless shrub taxa in *Tetratheca* (Elaeocarpaceae), from the Koolyanobbing region of south-western Australia. All of the taxa grow within the rocky and cliff environments, but each taxon is restricted to a single BIF range, with one taxon replacing another across adjacent ranges, within a relatively small geographic area (Butcher et al. 2007a, Fig. 1.1).

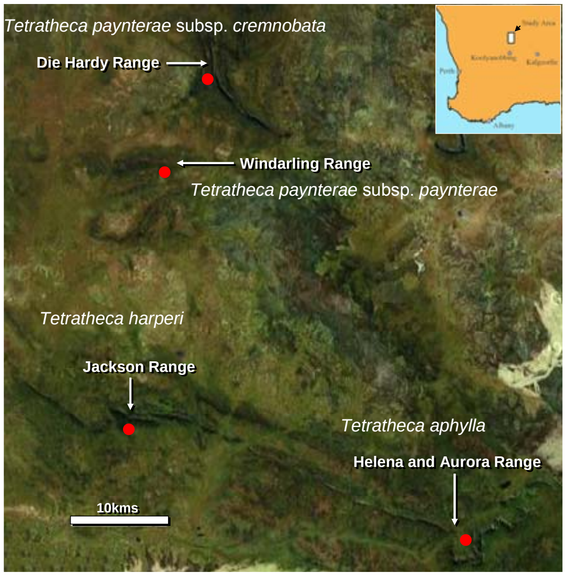


Figure 1.1. The study region and location of four of the BIF ranges where *Tetratheca* occurs. Source of image Google Earth.

Until recently two of the taxa were undescribed. Recent cladistic analysis of DNA sequence data for *Tetratheca*, including four of the Koolyanobbing region BIF taxa, showed that they belonged to three independent evolutionary lineages, indicating multiple colonizations of the BIF habitats, rather than speciation within a single BIF adapted lineage (Butcher et al. 2007a).

1.2 Iron ore mining and the BIF *Tetratheca* taxa

The recent growth in the world economy, particularly China has increased the global demand for iron-ore, and in south-western Australia, BIF ranges and their biodiversity are increasingly under pressure from mining (DEC and DOIR 2007). In the Goldfields region of the Yilgarn Craton, three of the BIF ranges where endemic *Tetratheca* taxa grow, are currently subjected to open-cut mining with operations directly impacting on one of the taxa, *Tetratheca paynterae* subsp. *paynterae* in the Windarling Range.

The history of the approvals process for Portman Iron Ore Limited to expand their Koolyanobbing iron ore mine operations by commencing new mines at Mt Jackson (*Tetratheca harperi*) and Windarling (*Tetratheca paynterae* subsp. *paynterae*) can be found in the Strategic Review of the Conservation and Resource Values of the Banded Iron Formation of the Yilgarn Craton (DOIR and DEC 2007).

At Windarling, subsequent to the appeals process, in June 2003 the Minister for the Environment issued a Statement that a Proposal May be Implemented (Statement No. 627) for a modified proposal. The approval of the project to proceed was on the basis of mining to be totally excluded from one part of the Windarling site (Area A) in order to ensure the viability of *T. paynterae* subsp. *paynterae*. This exclusion zone contains c. 50% of the total population, of some 7,000 plants. A second area (Area B) contains c. 20% of the known population and requires further approval from the Minister to access. Mining outside of Areas A and B could proceed, with the direct loss of 30% of the *T. paynterae* subsp. *paynterae* population.

The approval to mine the Windarling range, where *T. paynterae* subsp. *paynterae* grows, raised two important issues with respect to the persistence of the species.

- What effect will reducing the population in size by 30% initially, and possibly a further 20%, have on vital rates and population viability?
- What effect will disturbance associated with the proximity of the mine have on the genetic and ecological processes that influence vital rates and population viability?

Additional conditions provided with the approval for the Koolyanobbing expansion required Portman to initiate research and management measures to minimize the impacts of mining and maximize the viability of the remaining population of *T. paynterae* subsp. *paynterae*. The conditions included:

- development of a *T. paynterae* subsp. *paynterae* Research and Management Plan and Recovery Plan, with implementation of the plans demonstrating that ground disturbing activity will not affect the viability of the population;
- monitoring *T. paynterae* subsp. *paynterae* individuals for their health, viability and reproductive success;
- provision of secure conservation tenure for the remaining population of *T. paynterae* subsp. *paynterae*;
- development of a detailed risk management plan to avoid indirect impacts on the

remaining population of T. *paynterae* subsp. *paynterae*;

- research into the ecology, potential translocation and pollination vectors of *T. paynterae* subsp. *paynterae.*

Fig. 1.2. Windarling Ridge looking east into the W3 pit where 20% of the *T. paynterae* subsp. *paynterae* population occurred before mining. (Photo Penny Butcher, BGPA).

In 2004, ground disturbing activities commenced at Windarling and c. 2060 plants were removed from the *T. paynterae* subsp. *paynterae* population (Figs. 1.2 and 1.3). Portman Iron Ore Limited engaged Western Botanical to collect seeds from that part of the population to be destroyed (now lodged with the Department of Environment and Conservation, DEC and the Botanic Gardens and Parks Authority, BGPA). Western Botanical were also engaged to undertake monitoring of the remaining *T. paynterae* subsp. *paynterae* population, and the then Department of Conservation and Land Management (now DEC) and the BGPA to undertake research into the *ex situ* conservation techniques and translocation of *T. paynterae* subsp. *paynterae*, and population genetics and ecology of *T. paynterae* subsp. *paynterae* and three other *Tetratheca* taxa on adjacent BIF ranges.

Comparative studies of *T. paynterae* subsp. *paynterae* with the other BIF taxa *T. paynterae* subsp *cremnobata*, *T. aphylla*, and *T. harperi* were included to determine whether they are ecological analogues. If no differences are observed in the ecological characteristics of the four *Tetratheca* taxa, then the relatively undisturbed taxa may provide useful bench-marks for gauging the performance and viability of the *T. paynterae* subsp. *paynterae* population in the mine and post-mine environment.

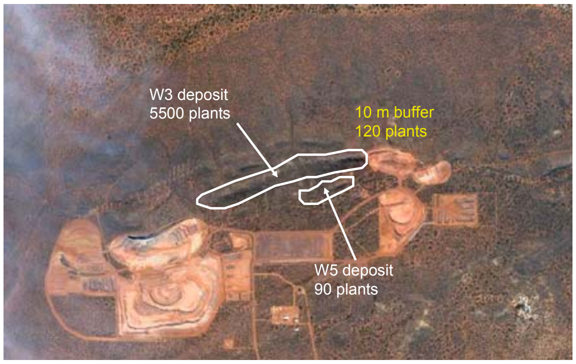


Fig.1.3. Areal view of Windarling Mine, showing location of the remaining *T.paynterae* subsp. *paynterae* population. Source of image Google Earth, figure compiled by Penny Butcher (BGPA).

1.3 Research objectives

The objectives of the DEC components of the research programme were to:

- describe and compare the physical environmental domains of the four BIF *Tetratheca* and associated floristic assemblages to assist with identifying sites and techniques for translocation;
- describe and compare the reproductive biology of the four BIF *Tetratheca* and investigate how reproduction is influenced by climate;

- describe and compare the population structures and demography of the four BIF *Tetratheca* and estimate annual rates of demographic parameters;
- construct models of population dynamics for exploratory investigation of the potential impact on population viability of further reducing the number of plants in the *T. paynterae* subsp. *paynterae* population and other disturbances.

2. Environments of the four BIF *Tetratheca* taxa

2.1 Background

Vegetation patterning on the Yilgarn BIF ranges is highly correlated with topography and substrate (Gibson et al. 1997; Gibson 2004 ab). Outcropping massive ironstone is prominent on the upper parts of each of the four ranges, and to a greater or lesser extent, forms the focal point of the habitat for each of the *Tetratheca* taxa. Faulting, weathering and exfoliation of the ironstone have created a mosaic of cliffs, tors and fractured rock surfaces with various slopes and aspects. Within these areas there are numerous micro-habitats that are important for the establishment and persistence of plants, including soil and moisture accumulating sites such as joint plates, fissures, and depressions.

2.2 Research Objectives

The objectives of the research described in this section are to describe and compare the:

- physical environmental domains of the four BIF *Tetratheca*, and
- floristic assemblages associated with each of the four BIF *Tetratheca.*

2.3 Methods

2.3.1 Measurement of environmental variables

For each of the four BIF *Tetratheca*, across the range of their occurrence, 140 plants were randomly chosen, and 20 environmental attributes in the immediate vicinity of each plant measured (Fig. 2.1, Table 2.1). The environmental variables encompassed spatial scales from the broad landform level to the immediate (Figure 2.2a), so that differences in environmental effects at different scales such as the landscape and plant scale could be distinguished. Slope types on which plants occur were also recorded as this is important in terms of moisture and nutrient accumulation for the individual plants (Figure 2.2b). In addition, for each of the 140 plants surveyed of each taxa, the five nearest plants within a 2m radius were identified. This was done to give some indication of the plant community in which each taxa belongs.

2.3.2 Characterization of environmental domains

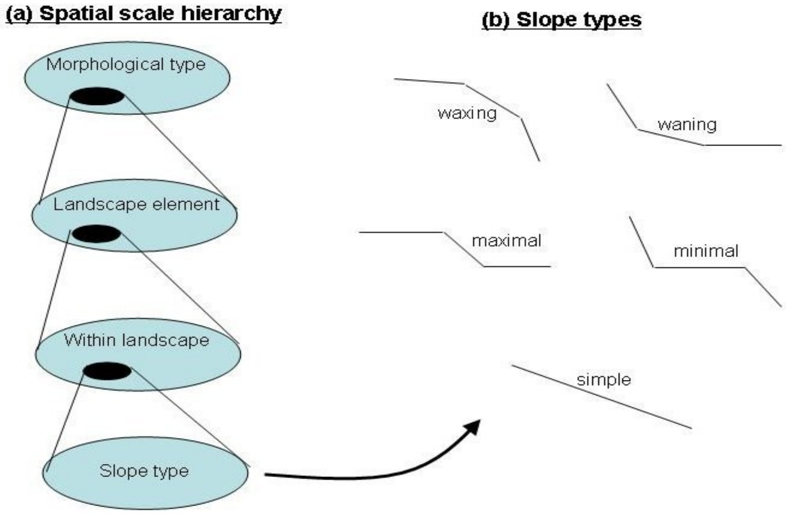
The environmental domains of each taxa were compared with multivariate ordination of the 20 environmental variables.

Fig. 2.1. BIF cliff habitat and *T. paynterae* subsp. *cremnobata*. (Photo, Penny Butcher, BGPA)

Table 2.1. Environmental variables recoded for each plant in each Tetratheca taxa.

Variable	Type	Description
Soil depth	continuous	mm
Landform slope	continuous	degrees
Local slope	continuous	degrees
Crack width	continuous	mm
Cliff height	continuous	m
Aspect	categorical	n; ne; e; se; s, sw; w; nw
Soil type	categorical	mineral, organic, none
Substrate type	categorical	massive, non-massive
Morphological type	categorical	crest, upper slope, mid-slope, lower slope, depression
Landscape element	categorical	Hillcrest, tor, cliff, cliff footslope, hillslope, breakaway, scarp footslope, talus, drainage
Within landscape	categorical	upper, middle, lower
Slope type	categorical	Simple, maximal, minimal, waxing, waning

Figure 2.2 (a) Spatial hierarchy indicating the nested nature of some of the environmental variables measured for each plant. **(b)** Slope types recorded for the plants. These are likely to be important in terms of moisture and nutrient accumulation for individual plants.



Patterns of similarity among environmental variables for the four taxa were assessed using Principal Component Analysis (PCA). The PCA axes scores provide a summary variable that characterises the main environmental gradient for each plant. Before analysis each variable was normalized (mean subtracted and then divided by the standard deviation) so that the variables would be on the same dimensionless scale. Euclidian distance was then used as a measure of dissimilarity of environmental attributes for each plant, from each other. The significance of dissimilarities in the environmental variable composition between the four taxa was tested using a permutation procedure applied to the dissimilarity matrix (Analysis of Similarity (ANOSIM), Primer v6.0; Clarke & Gorley 2001). For this permutation procedure, significance indicates that random allocation of environmental variables to each taxa did not produce an *R*-statistic that was higher than that obtained by chance alone (usually no greater than 0.1), and therefore that there are significant differences between groups (Clarke & Gorley 2001).

2.4 Results

2.4.1 Environmental domains

The PCA of the environmental attributes of the BIF *Tetratheca* found that the first two PCA axes (1 and 2) explain 54% of the variance in the original samples. This indicates that the two dimensional PCA ordination presented here gives reasonably good representation of the relationship among samples. The two-dimensional PCA ordination shows meaningful separation in environmental attributes of the four taxa, indicating clear differences in the environmental domains among taxa (Fig. 2.3). The closer individual plants (data points) are together in ordination space on the PCA diagram the more similar are their suite of environmental variables. *Tetratheca aphylla* and *T. paynterae* subsp. *paynterae* form the most clearly defined groups followed by *T. paynterae* subsp. *cremnobata* (with some distinct outliers) and *T. harperii,* the taxa with the most overlapping environmental space.

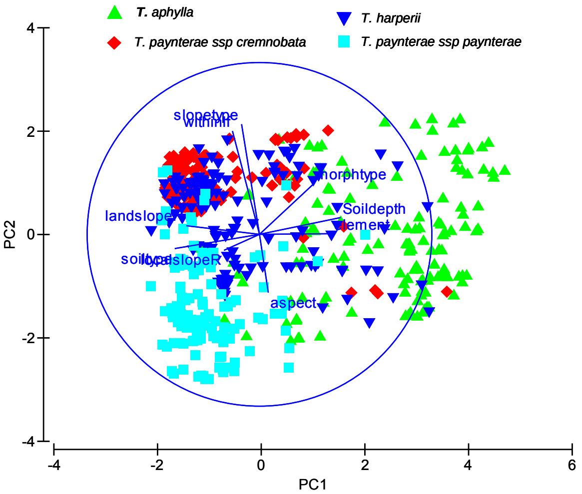


Figure 2.3. Principal Component Analysis (PCA) of the environmental variables for the four BIF *Tetratheca*. Each point represents a plant, the closer points (plants) are together, the more similar their measured environmental attributes. The blue lines and circle represents the vector plot which reflects the importance of an environmental variable's contribution to the PCA axes displayed.

The environmental differences or habitat preferences between the four taxa illustrated in the PCA ordination were confirmed with ANOSIM (Global R = 0.44, $p < 0.001$, Table 2.2). Pair comparisons show a significant difference in environmental domains between all taxa with the most different (highest R) *T. aphylla* and *T. panynterae* susbsp. *cremnobata*, and least different *T. panynterae* susbsp. *paynterae* and *T. panynterae* susbsp. *cremnobata*.

Table 2.2. ANOSIM R statistic and probability of differences between environmental variables for the four *Tetratheca* taxa.

Species	R statistic	p value
Global	0.44	<0.001
T. aphylla v *T. paynterae* subsp. *cremnobata*	0.65	<0.001
T. aphylla v *T. harperii*	0.48	<0.001
T. aphylla v *T. paynterae* subsp. *paynterae*	0.68	<0.001
T. harperii v *T. paynterae* subsp. *cremnobata*	0.11	<0.001
T. paynterae subsp. *paynterae* v *T. paynterae* subsp. *cremnobata*	0.49	<0.001
T. harperii v *T. paynterae* subsp. *paynterae*	0.37	<0.001

2.4.2 Influence of individual environmental attributes

The influence of individual environmental factors on the separation of taxa can be investigated with a number of procedures. By plotting the values for particular environmental variables on the PCA diagram the differences between taxa can be graphically illustrated (Fig. 2.4). In this example, the greater soil depth for *T. aphylla* plants and the lack of soil for *T. paynterae* subsp. *paynterae* is clearly shown.

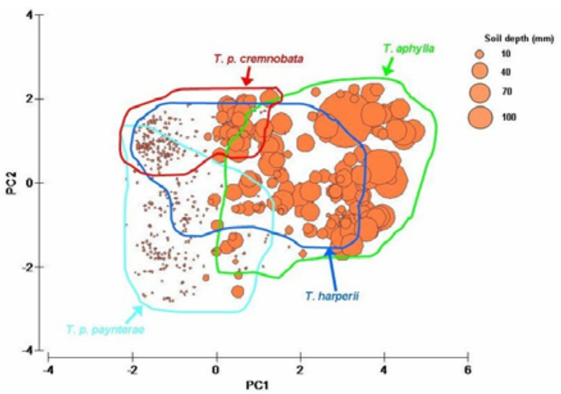


Figure 2.4. Bubble plot of soil depth for each sample plant on the PCA ordination diagram. Distribution of each taxa is indicated by the polygons. Size of the bubbles indicates the depth of soil recorded for each plant.

The influence of environmental factors on the separation of taxa can be further investigated with the SIMPER procedure (Primer v6.0; Clarke & Gorley 2001) which looks at the percentage contribution of environmental variables to the separation between points seen in the PCA ordination (Table 2.3). For example, slope type contributes 33% to the separation of the two subspecies of *T. paynterae,* with 89% of *T. paynterae* subsp. *paynterae* plants found on simple slopes, while 85% of *T. paynterae* subsp. *cremnobata* plants were found on waning slopes. Also, slope type contributes 27% to the separation of *T. paynterae* subsp. *paynterae* and *T. harperii,* with 84% of plants of this species occurring on waning slopes.

For continuous variables, differences between taxa can also be examined using simple one way ANOVA (Table 2.4). These results corroborate the patterns seen in the multivariate analysis, with *T. aphylla* growing in areas with significantly greater soil depth than the other taxa (Table 2.4). The significantly greater size of *T. aphylla* plants may also relate to the greater soil depth for this species. However, there was no relationship between soil depth and size of plants for any of the taxa (Fig. 2.5). In fact many medium to large plants were growing in rock cracks where there was no soil present.

Slope at the landform and local scale as well as cliff height were all significantly greater for *T. paynterae* subsp. *paynterae* and *T. paynterae* subsp. *cremnobata* which indicate their preference for the cliff habitat (Fig. 2.6). Three of the taxa *T. paynterae* subsp. *paynterae*, *T. paynterae* subsp. *cremnobata* and *T. harperii* showed a marked preference for the rock habitat with 100%, 96% and 94%, respectively of plants occurring on massive rock substrate, while for *T. aphylla* only 42% of plants were on a massive substrate. On the rock substrate plants occurred in cracks with the width of the cracks varying amongst taxa with *T. paynterae* subsp. *paynterae* occurring in significantly narrower cracks (Table 2.4). Growth of plants did not seem to be affected by the width of the cracks, with plant size not related to crack width for any of the taxa; many large plants were growing from very small cracks in the rocks.

Table 2.3. SIMPER routine (Primer) to describe the environmental variables which contribute the most to the separation between species seen in the PCA.

	% contribution		**% contribution**
T. aphylla* v *T. harperii		***T. harperii* v *T. paynterae***	
Landscape element	16.4	Slope type	26.6
Soil type	16.2	Aspect	16.9
Soil depth	14	Local slope	15.7
T. aphylla* v *T. paynterae		***T. harperii* v *T. cremnobata***	25.3
Morphological type	17.6	Local slope	20.4
Landscape element	17.3	Aspect	14.5
Soil type	15.6	Soil depth	
T. aphylla* v *T. cremnobata		***T. paynterae* v *T. cremnobata***	32.6
Landform slope	18.2	Slope type	20.3
Soil type	16.0	Local slope	17.8
Soil depth	14.1	Aspect	

Table 2.4. Results of the one way ANOVAs testing for differences between species in environmental variables. Means with the same letter are not significantly different (p = 0.01).

	T. aphylla	*T.cremnobata*	*T. harperii*	*T. paynterae*	F ratio	p
Plant width (mm)	677a	515b	381c	322c	34.1	<0.001
Soil depth (mm)	388a	67b	76b	21b	39.3	<0.001
Crack width (mm)	15.8a	9.5b	8.25bc	7.2c	9.16	<0.001
Local slope (°)	22.4c	53.7a	45.3b	57.2a	11.7	<0.001
Landform slope (°)	27c	65a	55b	64a	214	<0.001
Cliff height (m)	1.1c	7.7a	5.5b	6.2b	97.8	<0.001

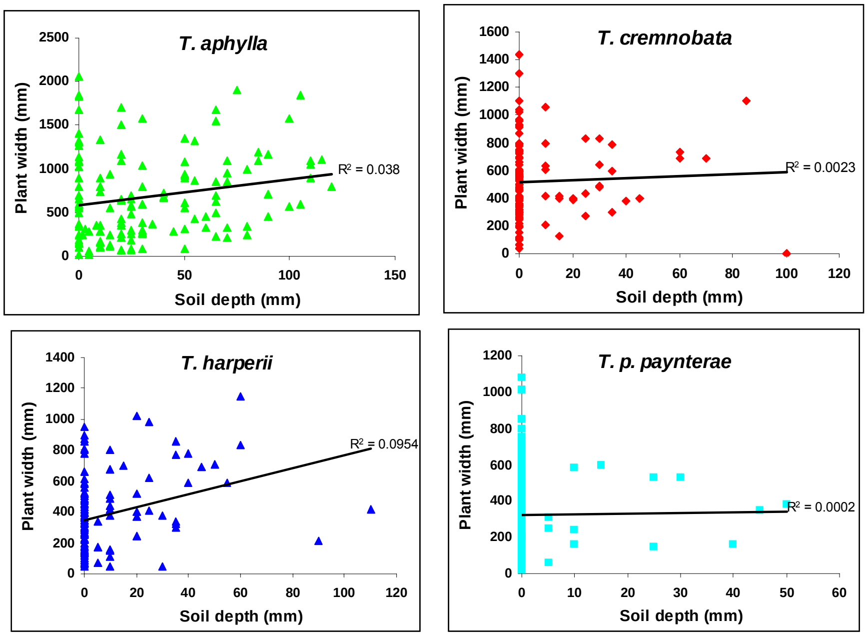


Figure 2.5. Relationship between plant width (as a measure of plant size) and soil depth for the four *Tetratheca* taxa.

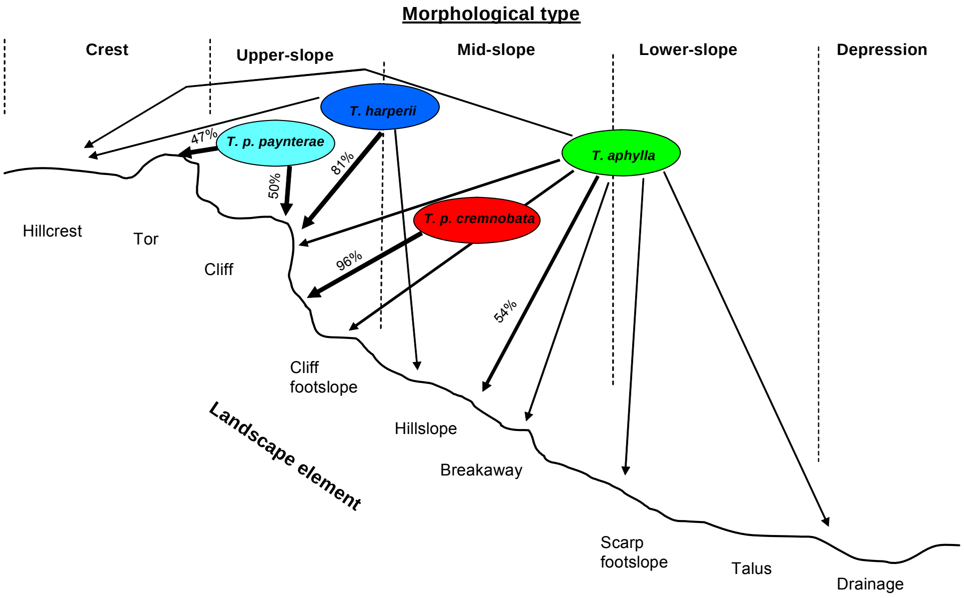


Figure 2.6. Stylised landscape of the ironstone ranges indicating differences in the habitat preference of the four *Tetratheca* taxa at the scale of the landscape morphological type and the landscape element. Arrows from each taxa indicate where the majority of the plants of this taxa were found and the thicker lines indicate where the greatest number were found. The actual proportions of plants of each taxa found in the particular landscape position are indicated by percentages.

2.4.3 Description of the fine scale environmental attributes for each taxa

T. paynterae subsp. *paynterae*

This taxon has a narrow environmental domain and occurs predominately on the massive substrate of rocky cliffs (Fig. 2.6) and particularly the upper sections of cliffs (50%) and amongst tors (47%). All plants that were surveyed were found in rock cracks and where soil occurred (10% of plants) it was very shallow (21 ± 6 mm) and predominantly organic (90%). Plants were found predominately on simple slopes (89%) which would tend to shed moisture or run-off sites (except for the rock crack itself). Plants were recorded facing all aspects but with the majority facing north (37%) and north-west (21%). Differences in aspect between taxa, may however, simply reflect the orientation of each ironstone range on which they occur.

T. paynterae subsp. *paynterae* growing on BIF tor on the Windarling Range (Photo Penny Butcher, BGPA).

T. paynterae subsp. *cremnobata*

Diehardy Range with BIF cliff habitat of *T. paynterae* subsp. *cremnobata*. (Photo Colin Yates, DEC).

T. paynterae subsp. *cremnobata* has a narrow environmental domain and occurs almost exclusively on the massive substrate of rocky cliff faces. The survey was restricted to the lower section of the cliffs where plants could be reached safely, but plants were observed growing across the height range of the cliffs. Most plants were found in rock cracks (92%) and where soil occurred (24%) it was shallow (67 ± 14 mm) with 54% having organic soils. Plants were found predominately on waning slopes (94%) which would tend to be moisture gathering or run-on areas. Plants were recorded facing all aspects but with the majority (31%) having an easterly aspect.

T. harperi

The environmental requirements of *T. harperi* appear to be quite broad and therefore overlap to a large extent with that of the other taxa (Fig. 2.3). As for the two *T. paynterae* subspecies, plants occur predominately on massive substrate of rocky cliffs but are more spread from the top to the bottom of the cliffs and continuing down to the cliff foot slopes and hillslopes. Plants were predominately found in rock cracks (92%) and where soil occurred (27%) it was shallow (76 ± 15 mm) with 70% of plants having organic soils. Plants were found mainly on waning slopes (85%) which tend to gather moisture or run-on sites. Plants were recorded facing all aspects but with the largest proportion facing south (21%) and south-west (33%).

T. harperi growing on BIF cliff at Jackson Range (above). *T. harperi* with J3 pit in the background (below). (Photos Colin Yates, DEC).

T. aphylla

T. aphylla habitat at Helena and Aurora Range (above) and *T. aphylla* (below). (Photos Colin Yates).

The environmental requirements of *T. aphylla* are the broadest of the four taxa surveyed but requirements differ distinctly from that of the other taxa as highlighted in the multivariate analysis (Figures 2.3 and 2.4, Table 2.2). Plants occur fairly evenly across the landscape from hillcrests (11%) to cliffs (17%) to hillslopes (54%) and even down into drainage lines (2%). Plants were predominately found in mineral soil (77%) with good soil depth (394 ± 49 mm) but a significant number were also found in rock cracks (42%). Plants had no preference for local slope type and were found over a range of types including simple (40%), waxing (23%) and waning (22%) slopes. Plants were recorded facing all aspects but with the majority facing south (25%) and south-west (20%).

2.4.4 The composition of floristic assemblages associated with each of the four BIF *Tetratheca*

The near-neighbour floristic assemblages associated with each of the four BIF *Tetratheca* varied. On the Windarling Range 15 different taxa were associated with *T. paynterae* subsp. *paynterae*. The most common of these included the shrubs *Melaleuca leiocarpa*, *Ptilotus obovatus* and *Dodonaea viscosa*. On the Die Hardy range 35 taxa were found associated with *T. paynterae* subsp. *cremnobata*. These included the shrubs *Ptilotus obovatus*, *Calycopeplus paucifolius* and *Dodonaea viscosa*. Plants associated with *T. harperii* on the Jackson range included 24 taxa with the most common being the shrubs *Jacksonia jackson* (Priority 1 sp), *Melaleuca leiocarpa* and the perennial fern *Cheilanthes* sp. On the Helena & Aurora Range there were 38 taxa associated with *T. aphylla*, the most common including the perennial grass *Neurachne anularis* (Priority 3 sp), the perennial herb *Chamaexeros macranthera* and the shrub *Ptilotus obovatus*.

For some of the near-neighbour plots, plants of *Tetratheca* were the only taxa recorded for the plot. This included 16% of the *T. paynterae* subsp. *paynterae* plots , 15% of *T. paynterae* subsp. *cremnobata*, 9% for *T. harperii* and 1% of *T. aphylla* plots. The proportion of the total number of plants that were a *Tetratheca* spp for each of the near-neighbour plots was 30% for the *T. aphylla* plots, 58% for *T. paynterae* subsp. *cremnobata*, 61% for *T. paynterae* subsp. *paynterae* and 52% for *T. harperii*. This indicates that the *Tetratheca* taxa were the dominant species within the habitat of the *Tetratheca* plants, except for *T. aphylla* where the community appears more diverse.

Ordination of the abundance of the nearest neighbour species for the four *Tetratheca* taxa (excluding the *Tetratheca* taxa themselves and the sites where only *Tetratheca* occurred, and with a dummy value added to all sites to eliminate the need to remove further singletons) using nonmetric Multi-Dimensional Scaling (MDS, Primer v6, Clarke and Gorley 2001) gave very similar results (Fig. 2.7) to the PCA analysis of the environmental data (Fig. 2.3).

The most variation in neighbouring species was associated with *T. aphylla* reflecting the wider environmental domain of this species. The species associated with *T. harperi* sites were intermediate between the bulk of the *T. aphylla* sites (on the left of the ordination) and those associated with the subspecies of *T. paynterae*, which are largely restricted to tors and cliffs (on the right of the ordination, Fig. 2.7). The *T. aphylla* sites occurring on cliffs appeared to be similar (in terms of neighbouring species composition and abundance) to the sites where the subspecies of *T. paynterae* occur (indicated by *T. aphylla* sites on the left of the ordination).

The results of the ANOSIM test indicated significant differences in the composition and abundance of close neighbours between the BIF *Tetratheca* (Global R = 0.204, p < 0.001). While highly significant, the lower value of the Global R compared with environmental data (Fig. 2.3) indicates more of an overlap in the flora data. All paired comparisons were significant at the $p < 0.001$ level, but differences in the R statistic (0.13 to 0.34), indicating the degree of difference between the close neighbours of the different *Tetratheca* species, was not uniform.

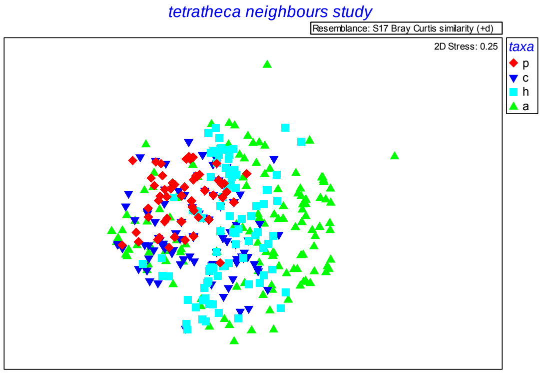


Figure 2.7. MDS ordination of the near-neighbours for each of the four BIF *Tetratheca*. Each point represents the floristic assemblage (excluding the *Tetratheca* plants) within a 2m radius of each 140 *Tetratheca* plants for each of the four BIF *Tetratheca*. Points close together indicate similar plant species composition and abundance.

2.5 Key findings

The environmental domains of *T. paynterae* subsp. *paynterae*, *T. paynterae* subsp. *cremnobata* and *T. harperi* are more similar to one another than they are to *T. aphylla*. The two *T. paynterae* subspecies and *T. harperi* are almost exclusively restricted to growing from fissures in massive banded ironstone landforms. In the cases of the two *T. paynterae* subspecies, on cliffs and tors on the upper slopes of BIF ranges, and in the case *T. harperi* on hillcrests cliffs and cliff footslopes on the crests and upper-slopes of BIF ranges. In contrast, *T. aphylla* is often found growing in skeletal soils on a wide range of landform elements across almost the whole range of slope morphologies on BIF ranges.

Massive rock substrates and steep, often precipitous slopes are characterized by high levels of exposure, a lack of soil and a general shortage of resources. These environments present a number of challenges for plant establishment, growth and survival. The fissures in the massive ironstone provide an anchorage point for plants, and in the semi-arid environment may harvest water from surrounding rock surfaces.

Plants which inhabit these environments are likely to be poor competitors and stress tolerators with life-histories characterized by low rates of intermittent recruitment, slow growth rates and longevity (Grime 1979).

The geographic restriction of the BIF *Tetratheca* to single BIF ranges, and the highly specific habitat, restrict options for translocating the taxa if habitat is destroyed by mining.

The common practice of using seedlings grown either from seed or cuttings will not be suitable for three of the BIF *Tetratheca* (*T. harperi*, *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp *paynterae*) which are almost exclusively restricted to growing from fissures less than 1cm wide. Translocation will have to rely on planting seeds into fissures within the massive banded ironstone. Currently there is no way of knowing which fissures will be suitable for germination and seedling establishment.

Although the environmental domains of *T. harperi*, *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp *paynterae* differ in some aspects, they are similar enough to be considered ecological analogues. The relatively undisturbed *T. harperi*, and *T. paynterae* subsp. *cremnobata* will provide useful bench-marks for gauging the performance and viability of the *T. paynterae* subsp. *paynterae* population in the mine and post-mine environment.

3. Climate

3.1 Introduction

Climate is a major driver of plant phenology, reproduction, growth and population dynamics. The region where the BIF *Tetratheca* grow has a semi-arid dry Mediterranean climate. The closest weather station with long term records (1891-present) is at Southern Cross c. 100 km south of Mt Jackson. Rainfall has been recorded at the Portman Iron Ore mines site at the Windarling Range since May 2004.

Rainfall patterns are likely to be particularly important for reproduction, seedling recruitment, plant growth and survival of the BIF *Tetratheca*. Long-term rainfall trends at Southern Cross show that annual rainfall is variable (coefficient of variation = 32%, Fig 3.1).

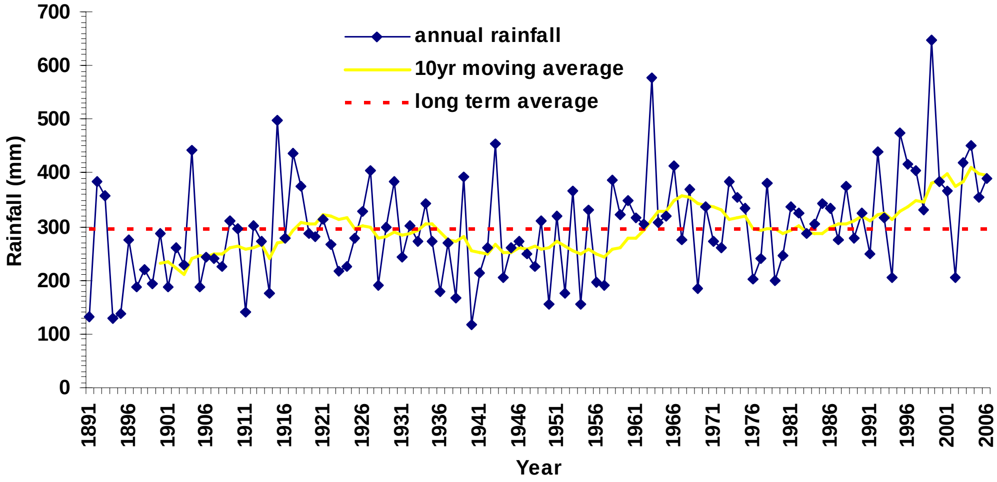


Figure 3.1. Long term annual rainfall pattern for Southern Cross (1891-2006) with 10 year backward moving average and long-term annual average.

There also appears to be a trend of wetting and drying cycles with periods of lower and higher rainfall over a 10-20 year sequence. These long-term cycles are likely to have implications for plant population dynamics as numbers build up in wet cycles through better survival and recruitment, and decline in the dry periods through the effects of drought. Rainfall patterns also indicate a trend of increasing rainfall, particularly over the last ten years. Looking at rainfall for the different seasons reveals that the trend of increasing rainfall over recent times is due to increased amounts of summer rainfall, while winter rainfall has not changed greatly over the same period. These patterns agree with the predictions for future rainfall trends in this region (CSIRO 2007). Monthly rainfall patterns indicate that the winter months are the period of highest rainfall (Fig. 3.2) from low pressure weather systems moving from the west and the north-west.

Summer rainfall is much lower and much more unpredictable than winter rainfall and is reliant on localized thunderstorms and ex-tropical cyclones occasionally drifting far enough south to bring rainstorms to the region. It is likely that an increase in frequency of these events occurring will lead to an increase in summer rainfall.

The combination of good winter rains, to stimulate seed germination, and a follow-up of summer rainfall, to increase survival rates of developing seedlings particularly for the critical first summer, are likely to be a requirement for episodic recruitment events as well as survival of plants such as the *Tetratheca* taxa occurring on the Yilgarn BIF ranges. For example, higher plant mortality rates of the *Tetratheca* taxa in 2004/5 can be linked to poor winter rains in 2004 followed by little rainfall throughout the spring-summer months and into autumn (Fig.3.3 and see section 5).

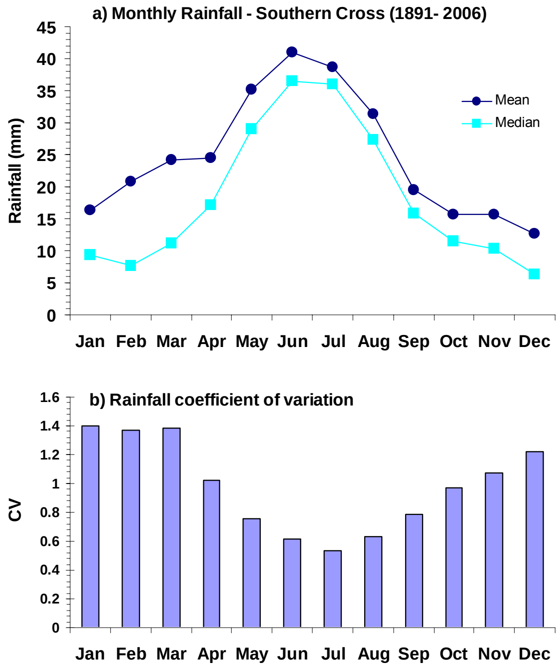


Figure 3.2. a) Long term (1891-2006) monthly and median rainfall, and b) monthly rainfall co-efficient of variation for Southern Cross.

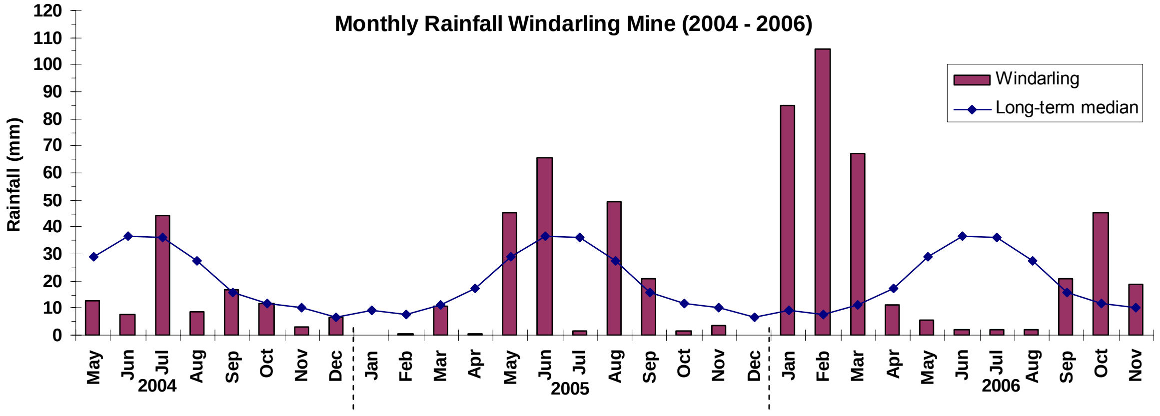


Figure 3.3. Recorded monthly rainfall over three years at the Windarling mine site and long term monthly average from Southern Cross.

4 Comparative reproductive biology of the four BIF *Tetratheca* taxa

4.1 Introduction

For sexually reproducing plants, population viability is in part dependent on seed production. For plants in semi-arid climates, rates of flowering and seed production are influenced by the size and condition of plants, availability of resources, the breeding system, and availability of mates and pollinators all of which may vary between years. The loss of part of the *T. paynterae* subsp. *paynterae* population through mining at Windarling has reduced the number of potential mates. In addition, disturbance associated with mining may affect flowering and pollinators. It is therefore important to investigate reproduction in the four taxa across multiple years.

The BIF *Tetratheca* can flower at any time of the year following substantial rain, but the main flowering period is at the end of the winter wet season when rainfall is most reliable (August to October). *Tetratheca* flowers do not produce nectar and pollen is held within a ring of tubular porocidal anthers that surround the flower style. Pollen is extracted from the anthers either by native bees sonicating and vibrating pollen loose from the anthers or by raking the anthers with their front legs. Pollen collected by the bees is stored on leg and abdominal hairs and may inadvertently be transferred between flowers if bees come into contact with the flower stigma, which, when receptive protrudes above the ring of anthers. Three species of native bee *Lasioglossum* and four unidentified native bee species have been observed foraging on flowers of the BIF *Tetratheca.* Bees are most active on warm (> 22º C) days when winds are light to moderate (0.25 to 5.26 m/sec) (McNee 2003).

Investigations of the mating system in three of the BIF *Tetratheca* found high rates of outcrossing, and controlled pollination studies showed that self-pollination produces fewer fruit compared to cross-pollination between plants (Butcher et al. 2007b). Self-incompatibility occurs in the style, allowing initial pollen tube growth, but preventing the majority of pollen tubes entering the ovary (Butcher et al. 2007b)

4.2 Research objectives

The objectives of the research described in this section are to describe and compare the:

- rates of flowering and fruit production of the four BIF *Tetratheca* taxa and
- rates of pollination and seed production of the four BIF *Tetratheca* taxa*.*

4.3 Methods and materials

4.3.1 Flowering and fruit production

For each of the four taxa we tagged up to 77 plants for annual investigations of flower and fruit production. The plants were subjectively chosen to encompass the size range of reproductive plants and their environments. At peak flowering in 2004, 2005 and 2006, we measured canopy diameter at the widest point, canopy condition on a five point ordinal scale, and counted the total number of flowers (unopened buds + open flowers) on each plant. In November of each year we returned to the plants and counted the number of fruit. In 2004 and 2006, at the time of counting, fruits on *T. aphylla* were dehiscing and being shed from plants. We were therefore uncertain about the accuracy of our counts and as a consequence, excluded *T. aphylla* from analyses of fruit production.

We examined the effect of taxon, year, and canopy width and condition, on flower and fruit production with analysis of covariance (ANCOVA). We fitted models using a randomized complete block design with two covariate terms, treating taxon as a fixed factor, year as a random blocking factor, and canopy width and condition as covariates. In this analysis, the effect of canopy width and condition are removed from the unexplained variability by regression analysis. The ANCOVA tests the difference between factor level means adjusted for the effect of the covariates.

ANCOVA models were fitted for flower and fruit production and the model residuals were examined. The plot of residuals against predicted number of flowers and number of fruit showed evidence of heterogeneity of variances. The models were refitted with √ transformation for both the number of flowers and the number of fruits. The distributions of residuals were much improved.

We investigated differences between the two subspecies *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp. *paynterae* in the √number of flowers and √number of fruit with single degree of freedom contrasts.

4.3.2 Rates of pollination and seed production

For each of the four BIF *Tetratheca* we tagged 50 plants for studies of pollination and seed set. The plants were subjectively chosen to encompass the range of environments, and were spread through the breadth of each population. At peak flowering in 2003, 2004 and 2005, 10 flowers were harvested into 70% ethanol from each plant. Flowers were collected following anthesis but still fresh. For each plant, the styles were dissected from five flowers. The styles were re-hydrated through a series of 30% ethanol and two distilled water soakings for at least 10 minutes each. They were later softened in 0.8N NaOH at 60^{o} C for 2 hours, soaked in the stain aniline blue (0.1% aniline blue in 0.1N K_3PO_4) for 10 minutes in the dark, and then mounted on slides in 80% glycerol and viewed under a microscope. Pollen grains and tubes fluoresced under ultraviolet light and pollen grains and tubes in the stigma were counted.

Annually from 2003-2006, 10 fruit were harvested from each of 50 tagged plants in each of the four *Tetratheca* taxa. Each fruit was placed in a separate seed envelope, subsequently dissected under a microscope and the number of fully formed (developed) seeds, and partially formed aborted (undeveloped) seeds counted.

We examined the effect of taxon and year on pollination and seed production using analysis of variance (ANOVA). We fitted models using a randomized complete block design, treating taxon as a fixed factor, and year as a random blocking factor. Models were fitted for the number of pollen grains/stigma, the number of developed seeds/fruit and the number of undeveloped seeds/fruit. Model residuals were examined. The plot of residuals against the predicted number of pollen grains on the stigma showed evidence of heterogeneity of variances. The model was refitted with √ transformation of the number of pollen grains. The residuals plot was much improved and residuals showed homogeneity of variances. The plots of residuals against the number of developed seeds/fruit and the number of undeveloped seeds/fruit showed homogeneity of variances and no transformations were required. We investigated differences between the two subspecies *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp. *paynterae* in the √number of pollen grains/stigma, the number of developed seeds/fruit and the number of undeveloped seeds/fruit with single degree of freedom contrasts.

4.4 Results

4.4.1 Flower production

There was a highly significant relationship between canopy width and √number of flowers ($F_{1,835} = 592.014$, $p < 0.05$), but there was no significant relationship between canopy condition and √number of flowers ($F_{1,835} = 0.465$, $p > 0.05$). The number of flowers produced by a plant increased as canopy width increased and the slopes of lines for each taxa were similar (Fig. 4.1).

After adjusting for canopy width there were no significant differences among species ($F_{3,6} = 0.353$, $p > 0.05$) or among years ($F_{2,6} = 3.861$, $p > 0.05$) in the mean √number of flowers produced by plants (Fig. 4.2). There was no significant difference in mean flower production pooled over the three years between *T. paynterae* subsp. *cremnobabta* and *T. paynterae* subsp. *paynterae* ($F_{1,835} = 2.041$, p = 0.153).

4.4.2 Fruit production

There was a highly significant relationship between canopy width and mean √number of fruit ($F_{1,630} = 287.22$, $p < 0.05$), and canopy condition and mean √number of fruit ($F_{1,630} = 7.87$, $p < 0.05$). The number of fruit produced by a plant increased as canopy width increased and the slopes of lines among taxa were similar (Fig. 4.3).

After adjusting for canopy width and condition there was no significant difference in the mean √number of fruits produced by plants among taxa ($F_{2,4} = 0.39$, $p > 0.05$), but there was a significant difference among years ($F_{2,4} = 12.53$, $p < 0.05$). Across the three taxa fruit production was lower in 2005 than in the other two years (Fig. 4.4). There was no significant difference between *T. paynterae* subsp. *cremnobabta* and *T. paynterae* subsp. *paynterae* in mean fruit production pooled over the three years ($F_{1,630} = 0.001$, $p = 0.970$).

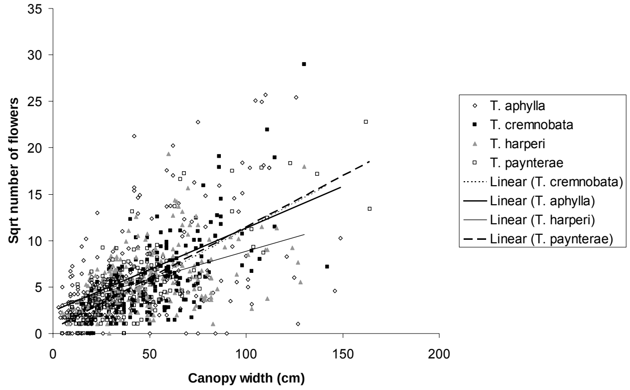


Figure 4.1. The √number of flowers + buds per plant versus canopy width and regression slopes for the four BIF *Tetratheca*.

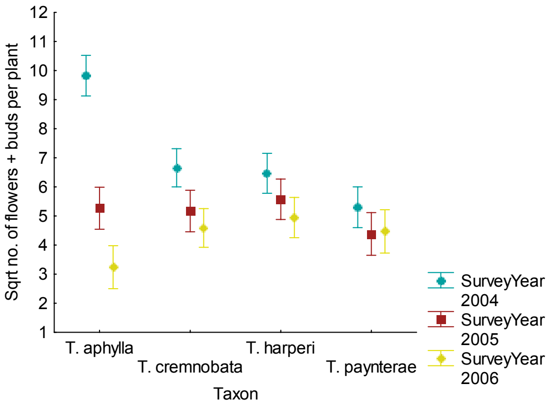


Figure 4.2. Mean √number of flowers + buds per plant for the four BIF *Tetratheca* for each of three years. Error bars are 95% confidence intervals.

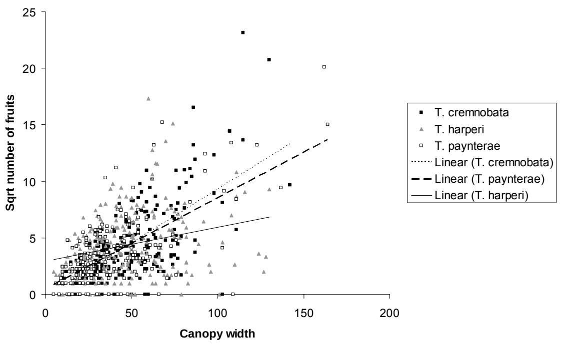


Figure 4.3. The relationship between the √number of fruits per plant and canopy width for three BIF *Tetratheca*.

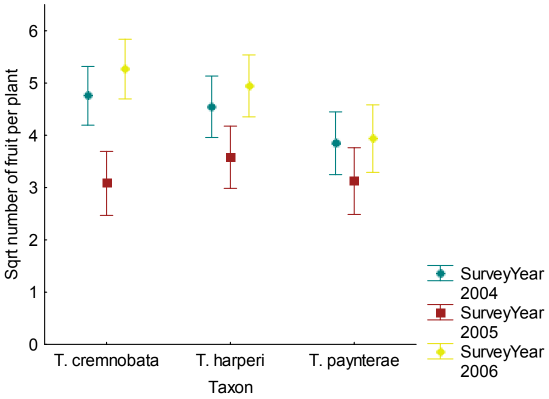


Figure 4.4. Mean √number of fruit per plant for three BIF *Tetratheca* for three years. Error bars are 95% confidence intervals.

4.4.3 Rates of pollination

There was no significant effect of taxa ($F_{3,6}$ = 1.516, $p > 0.05$) or year ($F_{2,6}$ = 1.625, $p > 0.05$) on the mean √number of pollen grains per stigma (Fig. 4.5). There were no significant differences between *T. paynterae* subsp. *cremnobata* and *T. paynterae* subsp. *paynterae* in the mean √number of pollen grains/stigma pooled over the three years ($F_{1,593}$ = 0.878, $p = 0.349$).

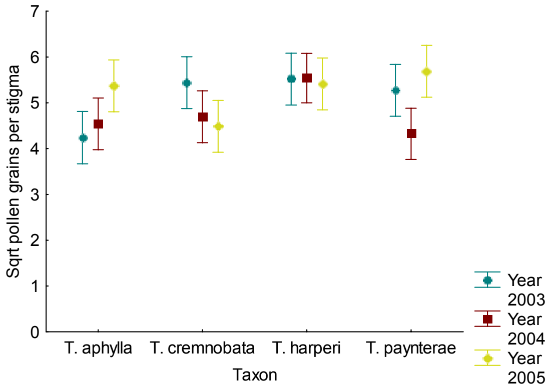


Figure 4.5. Mean √number of pollen grains per stigma for the four BIF *Tetratheca* in each of three years. Error bars are 95% confidence intervals.

4.4.4. Seed production

There was no significant effect of taxa ($F_{3,9}$ = 2.334, $p > 0.05$) or year ($F_{3,9}$ = 0.137, $p > 0.05$) on the mean number of developed seeds per fruit (Fig. 4.6 a). There was a significant effect of taxa ($F_{3,9}$ = 9.341, $p < 0.01$), but not year ($F_{3,9}$ = 0.231, $p > 0.05$) on the mean number undeveloped seeds per fruit (Fig. 4.6 b).

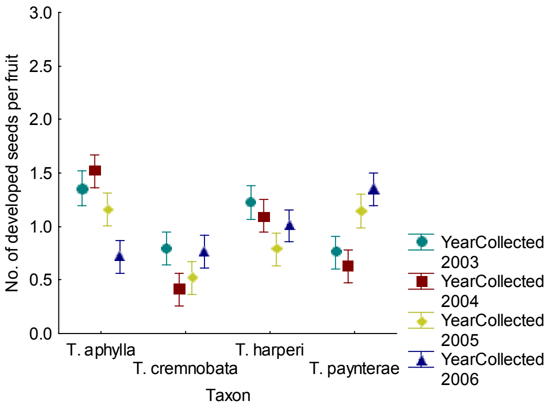


Figure 4.6a. Mean number of developed seeds per fruit for the four BIF *Tetratheca* in each of four years. Error bars are 95% confidence intervals.

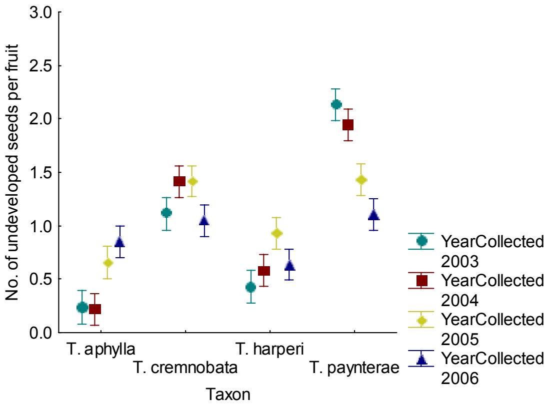


Figure 4.6b. Mean number of undeveloped seeds per fruit for the four BIF *Tetratheca* in each of four years. Error bars are 95% confidence intervals.

The mean number of developed and undeveloped seeds per fruit pooled over the four years was significantly higher for *T. paynterae* subsp. *paynterae* than for *T. paynterae* subsp. *cremnobata* ($F_{1,\,777} = 39.529$, $p = 0.000$; $F_{1,\,777} = 58.011$, $p = 0.000$).

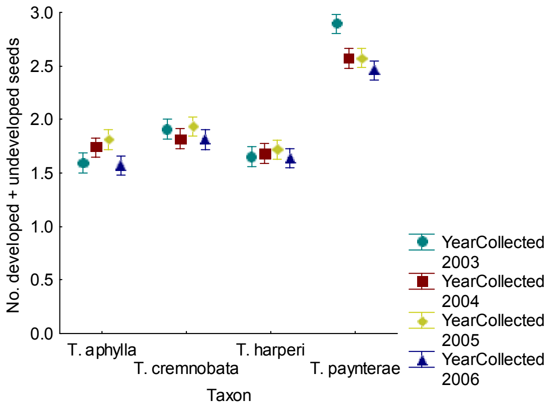


Figure 4.6c. Mean number of undeveloped + developed seeds per fruit for the four BIF *Tetratheca* in each of four years. Error bars are 95% confidence intervals.

4.5 Key findings

Flowering, fruit and seed production occurred annually in winter and spring in the four BIF *Tetratheca*. Larger plants produced more flowers. After adjusting for plant size there were no significant differences in the number of flowers produced by plants among the four BIF *Tetratheca* or between years.

Similarly, there were no significant differences in levels of pollination or the number of developed seeds per fruit among the four BIF *Tetratheca* or between years. The number of seeds per fruit varied substantially among years within the four taxa.

In 2005, three of the BIF *Tetratheca* produced significantly lower numbers of fruit compared to 2004 and 2006. This may be the result of well below average monthly rainfall from May 2004 to May 2005, which resulted in a decline in canopy condition (see section 5). At flowering in 2005, plants were still recovering from the drought and may not have had the resources to devote to fruit production.

5. Demography and population dynamics

5.1 Introduction

The dynamics of a population are captured by a simple equation that relates the numbers per unit area of an organism N_t at some time t to the numbers N_{t+1} one time unit (e.g. year) later.

$$N_{t+1} = N_t + B - D + I - E,$$

where B is the number of births, D the number of deaths and I and E are, respectively, immigrants into the population and emigrants from it. The dynamics of a population may be summarized by the ratio N_{t+1} / N_t which is called the annual or finite rate of increase (λ). The balance between the two demographic parameters (B and I) which increase N_t and those which decrease it (D and E) determines whether the population remains stable ($\lambda = 1$), decreases ($\lambda < 1$) or increases ($\lambda > 1$). Among other things, the values of B, D, I and E in natural plant populations are variously influenced by pollinators, herbivores, diseases, animals that disperse seeds, soil, climate and disturbances (Silverton and Charlesworth 2001).

Many of the interactions which influence the rates of demographic parameters may be affected directly by mining destroying habitat and reducing the size of BIF *Tetratheca* populations, and indirectly, by the effects of ground breaking disturbance in the immediate vicinity of populations.

In populations where recruitment is relatively frequent compared to the life-span of adults, such as long-lived perennial plants, there is an age structure in populations. At any one time, seeds, seedlings, juveniles and adults of various ages may be all found in the population. The proportion of individuals in each age class affects the trajectory of the population.

Plants are highly plastic in their rates of growth and development, so that two individuals of the same age but different local environments may be at quite different stages of their life-cycle. Therefore, as well as an age structure, plant populations have a stage structure with both affecting the population dynamics. The structure of a population is largely dependent upon the pattern and periodicity of recruitment. In semi-arid environments recruitment is often driven by rainfall and the age structure of populations is often related to the periodicity of high rainfall events. The existence of age and stage structure has to be taken into account in population models, because not all stages contribute equally to population growth.

Measurements and estimates of the rates of demographic parameters, and an understanding of the dynamics of the BIF *Tetratheca* populations are essential for assessing the impacts of mining on *T. paynterae* subsp. *paynterae*.

5.2 Objectives

The objectives of the research described in this section are to:

- describe and compare the population structures of the four BIF *Tetratheca*;
- estimate annual rates of demographic parameters for subsequent use in population models (see Chapter 6), and
- understand the influence of climate on rates of demographic parameters.

5.3 Methods

For each of the four *Tetratheca* taxa, permanently located quadrats were established in winter-spring 2004 to monitor annual rates of demographic parameters (seedling recruitment, plant mortality, plant growth). Quadrats were carefully searched and all plants were labelled with uniquely numbered UV light stabilized plastic tags glued to the rock next to the plant (Fig. 5.1). Up to 50 plants outside the plots were also tagged.

Figure. 5.1. Tagged *T. harperi* reproductive adult plants. (Photo Colin Yates DEC)

For each plant, we measured canopy diameter at the widest point and at right angles to this, canopy condition in five classes (1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-100% alive), and recorded life stage (seedling, seedling 1yr old, seedling 2yr old, juvenile, reproductive, vegetative, Figs. 5.1, 5.2, 5.3). We tagged and measured 203 plants for *T. aphylla*, 214 plants for *T. harperi*, 205 plants for *T. paynterae* subsp. *cremnobata* and 230 plants for *T. paynterae* subsp. *paynterae.*

Figure 5.2a. Tagged *T. paynterae susbp. paynterae* reproductive adult plants with tagged seedling. (Photo Colin Yates, DEC).

Figure 5.2b. Tagged *T. paynterae susbp. paynterae* seedling. (Photo Colin Yates DEC).

Figure 5.3. Tagged *T. paynterae susbp. paynterae* 1 yr old seedling. (Photo Colin Yates DEC).

In winter-spring 2005 we repeated the demographic survey, measuring the survival and growth of all tagged plants. In addition, we carefully searched quadrats for seedlings that emerged in the 2005 winter. These seedlings were easily recognized and when encountered were labelled with UV stabilized plastic tags. Tagged adult stage plants that died over the 2004/2005 summer were replaced with "new census plants" to ensure that our sample sizes remain constant. In winter-spring 2006 we repeated the demographic survey. The data for the 2004, 2005 and 2006 demographic surveys were entered into an Access database, and for Time Step 1 (2004-2005) and Time Step 2 (2005-2006) seedling recruitment, fecundity, mortality and transition rates in the life-cycles of the four BIF *Tetratheca* taxa calculated. Fecundity was calculated using the following formula

Number of seedlings that emerged at time step t + 1 (e.g. 2005) ÷ Number of reproductive adults at time step t (e.g. 2004).

5.4 Results

5.4.1 Population structure

Newly emerged seedlings, 1 year old and 2 year old seedlings, juveniles, reproductive and vegetative adult plants were observed in populations of the four BIF *Tetratheca* (Fig. 5.4). Most plants were reproductive adults and the size of these varied considerably either as a function of age or local conditions such as the volume of the fissure available to be exploited.

5.4.2 Seedling recruitment

Seedling emergence occurred in winter each year as long as there had been sufficient rain to provide consistent moist conditions for some weeks (Fig. 5.5, Table 5.1). Seedlings were only observed in rock fissures. Seedling emergence was highest for the BIF *Tetratheca* in 2005 following above average rainfall in the months May to September and lowest in 2006 when rainfall was well below average for the period May to September.

5.4.3 Mortality

Annual mortality was highest and most variable for seedling, juvenile and vegetative adult stages and was lowest and least variable in reproductive adult stages (Fig. 5.6). During the 3 years of census, mortality in juvenile, reproductive and vegetative adult stages was observed in only one year, 2005, following a 12 month period when rainfall was well below the long term median.

In seedling stages, mortality was observed in each of the three census years. A combination of the amount of rainfall which falls in the first summer after germination and the suitability of rock fissures, probably both contribute to the high rates of seedling mortality. Some rock fissures may be suitable for seed germination but may not be suitable for subsequent root development and seedling growth.

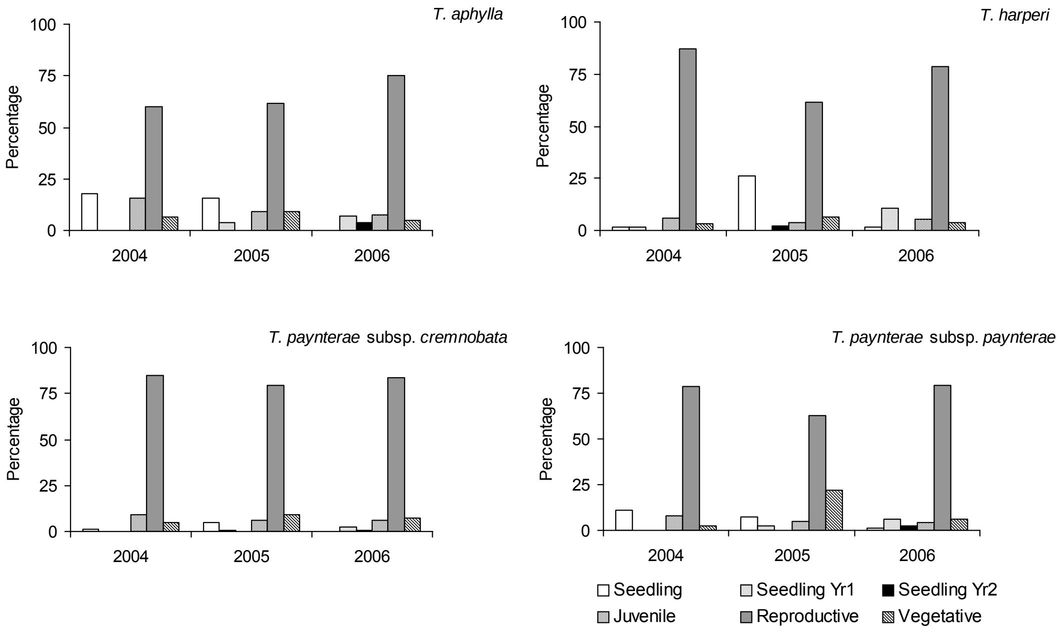


Figure 5.5. The frequency distribution of tagged plants among life-cycle stages in each of three consecutive years for the four BIF *Tetratheca* taxa.

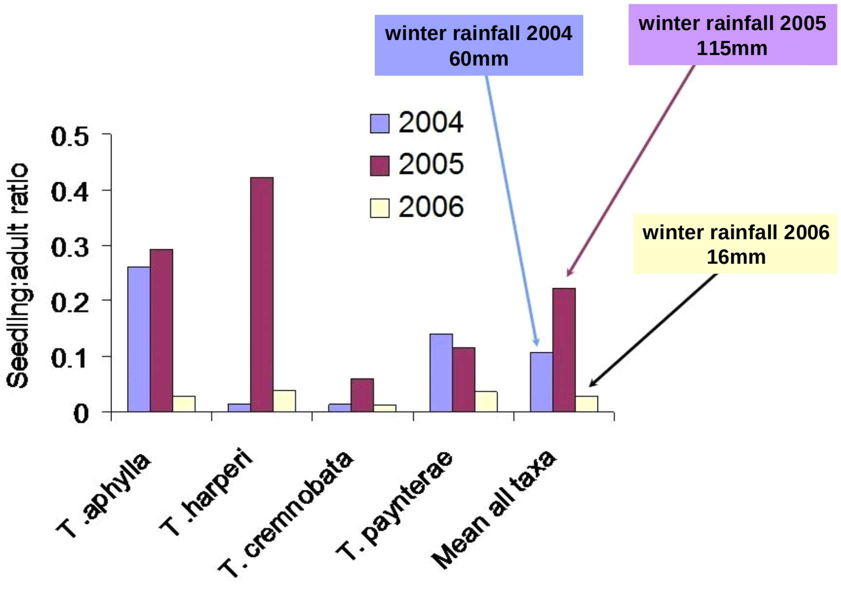


Figure 5.4. Annual seedling recruitment and June to August rainfall for the three years of survey highlighting the higher seedling recruitment rate in 2005 when winter rainfall was much higher compared to the other years. Long term mean winter rainfall is 110mm.

	T. aphylla			*T. harperi*			*T. paynterae* subsp.. *cremnobata*			*T. paynterae* subsp.. *paynterae*		
Year	Seedlings	Adults	Ratio	Seedlings	Adults	Ratio	Seedlings	Adults	Ratio	Seedlings	Adults	Ratio
2004	24	92	0.261	2	153	0.013	2	136	0.015	21	150	0.140
2005	27	92	0.294	60	142	0.423	9	150	0.060	17	146	0.116
2006	3	108	0.028	6	155	0.039	2	155	0.013	7	190	0.037
Mean			0.194			0.158			0.029			0.098

Table 5.1. The number of seedlings, reproductive adults and their ratio in fixed area quadrats for the four BIF *Tetratheca* taxa in 2004, 2005 and 2006.

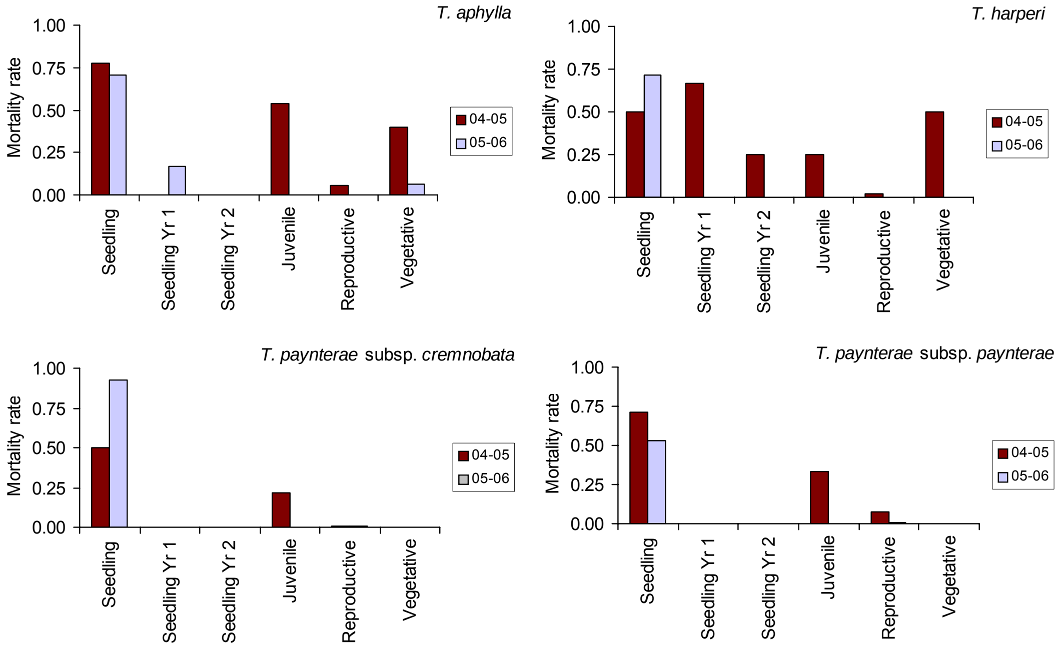


Fig. 5.6. Annual mortality in plant life-stages for the two 1-year time-steps from 2004 to 2005 for the four BIF *Tetratheca* taxa.

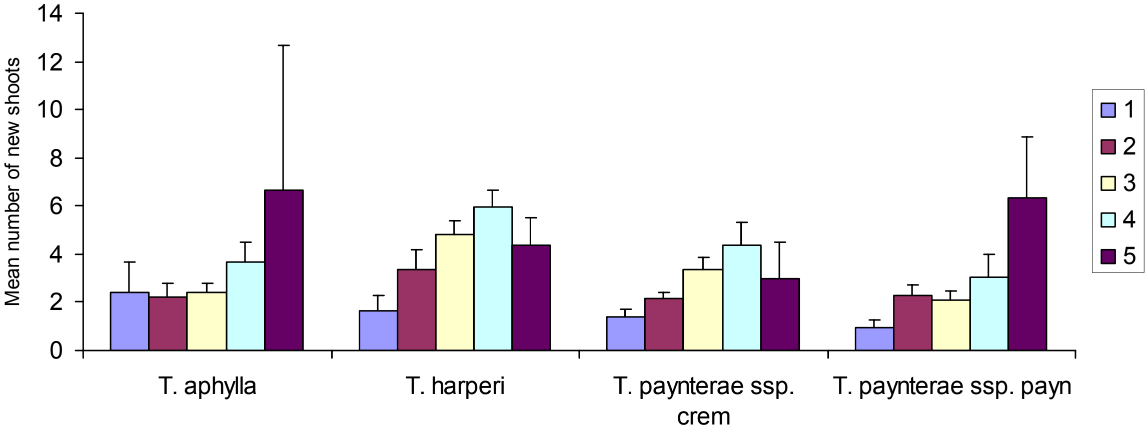


Figure 5.7. The relationship between the number of new shoots and canopy condition classes for the four BIF *Tetratheca* taxa.

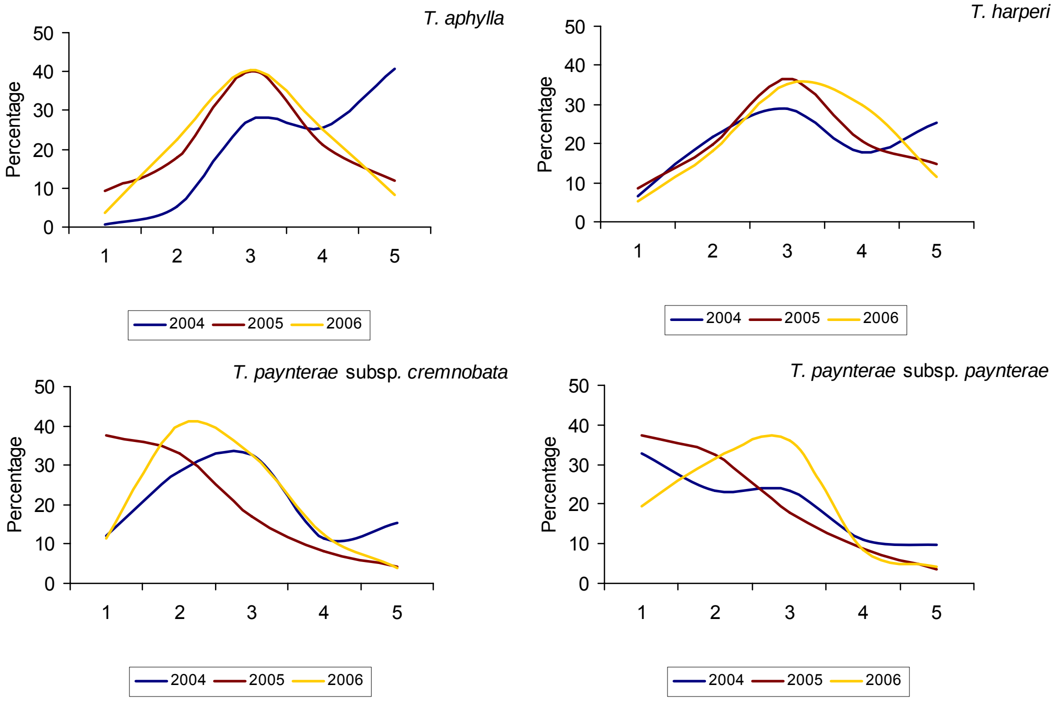


Figure 5.8. The percentage of plants in canopy condition classes (1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-100% alive) for the four BIF *Tetratheca* taxa in 2004, 2005 and 2006.

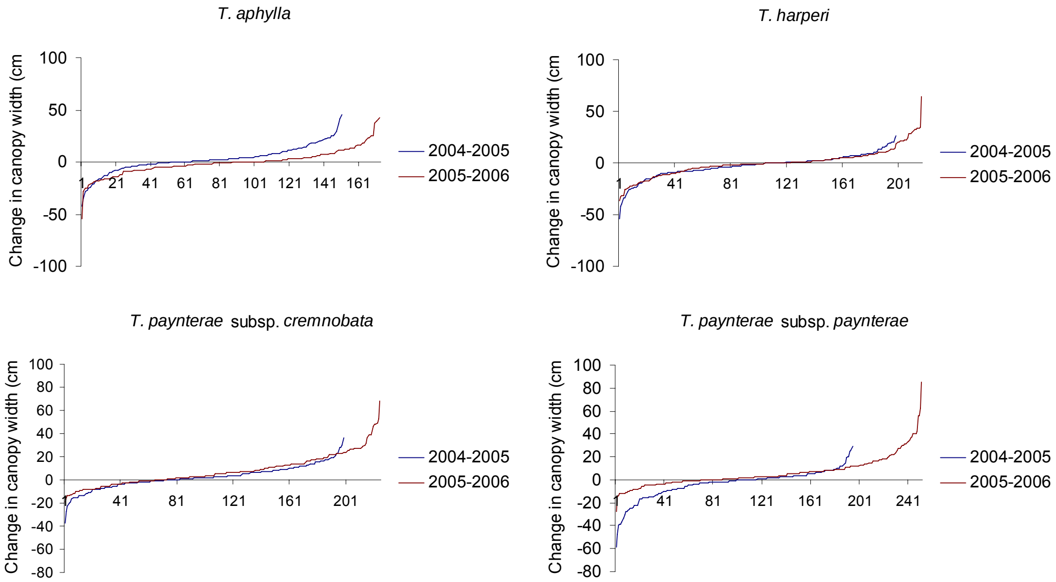


Figure 5.9. The change in canopy width of monitored plants for the four BIF *Tetratheca* taxa over two time-steps, 2004-2005-2006.

5.4.4 Plant growth and canopy condition

Plant canopy condition was positively associated with the number of new shoots produced in winter (Fig. 5.7).

Plant canopy condition declined across the four BIF *Tetratheca* taxa in time step 1 (2004-2005, Fig. 5.8). At the end of the time step, in 2005 there were fewer plants in the healthiest canopy classes 4 and 5 than for the beginning of the time step in 2004. Plant canopy condition in the four taxa began to improve in time-step 2 (2005-2006, Fig. 5.8).

Similarly, for the four BIF *Tetratheca* taxa, associated with the decline in canopy condition was a decline in canopy width (Fig 5.9). The changes in canopy condition recorded for *T. paynterae* subsp. *paynterae* are within the ranges recorded for the other *Tetratheca* taxa.

5.5 Key findings and outcomes

Climate variables particularly the amount and season of rainfall are key drivers of population dynamics and plant growth in the four BIF *Tetratheca* taxa.

Seedling recruitment occurred each winter but was highest in the wettest winter when rainfall in the months May to September was above the long term average.

Rates of mortality varied among life-stages, and were highest in seedling stages and lowest in adult stages. Mortality in seedlings occurred in each of the three census years, but in adults was restricted to a year when rainfall in the previous 12 month period was well below the long term median. The condition and size of plant canopies were also affected by the drought with plant canopies dieing back, having fewer green shoots and becoming smaller.

The high rates of seedling mortality may be a consequence of both the amount of rainfall in the first 12 months following seedling emergence, and many rock fissures being suitable for germination, but not for subsequent seedling growth and survival. Reasonably high rates of mortality also occur in juveniles, indicating that fissure suitability may still be influential in determining which plants survive. Relative to other life stages the low mortality rates in adult plants indicate that individuals that survive to maturity are quite resilient.

The low frequency of winters in the region when rainfall is sufficient to stimulate high rates of seed germination, coupled with consistently high rates of seedling mortality in most years, and no way of determining which rock fissures will be suitable for plant establishment, contribute to making translocation an extremely high risk strategy for conserving BIF *Tetratheca* affected by mining.

Windarling from the Diehardy Range (Photo Colin Yates DEC).

Diehardy Range from Windarling (Photo Colin Yates DEC).

6. Population viability analysis

6.1 Introduction

Modelling is a process of building simple, abstract representations (e.g. as mathematical equations) of complex systems (e.g. a natural plant population) to gain insights into how the system works, in order to predict how it will behave in the future, to guide further investigations, and to make decisions about how it can be managed (Akçakaya 2004).

Population viability analysis (PVA) is a process of using species-specific data and models to evaluate the threats faced by species in terms of their risks of extinction or decline (Akçakaya 2004).

Results of PVA can be used to:

- compare parameters that have the most effect on population viability, and thus to guide monitoring especially in cases where data are uncertain or lacking;
- assess the impact of human activities such as habitat destruction on population viability; and
- examine the influence of climate on population viability.

Mining has destroyed c. 30% of the *T. paynterae* subsp. *paynterae* population at Windarling. A further 20% of the original population may be destroyed if mining is approved in Area B.

6.2 Objectives

The objectives of the research described in this section are to determine for *T. paynterae* subsp. *paynterae*:

- the potential impact on population viability of further reducing population size by allowing mining in Area B; and,
- life-history stages that have the greatest influence on population viability.

6.3 Methods

6.3.1 Defining life history stages

For the three BIF *Tetratheca* that are restricted to growing in fissures (*T. harperi*, *T. paynterae* subsp.*cremnobata*, *T. paynterae* subsp. *paynterae*) we used a biological classification combining reproductive state and plant size to classify each individual into one of eight stages; seedling (first year emergent), seedling (1 year old), seedling (2 years old), juvenile (3 years after emergence until reproductive), reproductive size class 1 (canopy width < 30cm), reproductive size class 2 (30 – 60cm), reproductive size class 3 (> 60cm) and vegetative (non-reproductive adult plants). Plants in seedling stages either die or grow to the next stage. Plants in the juvenile stage may die, reach reproductive maturity, or remain in the stage until they are reproductive. Plants in mature stages may die, remain in their stage, grow to the next stage, regress to a previous stage or become vegetative (senescent). We calculated the proportion of individuals in each stage that remained the same or changed to a different stage for the two one-year time steps (2004-2005 and 2005-2006, Fig. 6.1).

6.3.2 Fecundity

In section 4.4.1 we described a significant linear relationship between plant canopy width and total number of flowers per plant, for each of the three BIF *Tetratheca* taxa. Using the regression equations, we calculated for each reproductive plant the total number of flowers per plant. For each reproductive class we summed the number of flowers produced by plants, and calculated the proportional contribution of each reproductive class to the total number of flowers produced by all plants. To estimate fecundity we partitioned seedling numbers among the three reproductive classes in proportion to their estimated contribution to flowering. We calculated the fecundity of each reproductive class as: *number of seedlings produced by the reproductive class ÷ number of plants in the reproductive size class*.

We assumed that there is no seed bank carried over from one year to the next.

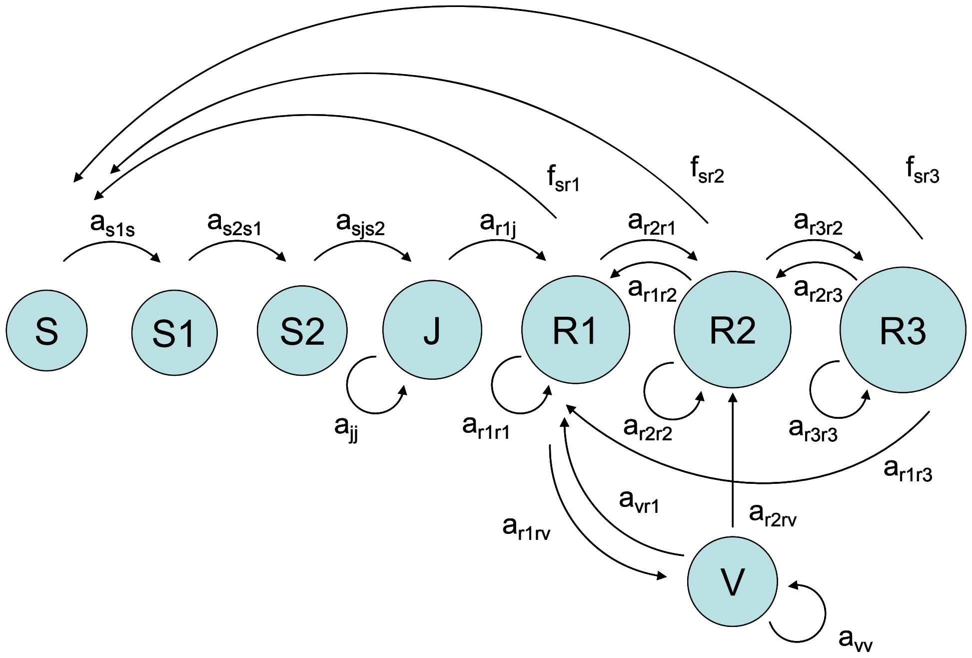


Figure 6.1. Conceptual model of the life-cycle of *T. paynterae* subsp. *paynterae*. Each arrow represents the possible transitions between life-stages. Arrows labelled with “a” represent survival and change of stage of plants. Arrows labelled with “f” represent fecundity. Stages identified in this model are first year seedling (S); 1 year old seedling (S1); 2 year old seedling (S2); plants that have not reached reproductive maturity (J), three sizes of reproductive plants (R1, R2, R3) and vegetative adult plants (V).

6.3.3 Matrix formulation and analysis

For each of the three *BIF Tetratheca* taxa and the two one-year time-steps, rates of fecundity and proportions of individuals that remained the same or changed to a different stage were organized as transition elements in a matrix following standard methods, and according to our conceptual model of population dynamics (Fig. 6.1). In total, six annual transition matrices were constructed (3 taxa x 2 annual time steps). These were used to calculate a mean and standard deviation matrix, representing the transition probabilities and their variation for life-stage in a generic “fissure dwelling BIF *Tetratheca*”. This was done to increase sample sizes in the seedling and juvenile life-stages and the robustness of the transition estimates. This is unlikely to have resulted in significant loss of information as in previous sections we showed that *T. paynterae* subsp. *paynterae*, *T. paynterae* subsp. *cremnobata* and

T. harperi were all primarily restricted to fissures in massive ironstone and had similar population dynamics, structure and reproductive potential.

6.3.4 Modeling population trend and viability

We used the stochastic simulation program RAMAS Metapop version 5 (Akçakaya 2005) to model the stochastic sensitivities and extinction probabilities for *T. paynterae* subsp. *paynterae* under different disturbance and rainfall scenarios. The model included demographic and environmental stochasticity. RAMAS incorporates demographic stochasticity by sampling the number of survivors from binomial distributions and fecundity from a Poisson distribution (Akçakaya 2005). RAMAS implements environmental stochasticity at each time step by randomly selecting matrix elements within the observed variance (SD) around their mean. To reduce likely truncations due to high survival rates, we sampled from a lognormal distribution and imposed a negative correlation between the largest survival rate and other survival rates for each stage. Constraints were imposed to ensure that all survival rates were within the bounds of 0 and 1 (Akçakaya 2005).

Populations with abundant resources (compared to the number of individuals in the population) can grow exponentially for a period of time. As population size increases, it must approach a point at which there are more organisms than can be supported by the available resources. The effect of limited resources on population growth must eventually result in some kind of feedback that limits growth. There are many possible mechanisms for density dependence: fecundity may decrease; mortality may increase with competition for limited resources; and the occupation of available space may limit opportunities for new recruitment. Population growth may also be affected negatively as population size reaches very low levels (Allee effects).

For the BIF *Tetratheca* taxa we do not have any estimates of how population size and density influences demographic parameters. As a consequence, we assumed that increases in population size did not affect the rates of demographic parameters. Similarly, we assumed that declines in population size did not result in Allee effects. However, we did assume that because *T. paynterae* subsp. *paynterae* has such a specialized habitat, there would be a limited number of suitable fissures and this would cap population size. We modelled density dependence using a simple ceiling model in which the population grows exponentially until it reaches the ceiling; in this case when all suitable fissures are occupied. We assumed population ceiling was 10,000 plants, approximately twice the extant population. All simulations were run for 50 one year time steps replicated 1,000 times.

6.3.5 Population trend and viability under different disturbance and rainfall scenarios

We parameterized a base model to represent the status of the *T. paynterae* subsp. *paynterae* population in 2006. We calculated an estimate of the number of plants in each life stage for the whole population (c. 5,000 plants) based on the proportion of individuals in each life stage at the last census (S = 1945; S1 = 0; S2 = 0; S3 = 17; J = 337; R1 = 432; R2 = 381; R3 = 367; V = 20 plants).

In Section 4 we showed that for the BIF *Tetratheca*, recruitment increases with increasing winter rainfall. In semi-arid environments in south-west Australia, infrequent high winter rainfall years result in pulses of recruitment. For example, in *Verticordia staminosa* subsp. *staminosa*, a rare shrub that inhabits fissures in massive granite pavements, recruitment was 10 times higher in a very high winter rainfall year compared to average or below average winter rainfall years (Yates and Ladd 2004; Yates *et al*. 2007). Because these events are infrequent there is a high probability they may not occur within the life of a research program.

However, if the probability of “high rainfall” years which result in pulse recruitment can be estimated, these events can be incorporated into PVA. We assumed that for *T. paynterae* subsp. *paynterae* pulse recruitment events are likely in years that have experienced higher than average winter rainfall, which is critical for good germination, coupled with the occurrence of higher than average rainfall in the following summer, which will greatly improve survival of the new seedlings (see previous sections). By checking the long-term rainfall records for nearby Southern Cross the coincidence of these rainfall patterns has occurred 16 times in the past 114 years of record. Therefore this would give a probability of a pulse recruitment rainfall year occurring of P = 0.14.

Based on our understanding of the population dynamics of the fissure dwelling shrub *V. staminosa* subsp *staminosa*, we assumed that “high rainfall” years would increase fecundity (seedling:adult ratio) in *T. paynterae* subsp. *paynterae* tenfold. We also investigated the influence of “high rainfall” years on population viability by increasing the transition probability of seedling survival (S to S1) from the measured probability of survival in a ‘normal year’ (0.3521) to (0.3521 x 1.25 = 0.44), (0.3521 x 1.5 = 0.53), (0.3521 x 2 = 0.71) and (0.3521 x 2.75 = 0.97).

We examined the potential impact of mining Area B on the viability of the *T. paynterae* subsp. *paynterae* population by reducing the initial population size in the base model from 5,000 plants to 4,000 plants. We ran the model with pulse recruitment (P = 0.14) and with the range of seedling survival probabilities.

Two measures of population viability under the different rainfall and disturbance scenarios are presented. Firstly, interval extinction risk curves, which give the probability that the population will fall below a range of abundances at least once during the 50 years of a simulation. Secondly, the expected minimum population (EMP) which is an estimate of the smallest population size that is expected to occur within the 50 year simulation and can be used as an index of the propensity of a population to decline (Alçakaya 2005). Population trajectory summaries are also presented which show the mean population abundances through time and are a general summary of the trend of the population.

6.3.6 Stochastic sensitivities

A stochastic sensitivity analysis was also undertaken to examine which life stages of the population are most sensitive to perturbations. This was done by looking at the effect on EMPs of a 10% increase and decrease in the mortality, growth and fecundity of each life stage. The effect of these perturbations was assessed by looking at the proportional change in EMP relative to the change in EMP without the 10% change. Sensitivity analysis was undertaken using the base population model.

6.4 Results

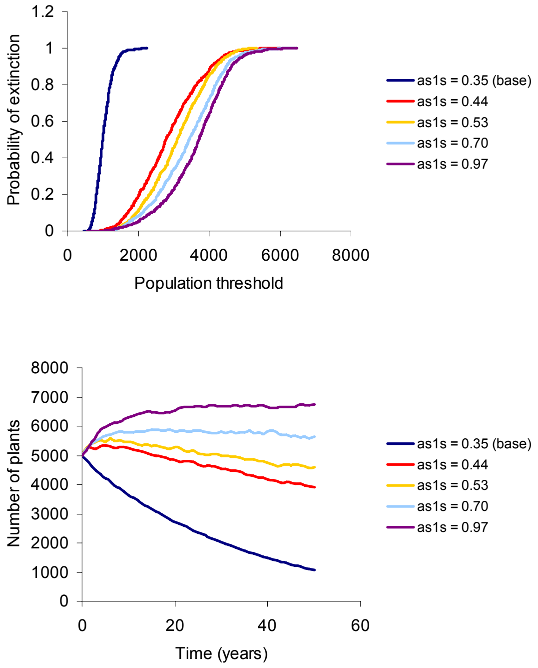


Figure 6.2. a) risk curves and b) population trajectory curves for base model and pulse recruitment with different probabilities of seedling survival a_{s1s}. Initial population size was 5000 and the probability of a pulse year was p = 0.14.

The base model did not result in extinction of the population over the 50 year simulation (Fig. 6.2a), but it does predict that the population will decline considerably over that time (Fig 6.2b) and, indeed, under this scenario based on the levels of recruitment measured over the three years of the study the EMP is 1031 (Table 6.1). Including pulse recruitment in high rainfall years and increasing survival of seedlings (a_{s1s}) increases the viability of the population (Fig. 6.2a,b, Table 6.1).

Reducing the population size from 5,000 to 4,000 plants did not result in extinction in the base model or any of the pulse recruitment scenarios, but all models did result in lower EMP's and increases in the probability of population decline (Fig. 6.3a,b, Table 6.1).

There was almost a 100% change in EMP in response to a 10% reduction in the survival of adult stages, which was more than three times the sensitivity of any other demographic parameter. A 10% decrease or increase in seedling growth had a moderate impact on EMP (22% and 31% change, respectively). The model was largely insensitive to 10% changes in the remaining survival, growth and fecundity parameters (Fig. 6.4)

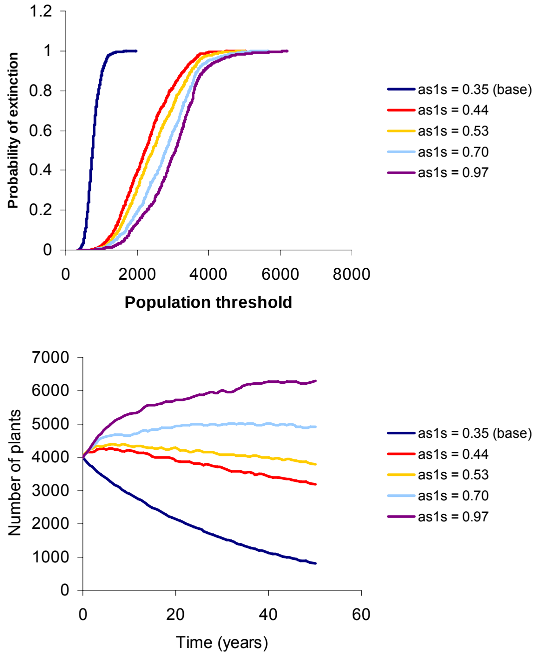


Figure 6.3. a) risk curves and b) population trajectory curves for base model and pulse recruitment with different probabilities of seedling survival a_{s1s}. Initial population size was 4000 and the probability of a pulse year was p = 0.14.

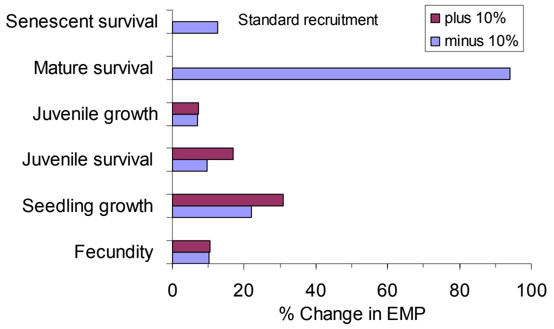


Figure 6.4: Sensitivity of expected minimum population size to variations of ±10% in parameter estimates.

Table 6.1. Expected minimum population sizes for the different simulation scenarios.

Simulation	Initial pop. size	Pulse year probability	Seedling survival probability	EMP
Base model	5000	0	0.3521	1031
Pulse recruitment*	5000	0.14	0.3521 x 1.25 = 0.44	2825
Pulse recruitment	5000	0.14	0.3521 x 1.5 = 0.53	3151
Pulse recruitment	5000	0.14	0.3521 x 2.0 = 0.71	3566
Pulse recruitment	5000	0.14	0.3521 x 2.75 = 0.97	3842
Base model	4000	0	0.3521	780
Pulse recruitment	4000	0.14	0.3521 x 1.25 = 0.44	2275
Pulse recruitment	4000	0.14	0.3521 x 1.5 = 0.53	2481
Pulse recruitment	4000	0.14	0.3521 x 2.0 = 0.71	2771
Pulse recruitment	4000	0.14	0.3521 x 2.75 = 0.97	2996

*for all pulse recruitment simulations fecundity was increased by x10.

6.5 Key findings and outcomes

Measurements of demographic parameters are confined to two annual time-steps encompassing a sample of the variation in climate but not the entire range and extremes that are likely to drive population dynamics of the BIF *Tetratheca*. The models therefore should be treated as exploratory and not definitive.

The base model parameterized with the demographic census data predicts that the *T. paynterae* subsp. *paynterae* population will decline substantially in the next 50 years. This may be a consequence of the study period not including a “high rainfall” year when there is likely to be a pulse of seedling recruitment.

Pulse recruitment is a common strategy of plants particularly in arid and semi-arid environments with highly variable rainfall. For *T. paynterae* subsp. *paynterae*, we assumed pulse recruitment would be associated with high winter rainfall stimulating germination followed by high summer rainfall allowing seedlings to survive the critical first summer and establish an extensive root system. This is particularly important for cliff dwelling plants which require an adequate root system to exploit cracks for water and nutrients and provide stability (Larson et al. 2000). Inclusion of pulse recruitment in the model reduced the probability of population decline relative to the base model. Increasing the probability of seedling survival in the models also reduced the probability of population decline relative to the base model.

Reducing the *T. paynterae* subsp. *paynterae* population from 5,000 to 4,000 plants did not result in extinction in the next 50 years under the base model or any of the pulse recruitment scenarios, but did reduce the viability of the population. Because of the uncertainty in estimating recruitment in the PVA, the predictions of the different scenarios should be seen as an ensemble of potential futures which range from decline to population stability.

Further research investigating the influence of rainfall amount duration and seasonality is needed to confirm whether the infrequent congruence of high winter and summer rainfall is a major driver of pulse recruitment in the BIF *Tetratheca* taxa.

Although seed output and seedling recruitment rates are important in the longer term viability of the population, adult plants will sustain populations through adverse periods. The BIF *Tetratheca* are likely to have developed specific adaptations to variability in climate over millennia and have morphological and physiological adaptations that allow them to persist.

The stochastic sensitivity analysis indicates that the viability of the *T. paynterae* subsp. *paynterae* population may be very sensitive to an increase in the mortality of reproductive adult plants. This is typical of stress tolerators which are able to persist under adverse conditions (Grime 1979).

Consequently, events which increase the mortality of adult plants may have a significant impact on the viability of the population. There has been a demonstrable impact of mining on the *T. paynterae* subsp. *paynterae* population at Windarling. The mine generates considerable amounts of dust that accumulates on the stems of *T. paynterae* subsp. *paynterae*, especially during prolonged dry periods. In 2004 -2005 when rainfall was well below the long term median, mortality of adult plants was significantly higher in the 10 m “buffer zone” at the edge of the W3 open cut compared with the rest of the population (Yates and Williams 2005, McNee and Cockerton 2006). Plants immediately adjacent to the mine were under more water stress than plants 150 m from the mine (Close et al. 2005). The causes of increased water stress and elevated mortality at the edge of the mine may be due to increased exposure to drying winds and/or reduced ability to regulate water loss because of dust occluding and preventing closure of stomata.

If the impacts of mining on *T. paynterae* subsp. *paynterae* are cumulative then increased water stress and mortality may occur further from the mine edge as the life of the mine progresses and the stochastic sensitivity analysis indicates that this could have a significant impact on the viability of the *T. paynterae* subsp. *paynterae* population.

Monitoring of the whole *T. paynterae* subsp. *paynterae* population should be given a high priority and any increase in adult mortality should be a cause for concern.

7. Acknowledgements

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