Patterns of plant mortality and changes in condition in the *Tetratheca paynterae* subsp. *paynterae* population at Windarling W3 between 2003 and 2005

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1 Introduction

In this report we examine mortality rates and changes in the condition of *Tetratheca paynterae* subsp. *paynterae*, and determine how these may have been affected by mining of the W3 ore body at Windarling. We aim to determine first, whether there was any increase in plant mortality, and second if there were declines in the condition of live plants related to the presence of the mine.

We tested the following null hypotheses

Hypothesis 1: Observed plant mortality in the 2004/2005 summer is independent of the distance of a plant from the mine edge, the aspect of the plant, and the type of landform on which the plant occurred.

Hypothesis 2: Patterns of observed plant mortality in 2004/2005 do not differ from patterns observed pre 2004 before mining commenced.

Hypothesis 3: The average condition (vigour) of extant plants has not changed substantially since mining commenced.

Hypothesis 4: If any change in average condition (vigour) of extant plants has occurred, this is independent of the distance of a plant from the mine edge and the type of landform on which the plant occurred.

2 Methods

2.1 Data Collection

This report should be read with the accompanying report prepared by Western Botanical, in which methods of data collection are described.

2.2 Statistical analyses

2.2.1 Plant Mortality

We used binomial logistic regression models to investigate hypotheses one and two. The advantage of using logistic regression in this situation is that it enables all the factors potentially affecting mortality to be assessed simultaneously. Thus the independent effect of each factor can be determined whilst controlling for the effects of all other factors. This is important in surveys such as this one, as the factors potentially related to mortality are not evenly spread across the range. For example, most outcrops are at the eastern end of the range, and many of the plants on these outcrops have aspects different to those on the ridge (see results). Background information on the logistic regression is provided in Appendix 1.

Following discussions with Shapelle McNee we recognized three independent variables that could be derived from the Western Botanical data set, that were amenable to statistical analysis, and which may influence plant mortality. These were:

1. The distance of a plant from the mine edge. This distance would be expected to reflect any gradient in disturbance associated with mining that might place plants under stress and have a negative effect on plant growth and survival. For example dust loads on the threatened plant taxa *T. paynterae* subsp. *paynterae* and *Ricinocarpus brevis* plants at W3 decline exponentially with distance from the mine edge (Western Botanical unpublished data).
2. The aspect where the plant grows. Plants on hotter northerly aspects may be expected to experience more stress than plants on cooler southerly aspects particularly during extended droughts characteristic of semi-arid environments.
3. The landform where the plant grows. At Windarling W3, *T. paynterae* subsp. *paynterae* grows on the northern face of the main banded ironstone ridge and on a series of banded ironstone outcrops or tors south of the ridge. The tors provide a greater range of aspects and exposures to disturbance associated with the mine.

We used logistic regression models to investigate the influence of the above independent variables on two dependent variables. These were:

1. Plant mortality following the 2004/2005 summer, this is equivalent to plant mortality in the post mine environment.
2. Plant mortality prior to 2004, this is equivalent to plant mortality in the pre-mine environment.

2.4 Plant condition

We examined the influence of two variables, distance from the mine edge and the landform on which the plant occurs, on changes in plant condition between years of observation. For each of the three sampling years (Sept-Nov, 2003; Oct 2004 and June-

July, 2005), we calculated the average condition of individual plants in each of the six sampling locations (loci) comprised of four ridge and two outcrop plots all of which were different distances from the mine edge. We then estimated *changes* in the average condition of plants between years by subtracting average condition at time t from average condition at time $t + 1$.

The influence of location in relation to the mine and landform on annual changes in plant condition was assessed using one way Analysis of Variance (ANOVA). To determine if there were greater changes in plant condition close to the mine, we treated the sampling locus furthest from the mine as a reference (or control) group, and compared annual changes in condition for plants close to the mine with this group using single degree of freedom contrasts (equivalent to pairwise t-tests). This allowed us to determine if changes in plant condition on outcrops or the ridge close to the mine were substantially greater than those occurring at the western end of the range, where any effect of the mine was assumed to be least.

3 Results

3.1 Patterns of plant mortality

Hypothesis 1: Observed plant mortality in the 2004/2005 summer is independent of the distance of a plant from the mine edge, the aspect of the plant, and the type of landform on which the plant occurred.

Hypothesis 2: Patterns of observed plant mortality in 2004/2005 do not differ from patterns observed pre 2004 before mining commenced.

The distance from the mine and aspect were both related to plant mortality. There were typically higher death rates close to the mine (Fig.1), and considerable variation in the pattern of deaths in 2004/2005 and pre 2004, in relation to aspect (Table 1). However, there appeared to be similar mortality rates on outcrops and the ridge, although more deaths on outcrops in 2004/2005 (Table 2). Interpreting the results of each of these factors individually is difficult, because distance from the mine, aspect and landform are strongly interrelated. For example plants with southerly and easterly aspects are largely restricted to outcrops and plants with northerly aspects predominate on the ridge(Table 3).

Figure 1. Observed plant death rates prior to 2004 and following the 2004/2005 summer in 100m distance intervals from the edge of the mine. The intervals 500-600m and 600-700m were combined into one class because of the low number of plants.

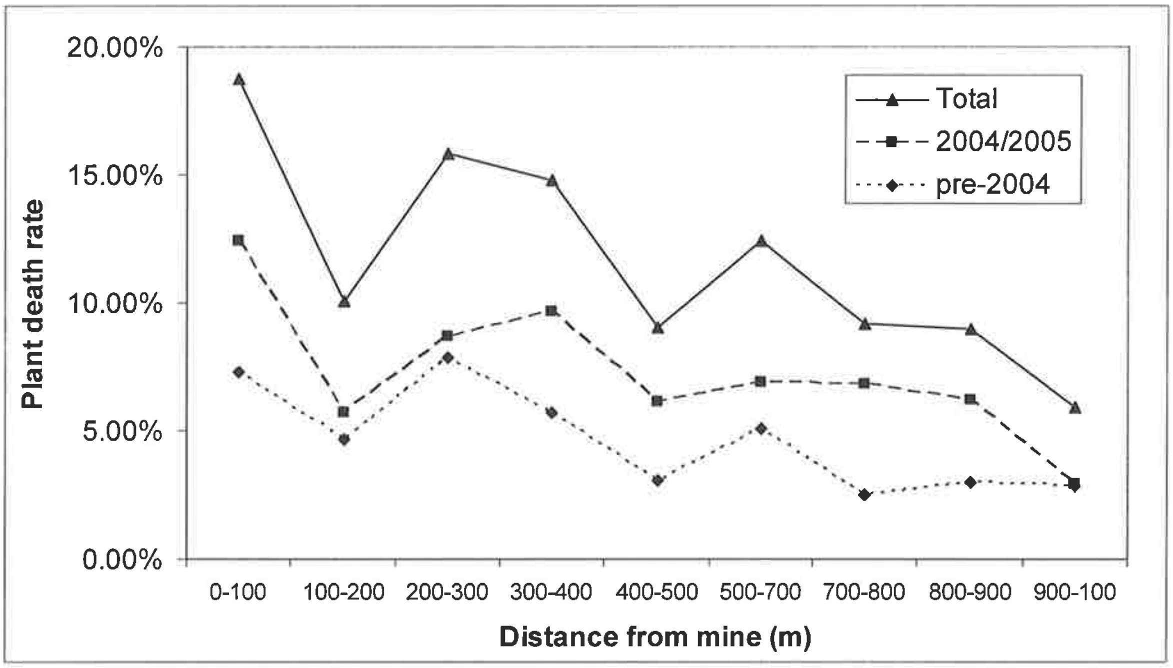

Table 1. The observed and expected frequencies of plant deaths for each aspect category prior to 2004 and in 2004/2005. The expected frequencies represent the situation where dead plants occur randomly across aspects.

Aspect	Frequency	Alive	2004/2005 mortality	Pre 2004 mortality	Total
E	Observed	240	39	9	288
	Expected	252.2	21.555	14.244	
N	Observed	2929	243	173	3345
	Expected	2929.2	250.35	165.44	
NE	Observed	858	72	53	983
	Expected	860.8	73.572	48.619	
NW	Observed	782	68	50	900
	Expected	788.1	67.36	44.514	
S	Observed	240	4	7	251
	Expected	219.8	18.786	12.414	
SE	Observed	85	11	1	97
	Expected	84.9	7.2599	4.7976	
SW	Observed	63	6	2	71
	Expected	62.2	5.314	3.5116	
W	Observed	150	14	7	171
	Expected	149.8	12.798	8.4576	
Total		5347	457	302	6106

Table 2. The observed and expected frequencies of plant deaths for each landform category prior to 2004 and in 2004/2005. The expected frequencies represent the situation where dead plants occur randomly across landforms.

Landform	Frequency	Alive	2004/2005 mortality	Pre 2004 mortaility	Total
Ridge	Observed	4623	379	271	5273
	Expected	4618	394.4	260.6	
Outcrop	Observed	728	78	31	837
	Expected	733	62.6	41.4	
Total		5351	457	302	6110

Frequency Missing = 13

Table 3. *The observed and expected frequencies plants for each aspect category in each landform. The expected frequencies represent the situation where plants occur randomly across aspects and landforms.*

Landform	Frequency	E	N	NE	NW	S	SE	SW	W	Total
Ridge	Observed	125	3230	887	837	37	23	21	109	5269
	Expected	248.5	2886.5	848.3	776.6	216.6	83.7	61.3	147.6	
Outcrop	Observed	163	115	96	63	214	74	50	62	837
	Expected	39.5	458.5	134.8	123.4	34.4	13.3	9.7	23.4	
Total		288	3345	983	900	251	97	71	171	6106

Frequency Missing = 17

Because the aspect of a plant influences mortality, and varies with landform and position across the range, any estimates of mortality in relation to distance from the mine must take into account or adjust for aspect differences. The effect of each of the variables, adjusted for the influence of one another, is shown in the results of the logistic regression. The distance from the mine and aspect both had a significant influence on plant mortality, but after accounting for these effects there was no significant relationship between plant mortality and landform (Table 4).

To determine if the relationship between deaths and distance from the mine is linear in the logit, an additional term (distance*ln(distance)) was added to the model (the Box-Tidwell procedure, see Appendix 1). As this term was significant for 2004/2005 mortality, this model was re-estimated using ln(distance). The distance trend was approximately linear for pre 2004 mortality, but non-linear for 2004/2005 mortality (Table 4, Fig. 2). Plant mortality was significantly higher at the eastern end of the range both before and after mining commenced. However, the nature of this trend differed markedly between 2004/2005 (post mine) and pre 2004 (pre mine) (Fig. 2).

In 2004/2005 there was substantially higher overall mortality than that estimated for the period prior to 2004. In the period prior to 2004 average mortality varied between 2-8% from west to east. In 2004/2005 mortality at the western end of the range was estimated to be 6%, increasing to approximately 14% at the eastern end of the range adjacent to the mine (Fig.2).

To determine the extent of the effect of distance from the mine edge, data for plants close to the mine were removed (blocks 90.1 and 90.2, and 50, see accompanying report for location of blocks). After excluding these blocks, the spatial trend in 2004/2005 mortality became linear, and similar to that estimated for pre 2004 mortality (Fig. 3). The change in the pattern of mortality after excluding blocks 90 and 50 indicates that the non-linear response in recently dead plants is due primarily to high mortality in these blocks.

Prior to 2004, aspect was not a significant factor affecting plant mortality, but plants with northerly aspects typically suffered higher mortality rates than other aspects (Table 4, Fig. 4). In 2004/2005 aspect became a significant factor affecting plant mortality, with plants on easterly and south-easterly aspects showing a disproportionately greater increase in mortality (Fig. 4). This pattern was extreme in block 90, an outcrop at the mine edge (Table 5). In addition in 2004/2005 plants on northerly aspects adjacent to the mine (block 50 and 90) showed a disproportionate increase in mortality compared to plants with northerly aspects further away from the mine (Table 5).

Table 4. Results of logistic regression analysis of plant mortalities in 2004/2005 and pre 2004. The significance of the effects of distance from the mine, landform and aspect were tested with the Wald Chi-Square statistic. In the first model the effect of distance from the mine was tested with a linear scale. The Box-Tidwell test assessed whether the relationship between distance from mine and mortality was linear. The relationship between total mortality and mortality in 2004/2005 was not linearily related to distance from the mine so a second model using the natural logarithm of distance from the mine was fitted. Probability (P) values less than 0.05 represent significant effects.

		Total mortality (n = 6099)		2004/2005 mortality (n = 5558)		Pre 2004 mortality (n = 6099)	
Effect	*DF*	Wald Chi-Square	*P*	Wald Chi-Square	*P*	Wald Chi-Square	*P*
A. Model 1. Linear distance, outcrop and plant aspect.							
Distance	1	32.5477	<0.0001	9.0888	0.0026	28.3847	<0.0001
Outcrop	1	0.3660	0.5452	2.6227	0.1053	1.2677	0.2602
Aspect	7	22.5663	0.0020	21.0918	0.0036	9.5182	0.2176
		Model -2LogL=4519.4		Model -2LogL=3150.3		Model -2LogL=2360.6	
B. Box-Tidwell test.							
Distance log (distance)	1	9.4874	0.0021	12.0106	0.0005		
		Model -2LogL=4510.2		Model -2LogL=3138.756			
C. Model 2. Log (distance), outcrop and plant aspect.							
Log(distance)	1	58.6851	<0.0001	39.3496	<0.0001		
Outcrop	1	0.0879	0.7669	0.1432	0.7051		
Aspect	7	17.1052	0.0167	15.5549	0.0295		
		Model -2LogL=4499.145		Model -2LogL=3123.942			

Figure 2. Logistic regression estimates of plant death rates (open symbols) and observed death rates (closed symbols) prior to 2004 and in 2004/2005, in relation to distance from mine edge. Logistic regression estimates are adjusted for plant aspect and landform differences.

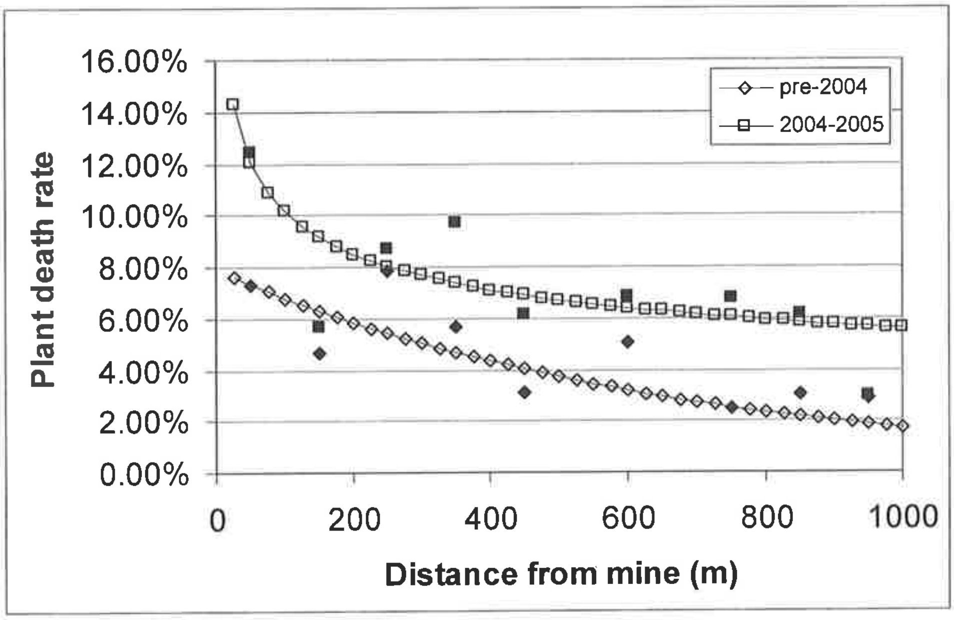

Figure 3. Logistic regression estimates of plant death rates (open symbols) and observed plant death rates (closed symbols) prior to 2004 and in 2004/2005 excluding blocks 90 and 50 in relation to distance from mine edge. Logistic regression estimates are adjusted for plant aspect and landform differences.

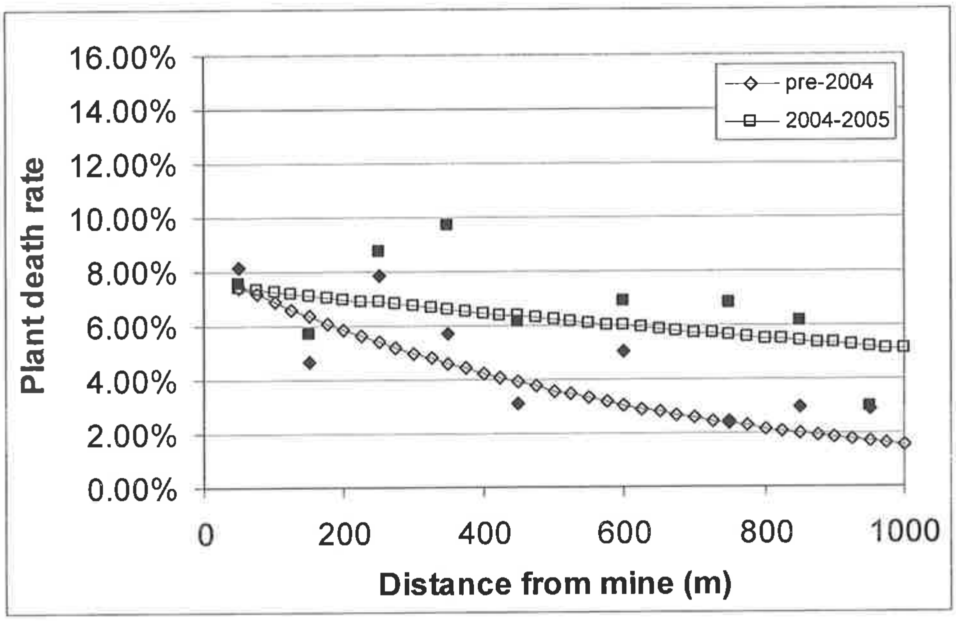

Figure 4. Logistic regression estimates of plant mortality rates prior to 2004 and in 2004/2005 in relation to aspect after adjusting for distance from mine edge and landform differences.

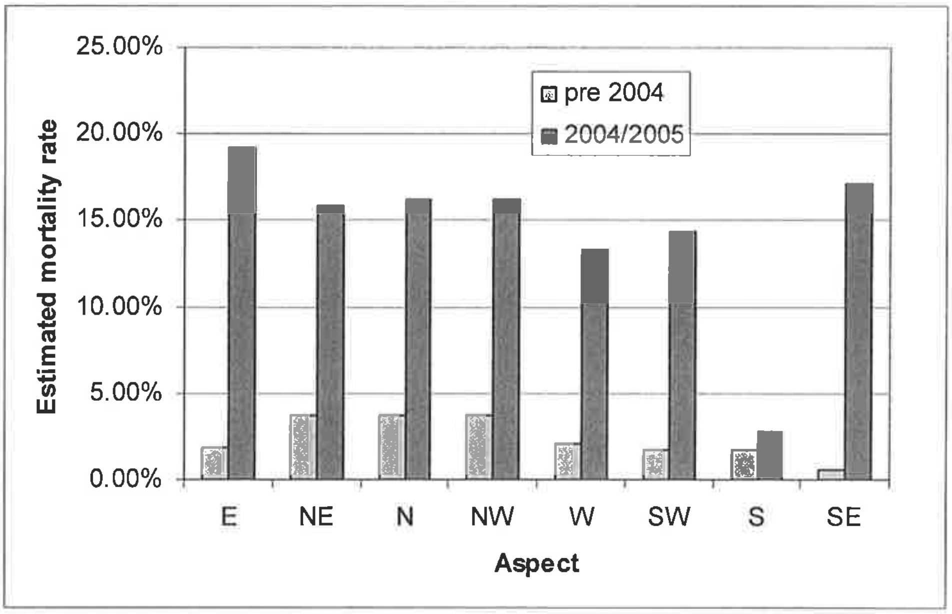

Table 5. The number of plants, total deaths, and post 2004/2005 and pre 2004 plant death rates for each aspect within blocks 50, 90 and all others.

				Plant death rate	
Block	Aspect	Plants	Total dead	2004/2005	pre-2004
50	E-SE	0	0	0.0%	0.0%
50	N-NE-NW	80	14	14.3%	3.8%
50	S-SW-W	1	0	0.0%	0.0%
90	E-SE	93	41	42.2%	3.2%
90	N-NE-NW	35	12	28.1%	8.6%
90	S-SW-W	3	0	0.0%	0.0%
All others	E-SE	292	19	4.2%	2.4%
All others	N-NE-NW	5113	633	7.5%	5.3%
All others	S-SW-W	506	53	4.9%	3.2%

3.2 Changes in plant condition

Hypothesis 3: The average condition (vigour) of extant plants has not changed substantially since mining commenced.

Hypothesis 4: If any change in average condition (vigour) of extant plants has occurred, this is independent of the distance of a plant from the mine edge and the type of landform on which the plant occurred.

There were changes in the average condition of live plants across the *T. paynterae* subsp. *paynterae* population between 2003 and 2005 but the direction of these changes showed no strong pattern in relation to the distance of plants from the mine edge (Fig. 5). The greatest overall decline was observed in locus 4, on outcrops closest to the mine edge. However, this change was not statistically significant (Tables 6 and 7).

There was inconsistency in the results arising from the two measures of plant condition. The live plant condition rating based on percent live volume showed a significant decline in plant condition across the entire population between 2004 and 2005. However, declines in plant condition in each sampling locus were generally of a similar magnitude (Table 7). The largest observed decline of 19% was for locus 4, on outcrops 5-120 m from the mine edge, but this was not significantly greater than that observed at the western extremity of the range (12%, $P = 0.08$, Table 7).

In marked contrast, live plant condition rating based on an ordinal scale showed no overall decline in plant condition between 2004 and 2005. Most loci showed a small increase in plant average condition, but plants on outcrops in the sampling locus 4 adjacent to the mine declined substantially but not significantly ($P = 0.12$, Table 6).

Figure 5. The mean condition of live plants in 2003, 2004 and 2005 at sampling loci across outcrops and ridges with increasing distance from the mine.

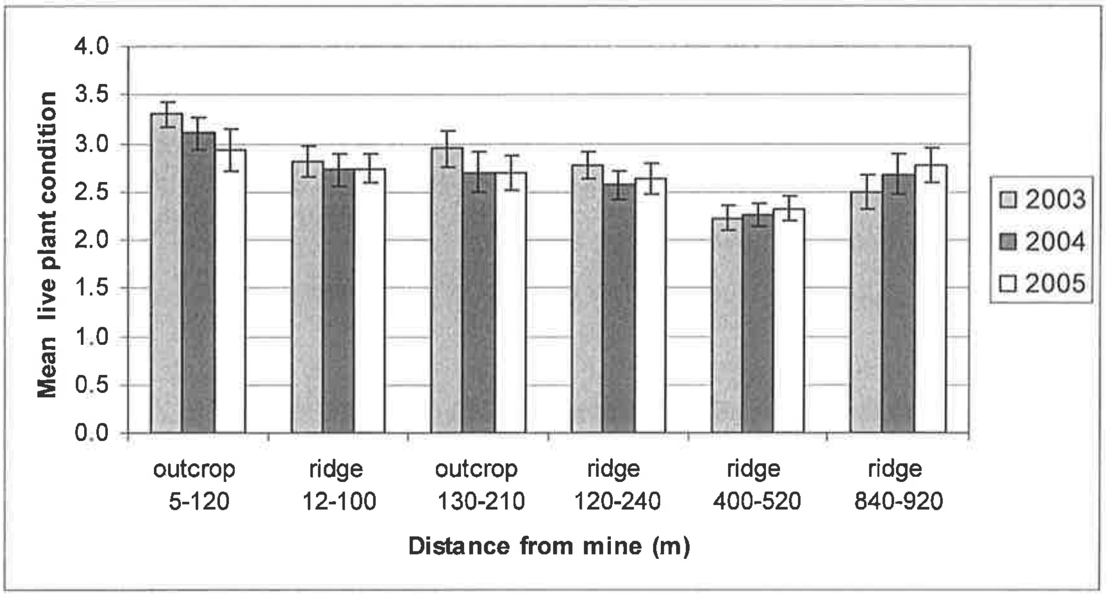

Table 6. The change in average condition rating of live plants, measured in ordinal classes between 2003 and 2004, and between 2004 and 2005. The change in condition for plants in loci 1-5 were compared with the change in condition for plants in locus 6 (pairwise comparisons). Probability (P) values less than 0.05 represent a significant change in average plant condition relative to locus 6.

Locus	Landform	Distance from mine (m)	Δ 2003-2004 (SE)	Pairwise comparison (*P*)	Δ 2004-2005 (SE)	Pairwise comparison (*P*)
4	Outcrop	5-120	-0.18 (0.15)	0.12	-0.21 (0.17)	0.12
1	Ridge	12-100	-0.02 (0.11)	0.42	0.06 (0.13)	0.75
3	Outcrop	130-210	-0.24 (0.13)	0.03	0.06 (0.15)	0.73
2	Ridge	120-240	-0.18 (0.09)	0.04	0.07 (0.07)	0.77
5	Ridge	400-520	-0.01 (0.09)	0.39	0.01 (0.10)	0.50
6	Ridge	840-920	0.10 (0.10)		0.13 (0.14)	

Table 7. The change in average condition rating of live plants, measured in percentage live volume between 2004 and 2005. The change in condition for plants in loci 1-5 were compared with the change in condition for plants in locus 6 (pairwise comparisons). Probability (P) values less than 0.05 represent a significant change in average plant condition relative to locus 6.

Locus	Landform	Distance from mine (m)	Δ 2004-2005 (SE)	Pairwise comparison (P)
4	Outcrop	5-120	-19% (3.1)	0.08
1	Ridge	12-100	-15% (2.4)	0.41
3	Outcrop	130-210	-15% (2.7)	0.34
2	Ridge	120-240	-15% (2.0)	0.30
5	Ridge	400-520	-16% (1.8)	0.14
6	Ridge	840-920	-12% (2.6)	

4 Discussion

4.1 Patterns of mortality

Hypothesis 1: Observed plant mortality in the 2004/2005 summer is independent of the distance of a plant from the mine edge, the aspect of the plant, and the type of landform on which the plant occurred.

Hypothesis 2: Patterns of observed plant mortality in 2004/2005 do not differ from patterns observed pre 2004 before mining commenced.

On the basis of our results we reject both hypotheses. The analyses show that distance from the mine and aspect both affect the observed patterns of plant mortality in 2004/2005.

Plant mortality in the 2004/2005 summer *is not* independent of the distance of a plant from the mine edge and the aspect of the plant. However, the type of landform on which the plant occurs does not appear to affect survival per se.

Patterns of observed plant mortality in 2004/2005 *are different* from patterns observed pre 2004 before mining commenced.

Patterns of observed plant mortality in 2004/2005 clearly differ from patterns observed pre 2004. Prior to 2004 there was an increased risk of plant death towards the eastern end of the range. The reasons for this trend are unknown. Mortality rates in the summer of 2004/2005 were considerably higher than pre 2004 across the breadth of the *T. paynterae* subsp. *paynterae* population, with the highest mortality occurring adjacent to the mine.

Prior to 2004, aspect was not a significant factor affecting plant mortality, but plants with northerly aspects typically suffered higher mortality rates than other aspects.

In 2004/2005 aspect became a significant factor affecting plant mortality, with plants on easterly and south-easterly aspects showing a disproportionately greater increase in mortality. This was largely due to the high death rates of plants with easterly and south-easterly aspects in block 90 on an outcrop at the mine edge. In addition in 2004/2005 plants on northerly aspects adjacent to the mine (block 50 and 90) showed a disproportionate increase in mortality compared to plants with northerly aspects further away from the mine.

There are two plausible explanations for the 2004/2005 pattern of mortality. Firstly, the higher mortality across the breadth of the *T. paynterae* subsp. *paynterae* population maybe attributable to extreme drought stress on plants caused by the exceptionally dry period between August 2004 and April 2005, combined with a local impact of the mine on the population at the extreme eastern end of the range. Alternatively, increased mortality may be entirely attributable to the impact of the mine.

However, in the absence of a control site, (for example, a nearby ironstone range without a mine), it is difficult to discriminate between the two explanations. Comparisons of *T. paynterae* subsp. *paynterae* mortality rates in 2004/2005 with mortality rates of other banded ironstone *Tetratheca* taxa on ranges adjacent to Windarling will help to resolve this issue.

If the assumption that the western end of Windarling W3 is not being impacted by the mine is tenable, then plants at this end of the range may be treated as controls for comparison with plants at the eastern end of the range adjacent to the mine. Making this assumption supports the first explanation above. Thus the most likely conclusion is that there is an impact of mining, but this is currently restricted to the eastern end of the *T. paynterae* subsp. *paynterae* population in the area adjacent to the mine.

4.2 Patterns of plant condition

Hypothesis 3: The average condition (vigour) of extant plants has not changed substantially since mining commenced.

Hypothesis 4: If any change in average condition (vigour) of extant plants has occurred, this is independent of the distance of a plant from the mine edge and the type of landform on which the plant occurred.

Compared to patterns of mortality, the analyses of patterns of condition in the *T. paynterae* subsp. *paynterae* population provide less conclusive results complicated by inconsistency between the two methods of measuring plant condition. Also, the methods of assessing plant condition do not take into account changes in canopy volume, which may decline when plants become stressed. Consequently, we expect plant condition measurements to be less sensitive than plant mortality measurements for detecting the potential impacts of the mine.

Notwithstanding, the observed pattern of condition in the *T. paynterae* subsp. *paynterae* population is generally concordant with the observed pattern of mortality. For the period 2004-2005 plants declined in condition across the entire population (% live volume method) and this decline was greatest for plants on outcrops adjacent to the mine edge.

Although we found no statistically significant effects of distance from mine edge on plant condition, both methods showed that plants declined most on outcrops adjacent to the mine compared to plants furthest from the mine. On the basis of our results we reject both hypotheses.

5 Conclusion

There has been an increase in mortality and a decline in plant condition (vigour) across the entire *T. paynterae* subsp. *paynterae* population between 2004 and 2005. The magnitude of these changes is larger at the eastern end of the population adjacent to the mine. The increases in plant mortality are strongly related to proximity of the mine, and plant aspect. Plants adjacent to the mine on northerly and easterly aspects experienced the highest rates of mortality.

Appendix 1

Binomial (or binary) logistic regression is a form of regression that is used when the dependent variable is a dichotomy, for example plant dead or alive, and when independent variables are of any type including continuous environmental variables, such as distance from a disturbance, or categorical variables such as aspect or landform.

Logistic regression has a number of applications which include

- predicting a dependent variable on the basis of independent variables;
- determining the percent of variance in the dependent variable explained by the independent variables;
- assessing the statistical significance of independent variables and determining their relative importance;
- assessing interaction effects between independent variables.

Logistic regression applies maximum likelihood estimation after transforming the dependent into a logit variable (the natural log of the odds of the dependent occurring or not). In this way, logistic regression estimates the probability of a certain event occurring. Note that logistic regression calculates changes in the log odds of the dependent, not changes in the dependent itself as ordinary least squares (OLS) regression does.

Logistic regression has many analogies to OLS regression: logit coefficients correspond to coefficients in the logistic regression equation, and a pseudo R^2 statistic is available to summarize the strength of the relationship. Unlike OLS regression, however, logistic regression does not assume linearity of relationship between the independent variables and the dependent, does not require normally distributed variables, does not assume homoscedasticity, and in general has less stringent requirements. It does, however, require that observations are independent and that the logit of the independent variables is linearly related to the dependent.

To test if the assumption of linearity in the logit is met for each of the continuous independent variables, the Box-Tidwell Test is used by adding to the logistic model interaction terms which are the product of each independent multiplied by its natural logarithm [(X)ln(X)]. If these terms are significant, then there is nonlinearity in the logit.