Distinguishing effects of natural disturbances such as droughts on natural vegetation from potential industrial influence in the Port Curtis area using regional reference sites and the differential response of closed and open canopy vegetation

Wayne Houston and Alistair Melzer,
Centre for Environmental Management, Central Queensland University

Abstract. The advent of a shale oil processing industry in Port Curtis region (approximately 15 km northwest of Gladstone) in addition to existing industries provided the impetus to establishment of 15 'Sentinel' monitoring sites to assess potential effects of industrially-sourced gaseous outfalls from the Gladstone airshed on natural vegetation. To provide a baseline for widespread regional natural disturbances a further 5 sites ('Reference') were established some 40 – 50 km southwest of Gladstone in the Kroombit Tops area. In addition to using passive gas gels to monitor gaseous outfalls of SO_2, NO_2, O_3, bioindicators monitored included foliar health indices (leaves per 1 m of branch, average leaf weight and a chlorosis – necrosis score), soil and litter associated invertebrate assemblages and lichen cover. Gaseous outfalls of SO_2 and NO_2 at Sentinel sites were 2 to 15 times greater than concentrations at Reference sites but O_3 was similar. Significant changes in average leaf weight, mostly with a declining trend as typical of effects of gaseous outfalls on vegetation and an increase in variability of invertebrate assemblages in 2001 were found. Significant changes in numbers of leaves per branch (no consistent increasing or decreasing trend) and the chlorosis – necrosis score were also found. The latter bioindicator actually declined and this is the reverse of the predicted response to effects of gaseous outfalls on vegetation and suggests an improvement in vegetation health. There was no clear linkage between these patterns in change in leaf weight and gaseous outfalls within the Sentinel area. Two lines of evidence point to the significant declines in average leaf weight and increases in invertebrate assemblage variability within Sentinel sites being a response to a widespread regional drought in 2001 and 2002. Firstly, similar patterns of declining leaf weight were observed in the regional Reference area relatively remote from Port Curtis where levels of SO_2 and NO_2 concentration are substantially lower. Secondly, response of two types of vegetation ('closed', > 70% canopy cover typical of dry rainforest and 'open', 30 – 70% canopy cover typical of sclerophyll woodlands and forests) differed with *closed* canopy vegetation consistently showing significant declines in average leaf weight irrespective of location whereas most *open* canopy vegetation sites were non-significant except those associated with ridge-tops in the Sentinel area. Within the Sentinel area only closed vegetation showed an increase in invertebrate assemblage variability in 2001. Dry rainforest vegetation is known to suffer seasonal water stress in the late dry season and a greater vulnerability to drought effects could explain the patterns of change in the bioindicators monitored. The usefulness of dry rainforest vegetation as a way of internally calibrating for drought effects by acting as a sentinel vegetation type for natural disturbance of this kind needs to be more widely tested. If this ability is confirmed for this vegetation type, then it may offer a more cost-effective protocol for testing for natural drought effects compared with regional reference areas, or they may provide an opportunity to have some ability to calibrate for regional effects of droughts where regional reference sites are lacking.

Introduction

Natural vegetation in the Port Curtis region in Central Queensland is subject to outfalls of gaseous emissions from power, chemical and mineral industries. Port Curtis is a major industrial region with a range of large industries and plans for future expansion. Controlled and fugitive emissions from these industries enter the Gladstone airshed. This airshed covers the Curtis coast and the catchments of the Boyne and Calliope Rivers extending to the north-west and north-east in autumn and winter, and to the south-east in spring and summer under the influence of prevailing winds.

In the late 1990's the arrival of a shale oil processing plant 15 km northwest of Gladstone prompted consideration of industrial impacts on regional vegetation and detecting potential impacts from the shale oil plant and broader industrial influences. To enable possible effects of Gladstone airshed (including shale oil contributions) outfalls on natural vegetation and associated invertebrate fauna, 15 sites were established to the north-west, west and south-west of the oil shale processing plant. To enable assessment of regional natural disturbance impacts on vegetation, a further 5 sites some 40 – 50 km southwest of Gladstone in the Kroombit Tops area were also established.

Biological parameters selected for monitoring included: vegetation (canopy, foliar health indices and leaf damage scores); invertebrate assemblages (epigaeic or ground-associated assemblages); and lichen cover (Treshow and Anderson 1989) at selected sites. Soil pH and airshed gases (SO_2, NO_2, O_3) were also measured at each site. Both reductions in leaf weight and leaf abscission (and reduction in leaf numbers) have been identified experimentally as symptoms of plant damage by air pollutants such as SO_2 (Murray 1984, Murray and Wilson 1988a, b, 1989, Nobby and Kozlowski 1981). The main leaf damage symptoms associated with air pollution impacts are chlorosis (Taylor 1973, Howe and Woltz 1981, Murray 1984, Kovacs 1992, Griffith 1998) and necrosis (Murray 1984; Griffith 1998) and these may be part of a continuum of symptoms with the same cause (Murray 1984; Treshow and Anderson 1989; Krupa and Legge 1998). Consequently chlorosis and necrosis can be combined in order to assess annual change in potential phytotoxic leaf injury.

Several studies have found changes in abundance of invertebrate taxa associated with airshed emissions e.g. a decrease in ant abundance and ant species richness in plots subjected to medium to high SO_2 outfalls at Mt Isa (Hoffmann et al. 2000); a study of grassland invertebrates reported both increases and decreases among soil arthropod groups but with a decrease in Coleoptera (Leetham et al. 1984); and another study also reported a decline in Coleoptera abundance associated with elevated SO_2 deposition (Freitag and Hastings 1973).

Distinguishing the influence of industrially-linked disturbances from natural disturbance is one of the challenges facing ecosystem health monitoring programmes (Jones and Heck 1980). Smith (1981) observed that symptoms of acute foliar response to air pollutants can resemble symptoms caused by other biotic or abiotic stress conditions. In central Queensland a common natural disturbance is widespread regional drought. The development of drought conditions within the region in 2001 and 2002 followed by a wetter year in 2003 provided an opportunity to examine response of chosen bioindicators to such conditions.

Traditionally, regional reference sites less likely to be impacted by the anthropogenic disturbance under investigation are used to separate industrial from natural or background disturbance. A regional reference site some 40 km distant from the Gladstone region was selected to enable this approach to be tested.

A second approach was also used and based on the possible differential response of two vegetation types to drought effects. Vegetation was classified based on canopy cover and two types distinguished: closed (>70%) and open (30-70%). Closed canopy vegetation corresponds to 'dry rainforest' vegetation common in this region where vegetation is protected from fire and gallery riparian forests. Open vegetation corresponds to sclerophyll woodlands and forests, the most widespread vegetation type in the region. Dry rainforests are known to shed leaves seasonally in the late dry period in response to water stress (Bowman 2000). It was hoped that a differential response of selected bioindicators to drought conditions provided by vegetation sensitive to water stress (dry rainforests) and those less sensitive (sclerophyllous vegetation) would provide an opportunity to differentiate between drought-related and anthropogenic disturbance.

Broadly this study aims to contribute to the development of robust bioindicators of ecosystem health for terrestrial vegetation and to aid in the assessment of the long-term ecosystem health of the terrestrial vegetation within the Gladstone airshed. Objectives of this study were (i) to determine if there was any evidence that industrial sources of airshed gases in the Gladstone region were impacting on natural vegetation and (ii) to examine the response of bioindicators to the 2001-2002 drought and to assess efficacy of regional reference sites and / or the differential response of closed canopy and open canopy vegetation types to these conditions as a means of distinguishing the influence of this natural disturbance from potential industrial disturbance.

Methods

Monitoring took place annually from 1998 to 2003 in the late summer period – February and March to coincide with peaks in foliage production. An exception was invertebrate assemblage data which was collected only until 2002.

Dominant canopy species were selected as target species at each site. A wide range of species was selected as species' sensitivities to phytotoxic gases vary widely (O'Connor et al. 1979). Sites were selected to represent a cross-section of landscape types (i.e. plains and ridge-tops). High points are important because exposure to airshed gases tends to be greatest at these locations (Fowler 1992).

Fifteen sites were within the Gladstone airshed ('Sentinel' sites, Fig. 1), and an additional 5 sites were greater than 40 km distant to the south-west and relatively remote from Gladstone ('Reference' sites, Fig. 2). Sentinel sites were arrayed to the north-west, west and south-west of the oil shale processing plant, 4 sites within 5 km of the processing plant, 6 sites within a 5 to10 km zone and 5 within a 10 to 15 km zone.

Two main vegetation types were targeted (i) sclerophyll woodlands with *open* canopies (4 Reference and 11 Sentinel sites) and (ii) *closed* canopy vegetation such as dry rainforest including vine thickets and gallery riparian forest (1 Reference and 4 Sentinel sites) (Table 1).

Table 1. Target species and vegetation type with Sentinel and Reference areas

Vegetation type / target species	Sentinel	Reference
Woodlands (open canopies)		
Corymbia citriodora	6	1
Corymbia trachyphloia		1
Eucalyptus crebra	1	
Eucalyptus melanophloia	1	
Eucalyptus melliodora		1
Eucalyptus moluccana	1	
Lophostemon confertus		1
Lophostemon suaveolans	1	
Melaleuca quinquenervia	1	
Vine thickets (closed canopies)		
Cryptocarya triplinervis		1
Hovea longipes	1	
Mallotus philippensis	1	
Bouchardatia neurococca	1	
Riparian (*closed* canopies)		
Dysoxylon sp.	1	

Environmental Conditions at Sentinel and Reference Areas - Airshed Gas Concentrations, pH & Rainfall

Soil pH was determined using a standard CSIRO test kit. Three samples were randomly taken at least five metres apart and the mean value to the nearest 0.5 (test kits only measure to 0.5) used as the site value.

An aluminium housing of 30 cm diameter was attached to each star picket at a minimum of 1.5 m above the ground. Slots under this housing permitted the passive gas monitors to be attached (Ayers et al. 1998). One set of monitoring discs (one each for SO_2, NO_2 and O_3) was left in place for approximately one month at each site. These discs were returned to CSIRO for analysis and data are presented as average gas concentrations calculated over the 28 to 32 day sample period (parts per billion by volume i.e. ppbv).

Rainfall data was obtained from the Bureau of Meteorology for Gladstone to characterize weather conditions at the Sentinel sites. No comparable weather station was available for the Reference area so data from the two nearest weather stations was gathered (Ubobo Store to the sooth-east and Calliope Station to the north-east of Kroombit Tops).

Foliar Bioindicators

To determine foliar health indices of canopy cover, a common native canopy species was chosen at each site. Five individual plants of this species within the lower canopy (i.e. a sapling or larger) were selected and tagged in order to allow comparisons of the same trees in successive years. From each of these five plants, three branchlets were removed. Twigs of these branchlets (not including portions of the twig with partially expanded leaves) were cut and assembled to a 1 m standard length. The number of fully expanded leaves per twig was recorded to give a total leaf count for the 1 m length.

Leaves were placed on ice in the field and refrigerated at 4^0C. To determine leaf weights, leaves were oven dried at 60^0C for three days and then weighed.

Three indices of foliar health were determined at each site for each tree sampled:

- Leaf count: number of leaves per metre of branch (leaves m^{-1});
- Leaf weight: average dry weight per leaf (g $leaf^{-1}$); and
- Leaf damage score: incidence of leaves in a sample affected by potential phytotoxic symptoms such as chlorosis and necrosis.

Invertebrate Assemblage Bioindicators

Ground-active and litter-associated invertebrates (epigaeic invertebrates) were sampled using pitfall traps (diameter 54 mm, depth 100 mm) filled with approximately 200 ml of 70% ethanol and 1% glycerol. Five pitfall traps were placed at five metre intervals along the same compass bearing selected for the canopy photographs, the first pitfall trap being placed 10 m from the site marker. The traps remained open for three days and nights (approximately 72 hours).

Samples were preserved in 70% ethanol and sorted under stereo-microscopes in the laboratory. Except for a few taxa such as Acarina, invertebrates were sorted to Order and the abundance of each Order recorded. Taxonomy was based largely on CSIRO (1991). Exceptions to the Order level of classification were:

- Hymenoptera was split into Family Formicidae (ants), and Other Hymenoptera (wasps and bees).
- Hemiptera was split into suborder Heteroptera (true bugs), and homopteran bugs (an old taxonomic grouping that has since been subdivided into two suborders in CSIRO (1991), but retained here because the grouping Homoptera adequately reflects the uniform feeding habits – all phytophagous – of this group).

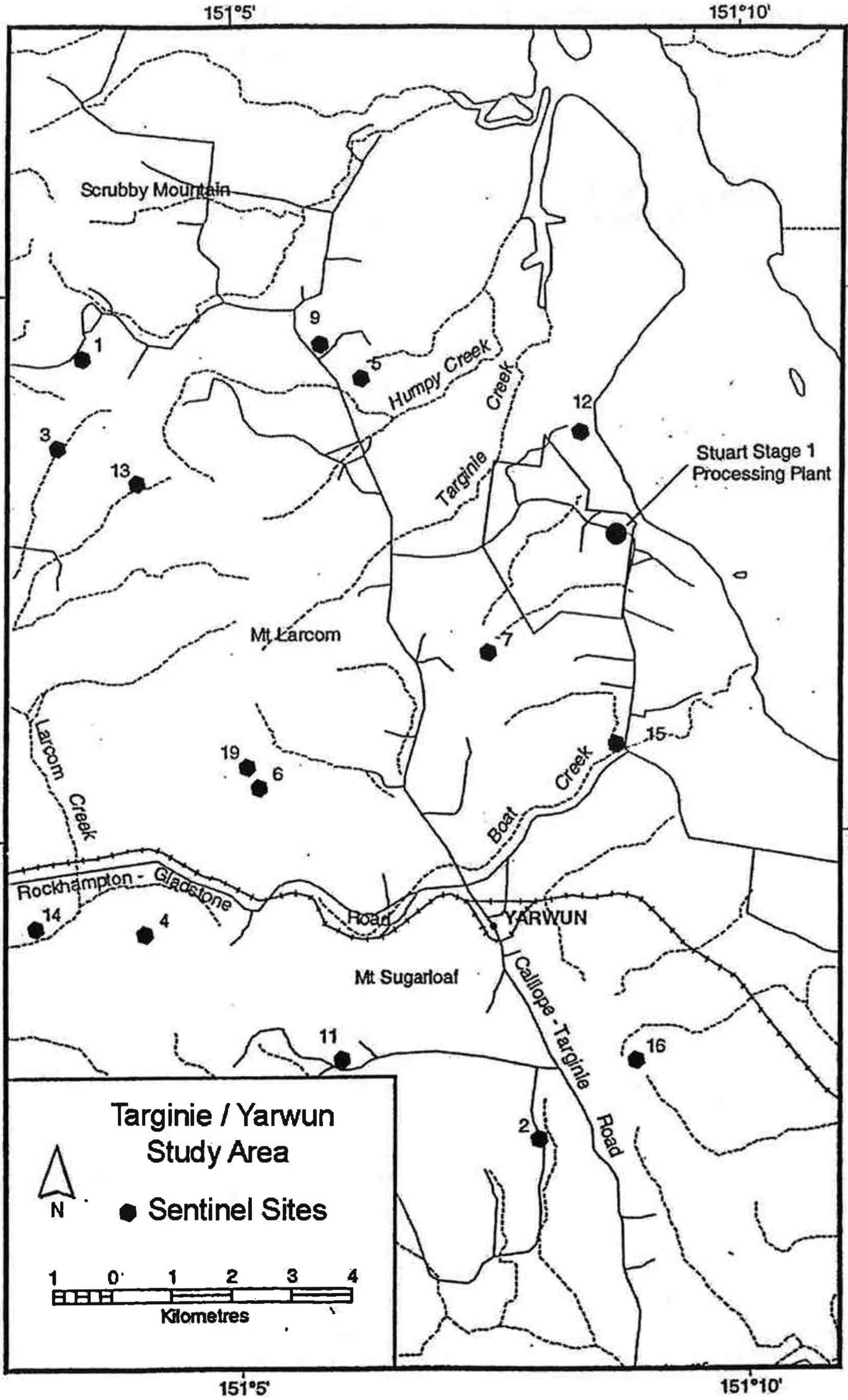

Fig. 1. Location of Sentinel sites to monitor potential effects of the Gladstone airshed on natural vegetation

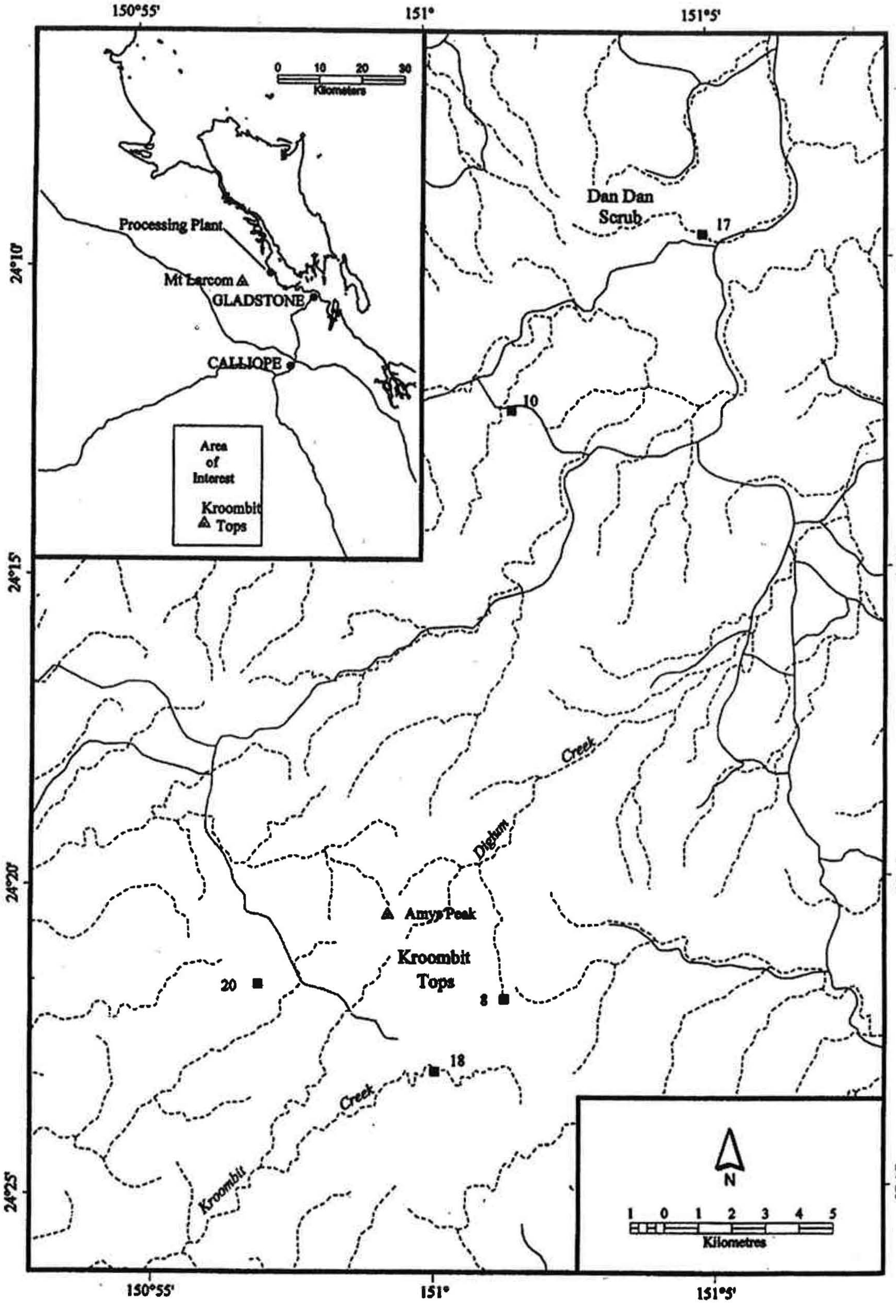

Fig. 2. Location of Reference sites providing a baseline for regional natural disturbance

Rock Lichen Assemblage Bioindicators

Photographic records of lichen were taken when present. Photographs were taken at four Reference and eight Sentinel sites. Within each site, five lichen-bearing substrates (rocks or trees) were permanently marked. Prior to taking photographs, a small quadrat (20 cm x 20 cm) was positioned in line with the permanently marked corners and a colour-neutral card was placed adjacent to the quadrat. A photograph of the quadrat and adjacent colour-neutral card was then taken and these photographs were subsequently scanned into a computer database to provide a permanent record of the area covered by lichens and type of lichen present (based on colour).

Data Analysis

Means of pH values were found to be proportional to the standard deviation and were analyzed in the original $\log_{10}$ units, the appropriate transformation for data of this type (Zar 1999).

Following repeated measures analysis of variance, a *post hoc* test was used to determine which pairs of means differed significantly. The Bonferroni multiple comparison test based on Student's t statistic was selected as it adjusts the observed significance level for multiple comparisons.

To determine if survey year or vegetation type was influencing invertebrate assemblages, a two-way analysis of similarity was carried out using sites as replicates (ANOSIM, Carr 1996, Clarke and Warwick 2001). Abundance data were transformed to reduce the influence of abundant taxa (square-root) and sites compared using a Bray-Curtis similarity index (Carr 1996). Two vegetation types were recognized based on canopy cover:

- *closed* canopy types such as vine thickets and gallery forests; and
- more *open* canopy types such as sclerophyll forests / woodlands (Table 1).

To assess the amount of variation among monitoring sites over time (years) based on similarity of invertebrate assemblages within a year, a programme called MVDISP (Clarke and Warwick 2001) was applied.

Significance of all statistical tests were assessed at the 5% probability level of making a Type I error.

Results

Environmental Conditions - Airshed Gases, pH & Rainfall

Soil pH of Sentinel sites varied little over time (Fig. 3) and repeated measures ANOVA was non-significant for this variable. A significant difference was found for Reference site pH values but this was attributed to sampling error in 2000 rather than an actual decline as values returned to 'normal' levels in subsequent years.

In 2003, average daily concentrations of SO_2 and NO_2 over the one-month standard monitoring period within Sentinel sites are three to four times greater than within Reference sites (Figs 4 and 5) and this difference was significant (ANOVA, $p < 0.001$). These elevated gas concentrations of SO_2 and NO_2 within the Sentinel airshed compared with the Reference airshed confirm that industrial outfalls have raised concentrations of these gases above background levels. In contrast, O_3 concentrations in 2003 were similar in both Sentinel and Reference areas (Fig. 6).

The drought conditions experienced in 2001 and 2002 were widespread in the region including Gladstone and the two closest weather stations to Kroombit Tops – Ubobo Store and Calliope Station (Fig. 7).

Canopy Cover, Foliar Health Indices and Leaf Damage

All three quantitative foliage health indicators – leaf count, leaf weight and chlorosis – necrosis score showed a significant change over time for some sites (Table 2). However, while six of the 15 Sentinel sites had significant changes in average leaf count index over time (repeated measures ANOVA, $P<0.05$), no consistent increasing or decreasing trend was apparent (*closed* canopy sites 11, 15, 19 plus *open* canopy sites 4, 5 and 13). Similarly, percentages of leaves affected by chlorosis – necrosis changed significantly over time at ten of the 15 Sentinel sites and two of the Reference sites (Friedman's test, P<0.05). Most sites (9 of the 12) showed a decline in the chlorosis – necrosis score indicating an improvement rather than a decline in leaf health, which would be expected if industrial gas outputs were impacting on the vegetation of these sites.

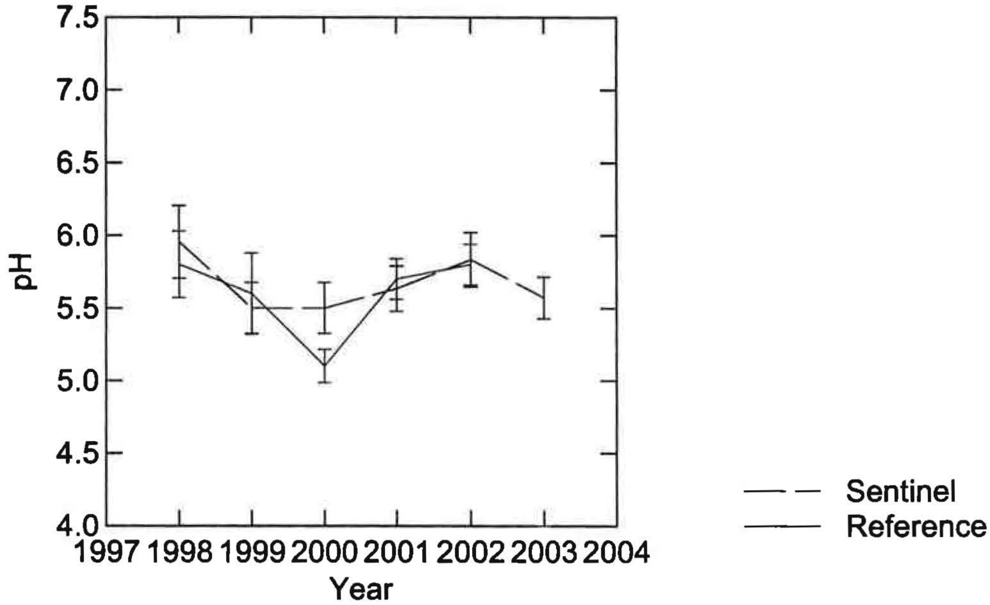

Fig. 3. Mean annual pH (1 $\log_{10}$) of soils (and standard error bars) from the five Reference sites and the fifteen Sentinel sites

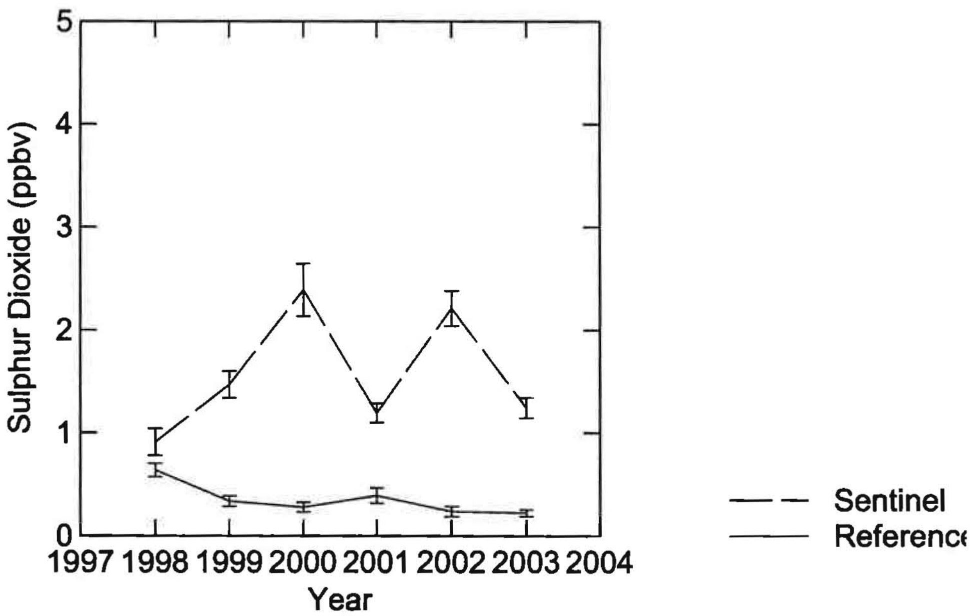

Fig. 4. Annual average daily concentrations (sampled during a standard one month period) in SO2 (ppbv) over time for Reference sites and Sentinel sites (Values are means of five Reference or fifteen Sentinel sites for each year and bars represent standard errors)

Only the leaf weight index showed consistent trends indicative of a widespread regional effect. Nine of the 15 Sentinel sites had significant changes in average leaf weight over time (repeated measures ANOVA, P<0.05) and several sites showed a decline in average leaf weight since monitoring commenced in 1998. Decreases rather than increases are of interest to this study as decreases in leaf count and weight indicators have been identified as possible indicators of phytotoxic effects on plants. Sites with such a trend were *closed* canopy sites, whether Reference (site 17) or Sentinel (1, 11, 15 and 19); one of the four *open* canopy sites (site 18) in the Reference area and 5, 6, 7 and 16 in the Sentinel area (examples of these conditions are shown in Fig. 8). One site (site 9) showed no obvious trend. Three of the 4 *open* canopy sites in the Sentinel area that showed significant declines in leaf weight were located on ridge-tops where gaseous outfalls are potentially greatest.

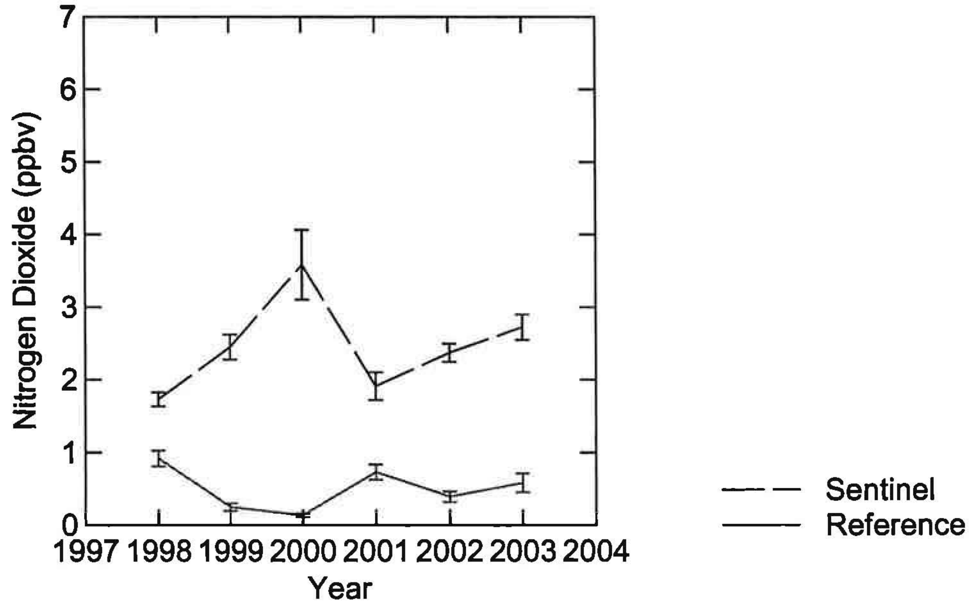

Fig. 5. Annual average daily concentrations (sampled during a standard one month period) in NO2 (ppbv) over time for Reference sites and Sentinel sites (Values are means of five Reference or fifteen Sentinel sites for each year and bars represent standard errors)

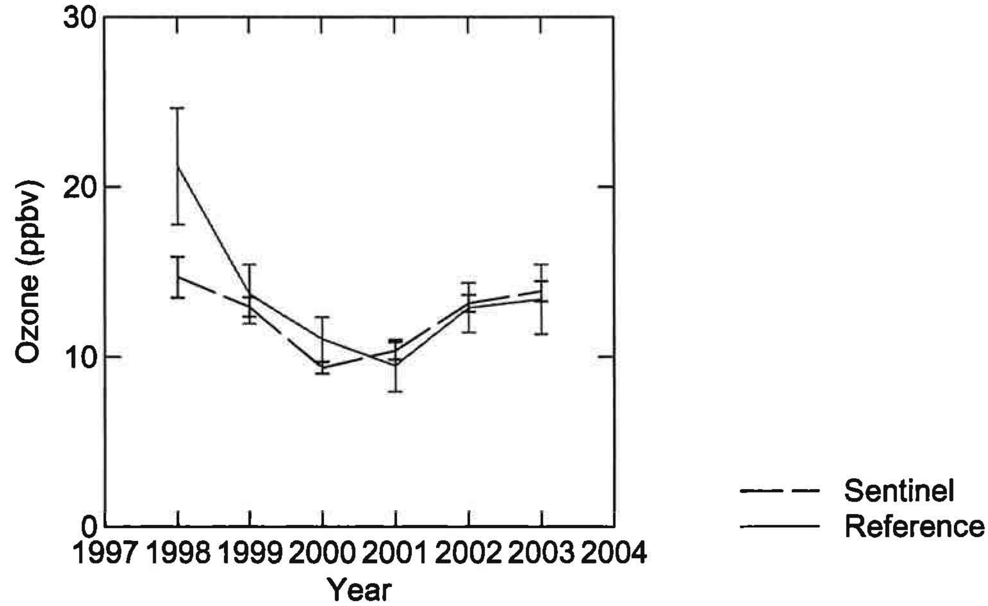

Fig. 6. Annual average daily concentrations (sampled during a standard one month period) in O_3 (ppbv) over time for Reference sites and Sentinel sites (Values are means of five Reference or fifteen Sentinel sites for each year and bars represent standard errors)

Summarizing (Table 2), sites showing significant changes in leaf weight and a declining trend belonged to the following groups (i) all *closed* canopy sites irrespective of area (Sentinel or Reference) or location (plains or ridge-top), and (ii) all *open* canopy ridge-top sites within the Gladstone airshed. This suggests a link between both vegetation type and topographic location with decline in average leaf weight.

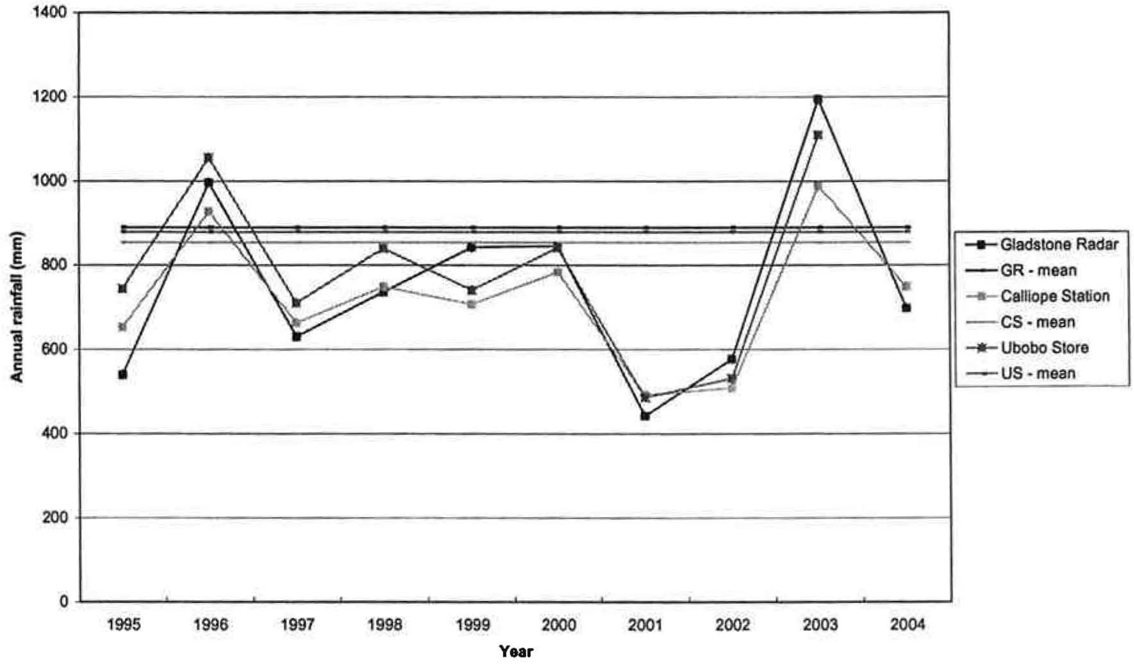

Figure 7. Rainfall data from Gladstone Radar Station and the two weather stations closest to Kroombit Tops – Ubobo Store and Calliope Station plus average rainfall data (Bureau of Meteorology)

Table 2: Summary of sites showing a significant change in leaf bioindicator index within Sentinel and Reference areas and canopy type / topographic location within the Sentinel area

Region / Zone/ Vegetation type	Closed	Open: Plains	Open: Ridge top	pooled by zone/area
Leaf count index				
Sentinel				
< 5 km	1 from 1	1 from 2	0 from 1	2 from 4 (50%)
5-10 km	1 from 2	1 from 3	0 from 1	2 from 6 (33%)
10-15 km	1 from 1	1 from 3	0 from 1	2 from 5 (40%)
Pooled Sentinel sites by vegetation type/area	**4 from 4 (100%)**	**3 from 8 (38%)**	**0 from 3 (0%)**	**6 from 15 (40%)**
Reference				
> 40 km	**0 from 1 (0%)**	**0 from 1 (0%)**	**0 from 3 (0%)**	**0 from 5 (0%)**
Leaf weight index (*Sentinel*)				
< 5 km	1 from 1	1 from 2	1 from 1	3 from 4 (75%)
5-10 km	2 from 2	1 from 3	1 from 1	4 from 6 (67%)
10-15 km	1 from 1	0 from 3	1 from 1	2 from 5 (40%)
Pooled Sentinel sites by vegetation type/area	**4 from 4 (100%)**	**2 from 8 (25%)**	**3 from 3 (100%)**	**9 from 15 (60%)**
Reference				
> 40 km	**1 from 1 (100%)**	**0 from 1 (0%)**	**1 from 3 (33%)**	**2 from 5 (40%)**
Chlorosis – necrosis (*Sentinel*)				
< 5 km	0 from 1	2 from 2	1 from 1	3 from 4 (75%)
5-10 km	0 from 2	2 from 3	1 from 1	3 from 6 (50%)
10-15 km	1 from 1	2 from 3	1 from 1	4 from 5 (80%)
Pooled Sentinel sites by vegetation type/area	**1 from 4 (25%)**	**6 from 8 (75%)**	**3 from 3 (100%)**	**10 from 15 (67%)**
Reference				
> 40 km	**1 from 1 (100%)**	**0 from 1 (0%)**	**1 from 3 (33%)**	**2 from 5 (40%)**

To examine the possible contribution of airshed gaseous outfall in the Sentinel area, average gaseous concentration (SO_2, NO_2 or O_3) and average soil pH of sites exhibiting a significant decline in leaf weight were compared to those sites with no significant change in leaf weight. No significant differences in these factors were found (t-test, all > 0.05) suggesting that industrial impacts were not the causative agent for these particular changes in bioindicators. Also the finding of similarly affected sites in the Reference area remote from the Sentinel area (2 of the 5 sites here had a significant decline in leaf weight, Table 2) indicates a widespread regional agent of disturbance rather than a Gladstone airshed effect. Such an agent may have been climate with below average rainfall in the region in 2001 and 2002 following several years of slightly below average years from 1997 to 2000 (Fig. 7). These below average rainfall conditions were experienced across the region including weather stations closest to the Kroombit Tops Reference area (Fig. 7).

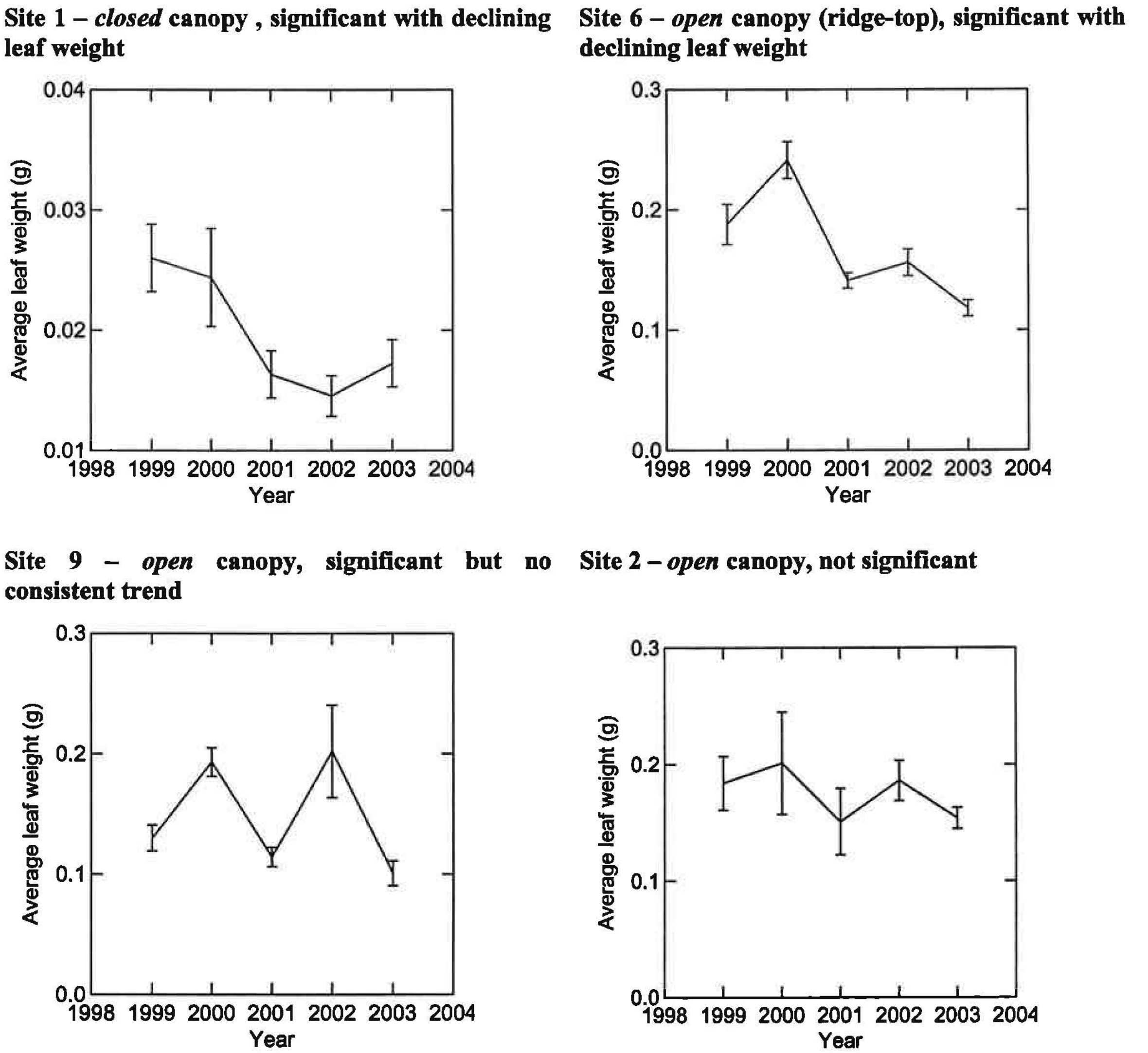

Fig. 8. Examples of yearly change in foliar leaf weight index illustrating four conditions: *closed* canopy & significant with declining trend, *open* canopy (ridge-top) & significant with declining trend, *open* canopy & significant but no consistent increasing or decreasing trend; *open* canopy & not significant (standard error bars from 5 trees at each site)

Invertebrate Assemblages

Two-way analysis of similarity on epigaeic invertebrate assemblages showed that both vegetation type (i.e. *closed* or *open* canopy) and year significantly affected the invertebrate

Order abundance composition (R=0.692, P<0.001, 999 random permutations and R=0.356, P<0.001, 999 random permutations respectively). Figure 9 illustrates these findings.

Examining Sentinel sites, both *open* and *closed* canopy types show a gradual shift in position of the yearly clusters of sites from 1998 to 2000 followed by a relatively large displacement in 2001 (Figs. 10 and 11), but with a much greater displacement for the *closed* canopy sites indicating greatly reduced similarity in invertebrate composition in 2001 (Fig. 11). By 2002 both *closed* and *open* canopy sites have returned to a similar position to sites in earlier years.

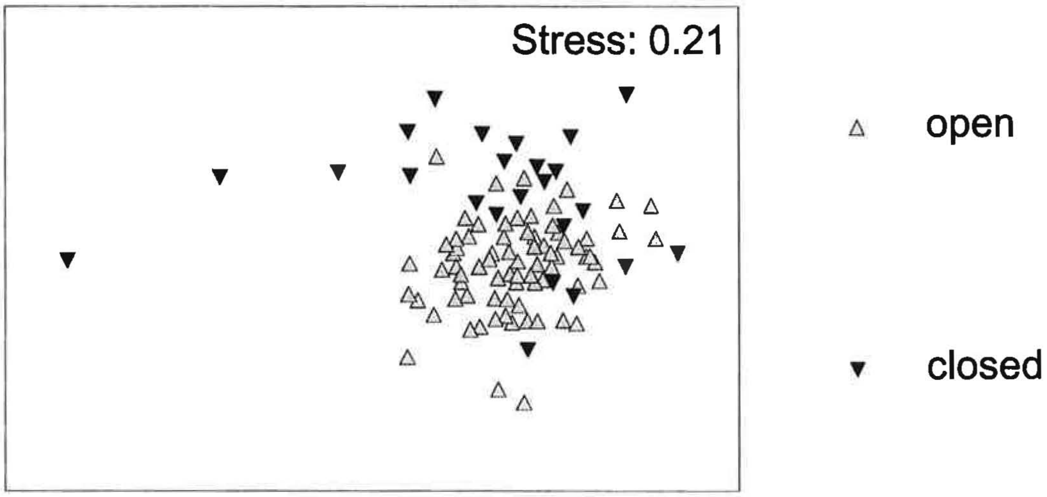

Fig. 9. Similarity of *open* and *closed* canopy sites showing the two dimensional NDMS ordination of epigaeic Order abundance (square root transformed, Bray-Curtis similarity index)

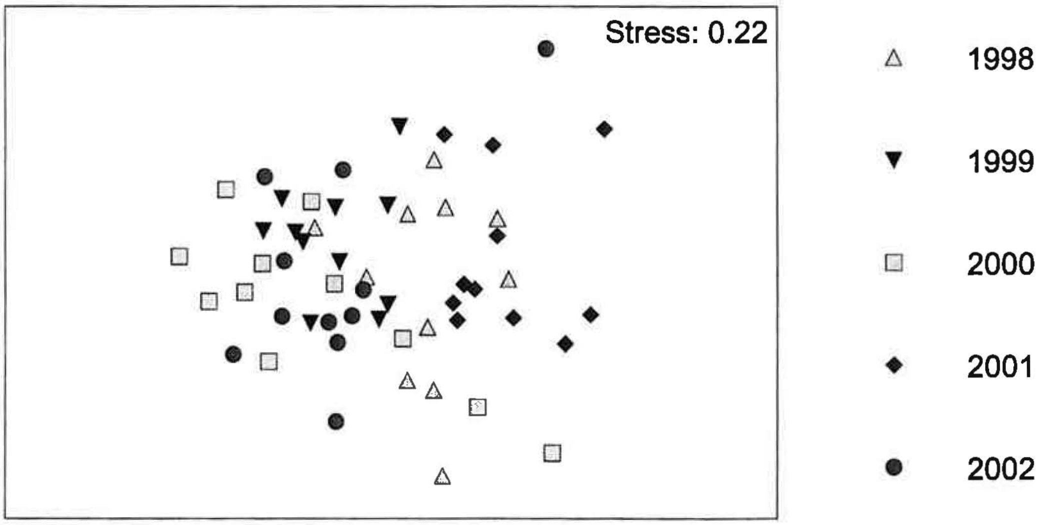

Fig. 10. Similarity of *open* canopy Sentinel sites showing the two dimensional NDMS ordination of epigaeic Order abundance (square root transformed, Bray-Curtis similarity index) by year

Sentinel *open* canopy sites showed similar patterns in the variability of their invertebrate assemblages (Fig. 12) and the Multivariate Dispersion Index fluctuated around a steady-state position from 1998 to 2002. In contrast, Sentinel *closed* canopy sites showed greatest variability in 2001 coinciding with onset of reduced rainfall followed by a return to lower levels in 2002 (Fig. 13).

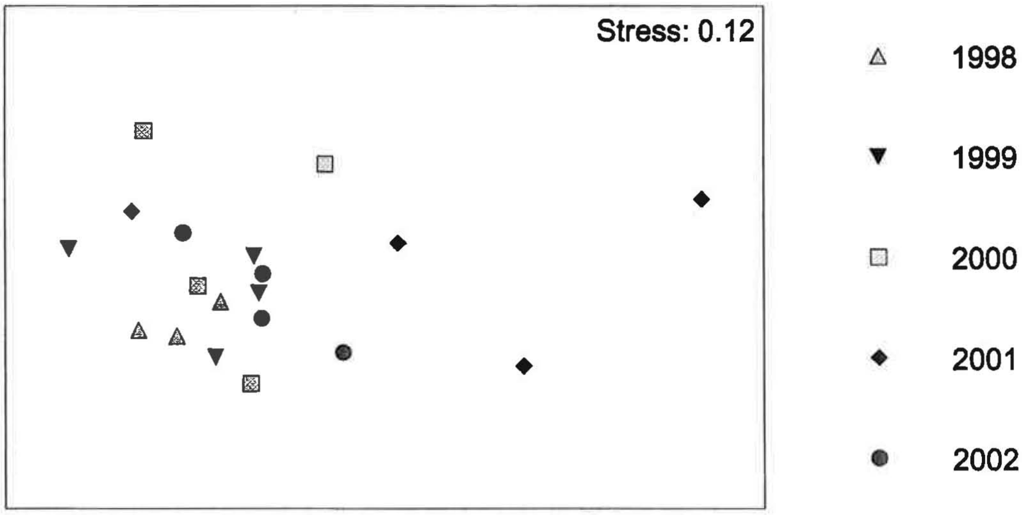

Figure 11. Similarity of *closed* canopy Sentinel sites showing the two dimensional NDMS ordination of epigaeic Order abundance (square root transformed, Bray-Curtis similarity index) by year

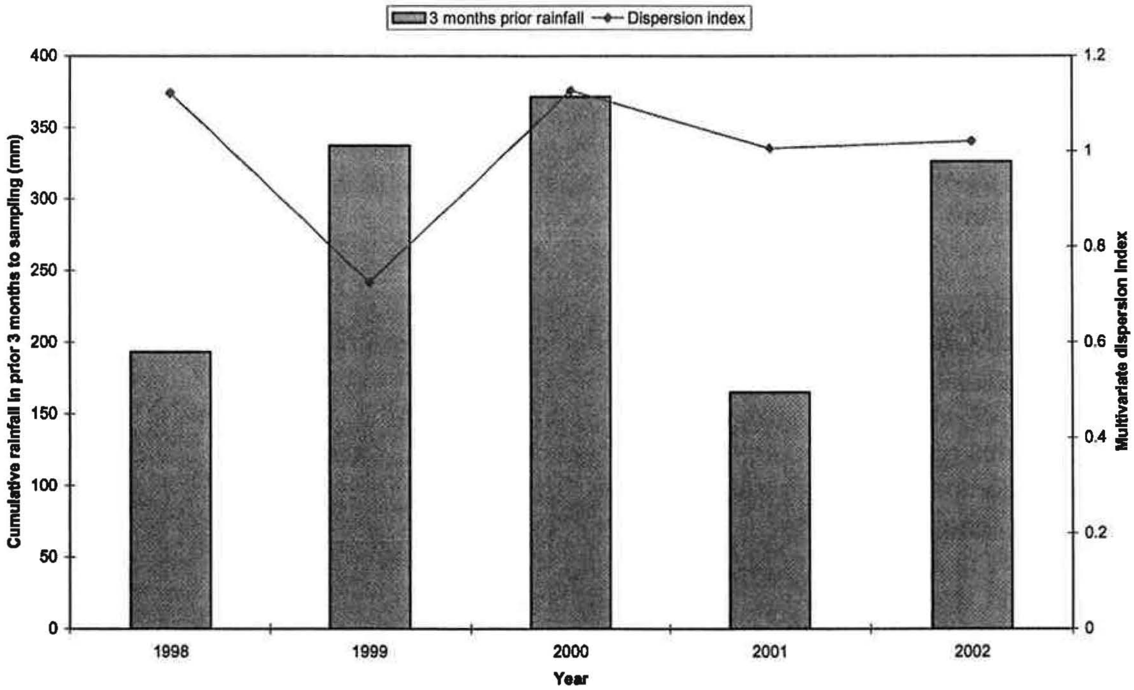

Fig. 12. Sentinel *open* canopy sites - yearly variability in invertebrate similarity matrices used to create NMDS ordinations

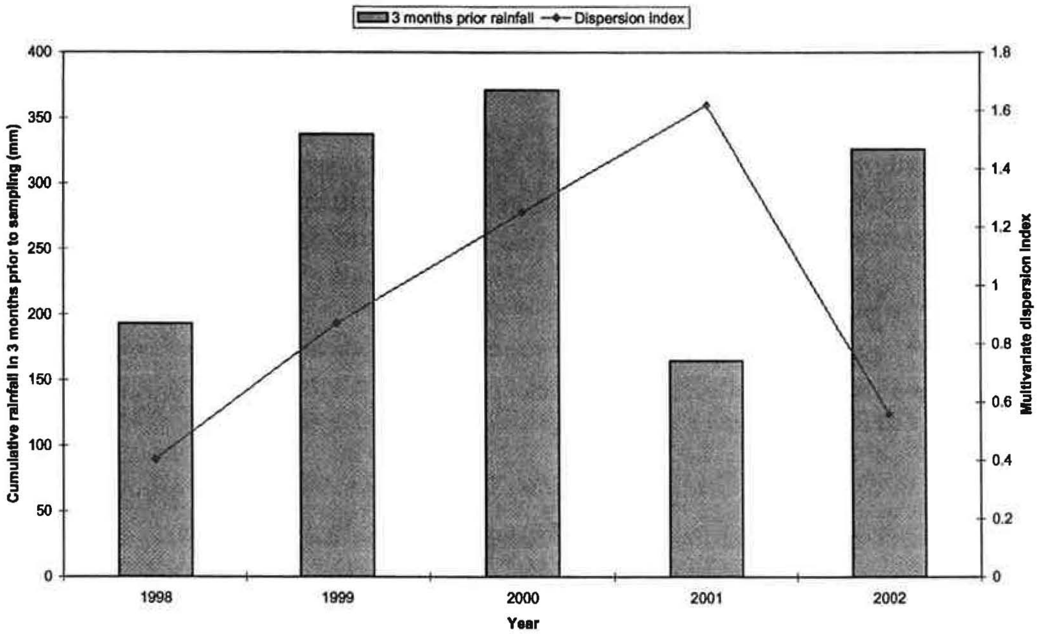

Figure 13. Sentinel *closed* canopy sites - yearly variability in invertebrate similarity matrices used to create NMDS ordinations.

Rock Lichen Assemblages

A visual comparison of 2002 and 2003 photos with previous years' photos was made and decrease in lichen cover was not detectable at any of the sites. An example comparing 1998 lichen cover with lichen cover at the same location (site 6, lichen station 5) in 2002 is shown in Figure 14.

Discussion

No effects of Gladstone industry could be detected using bioindicators tested in this study. However, widespread regional impacts such as drought have the capacity to confound the assessment of industrial disturbance using biological indicators. The use of regional reference sites remote from the disturbance area is the traditional way of dealing with this problem. Comparison of regional Reference area data with the Sentinel area indicated that both areas showed a similar change in leaf weight and invertebrate assemblage bioindicators in 2001and 2002 corresponding with a period of below average wet seasons following on from several years of slightly below average wet seasons. This suggested that a widespread climatic impact in 2001 was responsible for the observed changes in both Reference and Sentinel areas confirming the efficacy of this approach.

However, another approach, not necessarily reliant on regional Reference areas, also offers some usefulness in resolving these issues of natural versus anthropogenic disturbance to Sentinel sites. For instance, within the Sentinel area two vegetation types were sampled and these responded in different ways to disturbance that was consistent with their ecology. *Closed* canopy vegetation comprising vine thickets in Central Queensland is normally seasonally water stressed (Bowman 2000) as indicated by leaf drop in the mid to late dry season and this suggests that this vegetation type is more sensitive to drought effects than the more sclerophyllous *open* canopy vegetation. The findings in this study were consistent with this differential drought tolerance with all *closed* canopy vegetation types (vine thickets or riparian forests) showing (i) significant declines in leaf weight between 2001 and 2002 whereas *open* canopy vegetation types showed a mixed response with, the exception of ridge-top sites, very few significant declines in average leaf weight, and (ii) as a group, *closed* canopy sites had a much greater variability in invertebrate assemblage composition in 2001 than the *open* canopy vegetation types. Thus these findings, independent of the regional Reference area, also suggest possible drought effects as being responsible for some of the changes observed in the bioindicators. Of course, these changes may have been exacerbated by anthropogenic impacts but more sampling over several 'normal' wet season years will be needed to clarify these possibilities.

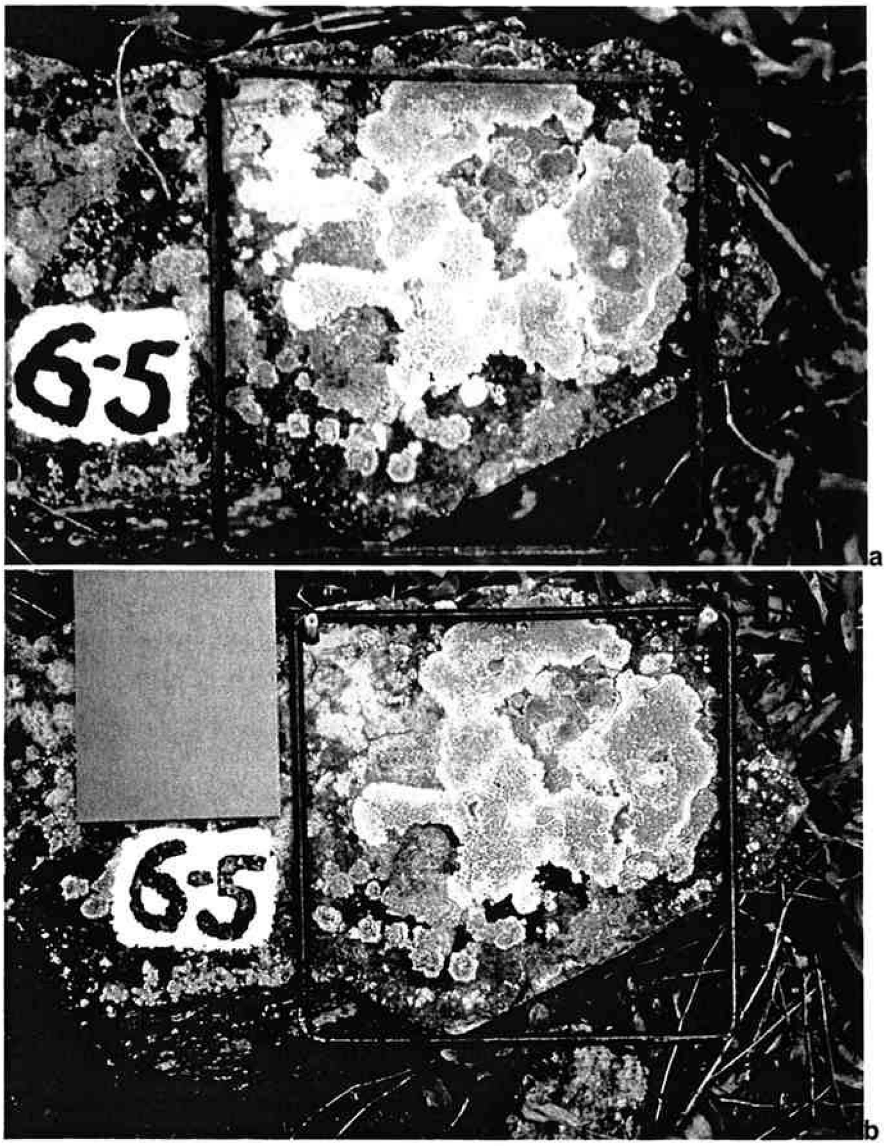

Figure 14. Example of lichen cover data - lichen cover at site 6 (station 5) in (a) 1998 and (b) 2002

In conclusion, no clear evidence for industrial impacts from the Gladstone airshed on natural vegetation within the period 1998 to 2003 was found, although further monitoring following recovery from the drought period is needed to confirm this. There is some data to suggest that plants under drought stress are more resistant to damage from gaseous air contaminants when they are under moisture stress (Smith 1981). The response of bioindicators, both at regional reference sites and within *closed* canopy vegetation, was found to be consistent with changes in bioindicators responding to the influence of widespread drought in 2001 and 2002. The usefulness of vine thicket vegetation as a way of internally calibrating for drought effects by acting as a sentinel vegetation type for natural disturbance of this kind needs to be more widely tested. If this ability is confirmed for this vegetation type, then it may offer a more cost-effective protocol for testing for natural drought effects compared with regional reference areas, or they may provide an opportunity to have some ability to calibrate for regional effects of droughts where regional reference sites are lacking.

Acknowledgments

Many thanks to all the Centre for Environmental Management staff who have contributed to the field work over the years, in particular Gail Tucker, Michael Price and Trent Attard, and also to Vanessa Lobegeier for sorting and identification of invertebrates. The funding support from SPPD (now QERL) and cooperation of landholders and managers was also much appreciated.

References

Ayers, G.P., Keywood, M.D., Gillett, R.W., Manins, P.C., Malfroy, H. and Bardsley, T. (1998) Validation of passive diffusion samplers for SO_2 and NO_2 under Australian conditions. *Atmosphere and Environment* **32**: 3587-3592.

Bowman, D.J.M.S. (2000) *Australian Rainforests: Islands of green in a land of fire.* Cambridge University press, Cambridge.

Carr, M.R. (1996) *Primer User Manual.* Plymouth Marine Laboratory, Plymouth.

Clarke, K.R. and Warwick, R.M. (2001) *Change in Marine Communities: an approach to statistical analysis and interpretation. 2nd edition.* PRIMER-E: Plymouth.

CSIRO (1991) *The Insects of Australia: A textbook for students and research workers, 2nd Ed. Vol 1 and 2.* Division of Entomology Australia , Melbourne University Press, Melbourne.

Fowler, D. (1992) Air pollution transport, deposition, and exposure to ecosystems. pp. 31-51 in *Air Pollution Effects on Biodiversity* (eds J.R Barker and D. T. Tingey). Van Rostrand Reinhold, New York.

Freitag, R. and Hastings, L. (1973) Ground beetle populations near a kraft mill. *Canadian Entomologist* **105**: 299-310.

Griffith, A.D. (1998*) Impact of Sulphur Dioxide Emissions on Savanna Biodiversity at Mt Isa, Queensland.* Report to Mount Isa Mines Ltd. CSIRO, Darwin.

Hoffmann, B.D., Griffiths, A.D. and Andersen, A.N. (2000) Responses of ant communities to dry sulphur deposition from mining emissions in semi-arid tropical Australia, with implications for the use of ant functional groups. *Austral Ecology* **25**: 653-663.

Howe, T.K. and Woltz, S.S. (1981) Symptomology and relative susceptibilty of various ornamental plants to acute airborne sulphur dioxide exposure. *Proceedings of the Florida State Horticultural Society* **94**: 121-123.

Jones, H.C. and Heck, W.W. (1980) Vegetation – biological indicators or monitors of air pollutants. pp. 117-121. in *Biological Monitoring for Environmental Effects.* (ed. D. Worf). Lexington Books, Toronto.

Kovacs, M. (1992) *Biological Indicators in Environmental Protection.* Ellis Horwood Ltd, West Sussex.

Krupa, S.V. and Legge, A.H. (1998) Foliar injury symptoms of Saskatoon serviceberry (*Amelanchier alnifolia* Nutt.) as a biological indicator of ambient sulphur dioxide exposures. *Environmental Pollution* **106**: 449-454.

Leetham, J.L., Lauenroth, W.K., Milchunas, D.G., Kirchner, T. and Yorks, T.P. (1984) Responses of heterotrophs. pp. 137-160 in *The Effects of SO2 on a Grassland: A Case Study in the Northern Great Plains of the United States.* (eds W.K. Lauenroth and E.M. Preston). Springer-Verlag, New York.

Murray, F. (1984) Effects of sulphur dioxide on three *Eucalyptus* species. *Australian Journal of Botany* **32**: 139-145.

Murray, F. and Wilson, S. (1988a) Effects of sulfur dioxide, hydrogen fluoride and their combination on three *Eucalyptus* species. *Environmental Pollution* **52**: 265-279.

Murray, F. and Wilson, S. (1988b) Joint action of sulphur dioxide and hydrogen fluoride on growth of *Eucalyptus tereticornis*. *Environmental and Experimental Botany* **28**: 343-349.

Murray, F. and Wilson, S. (1989) Sulfur dioxide-induced growth changes in *Eucalyptus calophylla*. *European Journal of Forest Pathology* **19**: 193-199.

Nobby, R.J. and Kozlowski (1981) Interactions of SO2- concentration and post-fumigation temperature on growth of five species of woody plants. *Environmental Pollution (Series A)* **25**: 27-39.

O'Connor, J.A., Parbery, D.G. and Strauss, W. (1974) The effects of phytotoxic gases on native Australian plant species: Part 1. Acute responses of sulphur dioxide. *Environmental Pollution* **7**: 7-23.

Smith, W.H. (1981) *Air Pollution and Forests: Interactions between Air Contaminants and Forest Ecosystems.* Springer-Verlag, New York.

Taylor, O.C. (1973) Acute responses of plants to aerial pollutants. pp. 9-20 in *Air Pollution Damage to Vegetation.* (ed. J.A. Naegele). American Chemical Society, Washington D.C.

Treshow, M. and Anderson, F.K (1989) *Plant Stress from Air Pollution.* John Wiley and Sons, Chichester.

Zar, J.H. (1999) *Biostatistical Analysis,* 4^{th} Ed. Prentice-Hall: Englewood Cliffs, New Jersey.