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J.L. Read

Are geckos useful bioindicators of air pollution?

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Abstract The response of an Australian arid-zone gecko community to sulphur dioxide and salt spray from a mine and industrial site was investigated from 1992 to 1995. Geckos were abundant and fecund at control sites in chenopod shrubland and annual capture rates were strongly influenced by minimum night temperatures. Capture rate and percentage of females gravid at sites exposed to high concentrations of air pollutants were significantly lower than at control sites. Discrepancies between control and impacted sites were greatest for the termite-specialist geckos *Diplodactylus conspicillatus* and *Rhynchoedura ornata*. An increase in capture rates and percentage of females gravid at sites close to the industrial site, followed a reduction in peak sulphur dioxide emissions. Geckos may be sensitive and useful bioindicators of the environmental impacts of some atmospheric pollutants.

Key words Gekkonidae · Bioindicators · Atmospheric pollution · Sulphur dioxide · Arid zone

Introduction

Industrial and automotive emissions can adversely impact ecosystems on local, regional and even global scales (Roberts 1982; Armentano and Bennett 1992; Barker and Tingey 1992). The monitoring of impacts and protection of the environment from airborne pollutants is therefore an integral facet of ecologically sustainable development. Rather than measuring abiotic concentrations of contaminants, air pollution monitoring is often more effectively achieved by measuring biotic responses (Hopkin 1993) since organisms can integrate the effects of environmental perturbations over time (Furness and Greenwood 1993). Organisms which respond in a predictable and measurable manner to environmental stresses may be useful bioindicators.

Although organisms may respond to pollution at the biochemical, cellular, or tissue level, stresses are unlikely to be ecologically significant unless they can be shown to have effects at the population level (McIntyre and Pearce 1981, cited in Gray 1989; Cormier and Racine 1992). Population-scale bioindicators are therefore appropriate to monitor environmental impacts, conserve biodiversity and maintain populations of rare species (Erhardt et al. 1992; Underwood 1995). The determination of useful population-scale bioindicators therefore forms an integral part of the quantitative and accountable ecological assessments which are required by modern industry (Peterson et al. 1992; Lemont et al. 1993; Paoletti and Bressan 1996).

Higher plants are useful in some cases (Woodwell 1970; Kapusta and Reporter 1993; Klumpp et al. 1994), but are not always effective indicators of air borne pollutants such as sulphur dioxide (SO_2), due to significant inter-plant variation (Taylor and Murdy 1975) or lack of sensitive response (Kaeding and Kidby 1986). With the exception of a few studies on insect, mammal, bird and amphibian populations (Alstaad et al. 1982; Newman and Schreiber 1984; Newman et al. 1992; Furness and Greenwood 1993), data concerning the impact of air pollution on wildlife are limited (Newman and Schreiber 1988; Peterson et al. 1992). In extreme cases animals may die as a result of exposure to pollutants, although debilitating injuries and lower survivorship (Newman 1980) or a reduction in fecundity (Newman et al. 1992) are more common.

Effective ecological bioindicators should be common, easily sampled, relatively sedentary, have a known life history and exhibit a proven response to the environmental perturbation under investigation (Moore 1966). Although terrestrial reptiles have been largely overlooked as bioindicators of pollutants (Peterle 1991;

J.L. Read
Environmental Dept., Olympic Dam Corporation,
PO Box 150, Roxby Downs, S. Australia, 5725
Dept. of Ecosystem Management,
University of New England, Armidale NSW, Australia 3501

Newman et al. 1992), Australian desert geckos, in particular, potentially fulfil all of the criteria for effective bioindicators. Geckos were second only to skinks as the most abundant reptiles trapped in several long-term Australian arid-zone pitfall trap studies (Reid and Gillen 1988; James 1989; Read 1992; Hobbs et al. 1994) and they are also readily sampled by spotlighting (Galliford 1981; Delean and Harvey 1981; Kitchener et al. 1988). Gecko populations are also buffered from extreme fluctuations in food availability because many species feed solely or predominantly on termites (Pianka 1986) which provide a regular food supply in an unpredictable environment (Morton and James 1988; James 1991; Read in prep). Therefore, unlike many arid-zone animals which respond dramatically to seasonal conditions, changes in gecko populations caused by environmental disturbances are less likely to be masked by climatic influences. Geckos also exhibit a range of life-history traits, ranging from small species such as *Rhynchoedura ornata*, which seldom live longer than 2 years (Read in prep), to long-lived species such as *Oedura reticulata* and *Gehyra variegata* which live for more than 16 years, (Kitchener et al. 1988; How and Dell 1994). Therefore, both long-term cumulative effects of pollutants, and short-term alterations to survivorship or fecundity, may be assessed through monitoring of gecko populations.

Nocturnal geckos are potentially one of the vertebrate groups most sensitive to air pollution. Australian desert geckos are active at night when wind speed tends to be low and temperature inversions concentrate industrial emissions near the ground surface (Fowler 1992). Geckos have large lidless eyes which are particularly sensitive to irritants such as SO_2 (Cralley and Cralley 1985) and unlike most other lizards which have movable eyelids, geckos regularly lick their eyes and face (Bustard 1963). Ingestion, which is a major pathway for contaminant accumulation (Arthur and Markham 1984), can therefore occur even when geckos are not feeding. Irritation by soluble contaminants would also be increased by face licking, since gekkonid skin sensory receptors are concentrated around the labial, nasal and orbital regions (Matveyeva and Ananjeva 1995). These cutaneous sensilla apparently serve a range of functions, allowing distant stimuli such as environmental conditions to be registered by the epidermis (Bauer and Russell 1988; Russell and Bauer 1987).

This study investigated the impacts of SO_2 and salt spray on geckos at an industrial site in northern South Australia. The diverse reptile inventory for the region exceeds 40 species (Read 1994) and includes ten gecko species. Impacts of the previous light cattle grazing and initial mining activity on the local reptiles were negligible (Read 1992). The most common gecko species trapped were *Rhynchoedura ornata*, *Diplodactylus stenodactylus*, *D. conspicillatus* and *D. damaeus* (Read 1992), which are all members of the sub-family Diplodactylinae. *Rhynchoedura ornata* and *D. conspicillatus* are both termite specialists, in contrast to the other species which eat a variety of invertebrate prey (Pianka 1986;). All of the local gecko species lay clutches of two eggs with the exception of *Gehyra* which lays a single egg. Over 80% of all adult female geckos captured at undisturbed sites in the region from November to January contain either enlarged vitellogenic follicles or oviducal eggs (Read JL unpubl.), suggesting that most species breed repeatedly throughout the summer. Sequential clutching throughout the summer months has also been recorded for several other *Diplodactylus* species (How et al. 1986).

This study aimed to determine whether the abundance or fecundity of geckos was affected by airborne industrial emissions and hence whether gecko populations could be used as bioindicators of environmental impacts at an Australian arid-zone industrial site.

Methods

Study area

The underground Olympic Dam mine (30°29′S, 136°55′E) is situated amongst linear orange sand dunes overlain upon a clay and gibber plain, 520 km north of Adelaide in arid South Australia (Fig. 1). Less than 5% of the 180 km^2 mine lease has been physically disturbed by the mining and processing operation and the

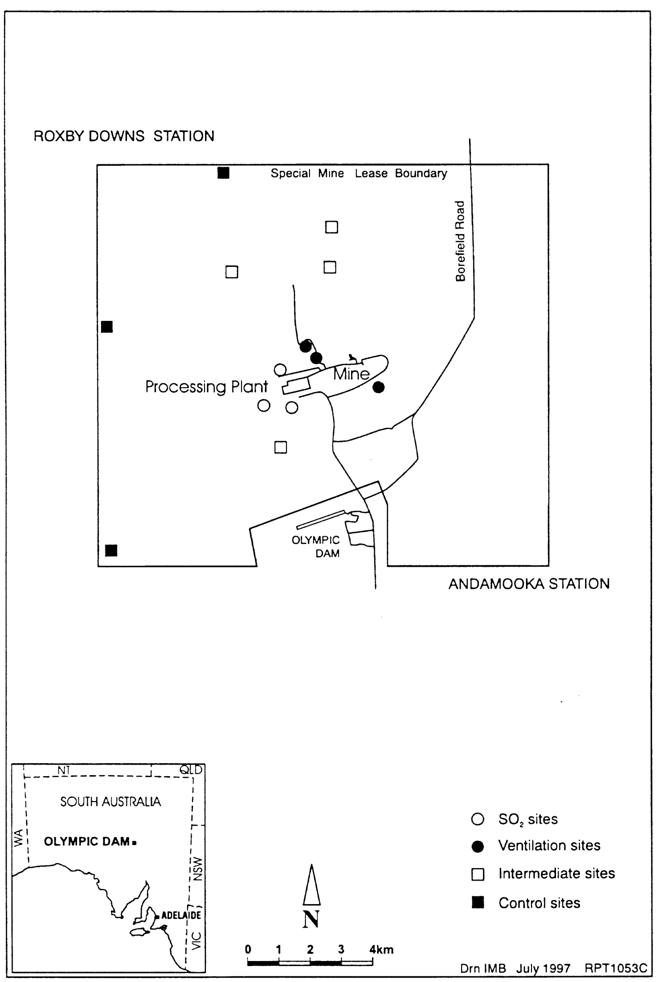

Fig. 1 Location of Olympic Dam and reptile monitoring sites

major environmental impacts are likely to be from SO_2 and salt-spray emissions.

Sulphur compounds are the by-product of on-site copper smelting by WMC Olympic Dam Corporation (ODC) at the Olympic Dam mine. Although in excess of 95% of the sulphur emissions have been trapped and converted to sulphuric acid since production commenced in 1987, between 1100 and 1400 tonnes per annum were initially released to the atmosphere (ODC unpublished work). These emissions were reduced to approximate 400 $year^{-1}$ following commissioning of a jet-bubble reactor scrubbing system in late 1994, although a commensurate reduction in proximal ground level concentrations did not eventuate (Olympic Dam Operations 1995). Average daily maximum SO_2 concentrations however decreased from 385 μgm^{-3} to 123 μgm^{-3}, following raising of the smelter stacks from 40 m to 60 m in November 1990, with a corresponding reduction in foliar damage in surrounding vegetation (Fatchen Environmental 1996). Salt water from an underground aquifer also causes localised damage to the environment when expelled by ventilation exhausts. Modifications to the ventilation outlets since 1992 significantly reduced both the amount of salt expelled and associated environmental impacts (Read 1996).

Data collection

Geckos were trapped in pitfall traps at three sites in a SO_2 enriched zone within 1200 m of the smelter; three sites in a salt spray zone within 450 m of the ventilation bores; four intermediate sites 1.8–5.1 km from the sources which received small pollutant loads; and at three control sites, over 6 km from the smelter (Fig. 1). All study sites were located in chenopod shrubland, dominated by *Atriplex*, *Maireana* and *Sclerolaena* shrubs, which supports the most diverse reptile community in the region (Read 1992). Each site consisted of 13 pits dug in a cross design and linked by a 25 cm flymesh fence. Traps were opened for a 10-day period each December from 1992 to 1995.

Traps were checked every morning and geckos were uniquely toe-clipped for future identification. Gravid females were identified by the presence of eggs, visible through their belly wall. All animals were released within 24 h at their site of capture. Capture rate, which provides an indication of abundance, was calculated by dividing the number of geckos trapped at each site by the number of trap-nights (130), and expressed as a percentage for ease of comprehension. Same-session recaptures were not counted in capture rate calculations.

Salt spray deposited from the mine ventilation bores was collected quarterly in beakers at each site. Conductivity of salt samples was measured in the beakers which were made up to volume with distilled water. Relative SO_2 loads at each site were modelled using known emission concentrations and the US EPA ISC2 Atmospheric Modelling Package (1992). Rabbits, which are the primary herbivore in the region, were monitored through dung collection in eight $1m^2$ permanent quadrats at each site immediately following trapping each year. Rainfall and temperature data were collected from a meteorological monitoring station at the processing plant, near the centre of the study region (Fig. 1).

Data analysis

Kolmogorov-Smirnov goodness of fit tests using EXCEL for Windows (Microsoft 1995) were employed to compare capture rates of geckos from different impact zones within each year. Repeated measures analysis of variance were used to test for significant differences between capture rates of geckos, and differences in pollutant loads, within treatments and years. Generalised linear models were constructed using GLIM4 software (Francis et al. 1993) to assess the response of capture rates of *R. ornata*, *D. stenodactylus* and all geckos combined to habitat and disturbance factors. Disturbance factors assessed were yearly salt concentrations, the distance of sites from the smelter and the peak and average SO_2 concentrations modelled prior to and following raising of the smelter stacks in November 1990. Since the capture rates were not normally distributed and Poisson models were untenable due to overdispersion, negative binomial models were used (Lawless 1987). Variables were deleted in turn from multiple regression models, commencing with terms with the least significant *t*-statistic until the minimum acceptable model, containing only significant terms, was achieved. In order to minimise the likelihood of rejecting significant terms, the $P \leq 0.05$ significance value was used as a criterion to retain terms.

Results

A total of 417 geckos from nine species were captured in this study. Two species, namely *D. stenodactylus* and *Rhynchoedura ornata*, accounted for over two-thirds of the total captures and were the dominant geckos trapped each year (Table 1). *Heteronotia binoei* and *D. damaeus*, which were rare or absent in 1992 and 1993, increased considerably in abundance in 1994. All gekkonid species which have been recorded in the study region were sampled in this study, with the exception of the arboreal *Strophurus cilliaris*.

Temperatures varied considerably over the four trapping periods with minimum nightly temperatures consistently exceeding 20°C in 1994, averaging just under 20°C in 1992 and 1993 but exceeding 20°C only once in 1995 (Table 2). Heavy rain fell during the 1992 and 1993 trapping sessions but dry conditions prevailed in later years (Table 2).

Average NaCl concentrations differed significantly between treatments ($F_{3,42}$ 8.668, $P \leq 0.001$) (Fig. 2). Concentrations were significantly higher at the ventilation sites than other sites in all years ($P \leq 0.001$). Modelled average and peak SO_2 loads were 2–4 times higher at SO_2 sites than controls (Fig. 3). Rabbit dung densities differed significantly between treatments ($F_{3,42}$ 5.229, $P = 0.002$) and on average were higher at mining impact sites than both intermediate and control sites (Fig. 4).

Average gecko capture rates at control sites dropped from 13.8 in 1992 to 9 in 1993 but peaked at 14.9 in 1994, indicating an annual variation of 60% of maximum capture rates (Table 3). Gecko capture rates varied significantly between years ($P < 0.001$) but did not

Table 1 Summary of the number of each gecko species captured from 1992 to 1995

Species	1992	1993	1994	1995
Diplodactylus conspicillatus	6	22	35	23
D. damaeus	0	0	4	2
D. stenodactylus	39	32	82	74
D. tessellatus	8	5	10	6
Gehyra sp.	1	0	1	4
Heteronotia binoei	0	1	21	8
Nephrurus levis	6	5	9	6
N. milii	0	1	1	2
Rhynchoedura ornata	41	34	53	45
Total	101	100	216	170

Table 2 Weather conditions during the trapping periods

Trapping period	8 Dec 1992– 24 Dec 1992	7 Dec 1993– 17 Dec 1993	13 Dec 1994– 22 Dec 1994	28 Nov 1995– 8 Dec 1995
Average max. (°C)	27.1	33.3	40.5	30.6
Maximum (°C)	36.3	38.8	48	38.8
Average min. (°C)	18.2	19	23.9	17.1
Maximum min. (°C)	22.9	23.4	30.5	26
No. of days > 20 °C	5	4	10	1
Rainfall (mm)	97	22	0.4	1.8

Table 3 Average mean ± SE of captures of all geckos in each impact zone from 1992 to 1995. (means with different superscripts differed significantly ($P < 0.05$) between impact zones within years using Kolmogorov-Smirnov tests)

Impact zone	1992	1993	1994	1995
SO_2	$3.3 \pm 0.7^{(a)}$	$7.0 \pm 2.7^{(ab)}$	$13.7 \pm 2.9^{(a)}$	$9.3 \pm 1.9^{(a)}$
Ventilation	$5.0 \pm 1.7^{(a)}$	$4.0 \pm 1.5^{(a)}$	$13.0 \pm 4.2^{(a)}$	$9.3 \pm 3.8^{(a)}$
Intermediate	$10.3 \pm 3.7^{(ab)}$	$8.0 \pm 3.7^{(ab)}$	$19.5 \pm 4.0^{(a)}$	$9.0 \pm 2.5^{(a)}$
Control	$18.0 \pm 2.0^{(b)}$	$11.7 \pm 0.9^{(b)}$	$19.3 \pm 1.2^{(a)}$	$13.0 \pm 2.5^{(a)}$

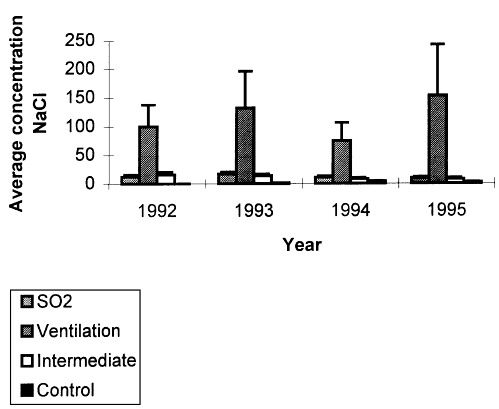

Fig. 2 Average concentrations of NaCl at the different impact zones 1992–1995

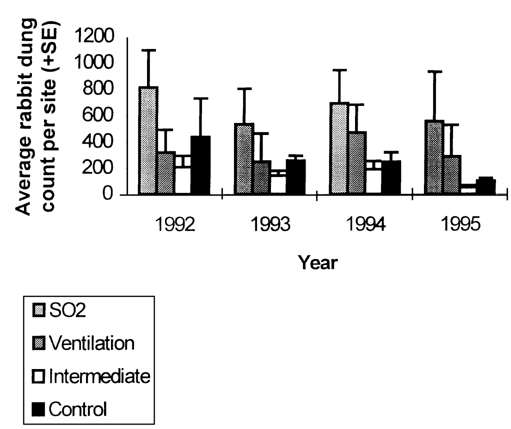

Fig. 4 Average rabbit dung counts from 8-m^2 quadrats at each site

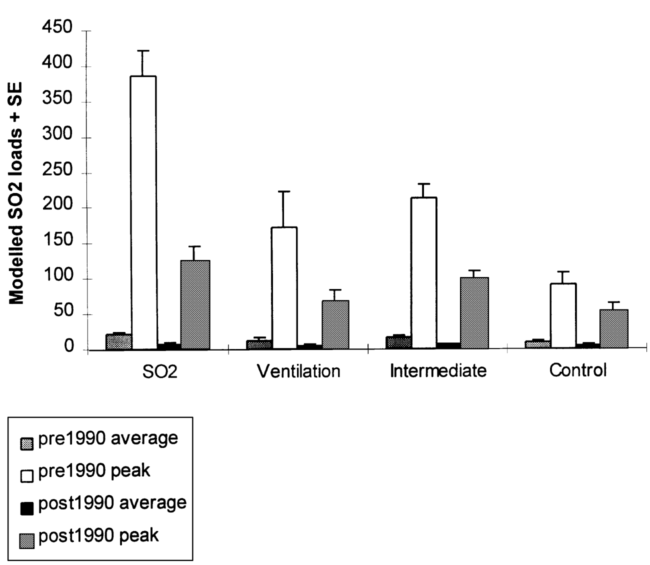

Fig. 3 Modelled average and peak annual SO_2 loads at the different impact zones prior to and after 1990

show a significant trend between impact zones in all years ($P = 0.36$). However, significantly more geckos were captured at control than SO_2 or ventilation sites in 1992 ($P < 0.05$) and significantly more geckos were captured at control than ventilation sites in 1993 ($P < 0.05$) (Table 3). Failure of the entire data set to reveal significant impact-zone effects was attributable to the lack of significant difference in capture rates in any of the treatments in 1994 and 1995 (Table 3).

The response of the gecko population to both seasonal and site impacts became more apparent when species relying on termites were analysed separately from species with generalist diets. Termite-specialist gecko numbers differed significantly in the four study zones ($F_{3,35}$ 14.29, $P \leq 0.001$) (Fig. 5), with termite-specialist capture rates typically less than half that of generalist geckos at both SO_2 and ventilation sites (Fig. 6). This contrasts markedly with the dominance of termite specialists at control sites (Fig. 6) and from another long-term control chenopod trapping site at Olympic Dam (Read 1995). The disparity in the two dietary types was greatest at the ventilation sites in 1995

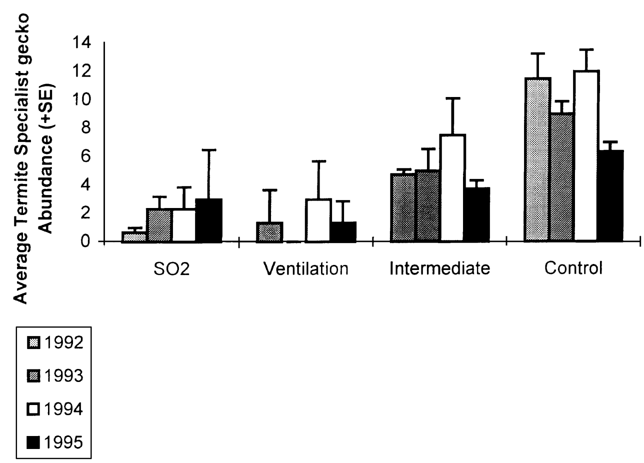

Fig. 5 Average abundance of termite specialist geckos at the different treatments throughout the study period

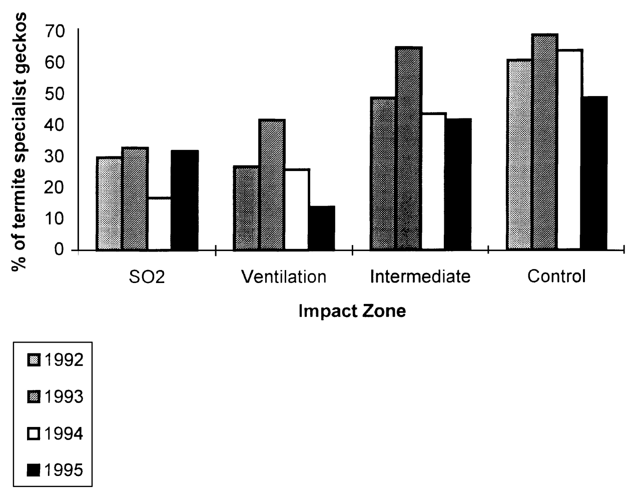

Fig. 6 Termite specialist geckos as a percentage of all gecko individuals in the different impact zones from 1992 to 1995

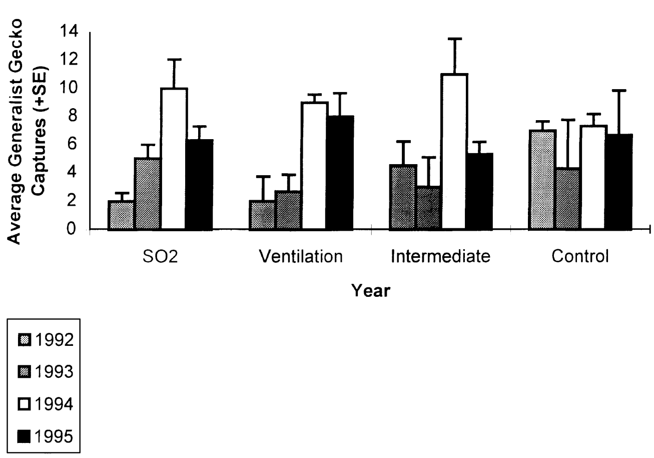

Fig. 7 Average abundance (+SE) of generalist geckos at the different treatments throughout the study period

Table 4 Generalised linear modelling significant terms for industrial impacts on gecko numbers. NaCl concentrations and distance to smelter were not significant for any terms

	SO_2 average pre 1990	SO_2 peak pre 1990	SO_2 average post 1990	SO_2 peak post 1990
D. stenodactylus	(***)	**		
R. ornata	(***)	ns	***	(**)
Total geckos	ns	(***)		

Negative binomial models used for each term: $***P \leq 0.001$, $**P \leq 0.01$, values in parentheses indicate a negative association

where only 4 of the 28 geckos trapped were termite specialists. Capture rates of termite-specialist geckos did not vary significantly between years ($F_{3,35}$ 1.426, $P = 0.252$), nor was there a significant interaction between years and treatments ($F_{9,35}$ 0.551, $P = 0.827$), although numbers increased slightly in the impacted areas throughout the study period (Fig. 5). By contrast, generalist gecko captures varied significantly between years ($F_{3,35}$ 7.58, $P \leq 0.001$), yet were not influenced significantly by the impact zone ($F_{3,35}$ 0.084, $P = 0.968$) (Fig. 7). The interaction term between year and treatment for generalist gecko captures was also not significant ($F_{9,35}$ 0.814, $P = 0.607$).

Since the predictor variables in generalised linear models are inevitably intercorrelated, individual terms in the models can not be interpreted in isolation. However, when carefully considered in parallel with other factors, significant terms can often be used to indicate the association between particular species and environmental factors. For example, a significantly positive association between *R. ornata* capture rates with average SO_2 concentrations following 1990 must be interpreted in the context of negative associations with both average SO_2 concentrations prior to 1991 and peak concentrations after 1990 (Table 4). Therefore, although peak SO_2 concentrations since 1991 continued to exert a negative impact upon *R. ornata* capture rates relative to other sites, amelioration of SO_2 concentrations allowed some recovery in the initially depressed *R. ornata* populations at impacted sites.

Only significant disturbance-related terms are presented in the generalised linear model table (Table 4) since detailed habitat associations of these species have been presented elsewhere (Read 1995). Sulphur dioxide concentrations were significantly associated with low gecko abundance while salt spray and distance from the smelter were not significantly associated with the abundance of total geckos or the two most common species (Table 4). Average modelled SO_2 concentrations prior to 1991 were significantly negatively correlated with the capture rates of *D. stenodactylus* and *R. ornata* and total gecko numbers were significantly associated with low peak SO_2 concentrations at this time. Both *D. stenodactylus* and total gecko capture rates were not significantly associated with modelled SO_2 concentrations after 1990 but *R. ornata* continued to be negatively associated with peak levels (Table 4). This analysis does

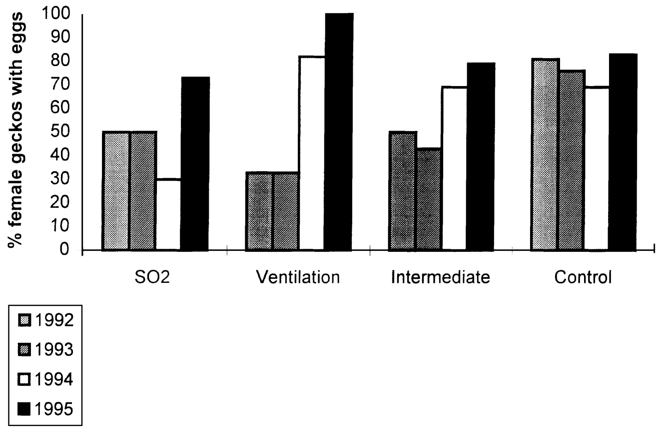

Fig. 8 Percentage of female geckos with eggs in the different treatments throughout the study period

not indicate that salt spray and proximity to the smelter did not have significant impacts upon gecko populations, since these factors were spatially correlated with the more powerful impact of SO_2 levels.

The percentage of females that were visibly gravid mirrored the capture rates to a certain extent, although sample sizes were too small for statistical analysis. At least 69% of adult females were gravid at the control sites each year, whereas this value did not exceed 50% for the impacted or intermediate sites in 1992 or 1993 (Fig. 8). Although gecko numbers declined at ventilation sites in 1995, the percentage of females gravid at these sites increased because adult females were only trapped at the two least impacted sites.

Discussion

This study showed that gecko numbers and fecundity were higher in control regions than at sites with high pollutant loads, which supports observations of limited gecko populations at a site subjected to acid mists at Olympic Dam (Read and Pickering in press.). The greatest disparity between impacted and control sites occurred early in the study and could be attributed to the higher initial concentrations of air-borne contaminants. Geckos may have been impacted directly by airborne emissions, or other anthropogenic factors associated with mining and processing. Alternatively, although invertebrate abundance was not measured, geckos may have responded to low invertebrate numbers which often decline due to industrial sulphur pollution (Paoletti and Bressan 1996).

An increase in geckos captured at impacted sites compared to control sites through time was largely the result of increases in generalist gecko abundance. Assuming that geckos respond to pollution levels, the most likely cause of this increase was the mitigation of the major sources of air pollution during or immediately prior to this study. Termite specialists however, did not respond significantly to these mitigatory measures which may suggest that termites were more inhibited by low concentrations of the pollutants than either generalist geckos or their prey. Alternatively, the biological effect of the pollutant may have persisted after control of the emissions, as has been demonstrated with other soil arthropods (Heneghan and Bolger 1996). Termites were also less common in mined areas than controls at Cobar (Halliger 1993) which was correlated with low *R. ornata* numbers although the small sample size precluded proof of causality. Termites may be more susceptible to air pollution than many other invertebrates because they are soft-bodied and form established colonies that are not highly mobile. Alternatively, other invertebrates eaten by generalist geckos may have responded more quickly to the amelioration of pollutants than termites, or may have been attracted to lights on the mine ventilation bores.

The decline in the ratio of termite specialists to generalist geckos at ventilation sites in 1995 coincided with the installation of an additional ventilation bore immediately adjacent to the ventilation site which consistently yielded the highest gecko captures. This decline therefore, further indicates that termite specialist geckos can respond quickly to changes in air pollution concentrations.

The increase in percentage of gravid females in the impact zones from the low levels early in the study may simply reflect the higher chance of being mated in a denser population, since the increase in fecundity was concomitant with a general increase in capture rates. However, remission from stress-related suppression of reproductive effort, as reported for other taxa (Newman et al. 1992), is more likely to be the primary cause. Monitoring of fecundity, or percentage of gravid adult females, may therefore provide a useful early indicator of harmful levels of environmental pollutants.

An unexpected, yet felicitous outcome of this study was that termites appear to be good indicators of air pollution impacts at Olympic Dam. Termites are an extremely abundant arid-zone fauna group which are particularly important in maintaining ecosystem function (Mackay 1991; Whitford et al. 1992; Morton and James 1988). Unfortunately, arid-zone termites are very difficult to study since they are primarily subterranean (MacKay 1991) and hence are not readily sampled in pitfall traps (James 1989; Predavec and Dickman 1993; Landsberg et al. 1996; personal observations). The commonest local termite species are grass and leaf foragers which are not readily attracted to baits (personal observations). The mechanism(s) by which geckos and other arid-zone fauna locate and procure termites are not understood (Pianka 1986; Predavec and Dickman 1993) but geckos are obviously successful termite feeders. Therefore, specialist termite-eating geckos, such as *D. conspicillatus* and *R. ornata*, which are easily sampled, perhaps serve as useful surrogates for measuring termite abundance.

In addition to an apparent response to air pollutant levels, long-term climatic variability and weather conditions during sampling also impacted gecko capture rates. Hot night-time temperatures in 1994 probably facilitated increased gecko activity and hence accounted for the high capture rates at all sites in that year. High capture rates at control and intermediate zones in 1992 were probably inflated by the exceptional rains of 1989 which influenced animal populations for several years (Read 1992).

Therefore, although the background effect of climatic conditions on gecko abundance and activity needs to be accounted for, geckos appear to be useful indicators of the environmental impacts of air pollution at Olympic Dam. The success of remediation of industrial emissions may also be detected through monitoring of gecko populations, although independent studies from other locations are required for confirmation. These results are particularly encouraging considering that the effects of air pollution on sensitive species may be subtle and variations in populations of affected communities may be statistically insignificant (Musselman et al. 1992). Additional research is required to establish the mechanisms by which air pollution affects both geckos and termites and the suitability of using these widespread animal groups to monitor pollution impacts in other regions.

In conclusion, air pollution possibly impacted gecko abundances in three interrelated ways. First, direct irritation and accumulation of contaminants may have caused a slight reduction in gecko populations in the polluted environment. Second, the most significant impacts were upon termite specialists, probably due to the suppression of their food supply. Finally, reduction in fecundity amongst geckos in the impacted zones probably resulted from pollution-induced stresses. The impacts of air pollution were partially reversed following remediation of the emissions, particularly with regard to population and fecundity increases amongst geckos with generalist diets. Geckos therefore have the potential to be useful indicators of both air pollution impacts and pollution source mitigation and warrant further attention as monitoring organisms for environmental management.

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