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Species richness, habitat and conservation of scorpions in the Western Australian wheatbelt

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Abstract – The distribution of 12 species of scorpions overlap that of the Western Australian wheatbelt, for five species the overlap is only marginal. In the south-west, species richness increases from two on the lower south coast to seven in the central wheatbelt before declining slightly further north. Species richness data from 7 districts indicated that with adequate sampling richness could be calculated from distribution maps. At the level of remnant, richness varied from two to six, with a significant correlation between area and species richness. In small areas (0.05 to 2.4 ha) within a remnant, area and number of trap nights were not significantly correlated with species richness, but the number of microhabitats did show a significant positive correlation. Detailed habitat data was only available for the Kellerberrin district. *Lychas alexandrinus* and *Isometroides vescus* were habitat generalists, whereas *Cercophonius michaelseni* and *Urodacus armatus* while using a variety of vegetation associations were dependent on microhabitat and soil type respectively. *L. marmoreus* and *U. novaehollandiae* were recorded too infrequently to assess habitat requirements. Data from this area suggested that all species can survive in small isolated remnants as small as 0.05 to 2 ha. However intensive grazing can lead to local extinction in remnants up to 7 ha. All species can survive fire, however, for *C. michaelseni* destruction of microhabitat eventually leads to local extinction.

INTRODUCTION

The Australian scorpion fauna is depauperate compared to other comparable regions of the world (Polis 1990). Koch (1977) described 29 species and more recent taxonomic studies have described a further nine species (Acosta 1990, Locket 1990 and pers com.). In contrast, 61 species have been recorded in Baja California (Due and Polis 1986), 37 in California (Polis 1990) and 100 in Southern Africa (Newlands 1978). While continental species richness is low, local richness is comparable with that in more speciose regions. Polis (1990) and Polis and Yamashita (1991) summarised the available data and showed that worldwide, local species richness varied from one to thirteen with most areas having three to seven; in desert locations the average was seven . There are no published data from Australia, but my, unpublished observations indicate that three to six syntopic species are frequently found in many areas of arid and semi-arid Australia.

Data on the habitats of Australian scorpions are few (Smith 1966, 1983, 1991; Shorthouse 1970; Locket 1993). The continental distribution of scorpions suggests that they are primarily influenced by temperature and rainfall regimes and that vegetation and soil characteristics exert relatively little influence (Koch 1977; Polis 1990). However, more detailed studies suggest that edaptic factors may influence local distribution and abundance (Smith 1966; Lamoral 1978; Polis 1990).

The impact of the widespread anthropogenic changes in Australia during the last 200 years has been detrimental for the majority of species (Saunders *et al.* 1990). In particular, the wholesale destruction of native vegetation in areas such as the Western Australian wheatbelt (Beard and Sprenger 1984) was particularly severe on many species. The effect on scorpion populations has not been recorded, although Koch (1977) considered that *Cercophonius* spp. has been eliminated from areas cleared for farming.

This paper presents data on scorpion species richness and habitat use in the wheatbelt of Western Australia and discusses the impact that agricultural development has had on scorpion assemblages. It is dedicated to Barbara York Main for her outstanding work on Arachnids and their conservation.

STUDY AREA AND METHODS

Study areas

The main study area was the 1680 km^2 CSIRO study area between Kellerberrin and Trayning, 200 km east of Perth (Fig. 1). The area has low relief

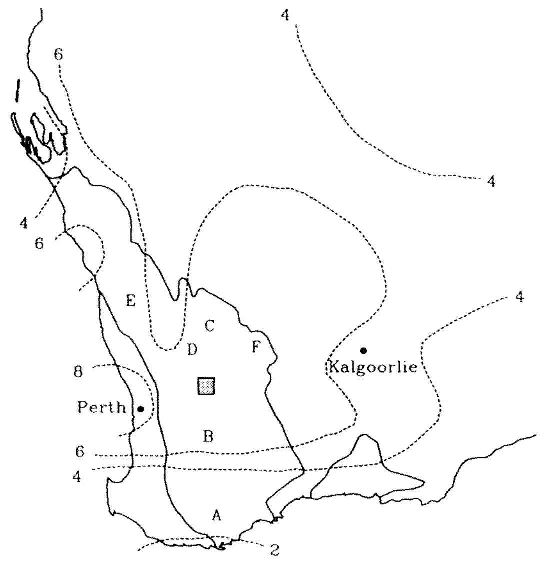

Figure 1 Scorpion species richness in the south-west of Western Australia. The stippled square is the CSIRO study area, the other locations are: A, Stirling Range National Park; B, Tutanning Nature Reserve; C, Goodlands; D, Burakin; E, Three Springs; F, Mukinbudin.

(100 m) with soils ranging from deep yellow sands to clay-loams and granite outcrops. The original vegetation was a complex mosaic of eucalypt woodlands, mallee, shrublands and heath; only 7.3% remains in more than 450 remnants, 77% of which are less than 20 hectares. Detailed descriptions are given in Arnold and Weeldenburg (1991) and McArthur (1993). The other areas surveyed were Burakin (30°31'S, 117°10'E), Goodlands (30°22'S, 118°12'E), Mukinbudin (30°55'S, 118°12'E) and Three Springs (29°32'S, 115°45'E). All were areas of wheat and sheep farming with broadly comparable topography, soils and vegetation to the CSIRO study area. Data were also available from Tutanning Nature Reserve (32°31'S, 117°23'E), 150 km south-east of Perth, and the south-east corner of the Stirling Range National Park (see Brown and Hopkins 1983, and Thompson *et al.* 1993 for descriptions).

Methods

Four methods were used to collect data on species richness and abundance:

1. Vertebrate pitfall traps (20 litre pails with 7 metre drift-fences 24 cm high).
2. Invertebrate pitfall traps (plastic cups 90 mm diameter and 110 mm deep).
3. Nocturnal searches with a UV lamp.
4. Daytime searches for scorpion burrows.

In the CSIRO study area, data was available from 39 vertebrate pitfall trap grids with 8 to 54 traps (covering an area of 0.05 ha to 2.44 ha) that were operated for five consecutive days, five to six times between October and April, for one to six years in the period 1987 to 1992. The total number of trap nights was 41000. The traps were located in the major vegetation associations. The number of grids, pits and trap-nights in each association was variable and depended on the requirements of the vertebrate studies. Quantitative data was available for 27 grids (see Table 2). A total of 163 person hours were spent searching in all vegetation associations with a UV lamp. Location of scorpion burrows were noted at all times. In addition, grids of 16 invertebrate pitfall traps were operated for one week in February, March, July and October 1992 in 24 remnants of Gimlet *Eucalyptus salubris* woodland.

At Burakin, *ad hoc* UV and burrow searches were carried out in 10 remnants from September to March over the period 1977 to 1982. Similar, but less intensive searches were undertaken at the other farming locations during the same period. In the Tutanning Nature Reserve, data were available from six vertebrate pitfall trap grids operated from Spring to Autumn in the period 1989 to 1992. The traps were set in Wandoo *E. wandoo* woodland, Kwongan, *Allocasuarina* woodland and Powder-bark Wandoo *E. accedens* woodland; the number of trap nights in each vegetation type were 4928, 7744, 4225 and 8448 respectively. In the Stirling Range National Park, data were obtained from invertebrate pit traps in mallee scrub on sand that ranged from shallow sand over laterite to deep white sand. There were 13 grids each with 36 pit traps, operated in all seasons from 1989 to 1992 for a total of 70,200 trap nights.

RESULTS

Regional species richness

Within the area of the wheatbelt, 12 species of scorpions from four genera have been recorded (Table 1). The distribution of five of these species (*Cercophonius granulosus* Kraepelin, *Urodacus hartmeyeri* Kraepelin, *U. hoplurus* Pocock, *U. planimanus* Pocock, *U. similis* L.E. Koch) have only a minor overlap with that of the wheatbelt (Koch 1977; Acosta 1990.)

The pattern of species richness over the south-west of Western Australia was calculated from the distribution maps of Koch (1977), supplemented by those for *Cercophonius* spp. (Acosta 1990) and from my own unpublished data. The number of species whose distribution covered each degree block was calculated and from this isoclines were drawn (Fig. 1). The lowest richness is on the lower south coast where only *Cercophonius sulcatus* Kraepelin and *Urodacus novaehollandiae* Peters have been recorded.

Table 1 District and local species richness of scorpions in remnants of native vegetation in seven districts in the wheatbelt of Western Australia. 1, approximate area over which pitfall traps were distributed. x, presence of species. 0, not recorded but distribution overlaps district.

	Area (h)	*Cercophonius granulosus*	*Cercophonius michaelseni*	*Cercophonius sulcatus*	*Lychas alexandrinus*	*Lychas marmoreus*	*Isometroides vescus*	*Urodacus armatus*	*Urodacus hartmeyeri*	*Urodacus hoplurus*	*Urodacus novaehollandiae*	*Urodacus planimanus*	*Urodacus similis*
Kellerberrin			**x**		**x**	**x**	**x**	**x**			**x**		
Durokoppin Nat. Res.	1200		x		x	x	x	x					
East Yorkrakine Nat. Res	81		x		x	x	x	x					
McClellands	10				x	x		x					
Ryans	50		x		x	x	x	x			x		
North Bandee Nat. Res.	174		x		x		x	x					
Deep Well	118				x		x	x					
Mission Rds	40				x		x	x					
Site 137	27				x		x	x					
Burakin			**x**		**x**	**x**	**x**	**x**			**0**		
Smith's Timber	20				x		x	x					
Thompson's Timber	11				x		x	x					
Borrikin Res.	260		x		x	x	x	x					
Goodlands			**0**		**x**	**0**	**x**	**x**		**0**	**x**		**x**
Cale's Timber	15				x		x	x					x
Mukinbudin			**0**		**x**	**0**	**x**	**x**		**0**	**x**		**0**
Campsite	20				x		x	x			x		
Three Springs		**0**		**0**	**x**	**0**	**x**	**x**			**x**		
Wilson's Timber	8				x		x	x					
Tutanning Nat. Res.	2250			**x**	**x**	**x**	**x**	**x**			**x**		
Stirling Range Nat. Park				**x**		**x**	**x**				**x**		
South of Bluff Knoll-12km	600[1]			x		x	x				x		
South of Toolbrunup Peak-10km	50[1]			x		x					x		

Richness increased to the north, reaching a maximum of seven species before slightly declining to the north and west. The highest diversity is around Perth with eight recorded species.

District species richness

The species richness in seven districts in the wheatbelt (Fig. 1) is given in Table 1. In the most intensively studied areas, Kellerberrin, Tutanning Nature Reserve and Stirling Range National Park, the maximum number of species were recorded, namely, six, six and four respectively. At Burakin five out of a possible six species were recorded, whereas at the other localities two or three species whose distribution encompassed the area were not recorded.

Detection of a species is dependent on sampling at the correct season. The variation in seasonal activity of the four most common species, from both UV lamp searches and pitfall traps is given in Fig. 2. *C. michaelseni* Kraepelin is only active between May and August, a period when *Lychas alexandrinus* Hirst and *Isometroides vescus* (Karsch) are inactive or have low levels of activity. Both these latter species are most active in summer. *U. armatus* Pocock rarely leaves its burrow and this is reflected in the low capture rates except in autumn when adult males actively search for females.

Local species richness

Local diversity was defined as the number of species found in a remnant of native vegetation. In the Kellerberrin district there were data for eight remnants, ranging in size from 10 to 1200 hectares (Table 1). *L. alexandrinus* and *U. armatus* were found in all sites, *I. vescus* in seven, *C. michaelseni* and *L. marmoreus* (C.L. Koch) in four and *U. novaehollandiae* in one site. The least diverse sites (Deep Well, Mission Rd and Site 137) had the three most common species and were all York gum/jam *E. loxophleba/Acacia acuminata* associations. The other sites all had a mosaic of vegetation formations ranging from heath to eucalypt woodland, and had from four to six scorpion

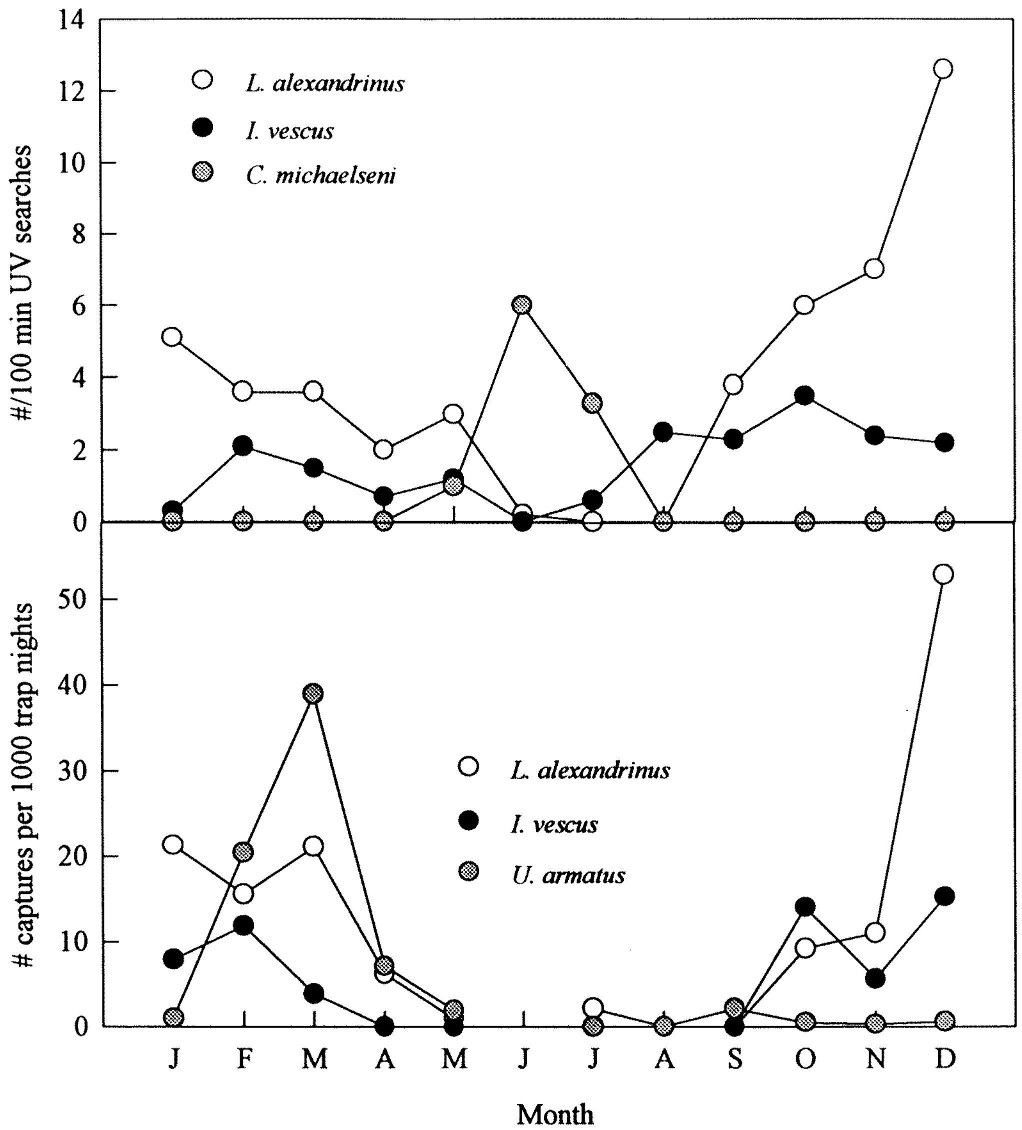

Figure 2 Number of individuals captured each month per 100 minutes searching with a UV lamp and number of captures per 100 vertabrate trap nights. *U. novaehollandiae* only caught between February and April, *L. marmoreus* between November and May and *C. michaelseni* only in August and May.

species. Ryans was the only remnant in which all six species recorded in the district were found.

In the other four central and northern wheatbelt districts, the remnants were eucalypt woodlands dominated by Salmon gum *Eucalyptus salmonophloia*. Borrikin reserve also had areas of heath, *Allocasuarina* shrubland and mallee. *L. alexandrinus*, *I. vescus* and *U. armatus* were common in all sites. *C. michaelseni* and *L. marmoreus* were recorded only on Borrikin reserve. *U. similis* was found only in Cales timber and *U. novaehollandiae* only at Mukinbudin. All six species whose distributions overlapped Tutanning Nature Reserve were recorded. In the Stirling Range National Park, the site south of Bluff Knoll had all four expected species, while at the site south of Toolbrunup Peak, *I. vescus* was absent (Table 1).

The relationship between area and number of species was calculated for all sites with a potential species richness of six or seven (Table 1). The correlation coefficient was significant ($r = 0.59$, $P<0.05$) and highlighted the fact that larger remnants are more likely to have a wider range of habitats, although even small remnants such as Ryans may have sufficient habitat for all species.

Point species richness

Point diversity was defined in two ways: firstly, the number of species in a small area, in this study, the area of pitfall trap grids; secondly, the number of species recorded in one pitfall trap.

Data for the 27 pitfall trap grids in the Kellerberrin-Trayning area are given in Table 2. Diversity ranged from one to five with a mean of three. Species richness was not correlated with the area of the trap grid ($r = 0.097$, $P>0.05$), or the number of trap nights ($r = 0.37$, $P>0.05$). However, in six grids with the smallest number of trap

Table 2 Number of individulas per 1000 trap nights for each species at various sites in the Kellerberrin district and the area of the pitfall trap grid and the number of trapnights. x - species not found in pitfall traps but recorded in the area of the pitfall trap grid.

Location/Site	*Cercophonius michaelseni*	*Lychas alexandrinus*	*Lychas marmoreus*	*Isometroides vescus*	*Urodacus armatus*	*Urodacus novaehollandiae*	Area (ha)	# Trap nights
Durokoppin Nat. Res.								
1	x	24.9		17	3.2		0.5	5664
2		16.6		5.1	11.7		0.5	5664
3	x	15.5	0.4	11	14.8		0.25	2832
4		0.6		3	29.4		0.3	3300
5		31.3		12	8.1		0.06	864
6	4.6	18.5		x	23.1		0.05	216
7		13.9		4.6			0.05	216
8		x		x	50.9		0.05	216
9		9.3		23	13.9		0.05	216
10		x		x			0.05	216
11		4.6		x	32.4		0.05	216
12		x	x	19	13.9		0.05	216
13		9.3	x	28	32.4		0.05	216
East Yorkrakine Nat. Res.								
14		9.3		10	4.1		0.11	2688
15	0.4	9.3	0.4	2.2	1.0		0.11	2688
16		14.1		5.6	7.1		0.11	1152
17		14.1		7.8	4.1		0.11	1152
18	x	21.2		6	16.7		0.11	1152
19		33		5.2	1.7		0.06	576
North Bandee Res.								
20	0.3	14.1		20			2.44	3190
Ryans								
21		11.7	0.6	2.5	3.6	6.2	0.2	1624
22	3	24.6	1.2	8.4	0.6		0.3	1664
McClellands								
23		15.9	0.6		2.3		0.25	1764
24		56.9	0.4				0.5	2848
Norrish								
25		18.5	4.6	23			0.05	216
26		18.5		28			0.05	216
27				9.3			0.05	216
# sites	7	24	7	23	20	1		

nights, not all species know to be present were recorded. The failure to catch *C. michaelseni* in three grids in which they were known to occur, was due to the lack of winter sampling. There is a significant positive correlation between the number of microhabitats (visual assessment, based on differences in vegetation structure) and the number of species ($r = 0.55$, $P<0.01$). The mean number and range of species in grids with one to three microhabitats was 2.0 (0–3), 3.2 (2–5), 4.0 (2–5) respectively.

The number of captures per 1000 trap nights (combined data) for each grid gave a measure of abundance (Table 2). The three common species, *L. alexandrinus*, *I. vescus* and *U. armatus* showed considerable variation, even in those grids sampled at the same time (1–4 and 6–13).

Capture rates were low (Table 2) and only data from grids with more than 1000 trap nights were used to calculate diversity in single traps (Table 3). The number of species caught in any one trap varied from one to three. Single traps only caught all species in those grids where only the most common species, *L. alexandrinus*, *I. vescus* and *U.*

Table 3 Percentage of pitfall traps that captured one or more species of scorpions and the number of pit traps in each grid that captured each species. Site numbers are for the same grids as listed in Table 2 and the number of species is the number recorded in the grid.

Site #	# Pit traps	# species	# species 0	1	2	3	*C. michaelseni*	*L. alexandrinus*	*L. marmoreus*	*I. vescus*	*U. armatus*
1	48	3	4	15	54	27		44		40	16
2	48	3	4	25	50	21		34		18	36
3	24	4	0	8	46	46		20	1	18	18
4	28	3	4	71	25	0		2		7	26
14	24	3	21	25	41	13		12		15	8
15	24	5	25	50	25	0	1	14	1	4	5
16	24	3	8	21	17	54		19		12	10
17	24	3	17	29	46	8		17		12	6
18	24	3	4	13	62	21		20		11	17
20	54	3	28	42	30	0	1	26		31	

armatus were found. The rare species *C. michaelseni* and *L. marmoreus* were never found in traps in which all three common species were found. The percentage of pits which captured no species ranged from zero to 28, a reflection both of differences in trapping effort and the abundance of scorpions. *L. alexandrinus* was the most abundant (Table 2) and widespread species, being found in 65% of traps, whereas *I. vescus* was found in 52% The occurrence of *U. armatus* was underestimated because its occurrence was largely determined by adult males which were only found in February and March. If sampling was too early or late and/ or the weather cool, the number of males captured was greatly reduced. Comparison of the data from individual pits suggested that the presence of any species was not influenced the presence or absence of any other species.

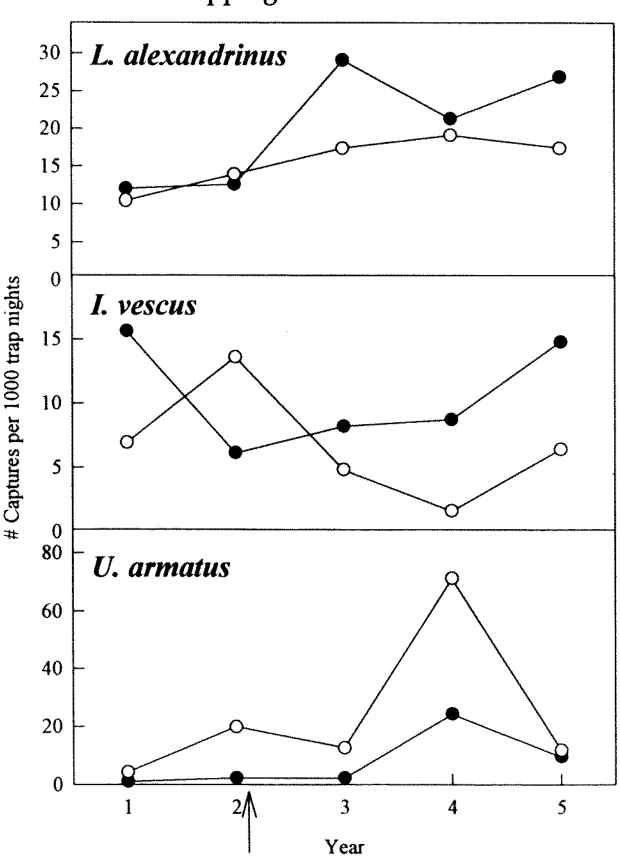

Figure 3 The numbers of *L. alexandrinus*, *I. vescus* and *U. armatus* captured per 1000 trap nights from 1987/88 (Y1) to 1991/92 (Y2) in an area burnt (●) after Y2 and in an adjacent unburnt area (O).

Habitat

In the Kellerberrin district scorpions were located in a wide variety of vegetation associations which were grouped into 17 associations based on the life form, dominant species and soil type (Table 4, Appendix). *I. vescus* was found in all associations and *L. alexandrinus* in all but Samphire, whereas *U. armatus*, *C. michaelseni* and *L. marmoreus* were found in fewer associations (12, 7 and 7 respectively), that ranged from heath to woodland. *U. novaehollandiae* was only found in one site in an area with Mallee A grading into *Leptospermum* heath on deep white sand. While *L. marmoreus* was found in a number of areas, all but one observation was of a single animal.

The vegetation associations in which a species was found did not fully define its habitat. Whereas, *L. alexandrinus* and *I. vescus* were habitat generalists, *C. michaelseni* was not, even though it was found in associations ranging from heath to woodland. In Wandoo woodland, it has only been found in a drainage line with deep litter and a closed tree canopy, or in areas with a dense stands of *Melaleuca uncinata*. In heath associations it was confined to small patches with *E. burracoppinensis*

Table 4 Presence of scorpion species in vegetation associations in the Kellerberrin district. Open woodland A - Wandoo *Eucalyptus capillosa* (>10m), Open woodland B - Salmon gum/wandoo *E. salmonoploia/E. capillosa* (>10m), Open woodland C - Gamlet/salmon gum *E. salubris/E. salmonophloia* (>10m), Open woodland D - Gimlet/salmon gum/wandoo (>10m), Woodland-York gum/Jam *E. loxophlba/Acacia acuminata* (>10m), Mallee A - shrubs, no herbs (3-8m), Mallee B - shrubs and herbs (3-8m), *Allocasuarina* shrubland A – on deep sand (<6m), *Allocasuarina/Acacia* shrubland B - on gravel (>5m), Dense heath A - *Allocasuarina campestris* on deep sand (>3m), Dense heath B - *Allocampestris campestris* on gravel (>3m), Mixed heath (>2m), Leptospermum heath (>3m), Low open heath (>3m), Chenopod shrubland A with *Melaleuca pauperiflora* (>3m), Chenopod shrubland B with *E. yilgarnensis* and shrubs (<6m), samphire (>1m).

Vegetation association	*Cercophonius michaelseni*	*Lychas alexandrinus*	*Lychas marmoreus*	*Isometroides vescus*	*Urodacus armatus*	*Urodacus novaehollandiae*	# species
Open Woodland A	x	x	x	x	x		5
Open Woodland B		x		x	x		3
Open Woodland C	x	x		x	x		4
Open Woodland D		x		x	x		3
Woodland		x		x	x		3
Mallee A		x	x	x		x	4
B	x	x	x	x	x		5
Allocasuarina shrubland A		x		x	x		3
B	x	x		x	x		4
Dense heath A	x	x	x	x	x		5
B	x	x		x			3
Mixed heath	x	x	x	x	x	x	6
Leptospermum heath		x		x	x	x	4
Open low heath		x	x	x	x		4
Chenopod shrubland A		x	x	x			3
B		x		x			2
Samphire				x			1
Total	7	16	7	17	12	2	

or *Xylomelum angustifolium* with a deep litter layer under them and fringed by dense shrubs and/or sedges. In open woodland B it was only found in areas with dense shrubs and large logs. The main habitat appears to be Allocasuarina shrubland B with dense stands of *Allocasuarina campestris*.

U. armatus was found in a wide range of vegetation associations, but at any given site its presence and abundance appears to be controlled by soil type. *U. armatus* was not found in areas with solodic soils, calcareous earth or gravelly soils. Also, the species was absent from areas with a heavy cryptogamic crust and even in areas where it was abundant, a light cryptogamic crust was associated with a reduced density of burrows (G.T. Smith, unpublished data). In areas with red duplex soils with Gimlet woodland, the species was only present where there was a layer of coarse alluvial sand derived from an adjacent area. Highest densities (3000 – 5000/h) were found in woodland or mallee associations on yellow duplex soils with intermediate densities on deep grey sand and lowest in areas of yellow sand over gravel. There were too few observation on *L. marmoreus* and *U. novaehollandiae* to provide data on microhabit use. However at Mukinbudin, *U. novaehollandiae* was found only in areas of litter under patches of mallee; in contrast *U. armatus* was in bare areas between the mallee patches. Habitat data from other areas are less detailed, but in general conform to that found in the Kellerberrin district.

Conservation

Data in Table 1 indicate that populations of all species can persist in small remnants and that remnants as small as 50 hectares, providing that they have a mix of habitats, can provide the resources for all species in the Kellerberrin district. In this district, *U. novaehollandiae* has been recorded from only one remnant; *C. michaelseni* and *L. marmoreus* were found in four remnants but with very small populations (Table 2), especially the latter. The other species were widespread and abundant.

Apart from the effect of climatic variation, small remnants can be affected by periodic disturbances such as fire and the chronic effects of disturbance by grazing livestock. There are limited data on both these factors. Data on the effect of a moderate to hot autumn fire on *L. alexandrinus*, *I. vescus* and *U. armatus* were available from two pitfall trap grids and their control grids in an area of heath. The population trends in the experimental grids and their controls were the same and the data were combined (Fig. 3). The numbers of *L. alexandrinus* in the control area increased over the first four years and then slightly declined. There was a similar pattern in the experimental area, however the increase after the fire was greater. This increase was not a result of immigration or recruitment but most probably was a result of increased activity resulting from the loss of vegetation. Population changes for *I. vescus* differ between experimental and control grids, but show no evidence that fire had any effect. Data for *U. armatus* are strongly influenced by the timing of sampling (two samples in March when males are most active), hence the extremely high values for Y4. Populations were low in the experimental area and there was no definite fire effect, however there is a suggestion that by Y5 there may have been a slight increase in the population. In contrast, *C. michaelseni* was eliminated from the one experimental area where it occurred. Here, its highly flammable microhabitat (see habitat above) was completely destroyed. Although *C. michaelseni* survived the fire and was seen during the winter following the fire, it has not been seen since (five years post fire). Its former microhabitat sites are only partially regenerated.

The effect of grazing was evaluated from pitfall trapping (plus burrow observations for *U. armatus*) in 24 remnants of Gimlet woodland all of which were small (<7 ha) heavily grazed and isolated for at least 60 years. *C. michaelseni* occurred in two remnants, *L. alexandrinus* in nine, *L. marmoreus* in four, *I. vescus* in eight and *U. armatus* in eight. The smallest remnant in which *L. marmoreus* was recorded was 0.5 ha, for the other species the smallest remnant was 2 ha. *L. alexandrinus* and *I. vescus* were the most abundant species, and both declined significantly with increased grazing (G.T. Smith unpublished data). Species richness also declined with increased grazing. In two remnants the populations of *U. armatus* were in excess of 100, the high populations were related to the layer of coarse alluvial sand eroded from an adjacent granite outcrop. In the other remnants, the populations were small and were confined to small patches of mallee within the woodland. Three remnants had two or three sub-populations that had four to six breeding females (calculated from the known fecundity of the species (Smith 1990) and the number of second instar burrows). The remaining three remnants had larger single populations with up to 20 breeding females.

DISCUSSION

Scorpion species richness varied from two on the lower south coast of Western Australia to seven in the central wheatbelt, reaching a maximum around Perth. This trend is typical of other areas of the world (Polis 1990). However, the decline in species richness in the arid areas to the north and west is in contrast to the increase with increasing aridity in North America (Polis 1990). The low species richness in Australia is only equalled by that of the former USSR where 14 species have been described (Fet 1980) and is highlighted by comparison with the most speciose region, Baja California which has 61 species (Due and Polis 1986) in an area equivalent to that of the wheatbelt, which has 12 species. Less extreme comparisons, California (37 species, Polis 1990), Southern Africa (100, Newlands 1978) with equivalent areas of Western Australia (the most speciose state) with 13 and 18 species respectively, still show low species richness. The low diversity of scorpions in the more arid areas is in marked contrast to the high diversity of burrowing spiders (Main 1981), ants (Greenslade 1984), termites (Watson and Perry 1981, Abensperg-Traun and De Boer 1990) and lizards (Pianka 1986) in arid regions of Australia. The factors leading to the low diversity of scorpions are unknown.

At smaller spatial scales, the species richness in wheatbelt sites ranged from four to six and is comparable with many communities throughout the world (Polis 1990, Polis and Yamashita 1991). Data from 100 sites worldwide collated by Polis (*loc. cit.*) showed that 36 sites had one to three species, 30 had four to six and 34 had more than six species. In desert sites, species richness ranged form 2 to 13 with a mean of seven (Polis and Yamishita 1991). Thus, despite low regional species richness, local richness is within the range found in other comparable areas. Polis (1990) also compared the evenness of species abundance at 68 sites and found that there was no relationship between species richness and evenness in abundance. Further, the abundance relationship may change between sites within the same habitat type. Similar analyses could not be done in this study because the sampling method did not give equivalent results for all species, because of differences in seasonal activity and behaviour patterns. Data on *L. alexandrinus* and *I. vescus* showed that the former was most common in 16 of 25 sites. However, within the same habitat, the degree of dominance varied, as did the species which was the dominant.

This suggests that small scale differences in habitat affect population densities (Table 2). Species richness declined with the reduction of the spatial scale of investigation because of the significant positive relationship between species richness and remnant size and microhabitats within a trapping grid. For single traps, diversity was on average lower still. Comparable data are not available for other areas, although Warburg *et al.* (1980) recorded from one to five species in 1000 m^2 quadrats in different vegetation associations in Israel.

With the exception of *U. novaehollandiae,* all species were recorded in a wide variety of vegetation formations. At this level *L. alexandrinus* and *I. vescus* were habitat generalists; *U. armatus* distribution and abundance was influenced by soil type and *C. michaelseni* was influenced by the availability of suitable areas of microhabitat. *L. marmoreus* was recorded too infrequently to provide data on its habitat requirements, although its generally mesic distribution suggests it requires cooler, moister microhabitats that are uncommon in the central and northern wheatbelts. *L. alexandrinus, I. vescus* and *U. armatus* are arid adapted species with a wide distribution and do not appear to have specific microhabitat requirements, although microhabitat (on the scale of metres) appears to influence their abundance. In contrast, *C. michaelseni* requires microhabitat that provides shade and cover. Studies of the evaporative water loss of this species showed a dramatic increase between 25°C and 30°C together with a 60% mortality (P.C. Withers and G.T. Smith, unpublished data). Survival of this species depends on the availability of appropriate microhabitat and its ability to seal itself in a burrow during the summer when temperatures above 30°C are common. Similar factors account for the survival of *Cercophonius* sp. at Ayers Rock (Smith 1983). In contrast, the three common species have only moderately elevated evaporative water loss at 40°C with little or no mortality. Of the two mesic species in the study area, *U. novaehollandiae* shows a similar pattern of water loss in relation to temperature as *U. armatus* and presumably depends on its burrowing habit and placement of burrows in cooler microhabitats to persist in semi-arid areas (Withers and Smith 1993, and unpublished data). *L. marmoreus* has not been studied, but it probably also needs specific microhabitat to persist in semi-arid areas. These conclusions probably apply over most of the semi-arid wheatbelt with comparable mixes of habitats and scorpion assemblages. In more southerly regions such as Tutanning Nature Reserve and the Stirling Ranges where temperature is lower and rainfall higher, the mesic species (*U. novaehollandiae, L. marmoreus, C. sulcatus*) are more abundant than the xeric species, some of which may be absent. These changes in species composition are mostly likely to be related to differences in temperature and rainfall than to edaphic or vegetational differences. Although studies of the evaporative water loss of *U. novaehollandiae* suggests that it should be able to cope with the higher temperature in semi-arid areas, its rarity in such areas suggest otherwise. Part of the explanation for this may be that its metabolic rate at elevated temperatures is greater than *U. armatus* and this factor may reduce its ability to persist in much of the semi-arid region.

Temperature and rainfall are probably the most important factors determining the distribution of scorpions on a continental scale (Koch 1981, Polis 1990) and as noted above, probably the most important factors influencing the change in the composition of assemblages from south to north. Vegetation does not appear to influence regional distribution (Koch 1981, Polis 1990 and references therein), however, on smaller spatial scales used in this study, it can influence both local distribution and densities e.g. microhabitat requirements for *C. michaelseni*. Koch (1981) found no relationship between edaphic factors and distribution, however at smaller spatial scales, edaphic factors may influence distribution (Polis 1990 and references therein) as well as densities as was the case for the distribution and abundance of *U. armatus*. More detailed studies at finer spatial scales are required to determine the factors influencing scorpion species.

Scorpions are hardy and resilient animals, a conclusion supported by the survival of all species in small, isolated and degraded remnants of woodland. Further, populations, in the case of *U. armatus* <20 breeding females have survived after 60 to 80 years of isolation and habitat degradation. Given that populations of some species no longer exist in most of the highly degraded small remnants and that the data suggests that many of the populations of all species are low, the future persistence of extant populations in small remnants, especially those exposed to grazing, remains uncertain because of demographic, environmental or genetic stochasticity (Shaffer 1987; Lande 1993). Within reserves as small as 10 ha, populations are probably large enough to ensure long-term persistence of most species, although the apparently small populations of some species in some remnants may be at risk (e.g. *U. novaehollandiae* which is only found in an area of about 0.5 ha within a 50 ha remnant). The only major disturbance that may affect the persistence of any species is fire. Intense fires in a remnants will eliminate *C. michaelseni* and if frequent enough may also lead to the extinction of other vagrant species; although in the Tanami desert *L.*

alexandrinus showed no adverse effects from fire, in an area which has had frequent fires in the past (Smith and Morton 1990). For most species, persistence will ultimately depend on the long term effects of chronic disturbances such as wind and water erosion, nutrient drift etc. and how society manages to control their effects.

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APPENDIX

List of the most common plant species in the vegetation associations listed in Table 4.

Open Woodland A – Wandoo (>10 m)
Eucalyptus capillosa, Hakea lissocarpha, Allocasuarina campestris, Gastrolobium parviflorum, Acacia acuaria, Melaleuca uncinata, Loxocarya sp, *Borya constricta.*

Open Woodland B – Salmon gum/Wandoo (>10 m)
Eucaluptus salmonophloia, E. capillosa, Pittosporum phylliraeoides, Acacia hemiteles, Acacia acuaria, Melaleuca uncinata, Olearia muelleri, O. revoluta, Enchylaena spp.

Open Woodland C – Gimlet/Salmon gum (>10 m)
Eucalyptus salmonophloia, E. salubris, Melaleuca pauperiflora, M. uncinata, Acacia hemiteles, A. merrallii, A. colletioides, Scaevola spinescens, Olearia muelleri.

Open Woodland D – Gimlet/Salmon gum/Wandoo (>10 m)
As for Open Woodland C, but with *E. capillosa* and lacking *Scaevola spinescens.*

Woodland A – York gum (>10 m)
Eucalyptus loxophleba, Acacia acuminata, Hakea recurva, Grevillea paniculata, Dianella revoluta, Stypandra glauca, Borya sphaerocephala, Opercularia vaginata, Cheilanthes austrotenuifolia.

Mallee A – shrubs, no herbs (3–8 m)
Eucalyptus erythronema, E. sheathiana, E. transcontinentalis, Melaleuca uncinata, M. adnata, M. cardiophylla, Olearia muelleri, Phebalium brachycalyx, Acacia hemiteles.

Mallee B – shrubs and herbs (3 to 8 m)
Eucalyptus subangusta, Melaleuca uncinata, M. acuminata, Allocasuarina campestris, Ecdeiocolea monostachya, Borya constricta, Dampiera stenophylla.

Tall Casuarina shrubland A – on deep sand (<6 m)
Allocasuarina huegeliana, Hakea coriacea, Grevillea pritzelii, Olearia revoluta, Astroloma serratifolium, Verticordia chrysantha, Leucopogon hamulosus, Comesperma scoparium, Ecdeiocolea monostachya.

Casuarina/Acacia shrubland B – on gravel (<5 m)
Allocasuarina acutivalvis, A. campestris, Acacia stereophylla, A. neurophylla, Grevillea paradoxa, Astroloma serratifolium.

Dense heath A – *Allocasuarina campestris* on deep sand (<3 m)
Allocasuarina campestris, Hakea erecta, H. scoparia, Melaleuca pentagona, Melaleuca sp., *Ecdeiocolea monostachya, Lepidosperma drummondii, Borya constricta.*

Dense heath B – *Allocasuarina campestris* on gravel (<3 m)
Allocasuarina campestris, Hakea scoparia, Grevillea paradoxa, G. petrophiloides, Hibbertia exasperata, Melaleuca radula, Calothamnus gilesii, Phebalium tuberculosum, Dodonaea pinifolia, Ecdeiocolea monostachya.

Mixed heath (<2 m)
Eucalyptus burracoppinensis, Xylomelum angustifolium, Grevillea integrifolia, G. eriostachya, G. pritzelii, Melaleuca conothamnoides, Melaleuca sp., *Mirbelia spinosa, Synaphea spinulosa, Verticordia picta, V. chrysantha, Acacia nigripilosa, Ecdeiocolea monostachya.*

Leptospermum heath (<3 m)
Leptospermum erubescens, Melaleuca sp., *Gompholobium* sp., *Allocasuarina microstachya, Hakea lissocarpha, Xanthorrhoea nana, Ecdeiocolea monostachya, Lyginia barbata.*

Open low heath (<3 m)
Allocasuarina campestris, Melaleuca conothamnoides, Verticordia chrysantha, Grevillea integrifolia, Dryandra cirsioides, Leucopogon hamulosus, Daviesia hakeoides, Ecdeiocolea monostachya.

Chenopod shrubland A with *Melaleuca pauperiflora* (<3 m)
Melaleuca pauperiflora, M. lateriflora, Atriplex paludosa, Enchylaena spp.

Chenopod shrubland B with *E. yilgarnensis* and shrubs (<6 m)
Eucalyptus yilgarnensis, Atriplex paludosa, Maireana sp., *Olearia muelleri, Enchylaena tomentosa, Eremophila oppositifolia, Exocarpos aphyllus.*

Samphire (<1 m)
Halosarcia pergranulata, Halosarcia sp., *Didymanthus roei, Carpobrotus* sp., *Gunniopsis septifraga.*