Effect of fire retardant application on heathland surface-dwelling invertebrate communities in Victoria

N.G. Collett[1,2] and C. Schoenborn[3]

[1]School of Forest and Ecosystem Science, The University of Melbourne, 123 Brown Street, Heidelberg, Victoria 3084, Australia
[2]Email: ncollett@unimelb.edu.au
[3]Forest Science Centre, Department of Sustainability and Environment, 123 Brown Street, Heidelberg, Victoria 3084, Australia

Revised manuscript received 5 May 2005

Summary

The effects of the application of fire retardant at varying rates on surface-dwelling invertebrates at ordinal and sub-ordinal level in heathland communities were assessed over a one-year period from March 2001 to March 2002. The study was conducted at two sites, one in East Gippsland at Marlo and the other in the Grampians region of south-western Victoria where a total of 136 190 specimens representing 30 ordinal and sub-ordinal taxa contained in 5400 pitfall trap samples was collected. It was concluded that despite the application of fire retardant at varying rates, there was no significant effect on invertebrate activity at ground level amongst the ordinal groups Acarina and Dermaptera. These ordinal groups appear to form a stable component of the heathland invertebrate community at both sites. Although significant changes were observed in other major taxonomic groups (total taxa, total insects, total non-insects, Araneae, Collembola, Coleoptera and Diptera) these changes were confined to either increased or decreased activity within a single plot and were judged to be not representative of treatment. While a significant change in activity was recorded for Formicidae at both sites, this was also due to single-plot variations in activity across different treatments. Such information indicates that any significant changes observed in invertebrate activity appeared to be due to site-related environmental factors rather than the effects of the retardant itself. When assessed in terms of general diversity, taxon richness and community evenness, ordinal and sub-ordinal taxa were unaffected by retardant application at the Marlo site. Significant changes in insect diversity at the Grampians site were again due to site-related factors rather than retardant effects. Further study is required to determine whether this stability is reflected at family, genus and species level, and if there are any seasonal and longer-term effects of retardant application. The combined effect of fire and retardant on invertebrate communities also requires further study.

Keywords: fire retardants, invertebrates, heathland, ecological disturbance, Victoria

Introduction

Victoria has some of the most bushfire-prone environments in Australia. Over the last 150 y more than half of the economic damage caused by bushfires in Australia has occurred in Victoria (Luke and McArthur 1978; CSIRO 2000). To minimise such damage, there is a heavy reliance on intensive fire suppression activities including the release of fire-retardant chemicals by aircraft. Fire retardants have been used operationally in Victoria's parks and forests since 1967, and today are used in about 10% of all fires on public lands. Each year, the Victorian Department of Natural Resources and Environment (DNRE, now DSE) applies an average of 120 000 L of fire retardant throughout Victoria (CSIRO 2000). Retardants are particularly useful in slowing the spread of fires in remote inaccessible terrain, as well as controlling spotfires, allowing time for the construction of control lines. The retardant applied, commonly known as Phos-Chek D-75®, contains ammonium sulphates, ammonium phosphates, guar gum, iron oxide and performance additives (CSIRO 2000). While it is approved for use in natural environments by the United States Department of Agriculture, a recent report by CSIRO (2000) has identified that no experiments have been conducted in Australia to examine the effects of Phos-Chek D-75® on the native flora and fauna. Given the highly endemic nature of Australian ecosystems, it is possible that their response to retardant application may be quite different from that of ecosystems in the United States. Research into this issue is therefore of importance to assist in the responsible management of fire suppression activities in the Australian landscape.

Only one previous study, by Bradstock *et al.* (1987), has investigated the effect of ammonium sulphate on Australian plants. This study was conducted in eucalypt forests, with results indicating significant short-term effects including widespread leaf death in trees, shrubs and ground-cover plants. While it may be argued that the latter effect is comparable to the effects of fire, there is concern that the resulting increase in phosphates and sulphates in the soil may deleteriously affect vegetation species that have evolved under low-nutrient conditions. It is anticipated that these changes may also affect other aspects of the ecosystem.

Invertebrates are closely associated with vegetation structure and composition, as they represent foliage-feeders, nectar-feeders, seed-gatherers, wood-suckers and woodborers, while others are predators and parasites of these first-order consumers (Majer and Greenslade 1988). The potential for direct toxicity to invertebrates has been studied only in earthworms: Phos-Chek D-75® was non-toxic to earthworms when applied at 1000 ppm (Beyer and Olsen 1996). However, that study did not examine the full diversity of invertebrate physiology and morphology, and nor did it explore the range of concentrations at which retardant is applied. Furthermore, there are potential indirect effects involving both the possible increase in nutrient concentration in plants and the subsequent toxicity to invertebrates that feed directly on, or decompose, this material (CSIRO 2000).

Fire management officers have a responsibility to minimise environmental damage during fire suppression operations. Without adequate knowledge of the environmental impacts of different suppression techniques, however, informed decisions cannot be made. This issue is of particular importance in vegetation communities that have evolved under low-nutrient conditions and/or are of high conservation value. Therefore, a multidisciplinary study was initiated in 2000 by the Fire Branch, DNRE, to assess the effects of fire-retardant application on vegetation, soil chemistry and surface-active invertebrates in fire-prone heathland communities.

The aim of the component of the study reported in this paper was to determine the immediate and longer-term responses of fire-retardant application on the composition and relative abundance of surface-dwelling invertebrates in heathland communities in Victoria. The results obtained will assist in developing management practices that minimise any potential adverse effects on invertebrates that may result from the application of fire retardant in these ecosystems.

Materials and methods

Study sites

Two study sites were selected in heathland areas in Victoria: one at Marlo Airstrip (37°47′ 26.58″S, 148°36′ 28.99″E) at an altitude of 20 m on a flat aspect about 20 km south-east of Orbost in East Gippsland, and the second site at Victoria Valley Airstrip in the Grampians (37°11′ 5.09″S, 142°20′ 27.90″E) at an altitude of 220 m on a flat aspect, about 25 km west of Halls Gap in western Victoria (Fig. 1).

Vegetation at the Marlo site is generally described as a ‘wet coastal heathland assemblage’ with the dominant overstorey species including *Leptospermum continentale* Joy Thomps. (prickly teatree), *Allocasuarina paludosa* Sieber ex Spreng. (scrub sheoak) and *Bossiaea prostrata R.Br.* (creeping bossiaea), while dominant understorey species include *Panicum simile* Domin. (hairy panic) and *Poa clelandii* Vickery (tussock grass). Plant heights range from 85 cm (*A. paludosa*) to 70 cm (*L. continentale*) while cover estimates for the dominant overstorey species range from 1% to 50% (using the Braun Blanquet scale (Kent and Coker 1992)). Soil pH at Marlo ranges from 5.4 to 5.7, and the soil contains 15–20 g kg^{-1} total C, 1 mg kg^{-1} extractable P, 0.4–1.0 g kg^{-1} total N and 10–20 mg kg^{-1} mineralisable N (T. Bell, The University of Melbourne, *pers. comm.* 2002).

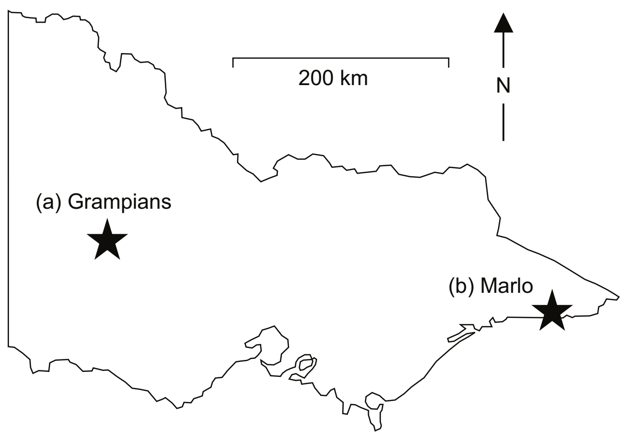

Figure 1. Location of the (a) Grampians and (b) Marlo fire retardant study sites in heathland areas of Western Victoria and East Gippsland

Vegetation at the Victoria Valley (Grampians) study site is generally described as a ‘sandy heathland assemblage’. The dominant overstorey species include *L. continentale*, *L. myrsinoides* Schltdl. (heath teatree), *Banksia marginata* Cav. (silver banksia), *Brachyloma daphnoides* Sm. Benth. (daphne heath) and *A. paludosa*, while dominant understorey species include *Hypolaena fastigiata* R.Br. (tassle rope-rush) and *Lomandra multiflora* R.Br. (many-flowered mat-rush). Plant heights range from 115 cm (*A. paludosa*) to 80 cm (*B. marginata*), while cover estimates for the dominant overstorey species range from 1% to 25% (using the Braun Blanquet scale (Kent and Coker 1992)). Soil pH at Victoria Valley ranges from 5.3 to 5.4 and the soil contains 5–10 g kg^{-1} total C, 1 mg kg^{-1} extractable P, 0.3–0.5 g kg^{-1} total N and 5–10 mg kg^{-1} mineralisable N (T. Bell, The University of Melbourne, *pers. comm.* 2002). The nomenclature of the aforementioned species is based on Walsh and Entwisle (1994, 1996).

At the Marlo study site, recent disturbance had been confined to a single fire in the mid-1960s and some slashing of the heath as a fire prevention measure which ceased in 1985/1986 (G. McCarthy, Dept of Sustainability and Environment, *pers. comm.* 2002) while at the Grampians study site, since records were commenced in 1939, the trial site has been prescribed burnt twice, once each in 1963 and 1985 (M. Wouters, Department of Sustainability and Environment, *pers. comm.* 2002).

Trial design and treatment application

At the Marlo study site, a randomised block design with five replicates × five treatments was used, while at the Grampians study site, a Latin square design was used with five replicates × five treatments. The five treatments applied at both sites in the study were:

- Treatment 1: ‘untreated control’
- Treatment 2: water at 1.0 L m^{-2} (‘water only’)
- Treatment 3: fire retardant at 0.5 L m^{-2} (‘low retardant’)
- Treatment 4: fire retardant at 1.0 L m^{-2} (‘medium retardant’)
- Treatment 5: fire retardant at 1.5 L m^{-2} (‘high retardant’)

with the retardant prepared at the recommended mixing ratio of 0.144 kg of retardant powder per litre of water (CSIRO 2000).Treatments 3 (low retardant), 4 (medium retardant) and 5 (high retardant) represent the range of application rates at which fire retardant is used operationally in fire situations in Victoria, with Treatment 4 (medium retardant) the desired rate of application (CSIRO 2000). Treatment 2 consisted of water only given that moisture can potentially act as a stimulatory trigger to epigeal invertebrate activity (Hutson and Veitch 1983, 1987; Holt 1985). Treatment plots at both sites consisted of a 20 m × 20 m plot to which each treatment was applied, with an internal measurement/sampling plot of 10 m × 10 m to minimise the effects of epigeal invertebrates migrating in from adjacent treatments or areas external to the study boundaries. The use of internal sampling plots also eliminated the potential of the immediate edges of treatments being 'contaminated' by the treatment application in the adjacent plot and thus possibly affecting invertebrate activity in the plot. The Marlo site had all five treatments applied within a five-day period from 2 to 6 March 2001, while the Grampians site had all five treatments applied within a six-day period from 29 March to 3 April 2001.

Sampling

Prevailing weather conditions, in terms of mean monthly rainfall, and maximum and minimum monthly temperatures, were recorded from January to December 2001 at weather stations at Marlo and Victoria Valley, close to both sites. Surface-active arthropods were sampled at each site within a 10 m × 10 m area within each plot over 12 weekly periods between 16 March 2001 and 14 February 2002 for the Marlo site, and 12 April 2001 and 15 March 2002 for the Grampians site. Within each 10 m × 10 m internal measurement plot, pitfall traps were positioned on a 5 m × 5 m grid, giving a total of nine pitfall traps per plot. A total of 5400 pitfall samples (2 study sites × 5 replicates × 5 treatments × 9 pitfall traps × 12 weekly samples) was collected during the entire study.

Each pitfall trap consisted of a test tube, 18 mm in diameter, in a PVC sleeve, half filled with 75% ethanol and providing a receptive surface area of 2.5 cm^2. The test tube proved to be generally effective in preventing overflow of the traps during rainstorms and yet did not tend to exclude the larger arthropods. Pitfall trap establishment effects were minimised by commencing sampling four weeks after positioning of the traps. Arthropod activity was measured as the number of individuals trapped per composite sample of nine pitfall traps over a seven-day period at the ground surface. Pitfall trapping estimates the relative population levels of epigeal invertebrates, and thereby measures their relative importance on the forest floor (Greenslade 1964; Greenslade and Greenslade 1971; Majer 1978; Collett 1996). The technique is considered appropriate for this study, which uses sampling over time to assess the effects of fire-retardant application on epigeal invertebrates. Limitations in sampling technique would apply equally across both study sites because sampling was done contemporaneously within all plots at each study site of similar age, aspect, elevation, vegetation and fire/general history, thus negating the effects of variable weather conditions and site characteristics on invertebrate activity.

The trapped arthropod specimens were counted and classified to ordinal and sub-ordinal level using a low-power microscope, with the nomenclature of families used and their varying feeding types based on information given by CSIRO (1991), Zborowski and Storey (1995), Pechenick (1996) and McGavin (2000).

Analysis

As the range and activity of arthropod taxa often varied among the nine pitfall traps within each plot, each set of nine contemporaneous trap collections was pooled into a composite sample. Examination of the arthropod data collected at both sites determined them not to be normally distributed. Different treatments at both sites were therefore compared using the Kruskal–Wallis H test that allows statistical comparisons to be made of non-normally distributed data between the medians of three or more samples by ranking observations within each treatment (Fowler *et al.* 1998; Zar 1999).

To determine whether or not the different treatments had any effect on the diversity of invertebrates at both sites, the Shannon–Wiener general diversity (Poole 1974), Margalef taxon richness (Southwood 1978) and Pielou community evenness indices (Pielou 1966) were compared using the Kruskal–Wallis H test. Although the three ecological indices have certain limitations (Hurlbert 1971), they were considered appropriate as sampling was relative over time, confined to sites experiencing the same set of environmental conditions, and not aimed at a complete census of the invertebrate community (Collett 2000). The three tests were considered necessary, as the Shannon–Weiner index is a general diversity index and requires further testing by the Margalef and Pielou indices to determine the precise cause of any significant change detected.

In order to determine the effects of fire retardant application on the taxon richness of invertebrates, two-dimensional chi-squared analyses were performed on the taxa totals for all treatments at both sites using 2 × 2 contingency tables (Zar 1999).

To examine whether trapping efficiency of invertebrates was affected by the trial design, where some treatment plots within replications were either bordered or totally surrounded by other plots, the five untreated control plots at both sites were compared using the Kruskal–Wallis H test to compare major taxonomic categories (Fowler *et al.* 1998).

Results

Weather conditions

At Marlo, the mean daily maximum air temperature per month varied from the highest recorded maximum of 25°C in February to the lowest maximum air temperature of 15°C in July (Fig. 2a), while the corresponding means for the Victoria Valley were 28°C (January) and 12°C (July) respectively (Fig. 2b). The mean daily minimum air temperature at Marlo varied from the highest recorded minimum of 15°C in February to the lowest minimum of 3°C in July (Fig. 2a), while the corresponding means for the Victoria Valley were 13°C (February) and 3°C (July) respectively (Fig. 2b). The mean annual rainfall was 920 mm and 700 mm for Marlo and Victoria Valley respectively. Mean monthly rainfall varied substantially between study sites, especially with reference to minimum rainfall, with a maximum and minimum of 93 mm in May and 67 mm in February respectively recorded at Marlo, while the corresponding figures for Victoria Valley were 84 mm in July and 27 mm in January (Figs 2a,b).

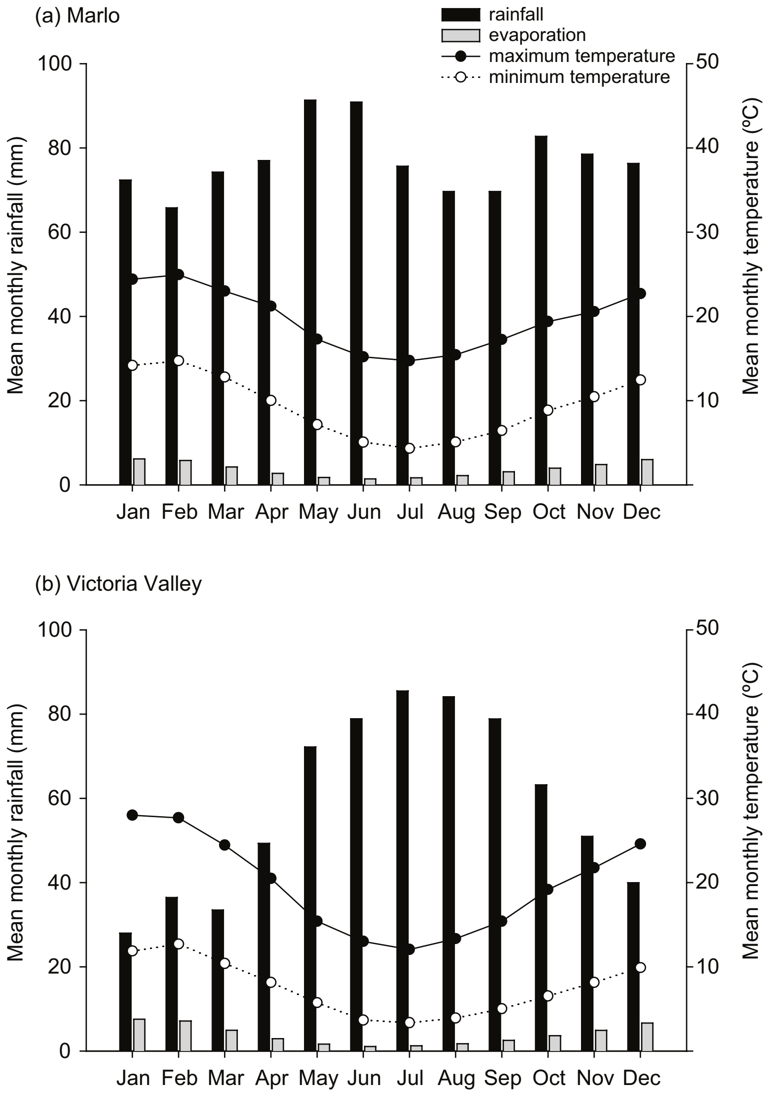

Figure 2. Mean monthly rainfall and mean monthly maximum and minimum temperature for a) Marlo and b) Grampians study sites January to December 2001 (T.Bell *pers. comm* 2002)

Overview of arthropod fauna trapped at the Marlo and Grampians study sites

A total of 30 ordinal/sub-ordinal groups were identified among the total of 136 190 arthropod specimens trapped at both sites across all treatments, with 26 groups totalling 79 853 specimens trapped at Marlo between March 2001 and February 2002, and 28 groups totalling 56 337 specimens trapped at the Grampians between April 2001 and March 2002 (Table 1). The total number of specimens collected among the Acarina (mites), Araneae (spiders), Collembola (springtails), Dermaptera (earwigs), Coleoptera (beetles), Diptera (flies) and Formicidae (ants) at both sites ranged between 1161 and 112 419, and represented 98.9% and 92.5% of the total arthropod fauna trapped at the Marlo and Grampians sites respectively. These were referred to as the 'major' taxa, to distinguish them from the 23 less commonly trapped 'minor' taxa, which represented 76.6% of the ordinal/sub-ordinal groups trapped across both sites while only representing 3.8% of the total individuals trapped. While 3891 individuals of the taxa Copepoda were trapped at both sites, only 96 individuals were trapped at Marlo. Unlike the other 'major' taxa where approximately similar numbers were trapped at both sites, the Copepoda were predominantly confined to the Grampians and were therefore excluded from the 'major' taxa group for the purposes of the study. Twenty-four (80%) of the ordinal/sub-ordinal groups were trapped at both sites. Two groups (Decapoda and Neuroptera) were trapped at Marlo only, while four groups (Protura, Mantodea, Psocoptera and Phasmatodea) were exclusively trapped at the Grampians site (Table 1). Up to 84 specimens of each of these six taxa were trapped at both sites over the period of the study, indicating that either they are a 'rare' component of the arthropod ground fauna or that pitfall trapping was not an efficient technique for trapping these taxa.

Of the 26 ordinal and sub-ordinal groups trapped at Marlo, 17 (65.4%) were found on all five treatment sites and represented over 99.9% of the total individuals trapped. At the Grampians site, 12 (42.8%) of the 28 ordinal and sub-ordinal groups were found on all five treatments and also represented over 99.9% of the total individuals trapped (Table 1). Of the nine groups not found on all five treatments at Marlo, four (Isopoda, Blattodea, Thysanoptera, Oligochaeta) were found on four treatments, one (Lithobiida) was trapped on three treatments, three (Opilionida, Orthoptera (Gryllidae), Hymenoptera (Symphyta)) on two treatments and one (Neuroptera) on one treatment (Table 1). Of the 16 groups not found on all five treatments at the Grampians, one (Oligochaeta) was found on four treatments, nine (Opilionida, Lithobiida, Polydesmida, Blattodea, Mantodea, Orthoptera (Acrididae), Psocoptera, Thysanoptera, Lepidoptera) was trapped on three treatments, three (Amphipoda, Hymenoptera (Symphyta), Phasmatodea) on two treatments and two (Protura, Orthoptera (Gryllidae)) on one treatment (Table 1). Of the feeding types, sap and seed-feeders, herbivores, algal feeding and omnivores were represented at both sites but most of the arthropod fauna trapped were predators and decomposers (Table 1).

Effects of fire retardant application at Marlo

The effects of the retardant application in terms of the Shannon–Wiener, Margalef and Pielou indices, expressed for the ordinal and sub-ordinal taxonomic groups, show that despite the application of retardant at low, medium and high rates, and the water-only treatment, none of the three indices were significantly different relative to the untreated control. Thus, diversity at the ordinal/sub-ordinal level in terms of general diversity, taxon richness and community evenness had not changed following application (H statistics for the Shannon–Wiener, Margalef and Pielou indices were 2.34 ($n = 298$; $P > 0.05$), 1.98 ($n = 298$; $P > 0.05$) and 2.78 ($n = 298$; $P > 0.05$) respectively for the five treatments (Table 2).

These results are consistent with the trend observed across all five treatments that activity was similar (i.e. no significant differences were observed) for the following major arthropod

Table 1. Taxa and numbers of individual adult epigeal arthropods trapped at the Marlo (M) and Grampians (G) study sites from March 2001 to February 2002, and from April 2001 to March 2002 respectively

Taxon	Feeding type	Retardant treatments and study sites									
		Control		Water only		Low		Medium		High	
		M	G	M	G	M	G	M	G	M	G
Arachnida											
Araneae (spiders)	Predators	79	165	88	136	107	133	75	142	85	151
Opilionida (harvestmen)	Predators	0	3	0	2	2	2	4	0	0	0
Acarina (mites)	Pred/decomposers	252	195	224	227	304	226	414	320	325	239
Malacostraca											
Amphipoda (landhoppers)	Decomposers	23	0	25	0	34	0	25	2	13	1
Decapoda (land crayfish)	Decomp/scavengers	16	0	17	0	16	0	16	0	19	0
Isopoda (woodlice)	Decomposers	0	1	12	0	4	0	2	0	3	0
Chilopoda											
Lithobiida (lithobiid centipedes)	Predators	0	1	0	0	2	2	2	0	1	2
Diplopoda											
Polydesmida (polydesmid millipedes)	Decomposers	4	1	16	0	7	0	10	2	8	1
Protura (proturans)	Fungus feeders	0	1	0	0	0	0	0	0	0	0
Collembola (springtails)	Decomposers	13 839	5 909	6 968	6 757	10 348	11 042	14 864	9 824	25 711	7 157
Insecta											
Blattodea (cockroaches)	Omnivores	4	2	4	1	3	0	0	0	3	1
Mantodea (mantids)	Predators	0	0	0	2	0	1	0	2	0	0
Dermaptera (earwigs)	Predators	360	386	418	317	428	250	388	236	372	243
Orthoptera											
Tettigoniidae (grasshopper)	Herbivores	30	24	36	9	12	5	7	20	21	13
Acrididae (locusts)	Herbivores	4	2	9	0	7	0	9	2	8	2
Gryllidae (crickets)	Herbivores	1	0	1	0	0	0	0	1	0	0
Psocoptera (psocids)	Decomposers	0	1	0	0	0	1	0	0	0	1
Homoptera (aphids, leafhoppers)	Sapfeeders	37	19	18	21	22	25	17	35	23	29
Heteroptera (true bugs)	Sapfeeders, predators	10	10	12	6	37	27	29	20	53	24
Thysanoptera (thrips)	Herbivores	1	4	0	3	2	0	2	1	2	0
Neuroptera (lace wings)	Predators	1	0	0	0	0	0	0	0	0	0
Coleoptera (beetles)	Various	104	373	129	422	167	466	132	421	222	392
Diptera (flies)	Various	59	226	59	230	75	287	122	311	164	344
Lepidoptera (moths, butterflies)	Herbivores	2	0	5	2	1	1	2	0	1	1
Hymenoptera											
Formicidae (ants)	Sap/seed feeders	448	1460	388	791	440	667	259	913	581	739
Apocrita (wasps)	Parasitoids, predators	4	8	4	8	4	29	10	26	14	22
Symphyta (wasps)	Parasitoids, predators	0	0	1	1	1	0	0	0	0	1
Phasmatodea (leaf/stick insects)	Herbivores	0	3	0	1	0	0	0	0	0	0
Copepoda (copepods)	Algal feeding	49	377	11	663	20	583	12	1047	4	1125
Oligochaeta (Lumbricina)	Decomposer	1	0	1	1	1	1	1	1	0	4
Total arthropods		**15 328**	**9 171**	**8 446**	**9 600**	**12 044**	**13 748**	**16 402**	**13 326**	**27 633**	**10 492**
Total taxa		22	22	22	20	24	18	22	19	21	21

categories: total non-insects, Acarina, Collembola and Dermaptera (Table 3a). However, with reference to the other arthropod categories, a short-term burst in activity from May to July 2001 was observed in the total taxa category, predominantly as a result of Collembola activity which increased substantially over the same period, on the high-retardant plots (Table 3a, Figs 3a,f). However, as Collembola activity, unlike total taxa activity, was not significantly different across all five treatments (Table 3a), it is most likely this is due to the activity of Collembola in conjunction with 'other' arthropod groups which is responsible for the significant increase in activity observed in the total taxa (Table 3a). A burst of activity in the total taxa and total non-insects categories was observed during September 2001 in the untreated control plots due to increased Collembola activity in

Table 2. Significance of differences between five fire retardant treatment data sets expressed by their mean rankings, for three ecological indices representing community aspects for total arthropods trapped at the Marlo and Grampians sites

	Shannon–Wiener (Diversity)	Margalef (Taxon richness)	Pielou (Evenness)
Marlo			
Untreated control (*n* = 60)[a]	161.32	139.52	158.57
Water only (*n* = 59)	144.21	148.03	141.78
Low retardant (*n* = 60)	141.00	160.47	143.42
Medium retardant (*n* = 59)	145.45	146.29	142.91
High retardant (*n* = 60)	155.37	153.10	160.59
H-statistic and significance	2.34NS[b]	1.98NS	2.78NS
Grampians			
Untreated control (*n* = 60)[a]	128.76	128.76	118.53
Water only (*n* = 60)	135.31	151.82	131.47
Low retardant (*n* = 60)	174.24	147.66	178.22
Medium retardant (*n* = 60)	160.43	164.07	168.01
High retardant (*n* = 60)	153.76	160.18	156.27
H-statistic and significance	10.97*	6.06NS	19.87***

[a]Number of observations in terms of differences between corresponding index values for the different treatments
[b]NS: no significant differences between specified data sets, *: $P < 0.05$, ***: $P < 0.001$ (Kruskal–Wallis H-test)

Table 3. Significance of differences between five fire retardant treatment data sets expressed by their mean rankings, for 10 major arthropod groups trapped at (a) the Marlo site and (b) the Grampians sites

Site and arthropod category	Treatment and mean rank (*n* = 59,60)[a]					H-statistic and significance[b]
	Untreated control	Water only	Low retardant	Medium retardant	High retardant	
(a) Marlo						
Total taxa	143.17	133.28	150.99	140.65	178.99	10.08*
Total insects	135.32	143.71	154.47	132.52	181.08	12.45*
Total non-insects	147.31	134.22	147.55	143.78	174.29	7.50NS
Araneae	142.84	161.63	172.26	142.52	128.50	10.30*
Acarina	136.51	126.85	158.33	165.57	160.68	9.28NS
Collembola	148.23	134.14	146.19	143.71	172.78	6.58NS
Dermaptera	140.77	154.29	150.58	147.03	154.85	1.09NS
Coleoptera	127.20	138.60	162.25	144.02	172.30	11.04*
Diptera	126.02	122.63	140.93	168.95	191.76	30.39***
Formicidae	150.76	149.10	155.98	117.34	173.77	13.42**
(b) Grampians						
Total taxa	131.82	132.52	164.35	165.94	157.86	9.22NS
Total insects	178.52	141.87	136.48	152.06	143.57	8.82NS
Total non-insects	121.72	135.29	169.57	165.36	160.55	13.91**
Araneae	142.90	140.81	143.72	173.72	151.34	6.11NS
Acarina	139.51	147.39	139.39	166.27	155.17	4.24NS
Collembola	120.17	136.70	172.79	166.81	156.18	15.27**
Dermaptera	163.90	161.20	151.96	132.89	142.53	5.41NS
Coleoptera	138.03	152.13	163.76	153.44	145.13	2.98NS
Diptera	146.51	140.21	139.88	151.02	164.60	3.42NS
Formicidae	186.41	143.41	130.95	152.48	139.24	14.79**

[a]Denotes number of observations with 59 and 60 observations per treatment at the Marlo and Grampians sites respectively.
[b]Levels of significant differences are: *$P < 0.05$, **$P < 0.01$ ***$P < 0.001$ and NS, not significant (Kruskal–Wallis H-test).

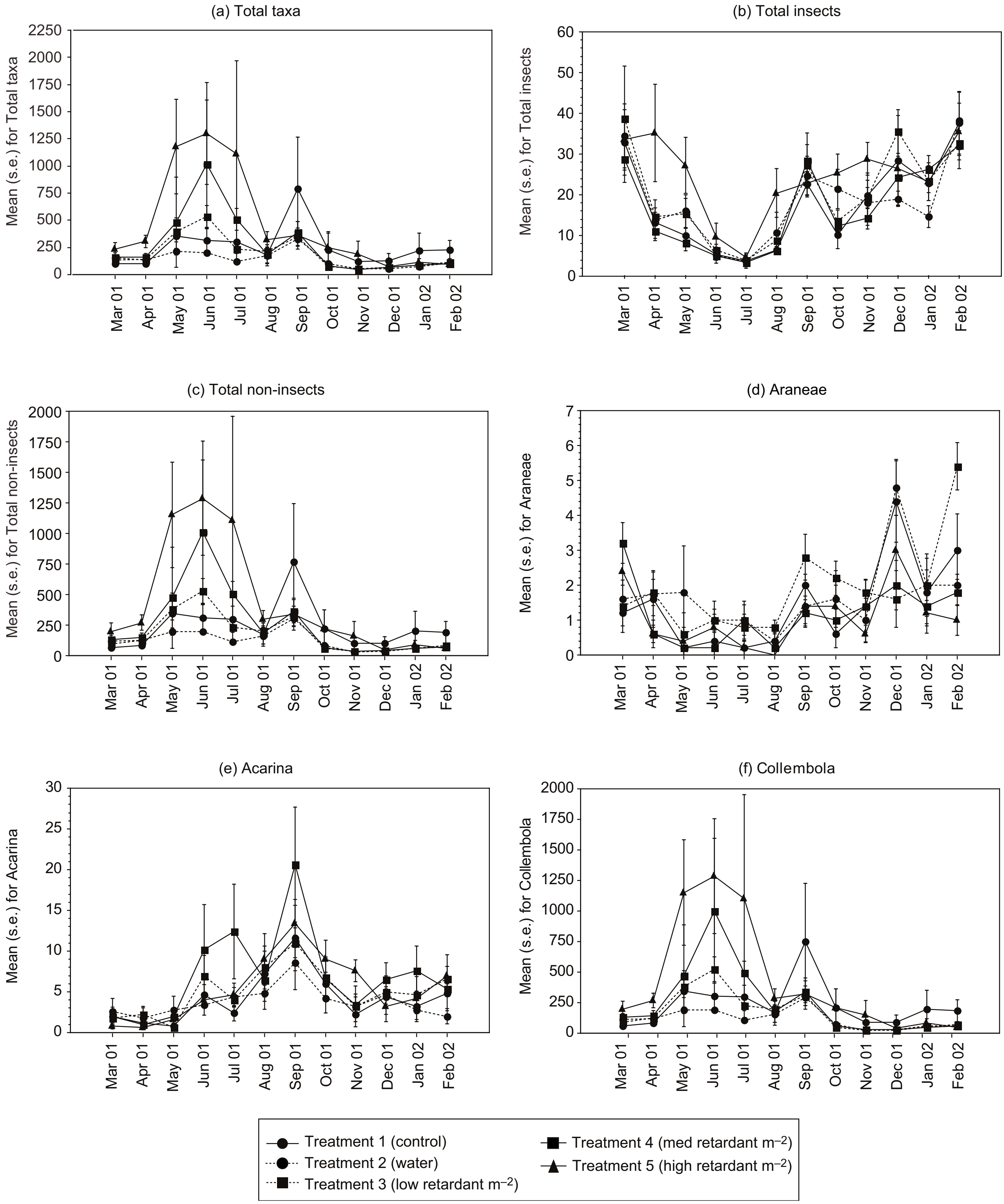

Figure 3. Monthly activity of (a) total taxa, (b) total insects, (c) total non-insects, (d) Araneae, (e) Acarina, (f) Collembola, (g) Dermaptera, (h) Coleoptera, (i) Diptera and (j) Formicidae from March 2001 to February 2002 at the ground surface of the Marlo study site treated with various rates of fire retardant and water compared to an untreated control

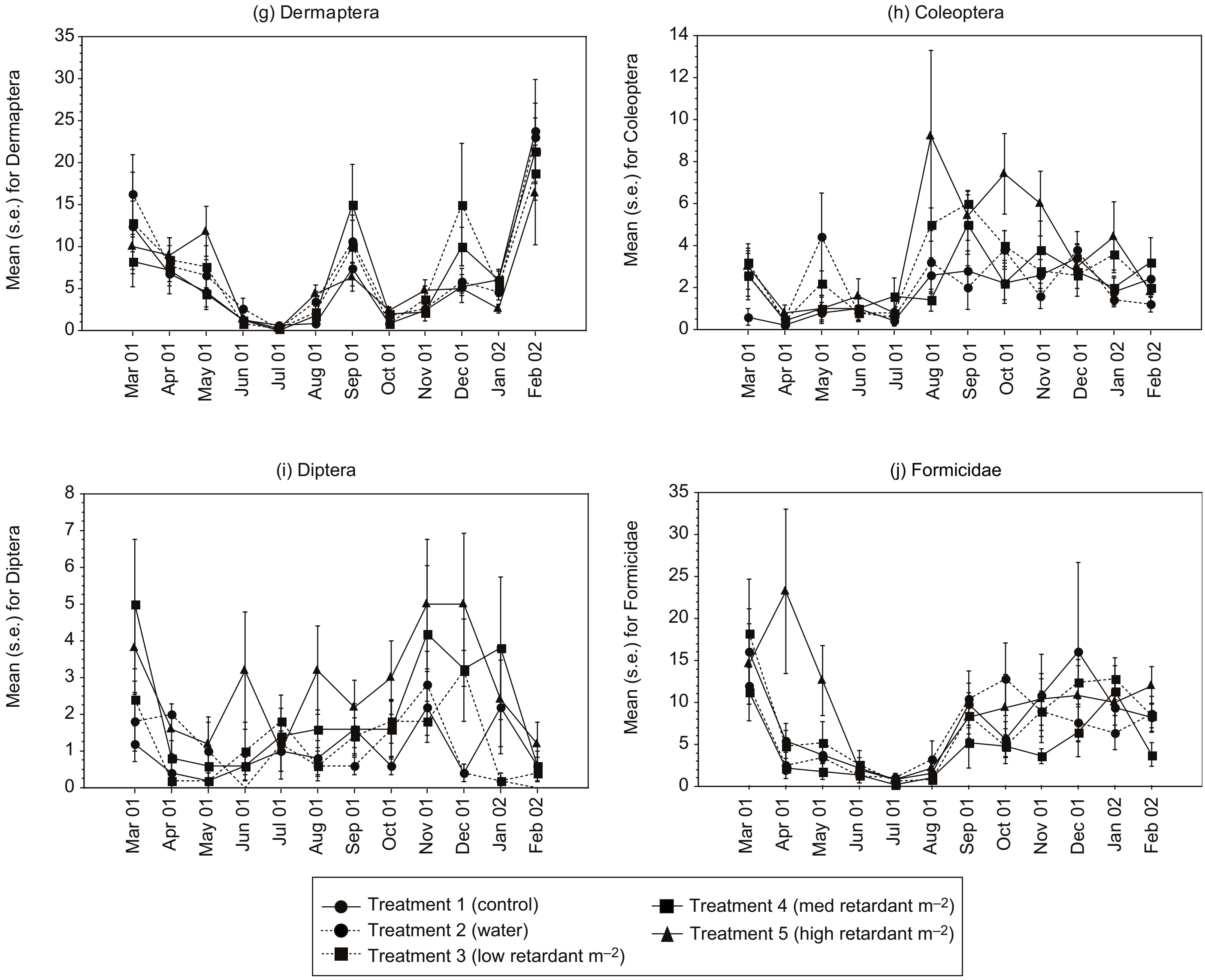

Figure 3 (continued). Monthly activity of (a) total taxa, (b) total insects, (c) total non-insects, (d) Araneae, (e) Acarina, (f) Collembola, (g) Dermaptera, (h) Coleoptera, (i) Diptera and (j) Formicidae from March 2001 to February 2002 at the ground surface of the Marlo study site treated with various rates of fire retardant and water compared to an untreated control

the same period although apart from this burst of activity, levels of activity for these three arthropod categories across all treatments from August 2001 onwards had stabilised to display similar trends (Figs 3a,c,f). Significantly increased levels of activity were also observed on the high-retardant plots in the category total insects during April and May 2001, due predominantly to the Formicidae which also displayed increased activity in the same treatment over the same period (Table 3a, Figs 3b,j). By June 2001, however, activity across all five treatments for both the total insects and Formicidae had stabilised to once again display similar trends in activity. The significant increase in total insect activity on the high-retardant plots compared to the other treatments is also due, apart from the activity of the Formicidae, to the combined activity of the Diptera and Coleoptera which were also significantly higher on the high-retardant plots than for the other treatments (Table 3a). For Diptera, peaks in activity on the high-retardant plots were observed during June and August 2001 (Fig. 3i) while for Coleoptera, peaks in activity for the same treatment were observed in August, October and November 2001 (Fig. 3j). The Araneae recorded significantly increased activity for the low-retardant plots compared with other four treatments (Table 3a), with peaks in activity observed during September 2001 and February 2002 (Fig. 3d).

The results of the two-dimensional chi-squared test for mutual independence between the different treatments within the site and the frequency of taxa in the three groupings (total taxa, total insects and total non-insects) were not significant ($\chi^2 = 0.949$, df = 4, $P > 0.05$), indicating that taxon richness in the three specified groups had not changed as a result of the different treatments.

Effects of fire retardant application at the Grampians

The effects of the retardant application in terms of the Shannon–Wiener, Margalef and Pielou indices, expressed for the ordinal and sub-ordinal taxonomic groups, show that despite the application of retardant at low, medium and high rates, and the water-only treatment, the Margalef (taxon richness) index value was not significantly different relative to the untreated control site (H = 6.06; n = 300, $P > 0.05$) (Table 2). Thus, diversity at the ordinal/sub-ordinal level in terms of taxon richness had not changed following application. However, the Shannon–Wiener (general diversity) and Pielou (community evenness) indices were significantly different (H statistics for the Shannon–Wiener and Pielou indices were 10.97 (n = 300; $P < 0.05$) and 19.87 (n = 300; $P < 0.001$) (Table 2) indicating that diversity had changed as a result of a significant change in community evenness. Examination of the data indicates that this difference is due predominantly to the activity of the Collembola, the most numerous taxa trapped at the study site. Collembola activity was significantly higher on the low and medium retardant treatments compared to the other treatments, which displayed similar levels of activity throughout the entire study period (Fig. 4f) (Table 3b).

No significant changes in activity were observed in the major arthropod categories, comprising total taxa, total insects, Araneae, Acarina, Dermaptera, Coleoptera and Diptera, indicating that over the course of the study, activity of these groups remained stable across the five treatments (Figs 4a,b,d,e,g–i) (Table 3b). For the other major arthropod category, total non-insects, however, a significant increase in activity was observed, predominantly as a result of Collembola activity on the low and medium retardant treatments (Table 3a) where during November 2001 peaks in activity over that observed in other treatments occurred (Figs 4c,f). From December 2001 to the completion of the study in March 2002, activity of the non-insects and Collembola had stablised to display similar trends in activity. For the Formicidae, significantly increased activity in the untreated control was observed throughout most of the study, with peaks in activity over those observed in other treatments occurring in April and June 2001, and again in February 2002 (Fig. 4j) (Table 3b).

The results of the two-dimensional chi-squared test for mutual independence between the different treatments within the site, and the frequency of taxa in the three groupings (total taxa, total insects and total non-insects), were not significant ($\chi^2 = 0.603$, df = 4, $P > 0.05$), indicating that taxon richness in the three specified groups had not changed as a result of the different fire retardant treatments.

Effects of trial design on trapping efficiency of invertebrates

An examination of the untreated control plots at both study sites found no significant difference in abundance between plots for the major arthropod categories, comprising Acarina, Araneae, Diptera, Coleoptera and Dermaptera, indicating trial design had not impacted on trapping efficiency for these ordinal groups. While the Collembola recorded a significant increase in activity in one plot at Marlo (H = 22.15, n = 12, $P < 0.001$) this was not reflected at the Grampians where no significant difference was observed in activity between plots. Conversely, at the Grampians site, a significant increase in Formicidae activity was observed on two plots (H = 19.42, n = 12, $P < 0.001$) while at Marlo, no significant difference in activity was observed. Examination of the data indicated that while there was an increase in Collembola activity at one plot at Marlo, this was not reflected at the other four plots of the randomised block design which all recorded approximately equal levels of activity. At the Grampians site, the increase in Formicidae activity was in both an 'edge' and in an 'internal' plot of the Latin square design, with the other three plots recording approximately equal activity levels.

Discussion

While the effects of fire on surface-dwelling invertebrate behaviour and activity to ordinal and sub-ordinal level, both in wildfire and prescribed burning situations, has been examined in detail both within Australia and overseas, this is the first study to examine the effects of fire-retardant application on the composition and relative abundance of terrestrial invertebrates. Previous Australian studies have concentrated on the effects of fire on invertebrates both immediately after and in the years subsequently following burning rather than on the effects of suppression activities (Springett 1976; Campbell and Tanton 1981; Abbott 1984; Abbott *et al.* 1984; Majer 1984; Neumann 1991; Neumann and Tolhurst 1991; Collett *et al.* 1993; Collett and Neumann 1995; Neumann *et al.* 1995; Collett 1996, 1998, 1999, 2000; York 1999, 2000). In terms of the effects of fire-retardant application, a review of the available literature shows that apart from an Australian study examining the effects of retardant application on plants (Bradstock *et al*. 1987), American studies looking at the effects of fire retardant on earthworms (Beyer and Olsen 1996) and benthic invertebrates (Poulton 1996), and some studies investigating the toxicity of retardant to mammals and birds (Dodge 1970; Vyas and Hill 1996), very little information exists as to the effects of retardant application on terrestrial plants and wildlife in general and invertebrates in particular (Adams and Simmons 1999; CSIRO 2000). The single study conducted on earthworms found that of the five different types of retardant applied at 1000 ppm (including Phos-Chek D-75® used in the current study), none was lethal to earthworms and none was likely to reduce populations if applied under field fire suppression conditions (Beyer and Olson 1996), while the study on benthic invertebrates found higher concentrations of foam retardant caused increased mortality over time (Poulton 1996).

Results indicate that no major taxonomic group was affected by the trial layout at the study sites. While a significant difference in Collembola and Formicidae activity was observed at Marlo and Grampians respectively, these changes were confined to elevated activity within a single plot (Collembola at Marlo) or two plots (Formicidae at Grampians), with all other plots recording approximately equal levels of activity. With reference to the Grampians site where the Latin square design meant some treatment plots were totally surrounded by other plots, no discernible pattern was observed in the location of the two plots with elevated Formicidae activity in relation to the three remaining plots. Consequently, it appears that trial design and the pitfall trap layout were not responsible for the differences observed within individual plots at both study sites.

An examination of both study sites indicated that at least 30 ordinal and sub-ordinal taxonomic groups inhabit the soil surface of heathland ecosystems. Of these groups, 24 (80%) (including the seven 'major' taxa) representing 99.9% of individuals trapped, were common to both study sites, indicating that pitfall trapping gave good comparable results for both sites across the five treatments. The only significant variation to this trend was observed within the Copepoda, where greater numbers were trapped at the Grampians relative to the Marlo site. However, as the proportions of Copepoda trapped between treatments within both sites remained relatively stable, this variation appears more indicative of site rather than treatment factors being responsible.

The results of the two dimensional chi-squared tests conducted on the different treatments within sites and the frequency of taxa in the categories (total taxa, total insects and total non-insects) satisfied the null hypothesis in that there was a nil effect of fire retardant, regardless of rate of application, on the frequency of taxa within different treatments. It therefore appears that the application of fire retardant at both study sites did not change the proportion of ordinal and sub-ordinal taxa totals on the treated plots relative to the untreated control plots. This conclusion is supported by the non-significant results of the Kruskal–Wallis H-tests on the fire retardant treatments for the Shannon–Wiener, Margalef and Pielou ecological indices at Marlo, and the non-significant result for the Margalef taxon richness index at the Grampians. While the Shannon–Wiener general diversity index was significantly different at the Grampians due to a significant change in the Pielou index, this change in community evenness was due more to short-term bursts of increased activity of the total taxa, predominantly due to the activity of the Collembola within the low and medium retardant treatments during August and November compared to the untreated control plots. As these bursts in activity were confined to single plots within a treatment, it appears that site factors rather than the retardant treatments were responsible for this change in community evenness at the Grampians site.

At both study sites, the non-significant variations between the Acarina and Dermaptera indicate that despite the application of retardant at low, medium and high rates, these ordinal groups appear to form a stable component of the heathland invertebrate community. This complements the findings of other studies concerning Acarina and Dermaptera by Neumann (1991), Neumann and Tolhurst (1991) and Collett (1996, 1998, 1999), in wet and dry sclerophyll eucalypt forests in Victoria which also found populations remained relatively stable despite the application of fire or being subjected to other site disturbance/alteration factors. This contrasts, however, with studies by York (1999) in coastal blackbutt forests of New South Wales, which found frequent low-intensity fire significantly reduced Acarina population levels.

Although the total taxa, total insects, Araneae, Coleoptera and Diptera categories recorded significant changes in activity at Marlo, corresponding changes were not duplicated within the same categories at the Grampians site where significant changes in activity were recorded within the total non-insects and Collembola categories. As changes within these categories were confined to one site, it cannot be concluded that retardant treatments are responsible for the observed changes. This finding is confirmed by the high variability recorded within the same treatments between replications. This indicates that short-term bursts of activity on one or two plots within a treatment were responsible for the significant changes observed, rather than a uniform increase/decrease in activity across all plots within the same treatment across all replications. Furthermore, changes observed were not confined to one particular retardant treatment but rather spread across all retardant treatments, water only and untreated control plots. This would indicate that site rather than treatment-related factors were responsible for the changes observed. The only arthropod category recording a significant change in activity at both sites was the Formicidae. Although it could be reasonable to conclude that there might be some treatment effect in this instance, closer examination of the data tends to discount this possibility. At Marlo the observed changes were due to significant increases in activity on the high-retardant treatment, while at the Grampians the change is associated with a significant increase in the untreated control. This, coupled with the high variability of Formicidae activity within individual treatment plots, indicates that site rather than treatment-related factors were most likely responsible for the observed changes.

The findings of this study should be interpreted cautiously as the number of ordinal and sub-ordinal groups identified during the study (30 across both sites) was based on cumulative totals of the activity of individual species within those groups. The disadvantages of an ordinal-level approach lies in the possibility of retardant effects at lower classification levels not being detected. This can result in incorrect assumptions being made if no effect at the ordinal or sub-ordinal level is translated as there being no effect at lower taxonomic levels. Consequently, no inferences can be made from this study regarding the effects of retardant application at lower taxonomic levels. Further research examining the effects of retardant application to lower taxonomic levels is required to address the question of whether individual groups at these classification levels are sensitive to fire retardant application. It was also not possible to examine in detail the effects of retardant application on functional groups due to the broad nature of some of these groupings (i.e. Coleoptera, Diptera and Acarina contain many different feeding types). Again, further research past ordinal level is required to assess the effects of retardant on various functional groups. Also pitfall trapping, while an effective technique for collecting certain taxa (e.g. Formicidae) may not be suitable for collecting other groups (e.g. Neuroptera) that occupy other ecological niches. Future studies should employ sampling techniques that also target these groups (Collett 2000). Studies to ordinal and sub-ordinal level, however, do provide useful indicators for further study. Many studies have initially examined ordinal-level effects prior to more detailed examination at lower taxonomic levels (Springett 1976, 1979; Neumann 1991, 1992; Collett *et al.* 1993; Collett and Neumann 1995; Neumann *et al.* 1995; York 1999, 2000). Also, problems of taxonomy of many insect orders, and the absence of sub-generic descriptions in most insect taxa, limit the level of classification that can be studied (Abbott 1984).

As the study was confined to a single year of sampling in a relatively small area, effects of season and any potential longer-term residual effects of retardant either directly on invertebrate activity or indirectly through potential alteration of vegetation cover due to changes in soil nutrient status could not be examined. It could be inferred, however, that if no changes related to retardant application occur in the short term (within one year), these are unlikely to translate into longer-term changes. This trend is supported by other studies examining site disturbance whether

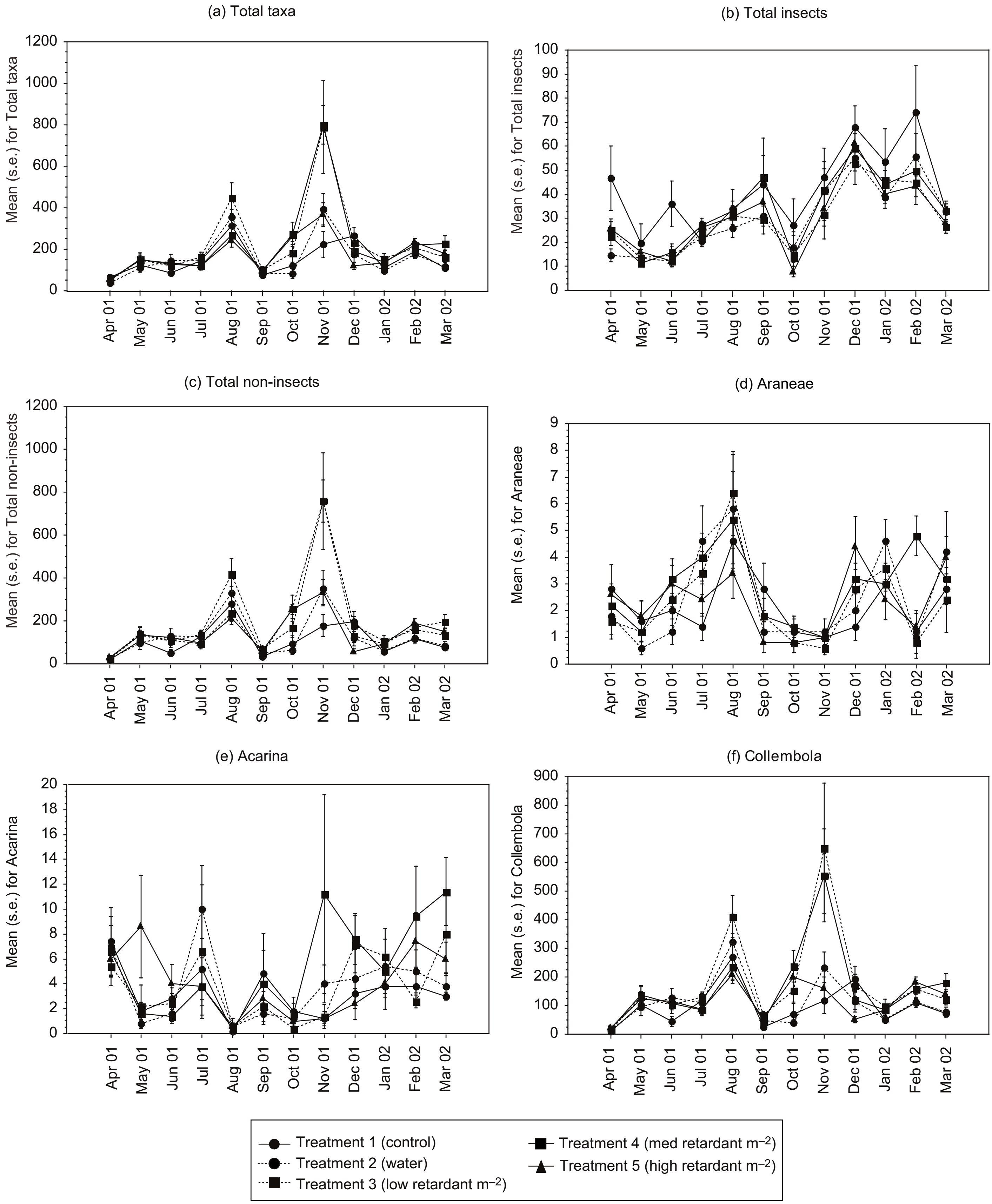

Figure 4. Monthly activity of (a) total taxa, (b) total insects, (c) total non-insects, (d) Araneae, (e) Acarina, (f) Collembola, (g) Dermaptera, (h) Coleoptera, (i) Diptera and (j) Formicidae from April 2001 to March 2002 at the ground surface of the Grampians study site treated with various rates of fire retardant and water compared to an untreated control.

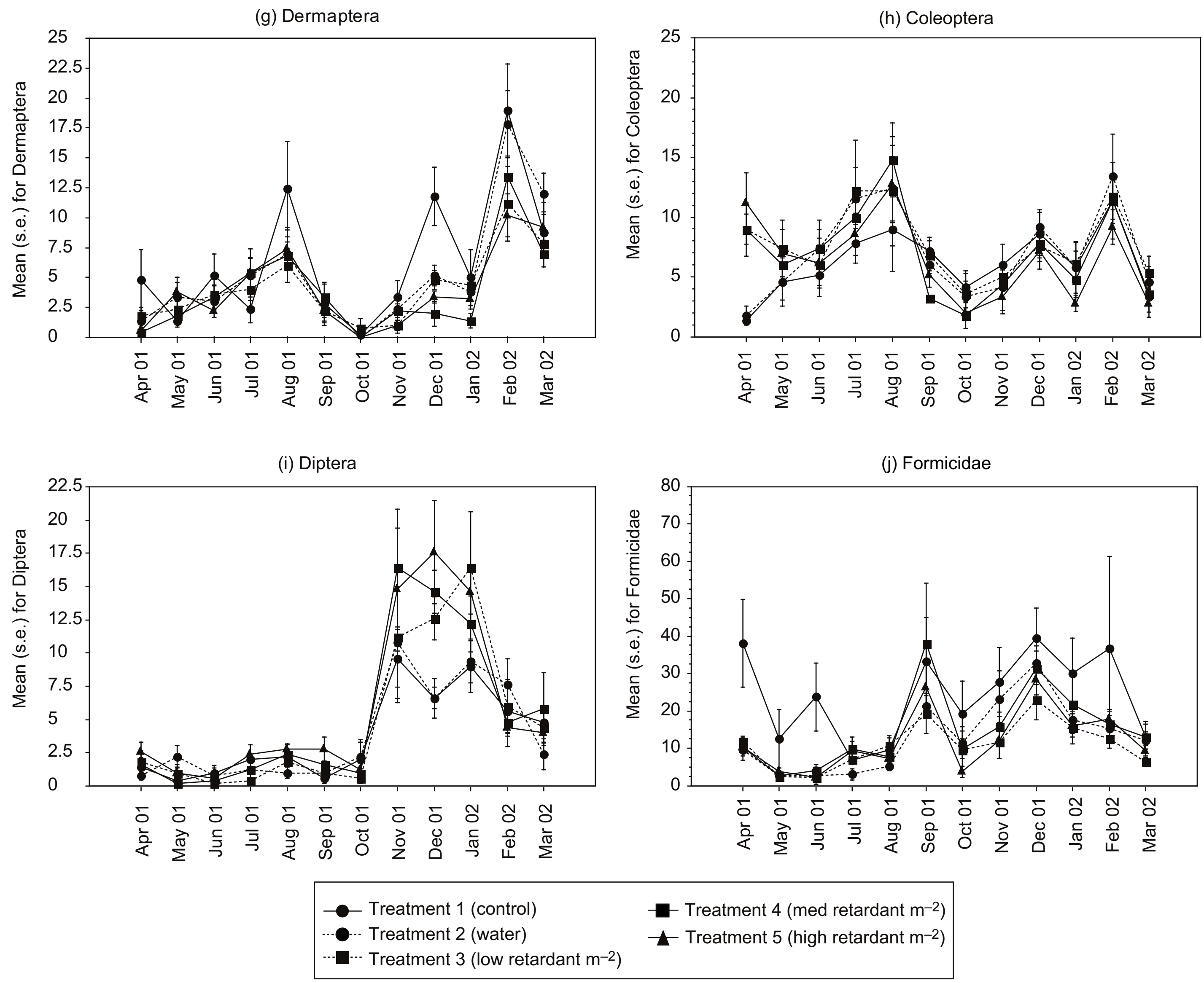

Figure 4 (continued). Monthly activity of (a) total taxa, (b) total insects, (c) total non-insects, (d) Araneae, (e) Acarina, (f) Collembola, (g) Dermaptera, (h) Coleoptera, (i) Diptera and (j) Formicidae from April 2001 to March 2002 at the ground surface of the Grampians study site treated with various rates of fire retardant and water compared to an untreated control.

by fire or other activities such as logging, which found that even where the activity of a taxonomic group declined after the disturbance event, recovery to pre-disturbance levels usually occurred within 2–3 y (Neumann 1992; Collett 2000). Studies by van de Westeringh (1972) and Cooke *et al.* (1992) examining the effects of copper fungicide and aldicarb (an acaricide and nematicide) (Crop Protection Publications 1995) application in orchards and on soil under wet conditions found that such applications led to reduced populations of earthworms and their predators. These studies, however, concerned potentially hazardous pesticide applications rather than fertiliser-based fire retardants. In forest fire situations, the application of retardant is generally followed by the 'treated' area being subjected to fire, an event not duplicated and examined during this study. However, given that fire retardant is generally not applied to high but rather to low-intensity fires to either extinguish flames or to provide barriers to prevent further spread, the possibility exists of unburnt fire retardant remaining in either large areas or small patches (CSIRO 2000). The little information available suggests that unless retardant when burnt over is subjected to very high temperatures, only partial, incomplete breakdown may occur (CSIRO 2000). Therefore, while further study is required to assess the combined effects of retardant and fire on surface-dwelling invertebrates, the current study is certainly representative of many operational conditions where retardant is not consumed by fire after application.

Notwithstanding the above issues, there appears to be no significant effect of applying fire retardant, at varying rates, on activity of surface-dwelling invertebrates when these are classified at ordinal and some sub-ordinal levels. The changes observed appear to have been due to site-related factors rather than the effects of the retardant itself. While the Formicidae recorded significant changes at both the Marlo and Grampians sites, these changes appear to reflect increased or decreased activity on individual plots rather than being representative of the effects of a particular treatment. However, more detailed research to the level of genus and species, especially within the Formicidae, is required to determine whether retardant causes changes in activity at these levels. More work is also required over a longer timeframe to examine the effects of season and the residual effects of retardant on invertebrates in heathland ecosystems. The combined effects of retardant and fire on invertebrates should also be considered for further study.

Acknowledgements

We would like to thank Mr Mike Wouters and Mr Greg McCarthy for their valuable assistance in both setting up the trials and in organising the monthly sample collections from both sites. Many thanks also to Dr Tina Bell for comments on the paper and for providing weather, vegetation and soil data used in the report, as well as to Paul Clements, Richard Stokes, David Smith and Glen Dooley for assistance in the field at various times during the study.

References

Abbott, I. (1984) Changes in abundance and activity of certain soil and litter fauna in the jarrah forest of Western Australia after a moderate intensity fire. *Australian Journal of Soil Research* **22,** 463–469.

Abbott, I., Van Heurck, P. and Wong, L. (1984) Response to long-term fire exclusion: physical, chemical and faunal features of litter and soil in a Western Australian forest. *Australian Forestry* **47,** 237–242.

Adams, R. and Simmons, D. (1999) Ecological effects of fire fighting foams and retardants: a summary. *Australian Forestry* **62,** 307–314

Beyer, W.N. and Olsen, A. (1996) Can earthworms survive fire retardants? *Fire Management Notes, USDA Forest Service* **56**(1)**,** 26–27.

Bradstock, R., Sander, J. and Tegart, A. (1987) Short-term effects on the foliage of a eucalypt forest after an aerial application of a chemical fire retardant. *Australian Forestry* **50,** 71–80.

Campbell, G. and Tanton, M.T. (1981) The effects of fire on the invertebrate fauna of soil and litter of a eucalypt forest. In: Gill, A.M., Groves R.H. and Noble, I.R. (eds) *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 215–241.

Collett, N.G. (1996) Short and long-term effects of a catastrophic wildfire on families of Order Coleoptera (beetles) in *Eucalyptus regnans* forest in the central highlands of Victoria. MSc thesis, Faculty of Science (Ecology and Evolutionary Biology), Monash University.

Collett, N.G. (1998) Effects of two short rotation prescribed fires in autumn on surface-active arthropods in dry sclerophyll forest of west-central Victoria. *Forest Ecology and Management* **107,** 253–273.

Collett, N.G. (1999) Effects of three short rotation prescribed fires in spring on surface-active arthropods in dry sclerophyll forest of west-central Victoria. *Australian Forestry* **62,** 295–306.

Collett, N.G. (2000) Catastrophic wildfire and its short-term effects on families of Order Coleoptera (beetles) in *Eucalyptus regnans* forest in the Central Highlands of Victoria. *Australian Forestry* **63,** 7–21.

Collett, N.G. and Neumann, F.G. (1995) Effects of two spring prescribed fires on epigeal Coleoptera in dry sclerophyll eucalypt forest in Victoria, Australia. *Forest Ecology and Management* **76,** 69–85.

Collett, N.G., Neumann, F.G. and Tolhurst, K.G. (1993) Effects of two short rotation prescribed fires in spring on surface-active arthropods and earthworms in dry sclerophyll eucalypt forest of west-central Victoria. *Australian Forestry* **56,** 49–60.

Cooke, A.S., Greig-Smith, P.W. and Jones, S.A. (1992) Consequenses for vertebrate wildlife of toxic residues in earthworm prey. In: Greig-Smith, P.W., Becker, H., Edwards, P.J. and Heimbach, F. (eds) *Ecotoxicology of Earthworms.* Intercept Ltd, Andover, England, pp. 139–155.

Crop Protection Publications (1995) *Pesticide Manual.* 10th edition (Clive Tomlin, ed.), 1341 pp.

CSIRO (1991) *The Insects of Australia.* CSIRO Division of Entomology, Melbourne University Press.

CSIRO (2000) *Assessment of the Effectiveness and Environmental Risk of the Use of Retardants to Assist in Wildfire Control in Victoria.* Research Report No. 50. CSIRO Forestry and Forest Products for the Department of Natural Resources and Environment. 43 pp.

Dodge, M. (1970) Nitrate poisoning, fire retardants, and fertilizers — any connection? *Journal of Range Management.* **23,** 244–247.

Fowler, J., Cohen, L. and Jarvis, P. (1998) *Practical Statistics for Field Biology.* Wiley and Sons, England.

Greenslade, P.G.M. (1964) Pitfall trapping as a method for studying populations of Carabidae (Coleoptera). *Journal of Animal Ecology* **33,** 301–310.

Greenslade, P. and Greenslade, P.J.M. (1971) The use of baits and preservatives in pitfall traps. *Journal of the Australian Entomological Society* **10,** 253–260.

Holt, J.A. (1985) Acari and Collembola in the litter and soil of three north Queensland rainforests. *Australian Journal of Ecology* **10,** 57–65.

Hurlbert, S.H. (1971) The non-concept of species diversity: a critique and alternative parameters. *Ecology* **52,** 577–586.

Hutson, B.R. and Veitch, L.G. (1983) Mean annual population density of Collembola and Acari in the soil and litter of three indigenous South Australian forests. *Australian Journal of Ecology* **8,** 113–126.

Hutson, B.R. and Veitch, L.G. (1987) Densities of Collembola and Acarina in the soil and litter of three indigenous South Australian forests related to layer, site and seasonal differences. *Australian Journal of Ecology* **12,** 239–261.

Kent, M., and Coker, P. (1992) *Vegetation Description and Analysis*. Bellhaven Press, London, England.

Luke, R.H. and McArthur, A.G. (1978) *Bushfires in Australia*. Australian Government Publishing Service, Canberra, ACT, 359 pp.

Majer, J.D. (1978) An improved pitfall trap for sampling ants and other epigaeic invertebrates. *Journal of the Australian Entomological Society* **17,** 261–262.

Majer, J.D. (1984) Short-term responses of soil and litter invertebrates to a cool autumn burn in jarrah (*Eucalyptus marginata*) forest in Western Australia. *Pedobiologia* **26,** 229–247.

Majer, J.D. and Greenslade, P. (1988) Soil and litter invertebrates. In: Specht, R.L. (ed.) *Mediterranean-type Ecosystems*: *A Data Source Book.* Kluwer, Dordrecht, pp. 197–226.

McGavin, G.C. (2000) *Insects, Spiders and other Terrestrial Arthropods*. Dorling Kindersley, London.

Neumann, F.G. (1991) Response of litter arthropods to major natural or artificial ecological disturbances in mountain ash forests. *Australian Journal of Ecology* **16,** 19–32.

Neumann, F.G. (1992) Responses of foraging ant populations to high-intensity wildfire, salvage logging and natural regeneration processes in *Eucalyptus regnans* regrowth forest of the Victoria Central Highlands. *Australian Forestry* **55,** 29–38.

Neumann, F.G. and Tolhurst, K.G. (1991) Effects of fuel reduction burning on epigeal arthropods and earthworms in dry sclerophyll eucalypt forest of west-central Victoria. *Australian Journal of Ecology* **16,** 315–330.

Neumann, F.G., Collett, N.G. and Tolhurst, K.G. (1995) Coleoptera in litter of dry sclerophyll eucalypt forest and the effects of low-intensity prescribed fire on their activity and composition in west-central Victoria. *Australian Forestry* **58,** 83–98.

Pechenick, J.A. (1996) *Biology of the Invertebrates.* Wm. C. Brown, Dubuque, USA.

Pielou, E.C. (1966) The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology* **13,** 131–144.

Poole, R.W. (1974) *An Introduction to Quantitative Ecology*. McGraw-Hill, New York.

Poulton, B.C. (1996) Effects of two fire suppressant foams on benthic invertebrates colonizing artificial substrates in portable limnocorrals. Ecological Studies at the Woolworth Area. *Proceedings of the North Dakota Academy of Science* **50,** 145–151.

Southwood, T.R.E. (1978) *Ecological Methods, with Particular Reference to the Study of Insect Populations*. Methuen, London.

Springett, J.A. (1976) The effect of prescribed burning on the soil fauna and on litter decomposition in Western Australia. *Australian Journal of Ecology* **1,** 72–82.

Springett, J.A. (1979) The effects of a single hot summer fire on soil fauna and on litter decomposition in jarrah (*Eucalyptus marginata*) forest in Western Australia. *Australian Journal of Ecology* **4,** 279–291.

van de Westeringh, W. (1972) Deterioration of soil structure in worm free orchard soils. *Pedobiologia* **12,** 6–15.

Vyas, N.B. and Hill, E.F. (1996) Toxicity of fire retardant chemicals and fire suppressant foams to vertebrate and invertebrate wildlife species. Ramsay, G.S. (compiler) *International Wildland Fire Foam Symposium and Workshop.* Proceedings. Thunder Bay, Ontario, 3–5 May 1994. Natural Resources Canada, Canadian Forest Service. Petawawa National Forestry Institute. Information Report PI-X-123, pp. 128–131.

Walsh, N.G. and Entwisle, T.J. (1994) *Flora of Victoria. Vol. 2, Ferns and Allied Plants, Conifers and Monocotyledons*. National Herbarium of Victoria and Inkata Press, Melbourne.

Walsh, N.G. and Entwisle, T.J. (1996) *Flora of Victoria. Vol. 3, Dicotyledons: Winteraceae to Myrtaceae.* National Herbarium of Victoria and Inkata Press, Melbourne.

York, A. (1999) Long-term effects of frequent low-intensity burning on the abundance of litter-dwelling invertebrates in coastal blackbutt forests of southeastern Australia. *Journal of Insect Conservation* **3,** 191–199.

York, A. (2000) Long-term effects of frequent low-intensity burning on ant communities in coastal blackbutt forests of southeastern Australia *Austral Ecology* **25,** 83–98.

Zar, J.H. (1999) *Biostatistical Analysis*. Prentice Hall International, London.

Zborowski, P. and Storey, R. (1995) *A Field Guide to Insects in Australia*. Reed Books, Australia.