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Author: Green, Ken

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Migratory Bogong Moths (*Agrotis infusa*) Transport Arsenic and Concentrate It to Lethal Effect by Estivating Gregariously in Alpine Regions of the Snowy Mountains of Australia

Ken Green

National Parks and Wildlife Service,
Snowy Mountains Region, PO Box
2228, Jindabyne, NSW 2627, Australia
kenneth.green@environment.nsw.gov.au

Abstract

The bogong moth migrates annually to the mountains of southeastern Australia in spring, to estivate at alpine altitudes, before returning to the plains in autumn to breed. Although occurring at low densities in the plains as larvae, when they estivate gregariously densities reach high levels, so that any chemicals carried by them are concentrated. One such chemical is arsenic, which is concentrated to phytotoxic levels in the soils surrounding estivation sites. Vegetation may recover as arsenic is made unavailable by time or by fire. This may be a cyclical process that has occurred many times in the past. Bogong moths are an important food for birds and small mammals, and arsenic has been found in the food chain, although bird deaths and population declines in small mammals cannot be positively ascribed to arsenic. Genetic studies and studies looking at the chemical form of the arsenic have so far been unable to confirm the source of the arsenic; however, interception of moths on their spring migration confirms that the source is away from the mountains.

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Introduction

The bogong moth *Agrotis infusa* (Noctuidae) is a multivoltine species in which the spring generation migrates annually from the western slopes and plains of eastern Australia to estivate more than 1000 km away in caves and rock crevices, predominantly in periglacial boulder fields and among rock tors (hereafter all grouped as 'caves') along and adjacent to the Great Dividing Range (Common, 1952). The larvae of this species are found from autumn to spring over a wide area of New South Wales (NSW), extending north to the Darling Downs in Queensland and south to northern Victoria (Fig. 1). These areas have historically been used for grazing and cropping. Bogong moth larvae feed during winter on annual dicotyledons, but the absence of preferred food plants and the preponderance of perennial grasses in the summer lead to food shortages. The sexually immature moths therefore migrate to mountains along the Great Dividing Range in September–October where, with an average bodily fat content of 65%, they fast while estivating gregariously in caves, returning to breed in the plains in the autumn (Common, 1954). Debris consisting of whole moths but mainly head, thorax, and wings collects on the floors of these caves reaching a depth of up to 30 cm in some locations such as at Mount Tingaringy (personal observation). Known moth estivation sites range from the most northerly at Mount Gingera, through the Bogong Peaks and Snowy Mountains to the Victorian Alps, extending to Mount Buller in the southwest (Fig. 1). In addition to estivation sites, bogong moths will also temporarily occupy buildings such as Parliament House in Canberra while migrating.

Heavy rains in November 2000 washed live moths and accumulated debris of dead moths out of many alpine estivation sites. In January 2001, complete mortality of grass in the outwash at one such site prompted an investigation of the affected soils and vegetation. This investigation determined that arsenic was present in moths, soil, vegetation, and the insectivore food chain (Green et al., 2001). The source of the arsenic could not be determined. If it was exogenous, was it derived from areas close to estivation sites by migrating adults, or by larvae from sites distant from estivation sites? Alternatively, was the available arsenic actually generated in estivation sites from chemical changes to the soil caused by the moths themselves?

Within the alpine area, the effects of arsenic in the insectivore food chain could not be determined because mammals were too small for useable blood samples and some were too rare to sample the whole animal or their organs (Green et al., 2001). In spring 2003, 14 birds died at Parliament House after eating bogong moths (Hansard, 2003). This event prompted the reexamination of the impacts on wildlife although the birds had not been collected for forensic examination. The present study was, therefore, aimed at (1) attempting to discover the source of the arsenic, (2) examining the long-term effects on vegetation in an alpine area where regrowth is naturally slow, and (3) examining the impacts on wildlife.

Methods

MOTHS

High Elevation

In the mountains in summer 2001/2002, bogong moths were collected live by hand at estivation sites at Mount Gingera, South Ramshead, and Mount Morgan, and by moth lights at Mount Blue Cow, Charlottes Pass, and Mount Tingaringy (Fig. 2). A further collection was made at South Ramshead in summer 2002/2003. Approximately 2.5 g of each moth sample was digested with a mixture of nitric and sulfuric acid and analyzed for arsenic on a Varian Vista ICP-MS (Inductively Coupled Plasma–Mass Spectrophotometer) with a detection limit of 0.01 mg kg^{-1}. Analysis was undertaken at the Department of Earth and Marine

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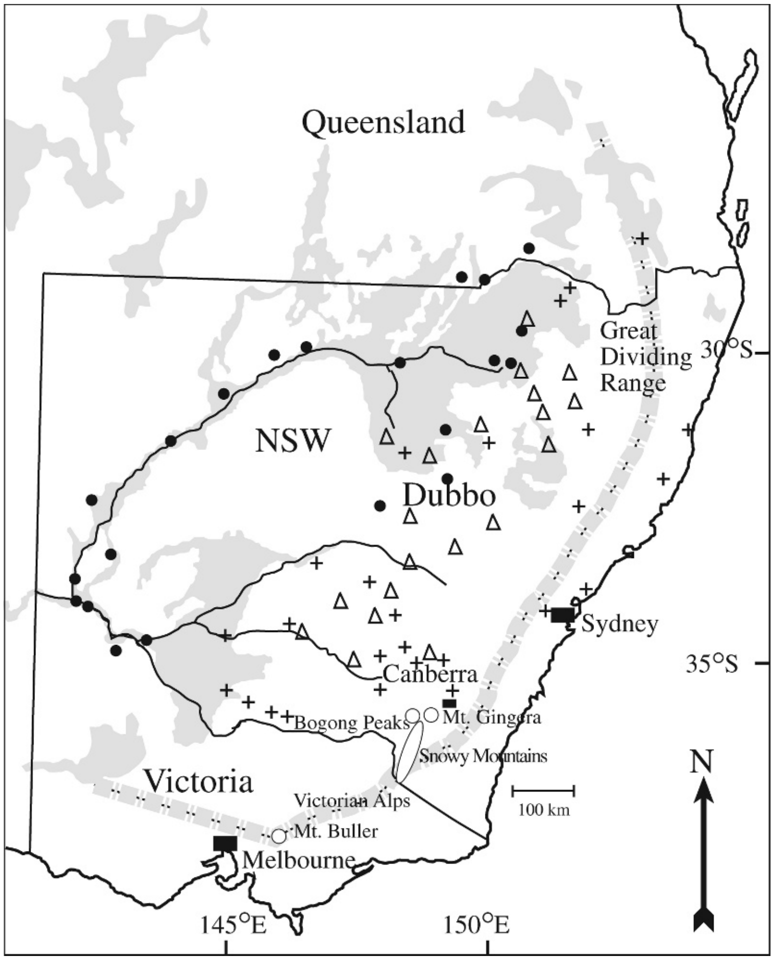

FIGURE 1. Map of southeastern Australia showing the self mulching soils (shaded) which are thought to be the important breeding areas of bogong moths, together with locations where larvae were collected by Froggatt (1900) (open triangles), Common (1954) (crosses), the present study (closed circles), and the sites outside of the Snowy Mountains mentioned in the text.

Sciences Analytical Facility, Australian National University, Canberra. Samples from moths were also analyzed for chemicals currently used in agriculture as a potential aid in identifying the source of the arsenic and to determine whether any other chemical was in sufficient concentration to account for the observed mortality in vegetation and wildlife. To this end, samples from moths collected in 2001 from South Ramshead were extracted in chloroform and analyzed for organic pesticides by the New South Wales Department of Agriculture.

Low Elevation

Two collections were made in spring 2003 using moth lights near Dubbo in western NSW, and one collection of dead moths was made at Parliament House, Canberra (Fig. 1) after walls had been sprayed with a pyrethrum-based insecticide. Moths were frozen as soon as possible after collection for transport to the laboratory. These were analyzed for arsenic on a Varian Vista ICP-MS as above. Moths collected in spring 2003 from Parliament House were also analyzed by the Australian Government Laboratories. Samples were extracted in various solvents and analyzed for synthetic pyrethroids, organochlorine and organophosphate pesticides, carbamates, fungicides, triazine herbicides, and acaricides (miticides). Analytical techniques included gas chromatography with mass selective electron capture, and nitrogen and phosphorus detectors, and flame photometric detectors. A sub-sample of the moths collected from Parliament House was freeze-dried and sent to Queens University (Canada) to determine the form of arsenic that was present: inorganic arsenic As(III) or As(V), or organic derivatives such as methylated arsenic and other compounds. Extraction was by acid digestion (aqua regia) and analysis by ICP.

Bogong moth larvae were collected at 20 sites west of the Great Dividing Range, between southern Queensland and northern Victoria (Fig. 1) from late July to late August 2002. Larvae were collected by digging the soil around weed and crop species to a depth of 100 mm over an area of 100 m^2, and sieving the soil through a 2 mm sieve. Altitude, and the estimated density of larvae were recorded for each site. Larvae were collected for genetic studies and were stored in ethanol and, along with legs from adult moths, sent to La Trobe University (Victoria). This rendered the larvae unsuitable for chemical analysis.

SOIL SAMPLES

In 2001, soil samples were collected from eight different bogong moth estivation sites. Soil samples were collected from (1) within estivation caves, (2) the area outside over which water-born moth debris from the caves drained (the outwash), and (3) as close as possible to this but outside of the drainage line. For each of these three sample areas, at all eight sites, up to five soil samples were taken to a depth of 100 mm and pooled for analysis. Soil exchangeable cations were determined using an ammonium acetate extraction (Lambert, 1978) and analyzed on a Varian Flame Atomic Absorption Spectrophotometer. Soil pH was

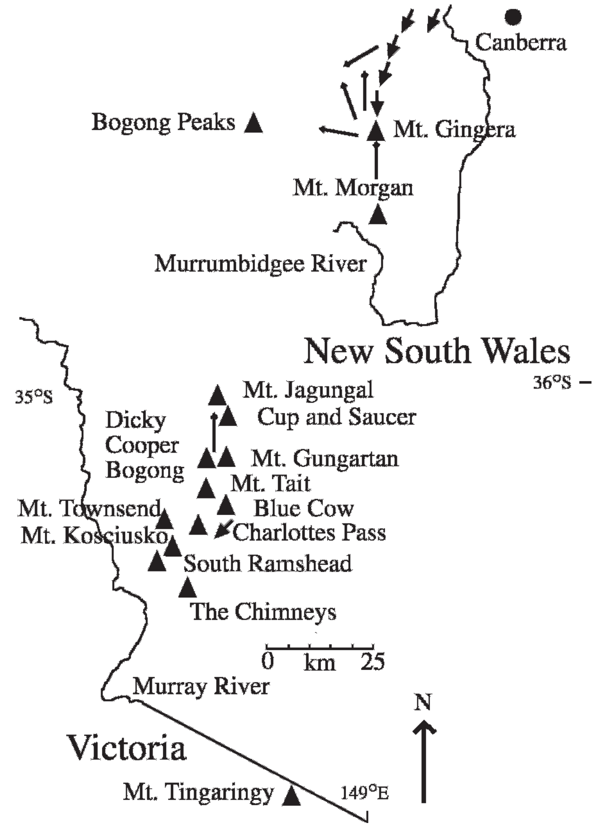

FIGURE 2. The Snowy Mountains showing sites where moths were collected or which had major estivation sites. Locally recorded migration directions are recorded for the spring migration (small arrows) and autumnal, post estivation migration (larger arrows). Migration data are from Common (1954) for the area around Mount Gingera and from Green (2006) and personal observations for the southern records.

determined in a 1:5 distilled water solution (Rayment and Higginson, 1992) at the Soil Analytical Facility at the School of Resource and Environmental Management, Australian National University.

In 2002, soil samples were collected at the same sites as larvae (between southern Queensland and northern Victoria). For each of 20 sites, eight soil samples were taken to a depth of 100 mm and pooled for analysis. Extraction was with nitric acid/hydrogen peroxide and then aqua regia for total cations, and ammonium acetate extraction for plant-available cations. Samples were analyzed on a Varian Vista ICP-MS at the Department of Earth and Marine Sciences Analytical Facility, Australian National University.

Following a wildfire in January–February 2003 that burned through much of the Snowy Mountains including 69.3% of the 139,900 ha above 1500 m altitude, soil samples were collected from seven locations at the South Ramshead site where it was still possible to differentiate between the arsenic-affected and unaffected sites. Samples were analyzed as in 2002 (above).

VEGETATION

To determine the extent of grass killed around moth estivation sites, all major ridges and peaks in the Snowy Mountains containing boulder outcrops were visited, and the presence or absence of estivation sites and the condition of the vegetation were noted. All moth locations were plotted using a hand-held GPS (Garmin Ltd., Kansas City, U.S.A.). On the most severely affected mountain, South Ramshead, six vegetation plots of 1 m^2 were established in 2001, with three plots each in dead and live vegetation. Two corners were marked with steel pegs and a 1 m^2 grid with 20 cm × 20 cm squares marked with string was placed on the ground and photographed. Percentage live vegetation was recorded. The sites were visited in each of the following four years and re-photographed. A wildfire burned through the area in February 2003, killing all vegetation on the northern slopes of South Ramshead where the plots were located.

WILDLIFE

A study population of small mammals was monitored from summer 1978/1979. At each trapping session, 80 Elliott folding metal traps (Elliott Scientific, Upwey, Victoria, Australia) were baited with a mixture of peanut butter, rolled oats, and honey, and were left open for three nights. Five further trapping grids of 50–80 traps were established between 2002 and 2004, specifically for long-term monitoring of the broad-toothed rat *Mastacomys fuscus*. The trapping regime was identical to that for the original grid. All *M. fuscus* were individually marked with microchips inserted beneath the skin. Other species were not of equal concern and were therefore only characterized by age and sex (dusky antechinus *Antechinus swainsonii*) or just age (bush rat *Rattus fuscipes*). Consequently, the minimum numbers of *M. fuscus* known to be alive on the grids could be calculated, whereas for *A. swainsonii* and *R. fuscipes* only the minimum numbers of individuals at each trapping session could be given (Green and Sanecki, 2006). In a continuing study of the mountain pygmy possum *Burramys parvus*, four trapping grids were monitored each year in November–December from 1987 and animals marked with ear tags (Linda Broome, personal communication, 2006).

Results

MOTHS

Bogong moth larvae west of the Great Dividing Range (Fig. 1) were found at densities of 0–4 m^{-2} (0.3 ± 0.8) at sites at an average altitude of 151 ± 67 m. Adult bogong moths were found to be distributed in most complex rocky tops across the Snowy Mountains, concentrated in the Main Range area around the highest peaks in Australia from 1870–2220 m with one outlier to the south at Mount Tingaringy (1450 m) and sites in the Bogong Peaks (~1700 m) and towards Canberra at 1850–1870 m (Fig. 2).

Between when arsenic was first reported from two mountain estivation sites in the summer of 2000/2001, and the following summer, the amount of arsenic found in moths increased by at least an order of magnitude (Table 1). Arsenic concentration was highest at two low elevation sites far removed from mountain estivation sites, on the migration route (Parliament House) and closer to larval sites (Dubbo 2).

Examination of moths from mountain estivation sites at South Ramshead in 2000/2001 revealed no traces of persistent organic pesticides that accumulate in fat such as dieldrin, DDT, chlorpyrifos (used on pastures), and endosulfan (used on cotton and other crops in NSW and Queensland). Moth samples from Parliament House in spring 2003, however, contained 0.95 mg kg^{-1} Deltamethrin (USEPA/OPP Pesticide Code: 097805) and trace concentrations (approximately 0.01 mg kg^{-1}) of organochlorine pesticides, beta endosulfan (a Schedule 6 [PESKEM] non-systemic insecticide and acaricide), HCB (hexachlorobenzene,

TABLE 1

Arsenic (mg kg^{-1}) contamination of bogong moths.

Location	2000/2001	2001/2002	2002/2003	Spring 2003
Mount Blue Cow		0.058		
South Ramshead	0.0023	0.028	0.068	
Charlottes Pass		0.055		
Mount Morgan		0.041		
Mount Gingera	0.0001	0.055		
Mount Tingaringy		0.029		
Dubbo 1				0.035
Dubbo 2				0.094
Parliament House				0.105

a minor impurity in agricultural pesticides), and DDD (a metabolite of DDT).

SOIL

The soil pH in eight control areas (3.84 ± 0.25) was significantly higher than in eight adjacent areas with high bogong moth content (3.43 ± 0.41) resulting from the outflow from caves (paired *t*-test, $t = 0.4998$, $p < 0.005$). Cave soils (3.23 ± 0.18) had a lower pH than outflow areas but not significantly so.

Chemical analysis of soil samples at South Ramshead from after the fire of January–February 2003 showed little difference in arsenic between cave, outwash, and control (Table 2). Concentrations of copper fell from within the cave to the outwash and the controls, while iron was highest in the outwash. Apart from sodium, which was at a much higher level in the outwash than elsewhere, other elements showed either no difference between within and outside of estivation caves or no trends attributable to bogong moth debris. Levels of iron and lead were similar in estivation sites and the plains; figures for all other elements tested (except sodium in the outwash) were lower in the mountains than in the plains. The amount of plant-available arsenic on outwash sites fell between 2001 and the spring sampling after the fire of January–February 2003 to the extent that values in the outwash were virtually the same as in the control (Table 3).

VEGETATION

Grass was killed at bogong moth estivation sites at the central sites of the Snowy Mountains (Fig. 2). Sites to the north (Bogong Peaks, Mount Morgan, and Mount Gingera) had shrubs in the outflow of the cave and these seemed unaffected even though arsenic was found in moths from Mount Morgan and Mount Gingera (Table 1). To the south, the cave in Mount Tingaringy is an open cleavage and most drainage would be vertical rather than out of the cave.

At the estivation sites on South Ramshead, in the two years before the wildfire, the control vegetation plots contained 100% cover of tussock grass (mainly *Poa fawcettii*) in both years while in the arsenic-affected plots there was <0.25% live vegetation (sheeps sorrel *Acetosella vulgaris*) in one quadrat and none in the other two. Of the main vegetation in the arsenic-affected plots, all grass tussock was dead but still rooted in the ground in year 1. By year 2, a mat of dead loose vegetation was lying on the ground. In year 3, fire removed nearly all dead vegetation and all remaining live vegetation at all arsenic-affected plots, leaving 100% bare ground. In year 4, 12 months after the fire, live tussocks of grass were sprouting on the arsenic-affected sites but not on the controls, which still had a mat of dead grass. Recolonization of vegetation on the control sites was by *A. vulgaris* rather than by grass, and by March 2005 the cover of vegetation was similar in controls and arsenic-affected sites (Table 4), although the vegetation type in the plots had completely reversed from before the fire.

WILDLIFE

Populations of the broad-toothed rat *M. fuscus* and dusky antechinus *A. swainsonii*, monitored in the Snowy Mountains from the summer season of 1978/1979, crashed in the winter of 1999; 75% of the population of *M. fuscus* existing over the previous two years disappeared, and both species fell to about 34% of average values over 13 years monitored between 1978 and 1999. The common bush rat *R. fuscipes* was not adversely affected. Subsequent surveys outside of the monitoring site showed that the crash occurred throughout the Snowy Mountains. In 2000, arsenic was found in the feces of three species of small mammal that were either omnivorous or insectivorous with, at most, only trace amounts found in one herbivorous species (Green et al., 2001; Table 5). Population levels in three of four small mammal species monitored in the Snowy Mountains in the past five years have declined, although not just those that might have ingested arsenic-affected moths, because one was a herbivore (Table 5). The species with the highest level of arsenic, *R. fuscipes*, actually increased in numbers.

Discussion

SOURCE OF ARSENIC

Green et al. (2001) concluded that the arsenic found in bogong moths and the insectivorous food chain came from beyond the mountains. Criticisms of this view were based on the two possibilities that (1) there was a source of arsenic close to estivation sites, and (2) available arsenic could be generated by the moths themselves from arsenic within the soil of the cave floor. The physicochemical conditions of lowered pH in caves due to the presence of decomposing moths, anoxic conditions, and a reducing

TABLE 2

Chemical analysis of soil samples at South Ramshead in 2003 ($n = 7$) and the Western Plains in 2002 ($n = 20$). All measurements are mg kg^{-1}.

		Total As	Avail As	Fe	Ba	Cu	Mn	Pb	Sr	Zn	Ca	K	Mg	Na
Cave	Mean	1.447	0.18	12781	24.0	11.2	65.2	5.7	2.3	17.5	222	4209	2111	93
	SD	0.257	0.08	1753	2.2	2.9	11.6	1.0	0.4	1.8	130	773	362	11
Outwash	Mean	1.366	0.20	15171	23.9	8.7	63.1	6.8	2.7	20.2	220	4761	2344	319
	SD	0.197	0.06	1976	3.8	1.4	13.4	1.1	0.8	5.9	126	339	174	574
Control	Mean	1.601	0.19	10296	29.9	7.6	68.2	7.2	2.8	22.5	261	3856	2079	97
	SD	0.479	0.05	2507	6.4	2.1	11.2	1.9	0.8	4.9	174	694	495	23
Plains	Mean	2.673	0.19	15008	39.8	24.5	286.1	5.6	25.9	28.7	4194	5838	2902	397
	SD	1.12	0.06	4652	20.6	16.9	251.2	1.9	27.8	12.5	4039	2886	1753	318

TABLE 3

Comparison between acetate-extractable and plant-available arsenic (mg kg^{-1}) at South Ramshead in 2001 and 2003.

	2001	2003
	8 sites[1]	7 sites
Outwash	1.079	0.20 ± 0.06
Control	0.001	0.21 ± 0.05

[1] Data for 8 sites from Green et al. (2001).

environment in the moth debris, together with microbial activity in the estivation caves, may favor the conversion of endogenous arsenic into the more toxic and mobile arsenite form. Under these conditions, the production of arsine gas (AsH_3) is also favored. There may well be a complex arsenic cycle within the caves, and it is possible that the estivating moths could have been exposed to arsine gas (Dr. Gary Vaughan, Ecotox Pty Ltd, personal communication, 2002).

The results presented here, however, show that arsenic was already present in moths before their arrival in the mountains. The arsenic in moths and implicated in plant death was therefore not generated by the moths during estivation. Neither was the arsenic obtained from near the mountains. Moths at Mount Tingaringy that had not settled into the estivation caves in October and that smelled strongly of nectar had a high level of arsenic. Unlike army cutworm moths *Euxoa auxiliaris* that were previously thought to estivate but, at least in the Rocky Mountains of Colorado, continue to feed while in the mountains (Kevan and Kendall, 1997), bogong moths do estivate (Common, 1952, 1954). Common (1954) found no evidence of mating during the estivation period despite 100 dissections of female moths per week. Bogong moths caged within an estivation site behaved in a similar manner to uncaged moths, making no attempt to escape until the normal migration period nearly three months later (Common, 1952). Kevan and Kendall (1997) suggested that bogong moths may undertake nightly summer nectarivory. This was not the case; feeding experiments were referred to by Common (1954), and snowgums were in full flower at the top of Mount Gingera at the time but moths were rarely noted settled on blossoms (I. F. B. Common, personal communication, 2005). Feeding by moths during the estivation period has not been reported since Common's 1954 paper and food for the autumnal (return) migration is taken en route (Green, 2006) rather than from fat stored during summer as in the case of army cutworm moths (Kevan and Kendall, 1997). Moths collected at Parliament House remote from the mountains (the nearest estivation site is at Mount Gingera 40 km away) and, more importantly, moths collected on the annual migration to the mountains by two collectors on a minimum three different nights at locations near Dubbo (Fig. 1) provide confirmation that the arsenic at mountain estivation sites came from a long distance. The arsenic concentrations were high before the moths reached the mountains (Parliament House samples) and before they had moved far from larval areas (Dubbo samples) and, therefore, feeding close to the estivation sites cannot be implicated in the importation of arsenic to the mountains. In fact, should the moths excrete arsenic over the summer they would actually lose it in the mountains rather than gain it.

TABLE 4

Average live vegetation cover (%) in three arsenic-affected and three control plots over five years, pre- and post-wildfire in 2003.

	2001	2002	2003	2004	2005
Arsenic	<0.08	<0.08	0.0	3.0	11.7
Control	100	100	0.0	2.7	15.7

TABLE 5

Elemental arsenic content of feces (mg kg^{-1}) of four species of small mammal in 2000 and five-year population trend.

Species	Diet	Fecal arsenic[1]	Population trend 2000–2005
Marsupialia			
Burramys parvus	Omnivorous	<0.3	Down[2]
Antechinus swainsonii	Insectivorous	0.5	Down
Rodentia			
Rattus fuscipes	Omnivorous	0.6	Stable/Up
Mastacomys fuscus	Herbivorous	<0.1	Down

[1] Green et al. (2001).

[2] On two of four monitoring sites (Linda Broome, personal communication, 2006).

The distribution of moth larvae shown in Figure 1 demonstrates the enormous area over which arsenic might have been derived. Natal site fidelity by bogong moths would be essential in determining their origin (and hence that of the arsenic). The possibility does exist that migrating moths from specific natal sites do not go to specific areas in the mountains. Wind-assisted migration occurs when insects ascend to altitudes at which they will be transported downwind by favorable winds (Gatehouse, 1997). For nocturnal insects this is usually in the geostrophic layer (Drake and Farrow, 1988). The spring migration of bogong moths is thought to be assisted this way (Gregg et al., 1994) with the assumption that navigation, and hence their end point, is not under the control of the moths.

However, there must be some control of direction for moths to return to the same estivation sites each year. The utility of favorable winds breaks down in autumn when moths must return into the generally westerly airstream. In nearly all autumnal records by Common (1954), the wind at ground level was head-on or a cross-wind. An autumnal return migration documented by Green (2006) also occurred with ground-level headwinds and with headwinds at all altitudes up to above 4000 m, suggesting that the return migration to natal sites is independent of favorable weather systems and might therefore be so in spring.

Attempts to use genetic markers to identify specific natal sites of adult bogong moths (Zoia Hristova, personal communication, August 2006) and army cutworm moths (Hillary Robison, personal communication, August 2006) have yet to be successful. Speciation studies that might have given a clue as to the form of the arsenic and hence its general source were confounded by low arsenic concentrations in moths (John Poland, personal communication, August 2006). Pesticide-derived arsenic might correlate positively with copper, whereas non-anthropogenic arsenic might well correlate more strongly with iron because arsenopyrite, FeAsS, is the most common primary arsenic mineral (O'Neil 1995). However, there is no apparent correlation between arsenic in the present soil samples and either metal. Cave and outwash samples (Table 2) had higher copper content than did controls; however, iron was also higher giving inconclusive results. As a result, we still cannot determine where the arsenic-bearing moths originate.

VEGETATION

The average body mass of bogong moths is about 0.33 g (Green, unpublished data). Total numbers of moths arriving in the mountains have never been determined, but they cover the walls of estivation sites at an estimated 17,000 moths m^{-2} (Common, 1981), giving a density of moths of 5.6 kg m^{-2} and, therefore, an arsenic load on the walls of about 0.3 g m^{-2}. It is this density, and the deaths of a high proportion of these moths, that leads to concentration of arsenic, which is then washed out of the estivation sites in toxic quantities. The levels of bioavailable arsenic found in the soils at South Ramshead in 2001 were sufficient to cause phytotoxicity, particularly if arsenic was present as arsenite As(III) (Gary Vaughan, personal communication, 2002). Therefore, the grass mortality was probably arsenic-related.

The dramatic reduction in the amount of available arsenic in the outwash zones of estivation sites between 2001 and after the wildfire in 2003 may have been caused by heat, which either reduced arsenic into mobile arsine gas (AsH_3) or caused arsenic to bind to organic material in the soil. The difference between available arsenic in controls in 2001 and 2003 may have come about because levels were close to the limit of detectability of 0.1 mg kg^{-1} (Table 3). At the time of the fire, the controls were covered by live green grass, which was killed by heat rather than by burning. This grass would have insulated the soils beneath to some extent, but arsenic may still have been mobilized by the heat. Following the fires of January–February 2003, the soils at South Ramshead had little available arsenic. A result of low bioavailable arsenic levels was the regrowth of vegetation comprising 3% cover on plots, a figure similar to other areas where fire, instead of arsenic, had removed vegetative cover (Catherine Pickering, personal communication, 2005). Subsequently, the increase in cover was approximately the same in controls and previously arsenic-affected sites (Table 4). Plant composition and, therefore, biomass was different with larger-sized grass tussocks in arsenic-affected sites and sheeps sorrel in controls.

The killing of grass in 2001 was not a unique event. In the following summer, a very wet February led to more moth debris being washed out of estivation caves in different locations and leaving lines of dead grass where it washed out. Similar periodic killing of grass outside of moth estivation sites has been observed in the past (Alec Costin and Harvey Marchant, personal communication, 2004), but no previous studies have tried to elucidate the cause. It is possible that the phenomenon is cyclical. Once debris is washed out from the caves, exposure of the arsenic to oxygen would cause oxidation to a non-bioavailable form, which in the present study may have been accelerated by fire.

WILDLIFE

Two suspected causes of avian mortality among the pied currawongs *Strepera graculina* were found in moths sampled at Parliament House in 2003: Deltamethrin and arsenic. Deltamethrin is the main constituent of Cislin 10, which was used to kill moths at Parliament House (Hansard, 2003). It has an LD50 in mallard duck *Anas platyrhynchos* of 4649 mg kg^{-1} (EXTOXNET, 1995). Pied currawongs weigh about 350 g (Wimbush, 1969) and so at the same susceptibility would require the ingestion of 1627 mg of Deltamethrin, or over 1700 kg of moths (at 0.95 mg kg^{-1}). Arsenic (reported as sodium arsenite), however, has a LD50 in wild birds of from 47.6 to 386 mg kg^{-1} (Sample et al., 1996). Taking the lowest LD50 level of 47.6 mg kg^{-1} (reported for California quail *Callipepla californica*), and the levels reported here for moths from Parliament House of 0.105 mg kg^{-1}, the LD50 level would require the ingestion of an order of magnitude less than for Deltamethrin, but still 160 kg of moths. A pied currawong would consume about 60–70 g of food per day (see Nagy, 2001), but like many species would probably gorge if food was abundant and immobilized (as in the case of the moths killed by Deltamethrin). Unless they are more sensitive to arsenic than other birds, it is unlikely currawongs could have ingested a lethal dose of arsenic from eating moths. The death of currawongs at Parliament House in 2003, therefore, remains unexplained.

Apart from Deltamethrin, the moths collected at Parliament House in spring 2003 contained trace concentrations of other pesticides. Examination of bogong moths from South Ramshead in 2001, however, revealed no traces of most agricultural chemicals, and therefore, the moths migrating to the Snowy Mountains appear to be carrying just the one major pollutant, arsenic.

Arsenic was found in feces of three species of mammal in 2000, two of which, the marsupials *A. swainsonii* and *B. parvus*, occur in their highest densities in the kinds of boulder habitat favored by bogong moths (Green and Osborne, 1994). During 2000 and 2001, Green et al. (2001) found no evidence consistent with animal mortality from ingestion of arsenic in the Snowy Mountains. However, wildlife mortality in the mountains may be missed due to low visibility of dead animals—the rocky habitat and large boulders could conceal dead animals or hinder the search for them. For example, although large flocks of up to 1000 little ravens *Corvus mellori* regularly feed on bogong moths (personal observation), die-offs of birds in the mountains have not been recorded and would be more difficult to observe than at Parliament House. The arsenic levels in moths found in 2000 by Green et al. (2001) were an order of magnitude lower than the levels found in moths sampled in 2001–2003 during the present study (Table 1). This may be a real result, a result of using different laboratories for chemical analyses, or, if contamination by arsenic led to an earlier mortality of moths, a result of sampling earlier in the seasons in 2001–2003. Either way, Green et al. (2001) published just before a decline in small mammal numbers that has only become fully apparent since, with two species that feed on bogong moths declining. These two species had 0.5 mg kg^{-1} and up to 0.3 mg kg^{-1} arsenic in their feces (Green et al., 2001). However, *R. fuscipes* had a higher level of 0.6 mg kg^{-1}, but its population is healthy. It is possible that marsupials are more susceptible to arsenic because of their physiology. However, the population of the herbivorous *M. fuscus*, a species that was found to have at most trace levels of arsenic in fecal samples (Green et al., 2001) has also crashed.

The impact of arsenic on these species is unknown because data for the toxicity of inorganic arsenical compounds to wildlife are few, and generally pertain to acute exposure rather than long-term effects on reproduction or development (Sample et al., 1996). Arsenic is known to be a teratogen (lethal to embryos) in some animals (Barlow and Sullivan, 1982) and if implicated in the declines may not be evident in *R. fuscipes* because of its high potential reproductive output. *Mastacomys fuscus* has lower reproductive potential (Happold, 1983) but in the absence of evidence of exposure to arsenic the cause of its decline may be unrelated.

The same transport and concentration of arsenic may well occur in other moth species. Army cutworm moths in North America and greasy cutworm moths *Agrotis ypsilon* in India both migrate from plains to mountains (Johnson, 1969). The army cutworm moth has similar seasonal migratory patterns to the bogong moth, forms dense aggregations during summer diapause, and is a major food for some populations of grizzly bears *Ursus arctos horribilis* in the Rocky Mountains (Chapman et al., 1955; Hendricks, 1998; Robison et al., 2006). However, whereas bogong moths migrate to the mountains in the geostrophic layer and do not feed once in the estivation sites, army cutworm moths fly at ground level to the mountains where they continue to feed and accumulate most of their fat in the alpine area (Kevan and Kendall, 1997). Army cutworm moths would have been a likely target for arsenic sprays in the past and would occur in affected soils. Other pesticides, however, have not been found in significant amounts in army cutworm moths (Robison et al., 2006), a similar result to that reported here.

Conclusion

From the furthest extent of larval sites of bogong moths in the northwest to the nearest estivation site at Mount Gingera involves a migration of approximately 1000 km. While the transport of arsenic into the mountains is now demonstrated, the provenance of the arsenic remains unknown. The transport of a pollutant to mountains over such a long distance by means of migrating insects and its concentration by gregarious estivation at mountain sites where vegetation was killed appears to be unique in the literature. Although the arsenic reported here has not been proven to affect wildlife, the concentration of arsenic is known to be lethal to plants outside of the caves and it may also be having an undocumented deleterious effect on decomposer organisms of the cave floor.

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