Ant (Hymenoptera: Formicidae) diversity influenced by tree thinning in the Western Australian jarrah (*Eucalyptus marginata*) forest

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The Western Australian Water Corporation has trialled a catchment – management program in the northern jarrah forest as a possible means of enhancing water runoff and yield. Thinning has been performed by chemical injection of trees and/or by logging. This paper reports on the impact of this program on a prominent indicator component of the biota, the ant fauna. Six plots were sampled in 2006, prior to treatment and afterwards in 2008 and 2009. Two plots were unthinned controls, two were thinned, one was thinned and logged and the other was thinned, logged and burned, resulting in representations of a gradient of intervention.

However, ant abundance increased in all treated plots, especially so in the thinned, logged and burned plot. Over the three years, species richness increased in Control Plot 2, in thinned by stem injection Plot 3, in thinned by logging and burned Plot 5 and in thinned by logging Plot 6 but declined in thinned by stem injection Plot 4 and recovered somewhat but did not attain 2006 levels in Control Plot 1. Ant species evenness declined in the two thinned by logging plots. An NMDS ordination indicated that the degree of change in ant assemblage composition was lowest in the controls, increased in the thinned plots and by a further increment in the thinned by stem injection and thinned by logging plot, and was greatest in the plot that had been burned.

In summary, the various shifts in ant dynamics do not present a clear pattern over all the plots. The most noticeable changes were a shift in equilibrium between ant ecological groupings noticed in plot 3 in 2008 and the loss of cover-loving species in Plot 5 and their replacement by those that favour open ground. Plot 5, where burning was conducted, produced results that suggest an ant fauna adapted to cool, moist conditions may be in the process of being replaced by one favouring warmer conditions; with under cover nesters also replaced by open soil nesters. Potentially, there could be a loss of some species with depauperisation of the ant fauna overall. At the same time, there were no signs that the environment was being so seriously degraded that native dominants such as *Iridomyrmex chasei* (Forel) and meat ants or exotics like *Pheidole megacephala* (Fabricius) or the Argentine ant (*Linepithema humile* (Mayr)) were establishing colonies. Such species appeared to be completely absent from the survey sites.

KEYWORDS: ant diversity, functional groups, Wungong catchment, Water Corporation, tree thinning, jarrah forest

INTRODUCTION

Until very recently, the drying of the southwest of Western Australia due to climatic change has posed particular problems for people living in the Perth Basin (Barron *et al*., 2013). The threat to the availability of potable water has to some extent been reduced by the construction of desalination plants at Kwinana and Binningup, although the increased use of recycling, dams and groundwater also continue to be important in supplying Perth's water needs (Water Corporation, 2011a). One possible way of improving the flow of water into forested catchments is by thinning of the tree cover (Bosch & Hewlett, 1982; Stoneman, 1993). However, jarrah (*Eucalyptus marginata* Donn ex Sm) forest also has a significant groundwater system. The interaction between these two systems has to be taken into account in interpreting stream-flow following thinning of the forest (Ruprecht & Schofield, 1989). What should also be considered, if the forest itself is to be maintained in a state of ecological health, is the impact of thinning on the resident biota. Overseas, thinning has mainly been concerned with good silvicultural practice and reduction of pest attack on commercial timber (e.g., Bennett, 1968; 1971; Hedden, 1982; Nebeker *et al*., 1985; Warriner *et al*., 2002), rather than improving hydrology. Data for Australia are scant indeed, especially where the thinning has been carried out for hydrological purposes. Where work has been done on the impact of tree-thinning on Australian fauna, e.g., in the Box-Ironbark Ecological Thinning Trial (Arthur Rylah Institute: http://www.dse.vic.gov.au/arthur-rylah-institute/research-themes/forest-and-woodland-ecosystems#thinning), this has been presented as website summaries or other popular scientific formats, rather than in learned, peer-reviewed articles.

This paper seeks to address some of these deficiencies by examining the effect of hydrological tree thinning activities on the fauna of the Wungong Catchment, near Perth, Western Australia, using ants as a surrogate for other forest organisms (including plants). For some years ants have been used as biomonitoring indicators of disturbance by Australian researchers (e.g., see Majer & Nichols, 1998; Andersen *et al*., 2002; Hoffman & Andersen 2003; Heterick *et al*., 2013; Majer *et al*., 2013), since they are well studied taxonomically, are diverse and numerous, are easy to collect and the different species respond in a measurable way to perturbations in their environment.

In this paper, we examine the immediate impacts of thinning on the ant fauna around the Wungong catchment in 2008 and 2009 (Figure 1), by comparing the situation prior to thinning in 2006. Further monitoring was not possible, as the thinning program was discontinued due to the combined factors of unusually dry years during the trial and an increased focus by the Western Australian Water Corporation on climate independent water sources (Water Corporation, 2011b).

METHODS

Plot descriptions

The Wungong Catchment Trial was a Water Corporation initiative to determine the ability to increase the quantity of water available for public water supply through alternative forest management practices (Loh *et al.* 2009). As part of the requirements**,** the Water Corporation was obliged to conduct various monitoring programmes, including fauna monitoring. Data from ALCOA's fauna monitoring programme was used as the baseline data. A similar fauna monitoring technique used by ALCOA was used in this instance in order to maintain the compatibility of fauna data collected.

Two types of catchment thinning were employed to reduce the catchment basal area to 15–18 m^2/ha, namely: (1) a non-commercial thinning (in areas where very few commercial size trees were present); and (2) a commercial logging in areas where they did exist. In both prescriptions, trees and logs to be retained were marked, and all other trees treated. Non-commercial thinning involved stem injection in the non-summer months. Commercial logging involved logging commercial-sized trees until the required BA was obtained, single tree selection, shelterwood (i.e., mature trees left standing to provide shelter for growing saplings) and the creation of gaps for regeneration. While a prescription burn after treatment was the intention for all of the treatment sites, only in Plot 5 was the burn actually carried out during the sampling period. This was done in December 2007. As at the end of 2009, the other three treatment sites had not been burnt. Some idea of the scope and impact of the fire can be gauged from Figure 2 (Plot 5).

All treated areas were situated in similar types of forest (Havel's (1975) P or P/S types). The detailed descriptions of each plot are provided in Appendix 1. Within each of the treatment types, two plots (i.e., Plots 3 and 4 – thinned non-commercially (Figure 3), and 5 and 6 – thinned by logging (Figure 4)) were set up, with two control plots (Plots 1 and 2 (Figure 5)) (marked out in non-treated forest. The six plots were established prior to treatment to provide baseline data from which change could be measured. Each plot consisted of two sets of 250 m transects, with measurements made each 20 m along the transect. An effort was made to select sites that were similar. However, logging and fire histories could not be completely matched. The thinned plots (Plots 3 and 4) had been heavily logged about 20 years previously and had not been burnt since that time. Plots 1 and 2 and Plots 5 and 6 had been selectively logged well over 50 years ago and had been prescribe burned within the past four-six years. In terms of degree of stress introduced into the environs of these four plots by the respective treatments, Plot 5 could be understood to have seen most stress as commercial logging and burning operations were both conducted in this plot within the monitoring period. Plot 6 was exposed to

Table 1. Summary of plot characteristics measured prior to treatment in 2006 and post-treatment in 2009 (in brackets) (adapted from Kabay, 2009).

	Control		Thinned		Thinned/logged and burned	Thinned and logged
2006(2009)	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 5**	**Plot 6**
BA (Basal Area (m2/ha))	41.5(46)	31*(34)	27.5(11.5)	29(13)	37.5(17)	31(19.5)
% Canopy cover	31.5(36)	49.5(48)	32.5(16.5)	30(15)	46.5(20)	49(21)
SPH (Stems per ha)	1,980(1500)	510(500)	1,886(161)	781(155)	702(317)	878(275)
% Total Forest Cover	131.1(104.8)	138(103.2)	46.3(37.9)	63.1(52.1)	75.2(52.9)	88.7(66.8)
% cover in 0–25 cm strata	16.4(9.6)	14.6(8.6)	3(2.8)	5.2(4.2)	8.5(3.4)	11.8(7.8)
% cover in 25–50 cm strata	23.1(13.8)	17(9.8)	3.1(3.4)	4(4.4)	11.8(5.1)	10.2(6.7)
% cover in 50–100 cm strata	24.4(17.3)	18.6(12.9)	3.8(4.2)	9.8(8)	11.2(9.3)	11.1(8.9)
% cover in 100–600 cm strata	21.8(18.7)	32.9(23.9)	19.2(12.5)	20.5(15.3)	23.9(15.3)	21.8(15.2)
% cover in >600 cm strata	45.4(45.4)	54.9(48)	17.2(15)	24.4(20.2)	19.8(19.8)	33.8(28.2)
Logs<10 cm diam	3.8(2.8)	4.5(3.4)	0.6(1)	1.6(1.6)	2.5(1.7)	8(9.1)
Logs10–30 cm diam	4.3(3.3)	4.5(3.3)	0.3(1.3)	2.6(2.7)	2.9(3.1)	6(9)
Logs>30 cm diam	7.1(3.9)	8.3(4.7)	0.7(1)	4.3(3.5)	3.2(3.9)	5.4(6.9)
Litter%	28.4(70.8)	26.2(67.3)	38.7(64.9)	47.5(64.3)	29.1(40.4)	67.9(63)

* mean of four measurements done early 2006

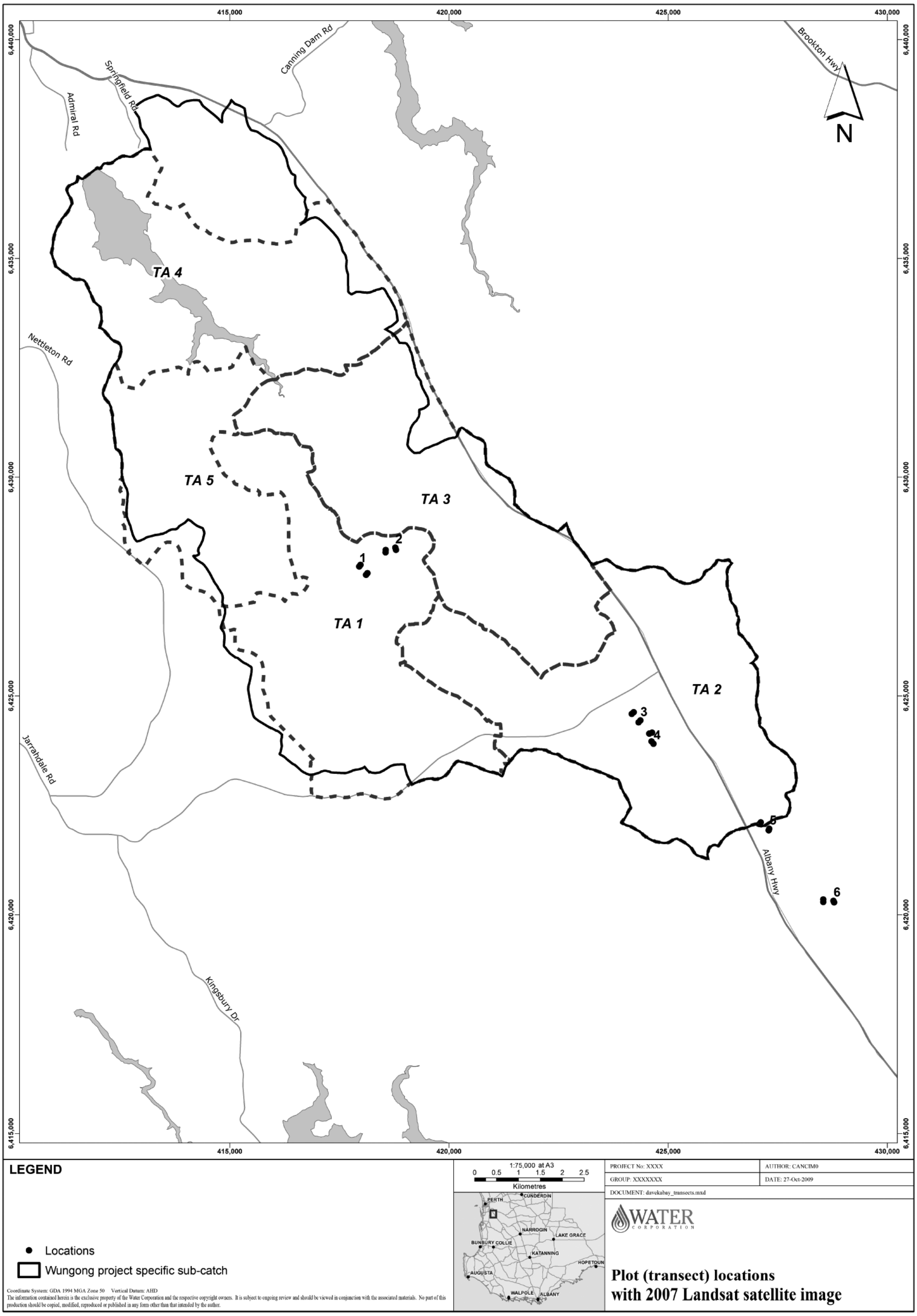

Figure 1. Location of the Wungong Catchment tree thinning project.

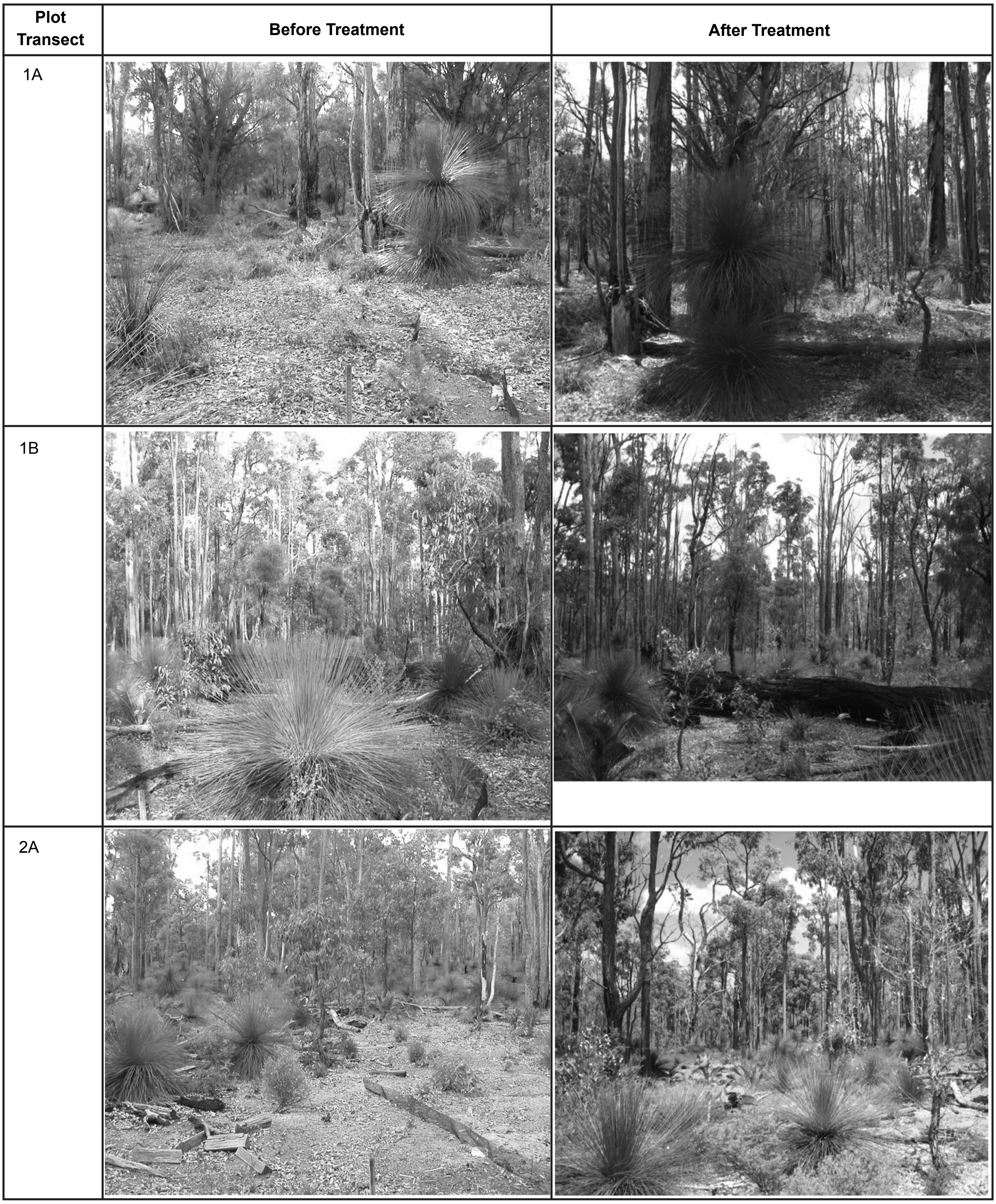

Figure 2. Photographs taken in 2009 of two forest Controls (Plots 1 and 2) two thinned plots (Plots 3 and 4), the thinned, logged and burned plot (Plot 5) and the thinned and logged plot (Plot 6). View A is the commencement of the transect (looking up the transect) and view B is the end of the transect (looking down the transect).

Plot Transect	Before Treatment	After Treatment
2B		
3A		
3B		

Figure 2 (cont.) See p. 104 for caption details.

commercial logging, and hence greater environmental stress than Plots 3 and 4, which were exposed to non-commercial thinning only. The effect on fauna was therefore hypothesised to form a descending gradient from Plot 5 to Plot 6, through to Plots 3 and 4 and down to the control Plots 1 and 2.

Prior to stem injection and logging operations, basic vegetation characteristics relevant to the study were measured (a summary is given in Table 1). (The low values for some parameters in Plots 3 and 4 reflect a heavy logging operation that was carried out on these sites during the time that adjoining areas were being mined for bauxite. This had limited the basal area that might have been expected given the many years that had passed since the last burn.)

Invertebrate sampling

While other fauna groups were also sampled, only ants are reported on here. Ants were collected in 20 pitfall traps (42 mm diameter x 100 mm depth) set in each plot, i.e., 120 traps in all. All traps contained 50 ml of Galt's Solution to preserve specimens. All ant sampling was performed in summer, when ant activity is greatest. In 2006, traps were opened between 7^{th} and 8^{th} of

Figure 2 (cont.) See p. 104 for caption details.

March and taken up on 14th or 15th March. Two post-treatment monitoring operations were performed for the same sampling length in 2008 and 2009, respectively. However, no monitoring was conducted in Plots 2 and 4 during 2008. The precise date of setting up of the traps and collection of the catch is not known for 2008, which took place over one week in January of that year, but the 2009 catch was collected from traps set up on 7th or 8th of March 2009 and taken up on 14th or 15th March 2009, as had been done in 2006. Relevant rainfall and temperature records for the known dates of collection (7th – 15th March 2006 and 2009) can be found in Appendix 2. Specimens were identified by the first author at Curtin University and voucher specimens for the species found are deposited in the Western Australian Museum.

Data analysis

The numbers of ants within each species were tabulated for each plot and summarised as ant abundance, ant species richness, species diversity (Shannon-Wiener index) and evenness (calculated by dividing the Shannon-Wiener index by the square root of species richness). These summaries were then presented as histograms for each plot over the three sampling periods. Regrettably, the absence of 2008 data for two of the plots means no comparative quantitative statistical analysis such as comparison of mean values is possible. Instead, a multivariate analysis of the sites was performed using the package PAST 3.0 (Hammer, 2013). Using this package, a non-metric multidimensional scaling (NMDS) ordination, based on Bray-Curtis matrices data, was performed. In order to represent the trajectories in each plot over time, the corresponding points have been joined up and the similarity index values drawn in. This is necessary because the length of a line on a two-dimensional diagram may not accurately represent the similarity in multi-dimensional space. It should be remembered that 2008 data do not exist for Control Plot 2 or Thinned Plot 4. However, the degree of similarity between the 2009 and the pre-treatment 2006 data is of the greatest interest, along with the magnitude of the change in 2008 after the forest treatment, as these represent longer-term and immediate responses, respectively.

RESULTS

A total of 6681 ants belonging to 88 species, 31 genera and eight subfamilies was collected over the three seasons (Table 2). Forty-six species were trapped in Plot 1, 24 in Plot 2, 51 in Plot 3, 43 in Plot 4, 42 in Plot 5 and 38 in Plot 6. The species data for Plots 2 and 4, however, should be treated with caution because no trapping was undertaken on these sites in 2008.

Plot Transect	
5A	
5B	
6A	
6B	

Figure 2 (cont.) See p. 104 for caption details.

Table 2. Ant species collected in the six forest plots over a three year sampling period (2006, 2008 and 2009).

	Control 1			Control 2			Thinned 3			Thinned 4			Thinned/logged and burned 5			Thinned and logged 6		
(Year)	2006	2008	2009	2006	2008	2009	2006	2008	2009	2006	2008	2009	2006	2008	2009	2006	2008	2009
Cerapachyinae																		
Cerapachys flammeus (Clark)	1				*						*							
Cerapachys gilesi (Clark)					*	17					*	1						
Cerapachys sp. JDM 1040					*		12		2		*							
Dolichoderinae																		
Anonychomyrma fornicata (Emery)		1	1		*	1				1	*	2		7	1			1
Anonychomyrma itineransperthensis Forel					*						*		1			16	1	2
Anonychomyrma nitidiceps André	1		2		*	6		5	1		*	2		1			6	13
Arnoldius flavus (Crawley)					*	1					*							
Doleromyrma darwiniana (Forel)	52	43	44		*		68	6	5	27	*	4	22	3	6	7	2	4
Doleromyrma rottnestensis (Wheeler)					*				4		*	38			1			
Dolichoderus ypsilon Forel					*						*		1	1				
Iridomyrmex bicknelli Emery					*		10		37	103	*	73			284			
Iridomyrmex calvus Emery	1				*					1	*		1					
Iridomyrmex conifer Forel					*		48	33	280	5	*				13			
Iridomyrmex discors Forel					*		4				*							
Iridomyrmex innocens Forel					*				1	1	*							
Iridomyrmex mjobergi Forel					*				7		*							
Iridomyrmex omalonotus Heterick & Shattuck					*			5										
Iridomyrmex splendens Clark		2	1		*			11	8	7	*	9			3			
Ochetellus glaber gp. sp. JDM 19			3		*		1	2		1	*	2		1	1	1	2	
Tapinomaminutum broomense Forel	3	11			*	1				3	*	1	3			12	4	1
Ectatomminae																		
Rhytidoponera inornata Crawley	19	4	27		*		1	1		8	*	16		1	8			1
Rhytidoponera metallica (F. Smith)	36	35	104		*	2	48	84	38	62	*	36	2		25		3	1
Rhytidoponera punctigera Crawley					*			8			*							
Rhytidoponera rufonigra Clark					*		2		4	1	*							
Rhytidoponera violacea (Forel)	10	25	9	1	*	2	7	2	16	29	*	45			1			
Formicinae																		
Camponotus claripes Mayr		1		1	*			1			*						2	
Camponotus marcens Forel	2				*		3	1	1	4	*	2						
Camponotus michaelseni Forel			3	2	*	2	7		2		*				1			
Camponotus minimus Crawley			4		*	2	1		2	1	*					1		10
Camponotus rudis McArthur	1				*						*							
Camponotus prostans Forel					*	1	4		3	1	*	1		5	3			
Camponotus scotti McArthur					*				1		*							
Camponotus terebrans (Lowne)			1		*			1			*		3	12	43			
Melophorus insularis Wheeler	29	25	18	3	*	5	21	46	36	43	*	50		6	17	3	8	38
Melophorus ludius Forel	18	9	30		*		37	9	71	41	*	192	1	11	11		2	11
Melophorus turneri perthensis Wheeler					*		6	10	11	23	*	62						
Melophorus sp. JDM 898					*						*	1						
Notoncus cf *capitatus* Forel					*					2	*	1						
Plagiolepis squamulosa Wheeler				3	*						*			1			2	
Plagiolepis sp. JDM 189					*						*		1				1	
Prolasius antennatus McAreavey	2				*						*							
Prolasius reticulatus McAreavey		1			*					1	*							

Stigmacros aemula Forel					*					5	*	1					2	
Stigmacros brachytera McAreavey					*				1		*							
Stigmacros clarki McAreavey					*		1				*		1					
Stigmacros debilis (Bolton)	1				*						*							
Stigmacros epinotalis McAreavey	1				*						*		1			5		2
Stigmacros glauerti McAreavey					*					2	*	1	3		5	5		8
Stigmacros occcidentalis (Crawley)					*					1	*		1				1	
Stigmacros sp. JDM 115		2	22	21	*	23	4		1		*		7	1	1	5		9
Stigmacros sp. JDM 443		18			*						*			12				
Heteroponera imbellis (Emery)					*						*					1	1	
Myrmeciinae																		
Myrmecia callima (Clark)					*			2			*							
Myrmecia chasei Forel					*				1		*	1						
Myrmecia mandibularis F. Smith	1				*				1		*							
Myrmecia vindex F. Smith	1				*						*							
Myrmicinae																		
Adlerzia froggatti (Forel)			1		*						*							
Anisopheidole antipodum (F. Smith)	5	1			*		2		5		*	3						1
Austromorium flavigaster (Clark)					*						*		2					2
Colobostruma mellea Shattuck	1		38		*						*							
Crematogaster dispar Forel	1		1	4	*	9					*		10	15		18	4	5
Crematogaster laeviceps chasei Forel					*		1				*				1			
Crematogaster queenslandica gp. sp. JDM 428			1		*						*					2	90	
Meranoplus ferrugineus Crawley	1				*		2			1	*							6
Meranoplus rugosus Crawley	9				*		4		1	1	*	4						
Meranoplus sp. JDM 74					*		5		1	1	*	7						
Meranoplus sp. JDM 491					*						*		1	1		1		
Meranoplus sp. JDM 677					*						*						5	
Meranoplus sp. JDM 1107					*			3			*						1	
Monomorium fieldi Forel					*						*			1			2	
Monomorium hildebrandti gp. sp. JDM 438	2				*					2	*							
Monomorium laeve Mayr		21			*	1		13		16	*	2		4	7		5	
Monomorium leae Forel	6	4	9	17	*	8	2		3	3	*		9		6	6	5	15
Monomorium sordidum Forel	106	66	99	224	*	96	43	1	42	16	*	183	22	19	116	132	43	265
Monomorium sublamellatum Heterick					*	1					*							
Monomorium sydneyense Forel	61	9	8	8	*	16	312	11		46	*		11	10	9		6	
Monomorium sydneyense complex sp. JDM 101			62		*	13			124		*	161		2	60			
Pheidole ampla perthensis Crawley	5	14	3	10	*	13		7			*		1	12		29	45	54
Pheidole rugosula Forel	2		36		*						*							
Pheidole sp. JDM 164					*		4		2	45	*	24			4		1	
Solenopsis clarki Crawley	9		2		*	1	3		2	5	*	4	1			1	1	
Tetramorium impressum (Viehmeyer)		1			*					5	*	3						
Tetramorium striolatum Viehmeyer	2				*		9		8	11	*	19			2			
Ponerinae																		
Austroponera rufonigra (Clark)					*		1				*							
Brachyponeralutea (Mayr)			1		*		1	3	5	2	*	3				1		1
Hypoponera congrua (Wheeler)	1				*						*							
Leptogenys neutralis Forel				1	*						*						1	
Platythyrea micans (Clark)					*		1	1	1		*							
Total abundance	**390**	**293**	**530**	**295**	*	**221**	**675**	**266**	**728**	**527**	*	**954**	**105**	**126**	**629**	**246**	**246**	**450**

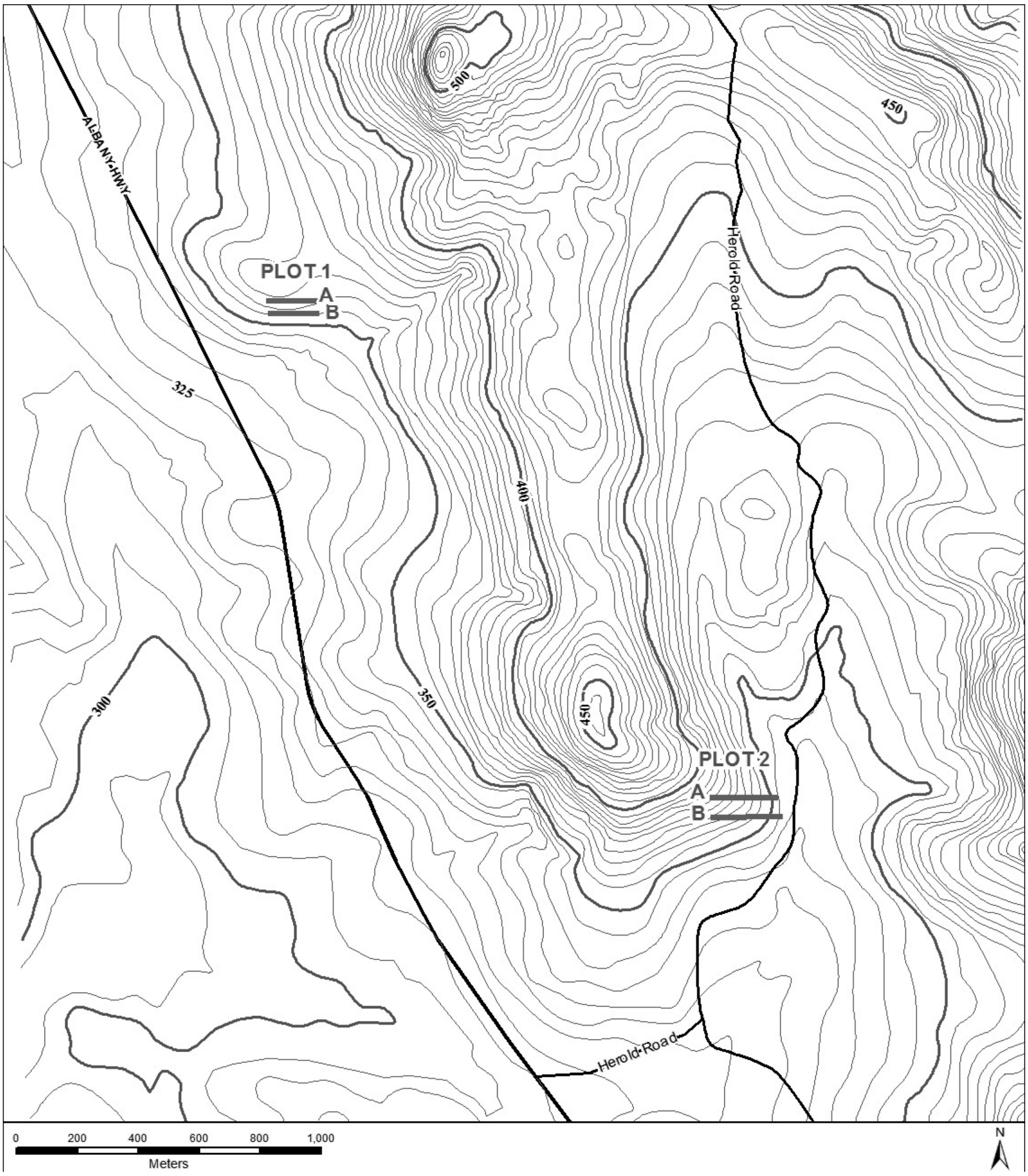

Figure 3. Catchment thinning treatments plots 3 and 4 (adapted from Kabay, 2006, Figure 2).

Ant summaries

Histograms of ant abundance, species richness, and evenness over the three sampling years are shown in Figures 5, 6 and 7, respectively; species diversity is not presented here as it is derived from components of richness and evenness and provides no additional information to that shown in the other graphs.

Ant abundance varied from 954 (Plot 4 in 2009) to as little as 105 (Plot 5 in 2006) (Figure 6). Ant abundance increased from the first survey to the last in one of the control plots (Plot 1), but not in the other. However, abundance increased from pre-treatment to the 2009 survey period in all four thinned or logged plots, with the increase being most pronounced in the thinned, logged and burned plot (Plot 5).

The greatest richness was found in Plot 4 in 2006, when 37 ant species were recorded, and the lowest richness was discovered in Plot 2 (also in 2006) when only 12 ant species were recorded. A simple regression of the abundance versus the richness data using the PAST program mentioned above indicated high abundance was associated with high diversity (r^2 = 0.458, r = 0.676, p = 0.004; Ordinary Least Squares algorithm). Despite this correlation, the trends in the treated plots did not reflect the trends in abundance so markedly, with only slight increases in richness by the time of the last survey in thinned Plot 3 and thinned, logged and burned Plot 5 and thinned and logged Plot 6; there was a slight decline in richness in thinned Plot 4.

A very low evenness index of only 0.41 was recorded for Plot 2 in 2006 while, at the other end of the scale, Plot 5 saw a high evenness index of 0.86 in 2008 (Figure 7).

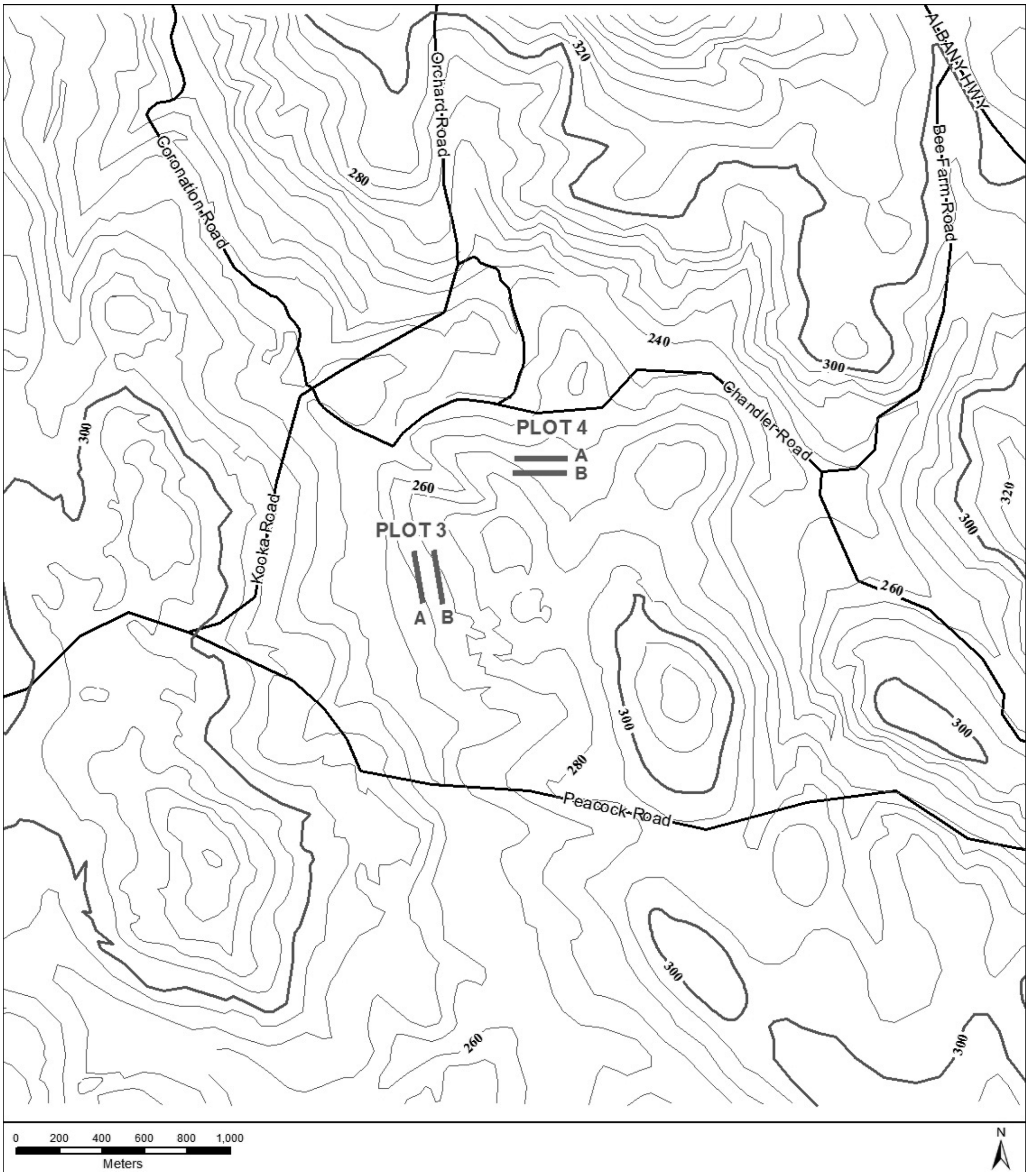

Figure 4. Catchment thinning, logging and burning treatment (Plot 5) and thinning and logging treatment (Plot 6) (adapted from Kabay, 2006, Figure 3).

Evenness was higher in the 2009 surveys than in 2006 for both control plots. However, it declined in the two plots that had been logged (Plots 5 and 6), stayed the same in thinned Plot 3 and increased in thinned Plot 4.

Identification of changes in the presence of individual species is complicated by the fact that trapping positions were not identical in each survey. Furthermore, even when placed in an identical position, the actual species caught are subject to chance foraging events, meaning that even if there are no changes in species present, the same set of species may not necessarily be sampled. Nevertheless, an analysis of the species lost or gained in 2009, three years after treatment, may provide some indication of the degree of species turnover in control and treated plots.

The two control plots (Plots 1 and 2) incurred two and three losses, and six and 11 gains, respectively. These losses and the relatively high number of gains illustrate the dynamic nature of ant assemblages. The losses in treated plots 4–6 were three, 11, three and three in that order, and the gains were six, six, four and six. Thus, apart from the high number of gains in thinned plot 4, these losses and gains were within the range found in the control plots.

Considering the changes in functional group (*sensu* Greenslade and Thompson, 1981, Andersen, 1990) is informative, however. If profiles for combined control plots are compared with combined treatment plots, there is evidence of a higher degree of gain in the treated plots of species from the Dominant Dolichoderinae (e.g.,

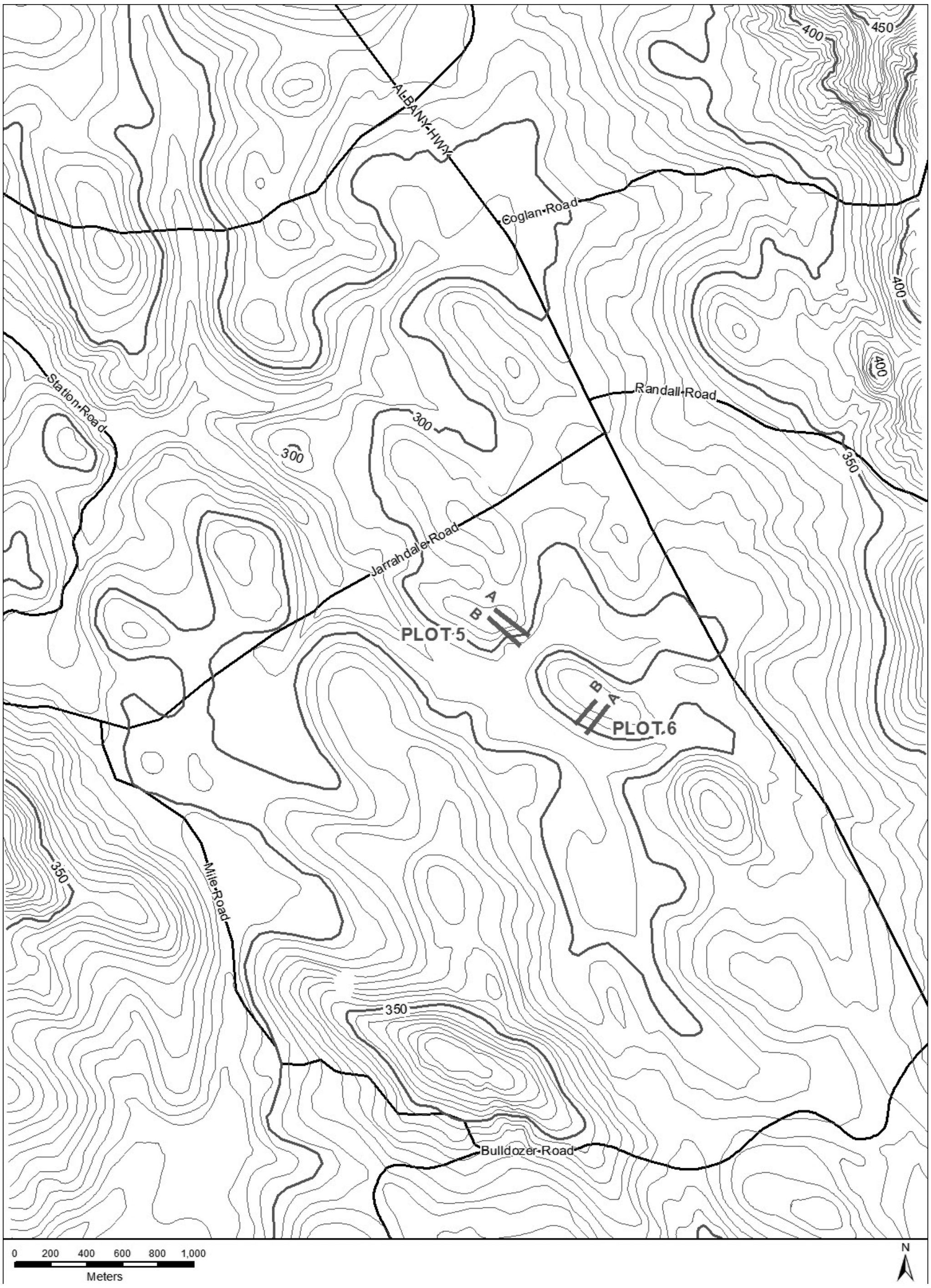

Figure 5. Control Plots 1 and 2 (adapted from Kabay, 2006, Figure 4).

Iridomyrmex spp.), Hot Climate Specialist (e.g., *Melophorus* spp.) and Opportunist (e.g., *Rhytidoponera* spp.) groups when compared with the situation in the controls.

Multivariate analysis

The four plots sampled in 2008 all exhibited shifts in ant assemblage composition from that present in 2006, with similarity being lowest in the thinned plus logged plots (0.642 and 0.669 in Plots 5 and 6, respectively), intermediate in thinned Plot 3 (0.690) and highest in control plot 1 (0.840). Over the longer term, both control plots exhibited the highest similarity (0.802 and 0.881 in Plots 1 and 2, respectively), intermediate values in thinned Plots 3 and 4 (0.746 and 0.776, respectively) and lowest similarity in the thinned plus logged plots (0.663 and 0.708 in Plots 5 and 6, respectively). Of particular note is the fact that the logged and thinned plot that had also been burnt (Plot 5) had the lowest similarity value. Thus, overall, increasing disturbance seems to result in the greatest change in ant assemblage composition (Figure 9).

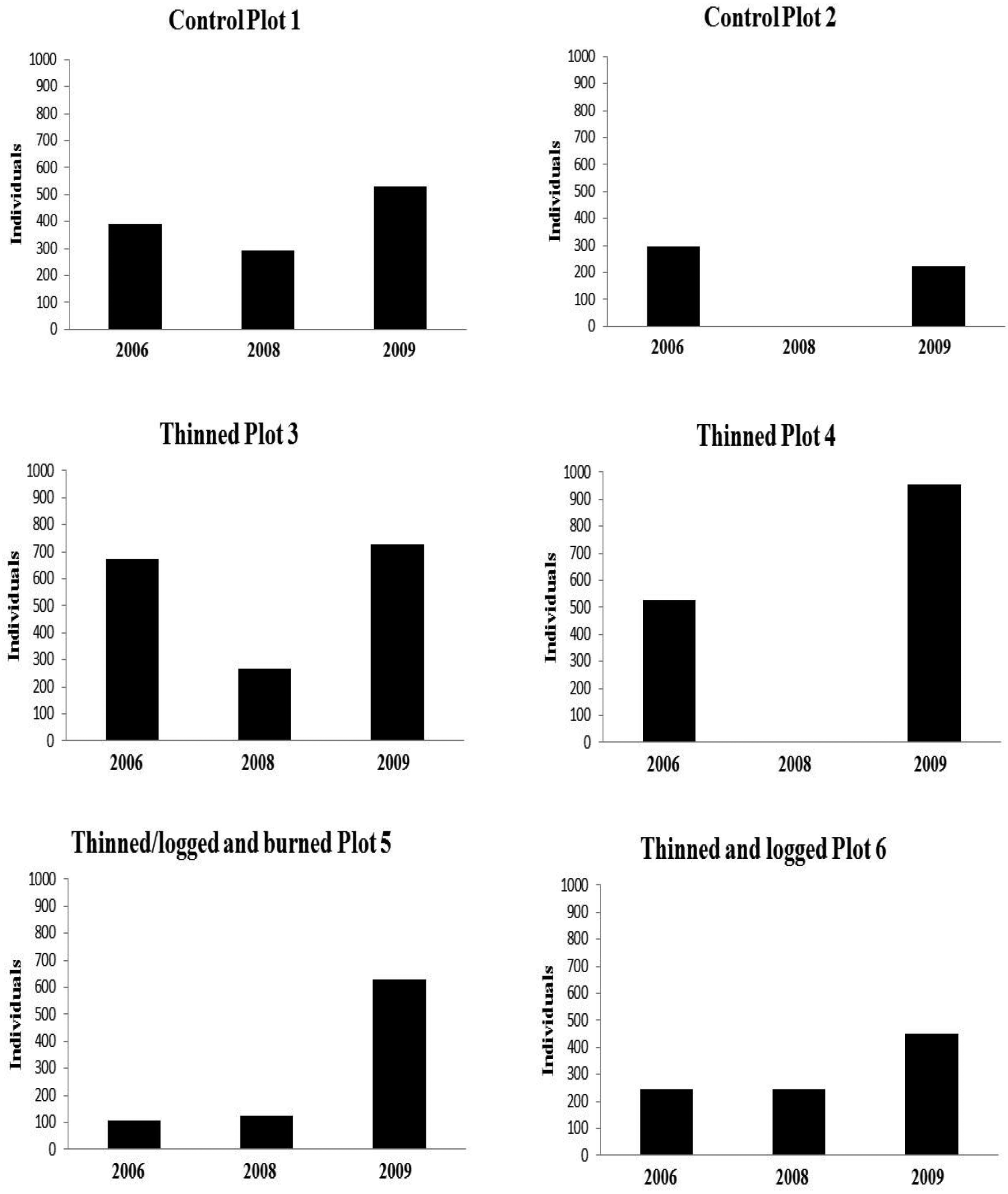

Figure 6. Ant abundance for the six plots.

DISCUSSION

General Trends

Any interpretation of the data is limited because of the incomplete sampling, and also the different months in which the ants were collected (January 2008 and March 2006 and 2009). While thermophiles are normally most active in mid- to late-summer when ground surface temperatures are at their highest, other species may be winter-active or forage early in the morning or at dusk when ground surface temperatures are cooler. Regrettably, this also means there is no exact correspondence between the datasets for the three years. Some idea of the surface conditions can be obtained from a composite picture of climate records from Karnet (Bureau of Meteorology 2014) and the Wungong Catchment (incomplete) (Kabay 2006, 2009). These indicate that rainfall in January 2008 was 0.0 mm (Kabay, 2009) and rainfall for March 2006 was 7.6mm (all but 0.2 mm falling before 15th March) (Kabay, 2006) and for March 2009 it was 8.4 mm (all falling after the 15th March) (Kabay, 2009). Average temperature maxima

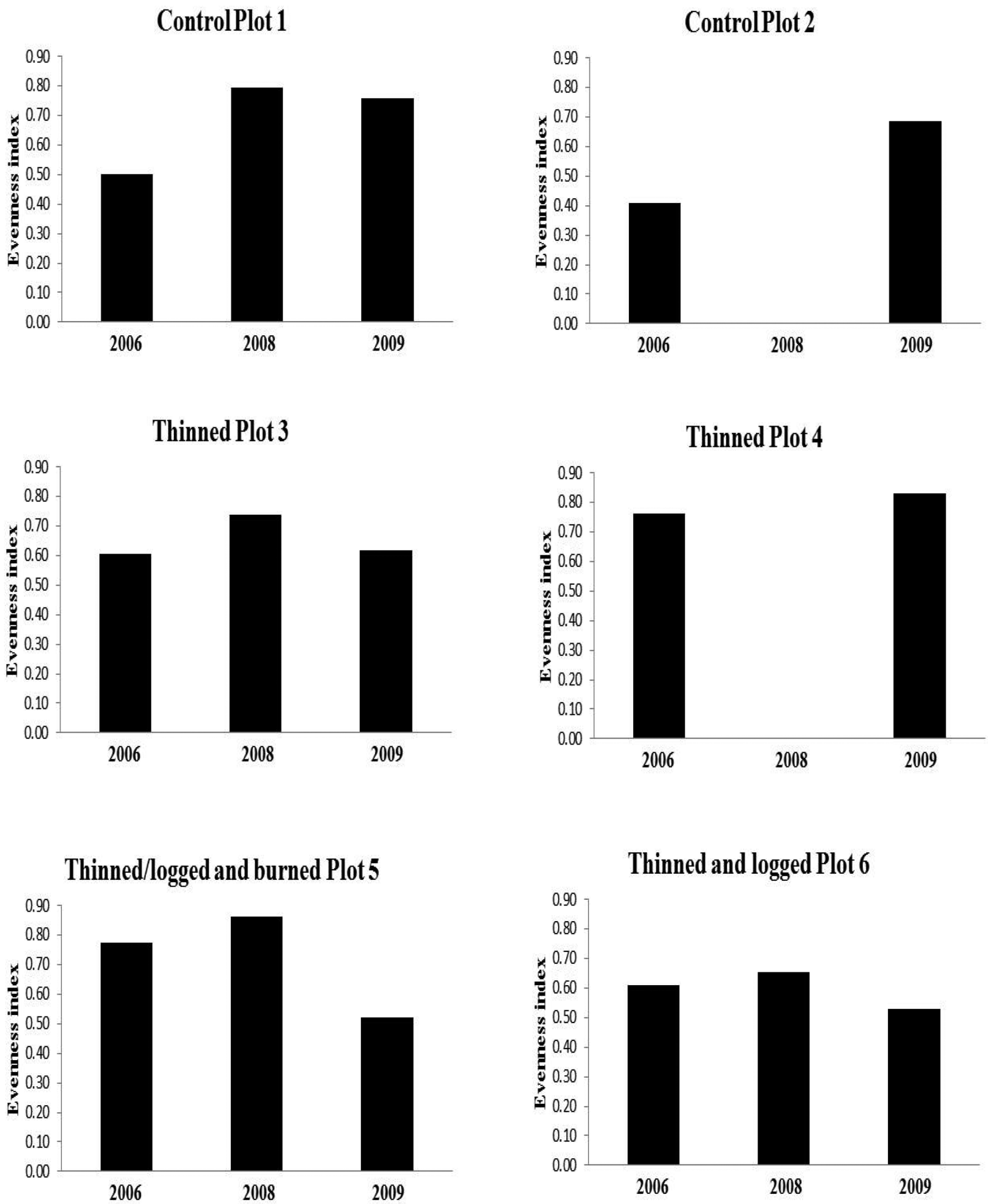

Figure 7. Shannon ant evenness index for the six plots.

for the same periods were 28.5°C (March 2006) (Kabay, 2006), 31.4°C (January 2008) and 26.9°C (March 2009) (Bureau of Meteorology). Average temperature minima were 14.3°C (March 2006) (Kabay, 2006), 15.9°C (January 2008) and 13.1°C (March 2009) (Bureau of Meteorology 2014). (Since Karnet is only 11 km away from the plots, temperature records from the two localities are likely to be comparable).

What these differences mean in effect is that species sampled in January (i.e., in 2008) may not be identical with those that would have been taken had the sampling been conducted two months later. While we make the tentative suggestion that the almost uniformly higher abundance recorded in the March sampling of 2009 may be related to slightly cooler, moister conditions, there are the additional caveats mentioned under the Results; i.e., the inherently stochastic nature of foraging activity in ants and the fact that the exact position of the pitfall traps may not have been identical in all years. However, the large turnover in ant species within the control plots suggests real differences in the ant fauna over the

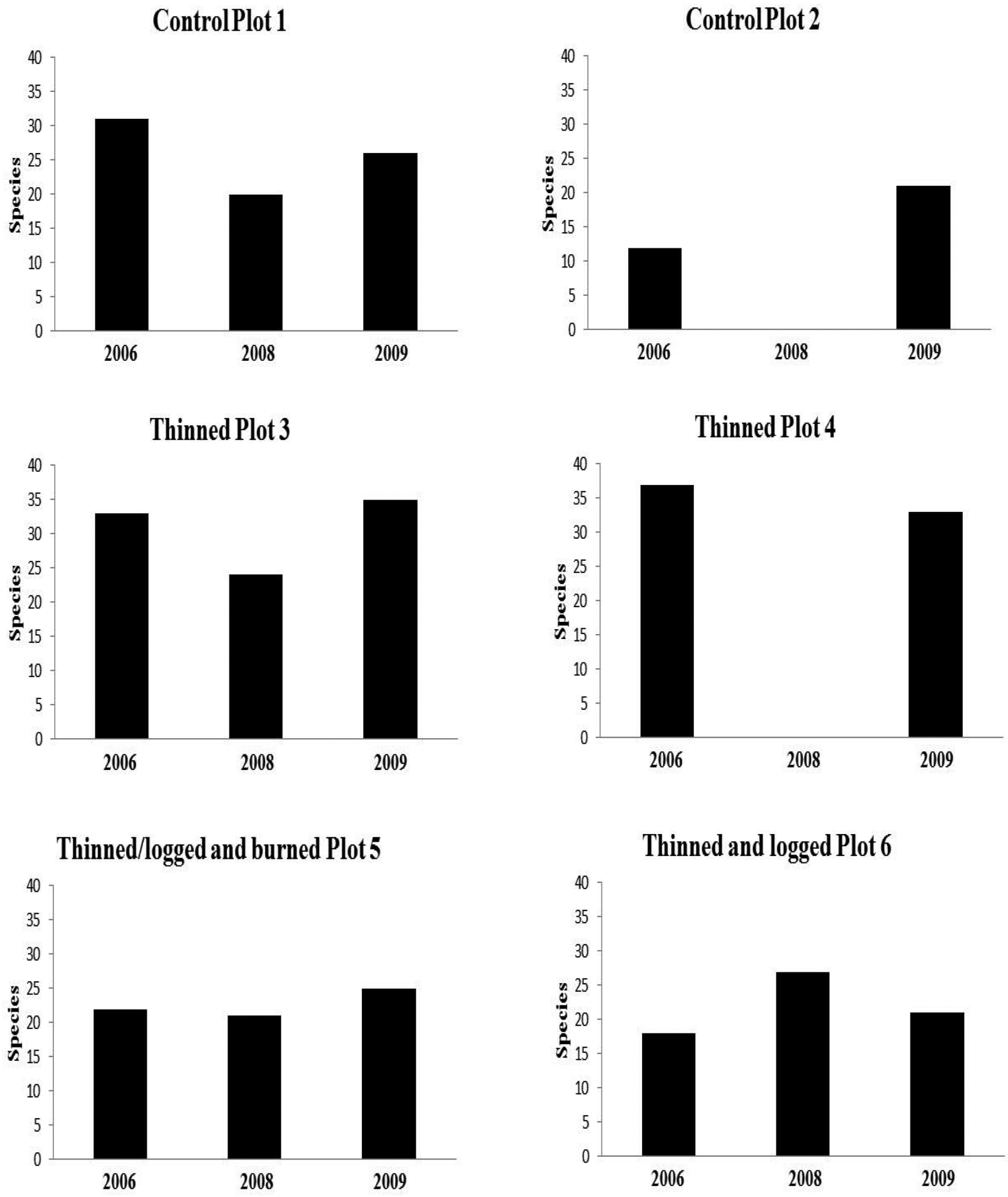

Figure 8. Ant species richness for the six plots.

three years and not just factitious dissimilarities due to the variables mentioned. What we also suggest is that although ant abundance data are amenable to being skewed by the month of collection (with ant activity being at a peak in late spring and declining by late autumn) the species richness is less so, since the colonies of most species will be dispersed over a relatively large area of suitable terrain and soils.

Keeping the various provisos in mind, the lower number of ant species collected in Plots 1, 3 and 5 may be a function of the dry, hot conditions obtaining during January 2008. More species appear to have been active in March 2006 and March 2009. Individual taxa and suites of taxa are discussed below, but clear trends are mostly lacking in the treatment plots compared with the control plots, although such groups as specialist predators were generally absent from the treatment plots. What can be detected is an upsurge in species richness in Plot 6 (discussed at greater length below) in 2008, followed by a reversion to near former levels in 2009. This is in marked contrast to the catch in 2008 in Plots 1, 3 and 5. The characteristics of the types of ant species collected in Plot 6 in 2008 (mainly small myrmicines) appears to be independent of time of year, rainfall or pitfall trap

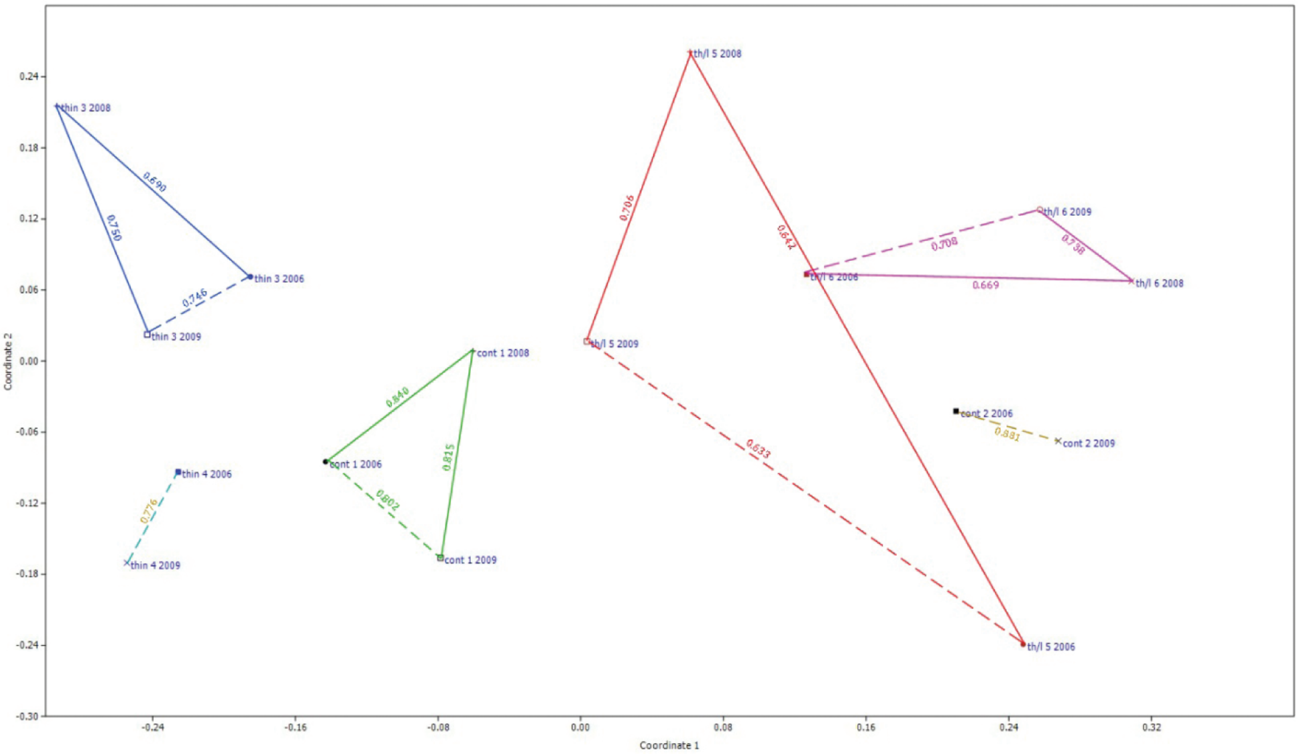

Figure 9. Ordination by non-metric multidimensional scaling (NMDS) of log-transformed ant data from six woodland plots; two controls (brown and green lines, respectively), two thinned (blue and aqua, respectively), one thinned and logged (red) and one thinned, logged and burned (pink). Direction of vectors: 2006→2008→2009. Proportions placed next to the vectors represent Bray-Curtis similarity indices (lower figures reveal increasing dissimilarity; higher figures increased similarity).

location. These species may have been temporarily favoured by extraction of commercial logs without the burning conducted in Plot 5, but this advantage did not extend into the following year, by which time some vegetative regrowth had occurred. Plot 5 also reveals interesting data (discussed below), but overall species richness was not affected. Within the control plots some gradual recovery of the respective ant assemblages might be expected following the burn several years before, but given the complicating factors connected with the way the project was conducted, it is hard to identify specifics from the data where that recovery may have occurred.

In all, general observations in this case are hampered due to deficiencies in the design of the project, incomplete sampling, the lack of temporal replication and, to a lesser extent, various other factors (i.e., different months in which sampling was conducted, questionable location of the pitfall traps and the inherent stochasticity of ant foraging behaviour). However, more substantial comments can be made when the catch is analysed at the functional group and species level.

Species Trends

Species variation in the plots over the three years that comprised the sampling period was not confined to the treated plots. The species turnover in control Plot 1 is significant; especially since three solitary predators (*Cerapachys flammeus* (Clark), *Myrmecia mandibularis* F. Smith and *Myrmecia vindex* F. Smith) and a cryptic predator (*Hypoponera congrua* (Wheeler)) were not recovered in 2008 or 2009. Along with these species 10 other ants, several of them rare and localised in their distributions, were not collected in 2008 or 2009. Of those ants that were novelties in 2008 or 2009 (16 spp. in all), there were no Hot climate specialists or Specialist predators and *Camponotus* species and small, generalised or seed-gathering myrmicines predominated (eight species). This suggests that natural environmental phenomena may have played a role in species persistence within the three year period in this particular plot. In general, ground cover and number of logs declined and total forest cover declined significantly in this plot. Possibly, this reduced herbivorous and sap-sucking insect populations and so the potential forage for large ant species that require larger prey and greater quantities of nectar and honeydew to provision their colonies. However, litter between 2006 and 2009 was greatly increased (from a percentage cover of 28.4 to 70.8). While this may have advantaged smaller, shade or litter-loving species such as the two *Stigmacros* species, *Adlerzia froggatti* (Forel) and *Prolasius reticulatus* McAreavey that were collected in 2008 and 2009, the data are ambiguous, since two other *Camponotus*, two *Stigmacros* and a *Prolasius* species collected in 2006 were not seen subsequently. The presence of the Opportunists *Tetramorium impressum* (Viehmeyer) and *Ochetellus glaber* sp. JDM 19 (to which should probably be added *Camponotus terebrans* (Lowne)) in 2008 and/or 2009 is an indication that some enhanced degree of disturbance – perhaps caused by opening up of the canopy – was also a feature of this period. Again, some caution is required in interpreting the data as four Opportunists (to which the myrmicine *Monomorium sordidum* Forel should probably be added) and two thermophilic *Melophorus* were among the handful of ant species collected in all three sampling events. The large number of Opportunists (at least seven in all) and thermophilic species (five) collected from this plot is a likely indicator that the ant fauna it contained is not indicative of a pristine environment, and the fairly recent burn history was still playing out when the sampling was done.

Plot 2 was characterised by lower ant richness in 2006 (just 12 species). No sampling was done in 2008 but the ant richness had climbed to 21 in 2009. While one Cryptic species (*Plagiolepis squamulosa* Wheeler) and one Specialist predator (*Leptogenys neutralis* Forel) were not seen after 2006, no fewer than 12 new species were recorded in 2009. These included several myrmicines and dolichoderines, the Specialist predator *Cerapachys gilesi* (Clark) and the very rare and possibly fossorial myrmicine *Monomorium sublamellatum* Heterick. Vegetation values showed an overall decline compared with Plot 1; litter increase was less (26.2–67.3% compared with 28.4% – 70%) and % cover was reduced at the 0–25cm strata level (14.6–8.6% compared with 16.4% – 9.6%) and the 100–600 cm strata level (32.9 – 23.9% compared with 21.8–18.7%), but overall forest cover remained similar (104.8% in Plot 1, 103.2% in Plot 2), and the % cover at the 100–600 cm strata level (32.9% – 23.9% in Plot 2, 21.8% – 18.7% in Plot 1) and >600 cm strata levels were somewhat higher in Plot 2. (Several of the new ants are normally found under twig and leaf litter, so these components of the forest floor must have been sufficiently plentiful in 2009 to encourage additional colony founding by queens of litter-loving species.) The recovery of two normally arboreal species (both in genus *Anonychomyrma*) in 2009 could best be interpreted as their colonies being more abundant and ground foraging strays being more likely to be taken in pitfall traps in 2009. What also should be taken into account is the recovery of the ant fauna an extra two years after recent burning. In all, Plot 2 reveals a healthy spread of ants from different behavioural niches despite the modest richness numbers.

Plot 3 reveals a significant dip in ant species richness in 2008 (from 33 to 24 species), and a return and reinstatement of large numbers of species in 2009 (35 species). No less than seventeen ant species were collected in 2006 and 2009 but not in 2008. A perturbation in the normal equilibrium of ant biodynamics is evident in the latter year, but this appears to have disappeared by 2009. Ants strongly connected with disturbed conditions include *Rhytidoponera metallica* (F. Smith), whose numbers rose from 48 individuals (2006) to 84 individuals (2008) and had declined to 38 workers by 2009. Heat loving *Melophorus insularis* Wheeler also recorded a much smaller peak (21→46→36) in 2008. The ants unique to 2008 (eight species from six ant functional groups) are too diverse for any clear-cut explanations to be offered, but some of these could have been responding to short-term effects from the opening up of the canopy and increase in leaf litter (38.7% in 2006 to 64.9% in 2009).

Plot 4 provides evidence of fairly stable ant richness but increased numbers of ants in 2009 (no sampling done in 2008). The greatest rises were seen in small myrmicines such as *Monomorium sydneyense* complex sp. JDM 101 (completely absent in 2006 but represented by 161 workers in 2009) and *Monomorium sordidum* (16 workers in 2006 and 183 workers in 2009), and in heat loving species (three species of *Melophorus*), among which *M. ludius* Forel (41→192 workers) exhibited the greatest increase. The massive decrease in SPH (820 to 154), increase in litter cover (47.5% – 64.3%) and general decline in forest cover would suggest that these small generalist scavengers and larger thermophiles found ready pickings of prey and edible vegetative matter as a result of the thinning.

The loss of four Cold climate specialists (three *Stigmacros* and a *Dolichoderus*) in Plot 5 over 2008/2009 is significant, since this plot, alone among the control and treatment plots, was burned during the survey period. A fifth Cold climate specialist returned in 2009 but was apparently not present in 2008. *Stigmacros* sp. JDM 443 was collected only in 2008, but no Cold climate specialists appeared among the novelties in 2009, although *Stigmacros glauerti* McAreavey was recovered again, after being absent from the catch in 2008. Three dolichoderines were added to the species totals in 2008/2009 and a fourth one (*Anonychomyrma nitidiceps* André) was collected in 2008 only. Opportunists not previously captured (four species) were also well represented among the novelties in 2008/2009, as were small generalised myrmicines (three *Monomorium* from the *M. Monomorium* group) and a *Pheidole* (*Pheidole* sp. JDM 164). The thermophile *Melophorus insularis* was likewise collected only in 2008 and 2009. The loss of the Cold climate specialists and the advent of those groups of taxa normally associated with a bare, insolated ground surface is consistent with the very marked reduction in canopy cover (from 46.5% in 2006 to 20% in 2009) and overall forest cover (75.2% to 52.9%) experienced by this plot during the sampling period. Most vegetative strata values also declined during this period. From a monitoring perspective, this plot shows perhaps the clearest and most easily interpreted signs of an alteration in the composition of its ant fauna that has been driven by deliberative acts.

Plot 6 is rather aberrant in that only one species present in 2006, the apparently very localised *Meranoplus* sp. JDM 491 (known from a small area in the Darling Range southeast of Perth), was not collected subsequently. No fewer than 12 ant species were collected only in 2008, including the solitary predator *Leptogenys neutralis*, three small generalist *Monomorium*, two *Meranoplus*, two *Stigmacros* species and two cryptic species (both *Plagiolepis*). Considering that commercial thinning, at least, took place in late December 2007, this surprising efflorescence of ants that utilise multiple environmental niches is counter intuitive, and not easy to explain. Since the collection took place not long after thinning operations, ant activity may have been correlated with scavenging of insects displaced or killed as a direct or indirect result of thinning and the deposition of branches and other tree waste on the ground surface. By 2009, the ant richness had declined to a roughly similar level to that of 2006 (i.e., 21 species, compared with 18 species in 2006 and 27 species in 2008). The abundance was much higher however, mainly due to very high numbers of the small myrmicine *Monomorium sordidum* (which is presumably treated as 'Generalised Myrmicinae' in

Andersen's papers but should probably be regarded as an Opportunist). Ants present in both 2006 and 2009 included no less than three *Stigmacros* species and the cryptic *Brachyponera lutea* (Mayr), which suggests some restoration of ground cover by the end of the survey period. Six ants were collected only in 2009, of which only two (*Anisopheidole antipodum* (F. Smith) and *Meranoplus ferrugineus* Crawley, both of which are Hot climate specialists) occupy the same ant functional group. The increase in functional groups that prefer to nest under cover and cool conditions may be partially explained by the increase in log density in the plot. *Stigmacros* species and *Brachyponera lutea* are commonly found in litter or under rocks or logs.

CONCLUSIONS

In summary, the various shifts in ant dynamics do not present a clear pattern over all the plots. Probably the change in equilibrium between ant ecological groupings noticed in plot 3 in 2008 and the loss of cover-loving species in Plot 5 and their replacement by those that favour open ground are most easy of interpretation. Plot 5, where burning was conducted, could presage the replacement of an ant fauna that was adapted to cool, moist conditions by one that favours warmer conditions and of under-cover nesters with open soil nesters. Potentially, permanent loss of some species and a depauperisation of the ant fauna generally could eventuate. By the same token, biological signals of serious degradation of the environment (such as drastic rises in abundance of 'weedy' dominants such as *Iridomyrmex chasei* Forel and meat ants, or the advent of exotics like *Pheidole megacephala* (Fabricius) or the Argentine ant *Linepithema humile* (Mayr)) appear to be completely absent from the survey sites.

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Appendix 1. Vegetation characteristics of plots (Adapted from Kabay, 2006, section 4.3).

VEGETATION CHARACTERISTICS OF PLOTS

NON-COMMERCIAL THINNING

Treatment Area 1, Coupe 3

SITE 1, off Chandler road

418107E, 427780N thence NNW, line 2 417957E, 427957N

Basal areas- 34, 38, 44, 20 Average= 34m2/ha

Jarrah dominant regrowth, cut-over forest with few Marri, to 35m, with very few commercial saw log trees. Allocasuarina, Banksia, Persoonia, Balga present. Burnt a long time ago, continuous ground fuel with deep skirts on Balgas. Last burn 1987–88, fuel age 19yo. Dwellingup surface, with some lateritic outcrops, possibly Havel P/S or P type. Access is by good gravel road. Clean-down using brush only. Near bauxite rehabilitation.

SITE 2, off Chandler road

418778E, 428389N thence W, line 2 418772E, 428337N

Basal areas- 36, 28, 22, 22 Average=27m2/ha

Jarrah dominant regrowth, cut-over forest with few Marri, to 35m, with very few commercial saw logs and a few large habitat trees. There are few Allocasuarina, and Banksia, but more Balga present. Burnt a long time ago, continuous ground fuel with deep skirts on Balgas. Last burnt 1988–89, fuel age 18 years old. Dwellingup surface, gravelly soils, possibly Havel S type. Access is by good gravel road. Clean-down using brush only. Near bauxite rehabilitation

COMMERCIAL LOGGING FOLLOWED BY NON-COMMERCIAL THINNING

Treatment area 2, coupe 1.

SITE 3, off Chinaman road

424352E, 424410N thence NNW, line 2 424212E, 424615N

Basal areas= 34, 46, 36, 36, Average= 38m2/ha

Jarrah dominant cut-over forest with some Marri, to 35m, with some large commercial saw log trees. Allocasuarina, Banksia, Persoonia, Balga present. Burnt some time ago, continuous ground fuel with deep skirts on Balgas. Burnt 2002–03, fuel age 4.5 years old. Dwellingup surface, with lateritic outcrops, possibly P or P/S type. Access is by reasonable gravel track, mostly in dieback and Jarrahdale road. Clean-down using brush only.

SITE 4, off Chinaman road

424621E, 423902N thence N, line 2424580N, 424127N

Basal areas- 32, 46, 44, 42. Average= 41m2/ha

Jarrah dominant cut-over forest with some Marri, to 35m, with some large commercial saw log trees. Allocasuarina, Banksia, Persoonia, Balga present. Burnt some time ago, continuous ground fuel with deep skirts on Balgas. Burnt 2002–03, fuel age 4.5 years old. Dwellingup surface, with lateritic outcrops, possibly P or P/S type. Access is by reasonable gravel track, mostly in dieback and Jarrahdale road. Clean-down using brush only.

Appendix 2. Wungong Catchment Environmental data for ant monitoring periods in 2006 and 2009 (adapted from Kabay, 2006, 2009).

Date	Maximum air temperature (°C)	Minimum air temperature (°C)	Precipitation to 9 am (mm)
7-Mar-06	34.5	17	0
8-Mar-06	33.7	17.5	0
9-Mar-06	31	17.2	0
10-Mar-06	27.2	15	0
11-Mar-06	23	13	0
12-Mar-06	26.5	11.5	0
13-Mar-06	29.6	12.2	0
14-Mar-06	29.6	13	0
15-Mar-06	29.5	14	0
7-Mar-09	28	14.5	0
8-Mar-09	31.5	15.8	0
9-Mar-09	32.5	15.6	0
10-Mar-09	35.1	15.2	0
11-Mar-09	28.8	12.5	0
12-Mar-09	no data	15.5	0
13-Mar-09	no data	no data	0
14-Mar-09	no data	no data	0
15-Mar-09	no data	no data	0