AN OVERVIEW OF TERMITE CONTROL METHODS IN AUSTRALIA AND THEIR LINK TO ASPECTS OF TERMITE BIOLOGY AND ECOLOGY

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"More than two thousand years ago, a Chinese sage wrote, "When planning for a year, plant corn. When planning for a decade, plant trees. When planning for life, train and educate people"

ABSTRACT

Subterranean termites ('termites') are a major pest of human structures throughout tropical and sub-tropical regions, causing billions of dollars in damage to timber-in-service worldwide. Most control systems, in the past, relied almost solely on the use of extensively applied organochlorines as the major termiticides. These chemicals were banned for use as termiticides through out most of Australia in 1995. The banning of organochlorines stimulated a fresh look and wholly biorational approach to termite control. The focus of research is now directed to finding more "environmentally friendly" termite control methods. In order to develop new possibilities for more acceptable termite control, it is necessary to have a clear understanding of their biology, including reproduction, division of labour, foraging, intra-specific and inter-specific interactions, hindgut microbial community and environmental influences. Improved understanding may lead to more efficient and more effective control strategies. The purpose of this review is to review the current research on Australian termites highlighting ongoing research related to development of alternative control methods and to identify areas in need of further study and funding

INTRODUCTION

In Australia the protection of timbers-in-service from termites had relied for many years upon the application of persistent organochlorines, as well as the organophosphate compound (chlorpyrifos) and the synthetic organic pyrethroid (bifenthrin) as soil chemical barriers (Lenz *et al*., 1990; Watson, 1990; NHMRC, 1993; AS 3660.1 2000). In the United States of America (USA) the persistent organochlorines were banned in 1987 and from June 1995 in all Australian states except the Northern Territory which had an exemption until 1987. Around 70% of total timber produced in Australia is used for building and construction purposes (ABARE, March/June quarter 2002).

Preservative treatment of timber according to Australian Standard 1604.1 (2000) prevents attack and damage of wood and wood products from biodeteriogens (namely fungi and insects). Above-ground interior timber framing is not liable to decay but is prone to damage by wood-destroying insects (namely wood borers and termites). In-ground exterior timbers are liable to damage by termites and wood decay fungi.

Termites are some of the most economically important insects known to humans. It has been estimated that termites cause over $100 million dollars in damage to wooden structures annually throughout Australia with almost 100% of that attributable to subterranean termites (French, 1986). In July 2007, it was estimated by the Archicentre Institute of Australia that the costs of termite damage, treatment and replacement costs are in the area of AUD$910 million annually (Archicentre, 2007).The economic loss to timber in service by termites constitutes the greatest problem compared to other wood-destroying insects in both urban and rural environments. Termites can attack and damage sound and decayed timber of native hardwoods, and native and exotic softwoods. *Mastotermes darwiniensis* Froggatt is by far the most destructive termite in Australia. It occurs in the region north of the Tropic of Capricorn, with Rockhampton being the southern limit of its natural distribution. *Coptotermes acinaciformis* (Froggatt), however, is responsible for greater economic losses than all the other Australian species of termites combined. This is due to its extensive range, to the severe nature of its attack, and to its extraordinary success in adapting itself to urban environment.

A major focus of termite research in the past was on chemical methods for control with less attention placed on understanding termite behaviour, biology and ecology (Lenz 1988; McDaniel and Kard, 1995). This trend has changed over recent years because of environmental concerns over side effects caused by the use of these broad-spectrum persistent chemicals. For instance, in 1986, the National Academy of Science in North America concluded that the "risks outweighed the benefits" when organochlorine usage in termite control was evaluated (United States Environmental Protection Agency, 1987). The research direction now being taken by many researchers is towards more environmentally friendly termiticides and alternative non-toxic or physical preventative measures and a re-examination of biological methods of control. Methods that are being investigated include baiting, gaseous environments of termite colonies, thermoregulation, termite resistant timber extractives, physical and chemical barriers of various types, juvenile hormone analogues, insect growth regulators, termiticides with delayed toxicity, (which could be used in combination with termite attractants), feeding deterrents, anti-metabolites, repellents, alarm pheromones, protozoicides, and biological control organisms (French, 1991; Jones *et al.*, 1996; Lewis, 1997; Su and Scheffrahn, 1998, 2000; Lenz, 2002). There is a need for an going research in these areas. Research is also needed to analyse the feasibility of colony eradication as opposed to control of a population size and its affect on human structures (Su *et al.*, 2001). The use of multiple combined strategies to prevent termite damage to wooden structures seems to offer great future potential (French, 1994). While, the total eradication of a population of termites seemed to be impossible during the organochlorine-era of termite control, the development and application of new bait and dust toxicants and physical barriers heralds a new era in the use of alternative control methods (Lenz and Runko 1994; Lewis, 1997; Su and Scheffrahn, 2000; Reinhard *et al.*, 2000, 2002b; Ewart, 2001).

Worldwide, some of the most economically important wood feeding species of termites found in the tropics, sub-tropics and temperate regions are in the genera Coptotermes, Odontotermes, Macrotermes, Microcerotermes, Microtermes, Reticulitermes and Schedorhinotermes (French and La Fage, 1989; Pearce, 1998). Coptotermes is completely pan-tropical, partially because of human dispersal, and some species have become serious pests, for example, *Coptotermes formosanus* (Edwards and Mill, 1986). In Australia, the major wood feeders, namely, Coptotermes, Nasutitermes, Mastotermes, and Schedorhinotermes occur sympatrically (i.e., overlapping) with each other. Because of similarities in phenotypic ratio, reproduction, and environmental requirements it would seem useful to discuss them together when considering alternative strategies of control. In the later sections of this review aspect of subterranean termite biology, behaviour and the influence of environmental conditions will be considered.

IPM Strategies in subterranean termite control in Australia

Integrated pest management (IPM) is a decision making process for determining

- If you need pest suppression treatments,
- When you need them,
- Where you need them, and,
- What strategy and mix of tactics to use.

In IPM programs, treatments are not made according to a predetermined calendar schedule; they are made only when and where monitoring has indicated that the pest will cause unacceptable economic, medical or aesthetic damage. Treatments are chosen and timed to be most effective and least disruptive to natural mortality factors. In urban settings, IPM has been used to manage insect pests in parks, gardens, in shade trees and in timber-in-service in and around buildings, both domestic and industrial (Olkowski, 1980).

Components of a termite IPM program

A termite IPM program contains the following key components:-

1. Identification of termite species causing damage.
2. A monitoring and record keeping system for regular sampling or inspections of termites.
3. Damage level - A determination of the economic or aesthetic damage level caused by termites sufficient to warrant control actions.
4. Action levels - the amount of termite activity is indicative of the population size, and a determination of other variables, such as season, amount of susceptible timber in the building, and so on, from which it can be predicted that damage levels will be reached within a certain time if no treatments are undertaken.

Table-1. Geographical distribution of termite species of economic importance in Australia, with particular emphasis on species damaging timber-in-service

Termite		**Australian regions**							
Family	**Species**	**NSW**	**VIC**	**SA**	**WA**	**QLD**	**TAS**	**ACT**	**NT**
Mastotermitidae	*Mastotermes darwiniensis* Froggatt				+	+			+
Kalotermitidae	*Neotermes insularis* (Walkeri)	+	+			+			+
	Kalotermes banksiae Hill		+	+					
	Glyptotermes brevicornis (Froggatt)	+				+			
	G. tuberculatus Froggatt	+							
	Cryptotemes brevis (Walkeri)	+				+			
	C. cynocephalus Light				+				
	C. domesticus (Haviland)					+		+	
	C. dudleyi Banks					+			
	C. primus (Hills)	+				+			
Termopsidae	*Porotermes adamsoni (Froggatt)*	+	+	+		+	+	+	
Rhinotermitidae	*Schedorhinotermes intermedius (Brauer)*	+				+			
	S. i. actuosus (Hill)	+		+	+	+			+
	S. i. breinli (Hill)					+			+
	S. i. seclusus (Hill)	+				+			
	S. reticulatus (Froggatt)	+	+		+	+			
	Heterotermes ferox (Froggatt)	+	+	+	+			+	+
	H. paradoxus (Froggatt)					+			+
	H. p. paradoxus (Froggatt)					+			+
	H. p. intermedius (Froggatt)				+				
	H. p. validus (Froggatt)								+
	H. p. venustus (Froggatt)				+				+
	H. vagus (Hill)								+
	Coptotermes acinaciformis (Froggatt)	+	+	+	+	+			+
	C. frenchi Hill	+	+	+		+		+	
	C. michaelseni (Silvestri)				+				
	C. Iacteus (Froggatt)	+	+			+		+	
	C. a. raffrayi Wasmann				+				
Termitidae	*Amitermes capito Hill*				+				
	A. herbertensis Mjoberg					+			
	Drepanotermes perniger (Froggatt)	+	+	+	+	+			+
	Microcerotermes boreus Hill				+				+
	M. distinctus Silvestri	+	+	+	+	+			
	M. implicadus Hill	+	+			+			
	M. nervosus Hill				+				+
	M. turneri (Froggatt)	+				+			
	Termes cheeli (Mjoberg)					+			+
	Nasutitermes centralis (Hill)				+	+			+
	N. exitiosus (Hill)	+	+	+	+	+		+	
	N. graveolus (Hill)					+			+
	N. walkeri (Hill)	+				+			

NSW = New South wales; **VIC** = Victoria; **SA** = South Australia; **WA** = Western Australia; **QLD** = Queensland; **TAS** = Tasmania; **ACT** = Australian Capital Territory; **NT**= Northern Territory. (Source: French 1986).

Major termite control strategies

There are five main strategies in subterranean termite control, namely:-

1 Installation of chemical barriers such as Dursban™ (and clones); Imidacloprid and bifenthrin applied as full or partial treatments either directly on soil or by reticulation systems for slab on ground construction (AS 3660.1-2000) to prevent termites from entering a building or attacking timber in contact with the ground.
2 Installation of physical barriers such Granitgard® (crushed granite stone); Termi-Mesh® (stainless steel mesh); termite cap, concrete slab designed and produced in accordance with AS 2870 in association with termite entry seal, such as service pipes (such as flanges) to prevent termites from entering the building or attacking timber in contact with the ground (AS 3660.1-2000).
3 Impregnating termite susceptible timbers with a wood preservative that incorporate a termiticide or termite resistant construction material such as West Indian mahogany timber (Swietenia mahogany), and rammed earth (AS 1604.1-2000, Anon 1993c and AS 3660.1-2000).
4 Destruction of the termite nest colony directly using dust toxicants such as arsenic trioxide and triflumuron, and fumigants, or using bait toxicants via baiting methods. The application of dust and/or bait toxicants involves aggregating large numbers of termites with an appropriate baiting system (French *et al*., 1995).

When using a dust toxicant, the aggregated termites are removed from the bait containers, dusted with an appropriate dust toxicant, and released back into the container, and from there, back into the active termite colony network. On grooming each other, the toxicant is spread throughout the colony, leading to the eventual collapse of the colony (French, 1991, 1994, French *et al*., 1995).

The insertion of bait toxicants, via application into or on suitable cellulosic substrates into the bait container is known as the "bait-block method of termite control" (Beard, 1974). The bait toxicants need to act as delayed action stomach poisons with minimum contact action. Baits containing hexaflumuron, sulfluramid, or diflubenzuron are currently available for the pest control industry (Su, 2002a).

Integrated termite control approach using modern architectural design and advances in construction technology coupled with any of the above termite control measures individually or in combination of both physical and chemical barriers to protect timber in buildings from termite attack and damage.

Recently, the destruction of dry wood termite nest colonies has become possible with the use of the Electro-Gun technique (Lewis and Haverty, 1996; Creffield *et al*., 1997).

Installation of Soil Chemical Barriers

In 2000, Standards Australia released the following Australian Standards:

- AS 3660.1-2000 (Protection of buildings from subterranean termites. Part 1: – New buildings),
- AS 3660.2-2000 (Protection of buildings from subterranean termites – Prevention, detection and treatment of infestations. Part 2: Existing buildings), and,
- AS 3660.3–2000 (Termite management - Assessment criteria for termite management systems. Part 3. New and existing buildings).

Current termite control measures

In Australia the termiticides presently registered for use in termite control by the Australian Pesticides & Veterinary Medicines Authority (APVMA) are arsenic trioxide, bifenthrin (Biflex®), chlorpyrifos (Dursban™ and clones); deltamethrin impregnated into a polymer barrier (Kordon®), imidacloprid (Premise®), triflumuron (Intrigue™ Termite Dust), and the phenyl pyrazole, fipronil (Termidor® Residual Termiticide) are registered as a soil termiticides in Australia.

The term pre-treatment refers to complete or partial soil chemical barrier and physical barrier treatments for buildings under construction, while the term post-treatment refers to complete or partial treatments of existing buildings using a termite eradication method, either chemical or non-chemical. Both these terms refer in turn to Australian Standards AS 3660.1-2000 and AS 3660.2-2000. The strategies available for termite control in Australia are in Table 2.

These standards set out methods of implementation during and after construction, for minimising the risks to new and existing buildings from damage by termites. The Standards include procedures and details for providing both chemical and physical barriers, and offer a range of options. Barriers may be used singly or in combination to provide an integrated system for the protection of timber in buildings.

The chemical soil barriers currently registered for use are the organophosphate, bifenthrin (Biflex®), the synthetic pyrethroid and the nicotinoid, imidacloprid (Premise®). Barrier treatments may be applied as full, under-slab treatments, and partial or perimeter treatments. Also, reticulation systems are permissible, using chemicals such as chlorpyrifos.

The phenyl pyrazole, fipronil (Termidor® Residual Termiticide), is currently in the "review stage" of the registration process. Fipronil and imidacloprid, are non-repellent liquid termiticides that have the property of acting like bait toxicants. That is, when applied to the exterior of a building, their effects extend inward and well beyond the exterior site of application (Potter and Hillery, 2002). The wide application of large volumes of active ingredient (> 600 litres) around building poses environmental, health and safety issue. This was one of the reasons that the use of organochlorines in termite control was curtailed (Anon., 1993a,b, c).

Installation of soil physical barriers

Physical barriers, such as metal and plastic shields (Plasmite®), graded granite stone (Granitgard®) and stainless steel mesh (Termi-Mesh®) that are fitted under slab constructions, around pipes through slab constructions and in cavity wall areas, and around posts and poles supporting buildings, are designed to impede and discourage foraging termites entering into a building (AS 3660.1-2000). Though not so designated in the present Standards, Granitgard® when retrofitted around test buildings in a field trial established at the Mallee Research Station at Walpeup, Victoria, it successfully prevented termite penetration for over five years (Ahmed and French, 1997).

It must be emphasised that termites can bridge and breach barrier systems and that regular inspections of the building are necessary. While termites can build around and over both chemical and physical barriers, they or evidence of their presence can then be detected more readily during regular inspections.

Impregnating termite susceptible timbers with wood preservatives

Australian Standard AS 1604.1-2000 (Timber-Preservative-Treated-Sawn and Round) specifies the preservative treatment levels required to protect timber from termite infestation in the three major hazard levels of timber performance. These are, interior above ground hazard level 2 (H2), exterior above ground hazard level 3 (H3), and exterior in ground contact hazard level 4 & 5 (H4 and H5). Timbers may also be protected against termites using remedial treatments. Borax and boric acid have been used for many years as active ingredients for wood preservatives because of their broad spectrum activity against a wide range of fungi and effectiveness against a number of wood destroying insects (Bateman *et al*., 1937; Cummins, 1938, 1939; Carr, 1959; Cockroft and Levy, 1973 and Bunn, 1975). Glycol borates, fused borate rods and pastes have also been found to be effective in arresting established decay (Baines and Levy, 1979; Edlund *et al*., 1983; Dicker *et al.*, 1983; Dietz and Schmidt, 1987; Dirol, 1988; Henningsson *et al*., 1989; Beauford and Morris, 1986; Beauford, 1990 and Dickinson, 1990). In recent years several novel copper boronaphthalene pastes and other diffusible copper-boron preservatives, that can treat both softwoods and hardwood, have been developed. The popularity of boron based preservatives arises from their ability to diffuse into many refractory species considered untreatable by pressure methods, their adaptability to treat a wide range of commodities, their low acute toxicity - LD_{50} values of 3,000-50000 mg/kg (rat), and their provision of an in-depth treatment reservoir of active ingredient which solubilises and diffuses at moisture contents that can lead to colonisation and decay of wood. However, the hazard level classes as proposed are more related to fungal activity than termite hazard levels. This needs to be rectified and termite standards established that tackle the problem of assessing criteria for termite management systems that reflect the termite hazard.

The use of naturally termite-resistant timbers (AS. 3660.1-2000) is mooted. However many of these species are difficult to obtain in any commercial quantity, and the different timber species listed have different levels of resistance to various species of termite. Over time, and with moisture and wood decay organisms present in or on timber, termites will eventually attack and damage nearly all known building construction timbers whether treated with preservative or not.

Table-2. Current subterranean termite control practices used in Australia

Strategy	Chemical/physical/ non chemical	Application	New Building		Existing building	
			full	partial	full	partial
Barriers	Bifenthrin	sprayed	+	+	+	+
	Bifenthrin	reticulated	+	+	+	+
	Chlorpyrifos	sprayed	+	+	+	+
	Termidor	sprayed	+	+	+	+
	Premise	sprayed	+	+	+	+
	Chlorpyrifos	reticulated	+	+	+	+
	Deltamethrin	Installed	+	+	+	+
	Granitgard®	Installed	+	+	-	+
	Termi-Mesh®	Installed	+	+	-	+
	Termiglass	Installed	+	+	_	+
	Plastic flange	Installed		+		+
	Plasmite®	Installed		+		+
	Metal shields	Installed		+		+
Wood preservatives	CCA	Timber	NA	NA	NA	NA
	Borates	Timber	NA	+	NA	+
	LOSP	Timber	+	+	NA	+
	PEC	Timber	NA	NA	NA	NA
	PROCCA	Timber	NA	NA	NA	NA
Nest colony destruction	As_2O_3	dust	-	-	-	+
	Borates	bait	-	-	+	+
	Flurox	Bait	+	+	+	+
	IGR's	bait	-	-	-	+
	Mirex	bait	-	-	-	+
	Termidor	bait				
	Triflumuron	dust	+	+	+	+
	Fumigant	gas	-	-	-	+
	OP or SP	spray	-	-	-	+

Key: As_2O_3 = Arsenic trioxide; CCA = Copper chromium and arsenic; IGR = Insect growth regulators (e.g., chlorflurazuron, diflubenzuron, hexaflumuron; hydramethylnon; imidacloprid,); LOSP = Light organic solvent preservative; NA = Not applicable; OP = organophosphate (chlorpyrifos); PEC = Pigmented emulsified creosote; Premise® = Imidacloprid; PROCCA = Oil based copper chromium arsenic.

Termite biology

Termites live in colonies and the different castes are morphologically and behaviourally specialised to perform the various functions. Countless generations of termites live together in insulated subterranean nests (Watson and Gay, 1991; Clement, 1998; Pearce, 1998 and Atkinson, 1998). The chemistry of kin and nest-mates recognition and pheromonal communication in termite colony is still under investigation (Hamilton, 1972; Miller, 1994; Eggleton and Tayasu, 2001; Reinhard and Kaib, 2001). The life cycle of a termite colony is about 25 to 50 years (Hill, 1942; Verkerk, 1990 and Pearce, 1998), though no individual termite lives that long, except for the reproductives.

The caste differentiation pathways proposed for Isopteran workers was one involving temporal polyethism (Crosland *et. al.,* 1998). Termite castes can be divided into two major types, the reproductives (queen and king), and the non-reproductives (workers, soldiers, instars and nymphs). The reproductives are divided into primary reproductives (colony initiators) which have well-developed compound eyes and larger body size and the secondary reproductives which replace or supplement the primary reproductives have poorly developed eyes (Hinton, 1974; Myles, 1999). The establishment, role and contribution of secondary reproductives in termite colonies is not understood. The other castes include the workers (the largest part of the population 80 – 90%), which feed colony members and maintain the nest by constructing galleries, clean and hatch the eggs and attend the queen (Noirot and Darlington, 2000). How an individual termite worker knows which task (e.g., forage, maintaining the nest, feeding the colony, construct galleries) to perform is still elusive. Termites separated from the nest mates and ideal environment exhibit altered individual behaviour and interactions (Hamilton, 1972; Thorne *et al.,* 1999). The other castes are the soldiers whose primary role seems to defend the colony from enemies and possibly locate and signal new food sources (Reinhard *et al.*, 2002b).

Initially, a termite colony is founded by a pair of flying alates, and it normally takes between five and ten years before the colony reaches mature size, which can then release flying alates (Henderson and Delaplane, 1994; Nalepa *et al*., 2001). The population size of a mature termite colony varies, depending on termite species, soil type, foraging territory, and available food and moisture sources (Lenz, 1994). Termites vary greatly in their nesting habitats, moisture requirements, food preferences, geographical distribution and nutritional physiology. The choice of nesting location, the rate of success of new colony and the main criteria of nest establishment in urban area is not understood. The distance covered by a foraging *Coptotermes acinaciformis* can range between 100 to 120m from the main nest (Hadlington, 1987; Verkerk, 1990). However, it is not yet known as to how they limit their foraging territory, and communicate within colony members and reproductives and population distribution within the territory. Other aspects of termite foraging, such as the measurement of task efficiency, the role of individuals and analysis of mechanisms of collective action also require additional study (Traniello and Leuthold, 2000).

Taxonomic studies based on new techniques like molecular genetics and chemotaxonomy have improved understanding of interspecific and intraspecific genetic variations and features of termites. This knowledge would possibly enhance termite control using genetic factors to distinguish between termite colonies (Clement, 1998). Another study revealed that some *Nasutitermes* species go through 5 larval and worker instar stages. These instars can be difficult to distinguish in the later stages (Watson and Abbey, 1985). A classification system was devised, based upon difference in size, dividing workers into 5 distinct groups: Small Larvae (SL), Large Larvae (LL), Small Workers (SW), Medium Workers (MW), and Large Workers (LW). Division of labour in the worker caste *Reticulitermes fukienensis* has been the subject of several extensive studies (Crosland and Traniello, 1997; Crosland *et al*., 1997; Crosland *et al*., 1998). Behavioural assays showed a clear division in labour among the *Nasutitermes* and *Reticulitermes* groups. The behaviours examined include tunnel construction, tunnel elongation, covered gallery construction, food consumption, exploratory behaviour, care of brood and queen, corpse burying, alarm signalling and bioenergetics of growth and development during circadian rhythms. For all tasks that were investigated, LW performed the labour more efficiently and more extensively than any other group

(Crosland *et al*., 1997, 1998; Watson and Abbey, 1985). MW were able to perform all of the tasks but not nearly as well, except in the case of gallery repair which was performed equally as well. SW was even less efficient and could not perform several tasks. SL, and LL were totally dependent upon larger castes.

Current knowledge indicates a need for research on foraging behaviours. Little is known about dependence of each caste upon foraging and the transport of food back to the colony from foraging tunnels and covered galleries (Crosland *et al*., 1998; Evans, 2001; Reinhard and Kaib, 2001). There was evidence to support the greater dependence of younger termites upon trophallaxis (mouth to mouth feeding) as a source of food (Crosland *et al*., 1997; Crosland *et al*., 1998). There was also evidence that a colony deprived of a large portion of their older workers could survive (Crosland *et al*., 1998). This is also the case with trapping foraging termites over extended periods from above-mound Coptotermes colonies (French *et al*., 1994). Laboratory bioassays performed on the incipient growth of *Reticulitermes flavipes* colonies by Thorne *et al*. (1997) suggest that developing colonies can produce smaller sized workers to perform the same tasks as larger workers in older colonies. The results of Thorne *et al*. (1997) seem to fit the pattern of flexibility in the system of temporal polymorphism described for *Reticulitermes fukienensis* by Crosland *et al*. (1997), Crosland & Traniello (1997) and Crosland *et al*. (1998). Field studies by French *et al.* (1997) showed that high emissions of methane, carbon dioxide, hydrogen, nitrous oxide and carbon dioxide were recorded for aboveground mound colonies of *Coptotermes lacteus* with the smallest surface area termite colonies. In another field study by Grace *et al*. (1995) on *Coptotermes formosanus* revealed that individual worker body mass increased over a 16-year period while population decreased exponentially. This relationship could allow an estimate to be made for the age of *Coptotermes formosanus* colonies based on population sampling over several years (Grace *et al*., 1995). Perhaps the trend towards employing smaller workers in the early stages of colony development of these similar species would indicate the possibility of a division of labour in some *Coptotermes* species, *C. formosanus* in particular. Further research is necessary on the foraging behaviour, division of labour between colony members and communication between castes in *Coptotermes* species.

Termite hindgut microbiota

After the withdrawal of organochlorines from the market, the priority of termite control focused on termite baiting, the success of which depends on the knowledge of termite biology, termite symbiotic relationships with microorganisms, nutritional physiology, foraging behaviour and population dynamics. These phenomena have led to renewed interest in termite nutritional physiology, mainly in the symbiotic microbial community in the hindgut, which plays an important role for the survival of termites on a cellulose diet (Yoshimura and Azuma, 1993; Itakura *et al.,* 1999; Ahmed, 2000; Kurtboke and French 2007, 2008).

Many insects and animals harbour a rich fauna of bacteria, actinomycetes, and protozoa in their hindguts, but in none is these is so prominent as in the hindgut of termites and ruminant animals. Termites are divided according to their symbiotic microbial community into two main groups, the higher termites have bacteria and the lower termites have bacteria and protozoa. The higher termites belong to family the Termitidae, which has around 80% of the genera and comprises about 75% of the species in the order Isoptera. These termites are more advanced in their digestive system, because they contribute cellulase enzyme during cellulose digestion in their hindguts. Few of the higher termites appear to feed on living trees (Lee and Wood, 1971). Many of these termite species feed on dead wood after the wood is decomposed and it is possible that fungi are more important components in their diet. However, higher termites do not rely on their hindgut bacteria for cellulose digestion (O'Brien and Slaytor, 1982; Slaytor, 2000). The microbial community (bacteria and protozoa) is transmitted from workers to offspring.

Lower termites harbour dense and diverse populations of hindgut bacteria, protozoa, spirochaetes and fungi, which assist termites in cellulose digestion (Yoshimura, 1995; Brune, 1998; Bignell, 2000; Slaytor, 2000). The biomass of the hindgut microbial community may account for one third to one fourth of the body mass (Katzin and Kirby, 1933; Yoshimura, 1995). Cellulolytic microorganisms have long been known to exist in lower termites. However, the role of the symbiotic microorganisms is in the metabolism of cellulose and supplying the termites with nutrient and an energy source (Yoshimura, 1995; Brune, 1998). Cellulose metabolism in termite and the protozoa symbiotic relationship was extensively reviewed by Hungate (1946, 1955); Honigberg (1967, 1970); Breznak (1975, 2000); O'Brien and Slaytor (1982); Yoshimura (1995) and Slaytor (2000).

Nutritional physiology of termites was the focus of many researchers over the last 80 years. Yet, despite all the research data available currently on termite hindgut microbial community, our knowledge on the termite hindgut microbial biology and nutritional physiology remains limited. This is primarily because many of the hindgut microbial communities such as the protozoa, actinomycetes, bacteria, fungi and spirochetes have proven difficult to isolate *in vitro* cultures and the interaction and specific roles of each microorganism is still awaiting clarification. Currently the majority of experimental studies on the diverse microbial communities in termite hindguts are described in morphological terms. With more information about hindgut microbial communities, this research will help design bait toxicants for controlling termite colonies in buildings (Kurtboke and French, 2007). Belitz & Waller (1998) show that environmental influences affect the digestion of cellulose in the termite hindgut by symbiotic protozoans. The food is quickly digested after a period of starvation. With more information about feeding patterns, this research will help design protozoicide treatments for controlling termite population.

Environmental conditions affecting termite control

Environmental factors affect termite behaviour, activity, symbiotic relationships with microorganisms, distribution and population growth. Moisture content of wood is one of the key factors in attracting biodeteriorating agents, such as insects, decay fungi and microorganisms. The distribution map of termites in Australia, (or around the world), says much about the ecological conditions and climatic preferences of termites (Calaby and Gay, 1956). *Coptotermes acinaciformis* for example, is characterised as a termite, which prefers a moist soil environment and warm climate (Gay *et al*., 1955; Lee and Wood, 1971; Lenz, 1994).

The distribution and survival of termites depend on moisture, temperature and suitable food sources (Ettershank *et al.*, 1980; Davis and Kamble, 1994). Termites vary in their moisture requirements. Termites, which live in a subterranean nest, require high moisture content (92-95 RH%), and are able to transport moisture to and from the food sources (Grace, 1986). Dampwood termites live in a highly moist environment (mainly dampwood) while the drywood termites, which live in nests above ground, require less moisture.

Moisture is one of the most important factors, closely linked to temperature that affects termite ecology. *C. acinaciformis* termites require relatively abundant and constant sources of moisture in soil, air and food (Leong *et al*., 1983; Ettershank *et al*., 1980). Termites require moisture, not only from the surrounding soil, but also from their food and air (relative humidity around 70 to 80%) (Luscher, 1961; Grace, 1986). Alates are usually released by most termite species on humid and still days (or in drizzling rain) (Higa and Tamashiro, 1983; Ewart, 1988). Foraging termites invariably gain entry into a building via moist soil. Thus, 'wet' areas in a building, such as laundries, bathrooms, and kitchen, and leakage from badly maintained water pipes, are usually the main entry points of termites (AS 3660.2-2000).

A comprehensive study of such conditions would require a combined effort by building architects, timber specialists and termitologists. Different soils have different moisture holding capacities and these affect the availability of water for the foraging termites (Lüscher, 1961; Lee and Wood, 1971; Brad and Weil, 1996). Termites and other soil dwelling insects are considered important biological agents that assist in maintaining soil water and organic nutrient for plants to grow (Elkins *et al*., 1986). The laboratory findings of Forschler and Henderson (1995) showed that the LT50 (lethal time of 50%) of completely submerged termites in water was 19.6 hrs for *Reticulitermes flavipes* 13.9 hrs for *R. virginicus* and 11.1 hrs for *Coptotermes formosanus*. This finding suggests that termites can survive in free water for a long period of time. Additional research on moisture and moisture limiting factors in the built environment would assist builders, designers and the general public to reduce termite damage in buildings.

Control methods

Termite control methods are continually evolving. A number of significant breakthroughs have recently been made in termite control; these include graded particle barriers (French *et al.*, 2003) and stainless steel mesh physical barriers, and insect growth regulators (IGRs) and chitin synthesis inhibitors (csi) for termite baiting systems (Ahmed *et al.*, 1997a,b). However, these breakthroughs alone are not adequate to control termites in the family Rhinotermitidae, because these termites are extremely successful social insects in different climate zones. *Coptotermes formosanus* has been introduced and thrived in Japan and North and South America. *Coptotermes acinaciformis* is distributed over mainland Australia despite different environmental conditions. A recent introduction of *Coptotermes havilandi* to southern Florida is continuing to spread (Su *et al*., 1997). C. *havilandi is* a wide-spread pest of live trees and wooden structures in Brazil (Ferraz and Cancello, 1998). Henderson (1996) described the tremendous growth ability of *C. formosanus* in New Orleans, Louisiana over a seven-year study period.

Many studies demonstrated the need for a sound knowledge of termite foraging behaviour and feeding attractants when applying baiting techniques for termite control. In a review of termite control strategies Lewis (1997) states that there is more variation in success with baiting than with any other method. He sites the need for research on delivery systems and better active ingredients. Research in this latter area is actively being pursued with the application of phagostimulant signals in bait systems for termite management (Reinhard *et al*., 2002a, 2002b). Chen andHenderson (1996) found that *Coptotermes formosanus* is attracted and preferentially feeds upon the amino acids glutamic acid and aspartic acid. These could be used to improve the effectiveness of baiting systems.

In laboratory bioassays, extracts from white cypress pine (*Callitris columellaris*) were found to be repellent to termites (French *et al*., 1979). Grace (1997) explored the influence of tree extractives on foraging preference of *R. flavipes*. Kennedy (2000) also found white cypress pine extractives have anti-termite properties, which can be incorporated, into susceptible timbers to protect against termite attack. Studies in Japan have indicated that steaming of the heartwood of the Japanese larch degraded or removed the chemicals responsible for the inhibition of termite attack (Doi *et al*., 1998). Grace and Yamamoto (1994) demonstrated that Alaska cedar, redwood and teak are resistant to termite attack. A tree native to dry forest areas of India, Pakistan, Sri Lanka, Malaya, Indonesia, Thailand, and Burma, *Azadirachta indicia* (Neem) was found to be a strong repellent to *Coptotermes formosanus* and was suggested as a barrier tree to protect more vulnerable plants (Delate and Grace, 1995). Naturally resistant woods and wood extractive have great promise for prevention of termite attack.

Fungi have been shown to be of importance to subterranean termites both as a pathogen and as an attractant (French 1978; French *et al.*, 1981, 1987). Milner (2000) demonstrated that various isolates (strains) of the fungus *Metarhizium anisopliae* have potential use as a biological control agent against *Coptotermes acinaciformis* in Australia and similar studies were reported with *Coptotermes formosanus* in USA. Rust *et al*. (1996) demonstrated that *Reticulitermes hesperus* was attracted to extracts of the decay fungus, *Gloeophyllum trabeum.* The pathogenic fungi *Metarhizium anisopliae* and *Beauveria bassiana* have potential for future use in termite control programs (Delate *et al*., 1995; Wells *et al*., 1995; Jones *et al*., 1996; Milner *et al*., 1998). These pathogenic fungi have shown promise but more studies are needed on these effectiveness against natural populations of termites in buildings.

Some of the newer least toxic methods for controlling termites include asphyxiant gases, extreme temperature, biological control agents, and physical barriers (Lewis, 1997). Delate *et al*. (1995) describe the successful use of high levels of carbon dioxide for extended period in controlling termites in a contained space. The use of heated air to kill termites was shown to be successful in laboratory bioassays (Woodrow and Grace, 1998). Liquid nitrogen has also been shown to be effective at eliminating termites in the laboratory (Lewis, 1997). These temperature based methods are showing great promise but require more field studies on effectiveness in a natural setting. Experimentation with liquid nitrogen and exhaust fumes from petrol driven vehicle into above-ground mound colonies of *C. lacteus* in Victoria proved ineffective in destroying the nest colony (French, unpubl. data).

Inundation with water was shown to cause a decline in foraging worker population in studies by Forschler and Henderson (1995). This could indicate possible applications to control, for example the controlled flooding of the territories of specific termite colonies to reduce damage by foraging termites. Graded particle barriers to foraging termites that are being tested include sand, coral, crushed granite, basalt, glass beads and splinters, and metal shields.

Conclusions

The development of new termite control technologies, chemical and physical barriers, biological control agents and wood preservatives is an investment for the future of the built environment involving wood and the industries that supply timber products (French and Ahmed, 2006). However, the new technology, control methods and termiticides must be objectively evaluated on the basis of control effectiveness, occupational health and safety, environmental impact and cost effectiveness, and performance data.

The new generation of termiticides (such as fipronil and imidacloprid) will have properties and characteristics vastly different from the chemicals previously used as termiticides in the 'organochlorine-era', (Potter and Hillery, 2002). Thus, innovative, flexible and performance based evaluative methods are required to screen potential termiticides that may act as soil barriers, baits, dusts, contact toxicants or repellents (Ahmed *et al.*, 1997a,b). Furthermore, physical barrier methods, which are basically monitoring systems, will need to be coupled with chemical application systems. There is a need to pursue and engage in an integrated pest management (IPM) approach to termite control based on sound ecological parameters and social priorities (French, 1991; Su, 2002b). These include adopting a mix of alternative strategies as mentioned above, plus planning to ensure on going R&D and training and education programs necessary to supply 'termite expertise' in the future.

Termite control technologies depend on sound understanding of termite biology, foraging and feeding behaviour, nutritional physiology, ecology and environmental factors. Research has been lacking, in the past, on termite nesting, reproductives, termite distribution and termite success as pests, foraging and feeding behaviours. Recently in Australia and USA research has focussed on termite baiting and mark-recapture release techniques for estimating termite population sizes. This research will bring about an understanding of termite colony population and distribution territory. Also, this study has indicated that relatively little is understood about many aspects of termite life. The division of labour and adaptability to a wide range of climatic zones in the *Coptotermes* needs to be better understood. Influences on foraging and feeding patterns are an area of study because of the direct effect on timber-in-service. Research is also continuing on termite attractants (Kurtboke and French, 2007, 2008), and resistant and repellents properties of wood extracts promise to allow some control of termite foraging patterns in the future. Biological and least-toxic methods are the areas in need of the most research because of their environmental low impact.

Other factors, which affect termite management are termite colony age, stages of individual termite development, size of termite population and possible effects of orphaned termite separation periods from the colony, soil type, pH, microbial biomass, (in soil and within termite guts) vegetation cover, and timber species. The use of pathogenic fungi, bacteria, virus and possibly predatory ants and other insects for control are valuable areas of research. Research into better termite physical barriers and building design is essential in the process of "building-out termites". These areas of research will produce more varied approaches to termite control. Research is also needed to define the scale of termite damage, rate of termite attack and cost of damage, treatment and repair in Australia.

The greater use of multiple methodologies in an integrated research strategy can prove valuable in termite research. It would be prudent to undertake further studies on integrated termite management approach which incorporates building design techniques, non-destructive detection methods for locating termites in inaccessible areas of buildings, physical and chemical termite barriers in conjunction with environmentally approved wood preservatives, and registered soil chemical barriers.

Finally, a case may be presented for microcosm studies using carefully controlled experimental manipulation of whole termite populations run in parallel with laboratory bioassays and the gathering of long term field data (Ewart and French, 1986; Ahmed *et al.*, 1997). This would give a sound theoretical basis for extrapolation between laboratory and field experiments particularly if accelerated field simulators are used to simulate natural conditions of test (Ahmed *et al.*, 2000).

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REFERENCES

Ahmed, B., J. R. J. French, P. Kwint and G. Webb, 1997b. Laboratory evaluation of fipronil (a phenyl pyrazole) as a candidate termiticide in the protection of wood against the subterranean termite, *Coptotermes acinaciformis* (Froggatt) Rhinotermitidae. 28th IRG Meeting, Whistler, B.C., Canada, Doc. IRG/WP/97-10225, pp.7.

Ahmed, B., J. R. J. French, A. Valcke and P. Blunt, 1997a. Laboratory evaluation of flufenoxuron as potential bait toxicant against the subterranean termite, *Coptotermes acinaciformis* in Australia. 28th IRG Meeting, Whistler, B.C., Canada, Doc. IRG/WP/97-10214, pp.12.

Ahmed, B. and J. R. J. French, 1997. Termite physical barriers: update on retrofitting Granitgard around ‘mock-up’ buildings after five years. 28th IRG Meeting, Whistler, B.C., Canada. Doc. IRG/WP/97-10226. pp. 6.

Ahmed, B., 2000. The effect of boron treated timbers against Coptotermes species in Australia. Ph. D. Thesis. The University of Melbourne, Australia.

Ahmed, B., J. R. J. French and P. Vinden, 2000. Protection of simulated wooden houses against *Coptotermes acinaciformis* (Froggatt) (Isoptera: Rhinotermitidae) in an accelerated field simulator. Mat. und Org., 33: 289-318.

Anonymous, 1993a. Cyclodiene insecticide use in Australia. Report prepared by the National Health and Medical Research Council’s working party on cyclodiene insecticides. Common. Govt. Printer, Canberra, pp. 255.

Anonymous, 1993b. Submission to the NRA Inquiry into the continued use of the organochlorine insecticides for termite control. Prepared by the CSIRO Institute of Plant Production and Processing, pp. 14.

Anonymous, 1993c. Transcript of proceedings. National Registration Authority for Agricultural and Veterinary chemicals. Inquiry into the continued use of the organochlorine insecticides for termite control. Wednesday, 8 September, 1993. pp. 258.

Archicentre, 2007. Termite problem from an architectural perspective.

AS 1604, 1997. Australian Standard: Timber-Preservative treated-Sawn and round. Standards Association of Australia, Homebush, NSW, pp.36.

AS 2870, 1996. Residential slabs and footings construction. Standards Association of Australia, Homebush, NSW.

AS 3660.1., 2000. Protection of buildings from subterranean termites. Part 1: New buildings. Standards Association of Australia, Homebush, NSW.

AS 3660.2, 2000. Protection of buildings from subterranean termites - Prevention, detection and treatment of infestations. Part 2: Existing buildings. Australian Standard AS 3660.2. Standards Association of Australia, Homebush, NSW.

Atkinson, L., 1998. Multiple queens and genetic relatedness in the termite *Nasutitermes corniger*. Social Insects at the Turn of the Millennium. Proceed. XIII Intern. Congr. of IUSSI. Adelaide, Australia. pp 39.

Australian Bureau of Agricultural and Resource Economics, 2002. Australian Forest and Wood Products Statistics, Wood Market March/June quarter.

Australian standard, 2000. 1604.1-2000. Specification of preservative, treatment. Part 1: Sawn and round timber.

Baines, E.F. and J.F. Levy, 1979. "Movement of Water through Wood" Journal of the Institute of Wood Sci., 8(3): 109-113.

Bateman, E. and R. H. Baechler, 1937. Some toxicity data and their practical significance. Proc. Ann. Meeting, AWPA, 33: 91-104.

Beard, R. L., 1974. Termite biology and bait-block method of control. Conn. Agric. Exp. Stn. Bull. 748. 19 pp.

Beauford, W. and P. I. Morris, 1986. "A new approach to the maintenance of wooden railway sleepers", The Inter. Res. Group on Wood Preserv. Doc. No. IRG / WP / 3392.

Beauford, W., 1990. "In situ and Supplementary Treatments using Solid Water Diffusible Preservatives" in The Chemistry of Wood Preservation. Proc. Royal Chem. Soc. Group on Wood Preservation, Stockholm, Sweden.

Belitz, L. A. and D. A. Waller, 1998. Effects of temperature and termite starvation on phagocytosis by protozoan symbionts of the Eastern subterranean termite *Reticulitermes flavipes* Kollar. Microbial Ecol., 36:175-180.

Bignell, D. E., 2000. Introduction to symbioses. In: Termites: Evolution, Sociality, Symbioses, Ecology. Abe, T., D.E. Bignell and H. Masahiko, (eds.). Kluwer Academic Publishers, Dordrecht, pp. 189-208.

Brad, N. C. and R. R. Weil, 1996. Soil water characteristics and behaviour. In “The Nature and Properties of soil (7th edition)”. (Ed. Adele Kupchik). Prentice-Hall, Inc., New Jersey. pp.143 – 175.

Breznak, J. A., 1975. Symbiotic relationships between termites and their intestinal microbiota. In: Symbiosis (Society for Experiment Biology Symposium Ser., No. 29), Jennings D.H. and D.L. Lee, (ed). Cambridge University Press, Cambridge.

Brune, A., 1998. Termite guts – the world’s smallest bioreactor. Trends in Biotechnology, 16:16-21.

Bunn, R., 1974. Boron compounds in timber preservation. New Zealand Forest Service. Technical Paper No. 60: 112.

Calaby, J. H. and F. J. Gay, 1956. The distribution and biology of the genus Coptotermes (Isoptera) in Western Australia. Austr. J. Zool., 4: 19-39.

Carr, D. R., 1959. Boron as wood preservative. Record of the Annual Convention of the British Wood Preserving Association.

Chen, J. and G. Henderson, 1996. Determination of feeding preference of formosan subterranean termite (*Coptotermes formosanus* Shiraki) for some amino acid additives. J. Chem. Ecol., 22:2359-2369.

Clement, J. L., 1998. Revolution in termite control in urban areas: new techniques and products. Social Insects at the Turn of the Millennium. Proceed. XIII Intern. Congr. of IUSSI. Adelaide, Australia. pp 103.

Cockcroft, R. and J. F. Levy, 1973. Bibliography on the use of boron compounds in the preservation of wood. J. Institute Wood Sci., 6 (33): 28-37.

Creffield, J. W., J. R. J. French and N. Chew, 1997. A laboratory assessment on the effectiveness of the Electro-Gun in eradicating adults of the indigenous Australian drywood termite, *Cryptotermes primus* (Isoptera: Kalotermitidae). CSIRO; Client Report, No. 163, pp.6.

Crosland, M. J., and J. F. A. Traniello, 1997. Behavioral plasticity in division of labor in the lower termite *Reticulitermes fukienensis*. Naturwissenchaften, 84: 208-211.

Crosland, M. J., S. X. Ren and J. F. A. Traniello, 1998. Division of labour among workers in the termite, *Reticulitermes fukienensis* (Isoptera: Rhinotermitidae). Ethology, 104:57-67.

Crosland, M. W. J., C. M. Lok, T. C. Wong, M. Shakarad and J. F. A. Traniello, 1997. Division of labour in a lower termite: the majority of tasks are performed by older workers. Animal Behavior, 54: 999-1012

Cummins, J. E., 1938. Recommendations for the commercial treatment of green veneer to render it immune from the attack of powder post borer (*Lyctus brunneus* Stephens) by impregnation with boric acid. Aust. Timber J., 4: 661-667.

Cummins, J. E., 1939. The preservation of timber against the attacks of the powder Post borer (*Lyctus brunneus* Stephens) by impregnation with boric acid. J. Coun. Sci. Ind. Res. Aust., 12: 30-49.

Davis, R. W. and S. T. Kamble, 1994. Low temperature effects on survival of the eastern subterranean termite (Isoptera: Rhinotermitidae). Environ. Entomol., 23: 1211-1214.

Delate, K. M. and J. K. Grace, 1995. Susceptibility of neem to attack by the Formosan subterranean termite, *Coptotermes formosanus* Shir. (Isopt., Rhinotermitidae). J. Appl. Entomol., 119: 93-95.

Delate, K. M., J. K. Grace and C. H. M. Tome, 1995. Potential use of pathogenic fungi in baits to control the Formosan subterranean termite (Isopt., Rhinotermitidae). J. Appl. Entomol., 119: 429-433.

Dicker, P. E., M-L. Edlund, B. Henningsson and A. Kaarik, 1983. A chemical and mycological evaluation of fused borate rods and a borate / glycol solution for remedial treatment of window joinery. The International Research Group on Wood Preservation Doc. No. IRG / WP / 3225.

Dickinson, D. J., 1990. Remedial Treatment: in-situ treatments and treatments of historical structures, Proceed. 1st Intern. Conf. Wood Protect. Diffus. Preserv., TN, Proceedings 47355. Madism, WI: Forest Prod. Soci., 87-90.

Dietz, M.G. and E.L. Schmidt, 1987. Borate rods as an on-site remedial treatment for control of decay in wood decks. J. Minnesota Acad. Sci., 53 (2): 26.

Dirol, D., 1988. Borate diffusion in wood from rods and liquid product application to laminated beams. The 19th Ann. Meeting of the International Research Group on Wood Preservation. Spain - Madrid. 11 pp.

Doi, S., M. Takahashi, T. Yoshimura, M. Kubota and A. Adachi, 1998. Attraction of steamed Japanese Larch (*Larix leptolepis* (Sieb. Et Zucc.) Gord.) heartwood to the subterranean termite *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae). Holzforschung, 52: 7-12.

Evans, T. A., 2001. Estimating relative decline in population of subterranean termites (Isoptera: Rhinotermitidae) due to baiting. J. econ. Entomol., 94 (6): 1602-1609.

Ewart, D. McG., 1988. Aspects of the ecology of the termite *Coptotermes lacteus* (Froggatt). Ph.D. thesis Dept. Zool., La Trobe University, Bundoora, Victoria, Australia, 343.pp.

Ewart, D. M., 2001. Termite barriers for new construction in Australia (Isoptera). Sociobiol., 37 (2): 379-388.

Ewart, D. M. and J. R. J. French, 1986. Temperature studies on two mounds of *Coptotermes lacteus* (Isoptera). 17th IRG Meeting, Avignon, France, Doc. No. IRG/WP/1295, pp. 8.

Ferraz, M. V. and E. M. Cancello, 1998. Developmental biology of incipient colonies of *Coptotermes havilandi* (Isoptera: Rhinotermitidae) using different substrates under laboratory conditions. Social Insects at the Turn of the Millennium. Proceed. XIII Intern. Congr. of IUSSI. Adelaide, Australia, pp. 161.

Forschler, B. T. and G. Henderson, 1995. Subterranean termite Behavioral reaction to water and survival of inundation: Implications for field populations. Environ. Entomol., 24: 1592-1597.

French, J. R. J., J. W. Creffield and B. M. Ahmed, 1994. Subterranean termite foraging behaviour and the development of baiting methods used for termite control by the Division of Forest Products. International Research Working Group on Wood Preservation annual meeting, Bali, Indonesia. Doc. No. IRG/WP 94-10058.

French, J. R. J., 1986. Termites and their economic importance in Australia. In: Vinson, S.B., ed. Economic impact and control of social insects. New York: Praeger. pp. 103 - 129.

French, J. R. J., 1991. Baits and foraging behaviour of Australian species of Coptotermes. Sociobiol., 19 (1): 171 - 186.

French, J. R. J., 1994. Combining physical barriers, bait and dust toxicants in future strategies for subterranean termite control (Isoptera). Sociobiol., 24 (1): 77 - 91.

French, J. R. J., B. M. Ahmed and D. Ewart, 1995. Bait box technique for remedial subterranean termite control. International Research Group on Wood Preservation, Doc. No. IRG/WP/ 95-10115.

French, J. R. J., 1978. Termite-fungi interactions. I. Preliminary laboratory screening of wood decayed blocks to *Coptotermes acinaciformis, Mastotermes darwiniensis* and *Nasutitermes exitiosus*. Mat. und. Org., 13: 207-221.

French, J. R. J. and J. P. La Fage, 1989. Termite standards questionnaire survey-Second Report. 20th Intern. Res. Working Group on Wood Preservation Annual meeting, Lappeenranta, Finland. Doc. No. IRG/WP/1395, pp.6.

French, J. R. J., R. A. Rasmussen, D. M. Ewart and M. A. K. Khalil, 1987. The gaseous environment of mound colonies of the subterranean termite *Coptotermes lacteus* (Isoptera: Rhinotermitidae) before and after feeding on mirex-treated decayed wood bait blocks. Bull. ent. Res. 87: 145-149.

French, J. R. J., P. J. Robinson, P. J. Pahl and J. D. Thornton, 1987. Termite-fungi interactions. III. Response of *Coptotermes lacteus* in field mounds to fungus decayed softwood blocks. Mat und Org., 22 (2): 111-126.

French, J. R. J., P. J. Robinson, J. D. Thornton and I. W. Saunders, 1981. Termite-fungi interactions. II. Response of *Coptotermes acinaciformis* to fungus-decayed softwood blocks. Mat. und. Org., 16(1): 1-14.

French, J. R. J., P. J. Robinson, Y. Yazaki and W. E. Hillis, 1979. Bioassays of extracts from white cypress pine (*Callitris columellaris* F. Muell.) against subterranean termites. Holzforschung, 33: 144-148.

Gay, F. J., T. Greaves, F. G. Holdaway and A. H. Wetherly, 1955. Standard laboratory colonies of termites for evaluating the resistance of timber, timber preservatives, and other materials to termite attack. Commonwealth Scientific and Industrial Research Organisation. Bull. No. 277, Melbourne, Australia pp.1-60.

Grace, J. K., 1986. A simple humidity chamber for maintaining subterranean termites (Isoptera: Rhinotermitidae) in laboratory. Pan-Pacific Entomol., 62 (3): 221 223.

Grace, J. K., 1997. Influence of tree extractives on foraging preferences of *Reticulitermes flavipes* (Isoptera: Rhinotermitidae). Sociobiol., 30: 35-42.

Grace, J. K. and R. T. Yamamoto, 1994. Natural resistance of Alaska-cedar, redwood, and teak to Formosan subterranean termites. Forest Prod. J., 44: 41-44.

Grace, J. K., R. T. Yamamoto and M. Tamashiro, 1995. Relationship of individual worker mass and population decline in a Formosan subterranean termite colony (Isoptera: Rhinotermitidae). Environ. Entomol., 24: 1258-1262.

Hadlington, P., 1987. Australian termites and other common timber pests. Published by New South Wales University Press, Kensington, Australia.

Hamilton, W. D., 1972. Altruism and related phenomena, mainly in social insects. Ann. Rev. Ecol. Syst., 3: 193-232.

Henderson, G., 1996. Alate production, flight phenology, and sex-ratio in *Coptotermes formosanus* Shiraki, an introduced subterranean termite in New Orleans, Louisiana. Sociobiol., 28: 319-326.

Henderson, G. and K. S. Delaplane, 1994. Formosan subterranean termites swarming behaviour and alate sex-ratio (Isoptera: Rhinotermitidae). Insectes Sociaux: 41: 19-28.

Higa, S. Y. and M. Tamashiro, 1983. Swarming of the Formosan subterranean termites, Coptotermes formosanus Shiraki in Hawaii (Isoptera: Rhinotermitidae). Proceed. Hawaiian entomol. Soci., 24 (2&3): 233-238.

Hill, G. F., 1942. Termites (Isoptera) from the Australian Region, CSIR, Melbourne. pp. 479.

Hinton, H. E., 1974. Reproduction and metamorphosis. In-The insects of Australia. A text book for students and research workers. Melbourne, Melbourne University Press. pp. 18-21.

Honigberg, B. M., 1967. Chemistry of parasitism among some protozoa. Chem. Zool. 1: 695-814.

Honigberg, B. M., 1970. Protozoa associated with termites and their role in digestion. In 'Biology of Termites". Vol. II K. Krishna and F M Weesner (ed.) Academic Press, New York and London. pp 1-36.

Hungate, R. E., 1946. The symbiotic utilisation of cellulose. J. Elisha Mitchell Sci. Soci., 62: 9-24.

Hungate, R. E., 1955. Mutualistic intestinal protozoa. In. Biochemistry and Physiology of protozoa. Vol. II, S H Hunter and A L Woff (ed.) Academic Press, New York pp. 159- 199.

Itakura, S., H. Tanaka and A. Enoki, 1999. Occurrence and metabolic role of the pyruvate dehydrogenase complex in the lower termite *Coptotermes formosanus* (Shiraki). Insect Biochem. Molec. Biol., 29: 625-633.

Jones, W. E., J. K. Grace and M. Tamashiro, 1996. Virulence of seven Isolates of *Beauveria basiana* and *Metarhizium anisopliae* to *Coptotermes formosanus* (Isoptera: Rhinotermitidae). Environ. Entomol., 25: 481-487.

Katzin, L. I. and H. Kirby, 1933. The relative weights of termites and their protozoa. J. Parasitol., XXV (5): 444-445.

Kennedy, M., 2000. Cypress sapwood preservation from natural residue extractives. FWPRDC, Project No. PN98.1400 and PN 98.703.

Kurtboke, D. I., and J. R. J. French, 2007. Use of phage battery to investigate the actinofloral layers of termite gut microflora. J. Appl. Microbiol., 103 (3): 722-734.

Kurtboke, D. I. and J. R. J. French, 2008. Actinobacterial resources from termite guts for regional bioindustries. Microbiology Australia. 29 (1): 42-44.

Lee, K. E. and T. G. Wood, 1971. Termites and soils. Academic Press, New York, pp. 225.

Lenz, M., 1994. Food resources, colony growth and caste development in wood feeding termites. Chapter 6: In: Nourishment and Evolution in Insect Societies. Hunt, J.H. and C.A. Nalepa, (eds). Westview Pr., Boulder, pp 159-209.

Lenz, M., 2002. Termite problem species and management of termite problems in Australia. Sociobiol., 40(1): 11-12.

Lenz, M. and S. Runko, 1994. Protection of buildings, other structures and materials in ground contact from attack by subterranean termites (Isoptera) with a physical barrier–a fine mesh of high grade stainless steel. Sociobiol., 24(1): 1-16.

Lenz, M., J. A. L. Watson, R. A. Barrett and S. Runko, 1990. The effectiveness of insecticidal soil barriers against subterranean termites in Australia. Sociobiol., 17: 9-36.

Lenz, M., J. A. L. Watson and R. A. Ba rrett, 1988. Australian efficacy data for hemicals used in soil barriers against subterranean termites. Canberra, Australia: CSIRO, Div. Entomol., Tech. Paper No. 27.

Lenz, M., J. A. L. Watson and R. A. Barrett, 1988. Australian efficacy data for chemicals used in soil barriers against subterranean termites. Canberra, Australia: CSIRO, Div. Entomol., Tech. Paper No. 27.

Leong, K. L. H., M. Tamashiro, J. Yates and N. Y. Su, 1983. Microenvironmental factors regulating the flight of *Coptotermes formosanus* Shiraki in Hawaii (Isoptera: Rhinotermitidae). Proceed. Hawaiian entomol. Soci., 24 (2&3): 287-291.

Lewis, V. R. and M. I. Haverty, 1996. Simulated field evaluation of six techniques for controlling the drywood termite *Incisitermes minor* (Isoptera: Kalotermitidae) in residences.

Lewis, V. R., 1997. Alternative control strategies for termites. J. Agric. Entomol., 14: 291-307.

Lüscher, M., 1961. Air-conditioned termite nests. Scientific American: 205 (1): 138-145.

McDaniel, C. A. and B. M. Kard, 1995. The latest in termiticide degradation. Pest Control Tech. May: pp. 80, 84,86, 90, and 91.

Miller, L. R., 1994. Nests and queens migration in *Schedorhinotermes actuosus* (Hill), *Schedorhinotermes breinli* (Hill) and *Coptotermes acinaciformis* (Froggatt) (Isoptera, Rhinotermitidae). J. Austr. Entomol. Soci., 33(4): 317-318.

Milner, R. J., 2000. Improved formulations of *Metarhizium* for biological control of termites. FWPRDC, Project No. PN97.605.

Milner, R. J., J. A. Staples and G. G. Lutton, 1998. The selection of an isolate of the hyphomycete fungus, *Metarhizium anisopliae*, for control of termites in Australia. Biol. Contr., 11(3): 240-247.

Myles, T. G., 1999. Review of secondary reproduction in termites (Insecta: Isoptera) with comments on its role in termite ecology and social evolution. Sociobiol., 33: 1-26.

Nalepa, C. A., L. R. Miller and M. Lenz, 2001. Flight characteristics of *Mastotermes darwiniensis* (Isoptera: Mastotermitidae). Insects Sociaux: 42(2): 144-148.

NAS (1986). USDA (1987).

NHMRC, 1993. Cyclodiene insecticide use in Australia. Report prepared by the National Health and Medical Research Council's working party on cyclodiene insecticides. Common. Govt. printer, Canberra, pp. 255.

Noirot, C. and J. P. E. C. Darlington, 2000. Termite nests: architecture, regulation and defence: In Termites, evolution; sociality, symbiosis, ecology. Abe, T., D.E. Bignell and M. Higashi (eds). Kluwer Academic Publishers Dordrecht. pp. 121-139.

O'Brien, R. W. and M. Slaytor, 1982. Role of microorganisms in the metabolism of termites. Aust. J. Biol. Sci., 35: 239-262.

Olkowski, H., 1980. What is IPM? Urban ecosystem management. IPM Practitioner, 2: 2-4.

Pearce, M. J., 1998. Termites: Biology and pest management. CABI Publishing, CAB International, Wallingford, Oxon, UK.

Potter, M. F. and A. E. Hillery, 2002. Exterior-targeted liquid termiticides: An alternative approach to managing subterranean termites (Isoptera: Rhinotermitidae) in building. Sociobiol., 39: 373-405.

Reinhard, J. and M. Kaib, 2001. Trail communication during foraging and recruitment in the subterranean termite *Reticulitermes santonensis* De Feytaud (Isoptera, Rhinotermitidae). J. Insect Behavior, 14: 157-171.

Reinhard, J., H. Hertel and M. Kaib, 2000. Systematic search for food in the subterranean termite *Reticulitermes santonensis* De Feytaud (Isoptera, Rhinotermitidae). Insectes Sociaux, 44: 147-158.

Reinhard, J., M. J. Lacey and M. Lenz, 2002a. Application of the natural phagostimulant hydroquinone in bait systems for termite management (Isoptera). Sociobiol., 39 (2): 213-229.

Reinhard, J., M. J. Lacey, F. Ibarra, F. C. Schroeder, M. Kaib and M. Lenz, 2002b. Hydroquinone: A general phagostimulating pheromone in termites. J. Chem. Ecol., 28 (1): 1-14.

Slaytor, M., 2000. Energy metabolism in the termite and its gut microbiota. In: Termites: Evolution, Sociality, Symbioses, Ecology. Takuya A., B. David and H. Masahiko, (eds). Kluwer Academic Publishers, Dordrecht, pp.307-332.

Su, N-Y., 2002a. Novel technologies for subterranean termite control. Sociobiology: 40(1): 95-101.

Su, N-Y. (2002b). Current and future trends of termite management. Sociobiol., 40(1): 1-2.

Su, N-Y. and R. H. Scheffrahn, 2000. Termites as pests of buildings. In: Termites: Evolution, Sociality, Symbioses, Ecology. Takuya A., B. David and H. Masahiko, (eds). Kluwer Academic Publishers, Dordrecht, pp.437-453.

Su, N-Y. and R. H. Scheffrahn, 1998. A review of subterranean termite control practices and prospects for integrated pest management programs. Integr. Pest Manage. Rev., 3: 1-13.

Su, N-Y., P. M. Ban and R. H. Scheffrahn, 2001. Control of subterranean termites (Isoptera: Rhinotermitidae) using commercial prototype aboveground stations and hexaflumuron baits. Sociobiol., 37: 111-120.

Su, N-Y., R. H. Scheffrahn and T. Weissling, 1997. A new introduction of a subterranean termite *Coptotermes havilandi* Holmgen (Isoptera: Rhinotermitidae) in Miami Florida. Florida Entomol., 80:408-411.

Thorne, B. L., J. F. A. Traniello, E. S. Adams and M. Bulmer, 1999. Reproductive dynamics and colony structure of subterranean termites of the genus Reticulitermes (Isoptera: Rhinotermitidae): a review of the evidence from behavioural, ecological, and genetic studies. Ethol. Ecol. Evol., 11: 149-169.

Thorne, B. L., N. L. Breisch and J. F. A. Traniello, 1997. Incipient colony development in the subterranean termite *Reticulitermes flavipes* (Isoptera: Rhinotermitidae). Sociobiol., 30: 145-159.

Traniello, J. F. A. and R. H. Leuthold, 2000. Behavior and ecology of foraging termites. In: Termites: Evolution, Sociality, Symbioses, Ecology. Takuya A., B. David and H. Masahiko, (eds). Kluwer Academic Publishers, Dordrecht, pp.141-168.

United States Environmental Protection Agency, 1987. Chlordane, Heptachlor, Aldrin and Dieldrin, Technical Support Document (draft). Office of Pesticide Programs, Washington, US.

Verkerk, R., 1990. Identifying Termites. Building out termites. Press Australia Limited. pp. 19-36.

Watson J. A. L., 1990. Alternative termiticides and alternative to termiticides. Pestalk, 10(1): 2-10.

Watson, J. A. L. and F. J. Gay, 1991. Isoptera (Termites). In "The Insects of Australia". Vol. I. University of Melbourne. pp. 330-347.

Watson, J. A. L. and H. M. Abbey, 1985. Seasonal cycles in *Nasutitermes exitiosus* (Hill) (Isoptera: Termitidae). I. Case development. Sociobiol., 11: 255-273.

Wells, J. D., J. R. Fuxa and G. Henderson, 1995. Virulence of four fungal pathogen to *Coptotermes formosanus* (Isoptera: Rhinotermitidae). J. Entomol. Sci., 30: 208-215.

Woodrow, R. J. and J. K. Grace, 1998. Thermal tolerances of four termite species (Isoptera: Rhinotermitidae, Kalotermitidae). Sociobiol., 32: 17-25.

Yoshimura, T., 1995. Contribution of the protozoan fauna to nutritional physiology of the lower termite, *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae). Ph.D. Thesis. Kyoto University.

Yoshimura, T. and J. Azuma, 1993. Cellulose metabolism of the symbiotic protozoa in termite, *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae). II. Selective defaunation of protozoa and its effect on cellulose metabolism. Mokuzai Gakkaishi, 39(2): 227-230.