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Review of the science of termite baiting

This talk will consider baiting's origins, how the origins shaped its development, and baiting's likely future. The concept of using a poisoned food to kill termites is old, however research on modern termite baiting really started around 25 years ago. Since then, around 100 studies have been published in 55 scientific publications. The reported efficacy of baiting has varied from zero to one hundred per cent, although efficacy of almost all studies was measured as absence of termites from bait stations. The reported time to control has varied enormously, from one week to over one year. These results varied according to the active ingredient, pest species and location. However, the information is very skewed, with around half of all studies on one active ingredient, against one genus in one country; i.e. on hexaflumuron, against *Reticulitermes*, in the USA. Research has shifted to more active ingredients to achieve faster control, against more species, around the world, but particularly in Asia. Future baiting is likely to target faster control, at cheaper costs

Introduction

Baiting is one of two related "trap and treat" pest management methods, whereby food is used to lure the target pest species to a trap where it is then treated with a poison. The older form of "trap and treat" is dusting, whereby the termites were "dusted" with a powdered form of poison. Dusting was one of the common forms of pest termite control in China and Southeast Asian countries before World War Two. The typical process was burying relatively short bamboo lengths into soil adjacent to buildings, filling them with wood and paper, then dusting the termites that attacked the bait with arsenic dust (usually Paris Green). Australians learnt this technique from Singaporean and Hong Kongese practitioners. This form of trap and trap was time consuming, difficult and dangerous, as arsenic compounds are toxic to humans.

People wanted barrier treatments to prevent termite access into buildings, as they were perceived to be simpler, safer and more persistent than trap and treat. However, the insecticidal or otherwise repellent compounds available at the time either leached away (like arsenic compounds) or degraded too rapidly to be useful. This situation changed completely in the 1940s when organochloride insecticides (OCs), such as DDT, were introduced. OCs were both repellent and toxic. They bound to soil so they did not leach away. They degraded very slowly, providing chemical barriers that persisted for years to decades. The chemical barriers of OCs in soil were considered so effective they replaced the other forms of termite control. Termite pest management options varied between various types of OC, such as dieldrin, chlordane and heptachlor. Older, more difficult methods, such as trap and treat, were no longer used in most countries.

OCs were utterly dominant in termite pest management for over 50 years, yet their use was discontinued too. This was due to environmental concerns, as the low degradation rates of OCs caused long term increases in residual levels of these chemicals in various habitats and organisms. Worse, the efficacy of OCs in killing insect pests were decreasing, due to the evolution of resistance. Both the high residual levels and the evolution of resistance were observed in insect pests of broad acre cropping; these effects were not observed in the use of OCs against termites. Nevertheless, most countries now do not allow the use of insecticidal OCs.

This change in attitude and regulation of OCs created the conditions for baiting, the second and newer form of "trap and treat". Research on baiting recommenced in the 1970s in the Australia, Canada and the USA, using the OC mirex as the active ingredient. This work was conducted in forests in order to try to control termite populations and reduce damage to trees; barrier treatments were not appropriate in this circumstance. Although there were good results, mirex baiting did not become established as a method of termite control, as it was an OC, and thus was de-registered along with all OCs.

The latest period of research on termite baiting started in the late-1980s. The research was motivated to find an environmentally benign management method as to replace chemical soil barrier methods. Baiting was considered to be ideal, as it would use a small amounts of active ingredient, which would be relatively specific to insects and generally of low mammalian toxicity, and the active ingredient would be contained in a food matrix, typically cellulose, of interest only to termites, and this food matrix would be confined within an impervious bait station.

In addition to these environmental benefits, baiting promised, or at least aimed for, colony elimination; i.e. death to all members of the colony. The specific advantage to colony elimination is rarely, if ever, stated, however it is usually assumed to reduce the possibility of re-infestation. Laboratory tests were used to assess various active ingredients with different modes of action. The active ingredients considered (i) interfered with insect specific metabolic pathways, and (ii) were "slow-acting", which would allow the foraging termites to collect the treated bait and return it to the colony.

After approximately 25 years of research on termite baiting, there are now around five to ten professional baiting systems, with some restricted to one country, others are sold in many. Therefore it is timely to consider the published information to determine whether baiting has met its aims. This review aimed to consider the evidence for the efficacy of baiting systems as published in the peer-reviewed scientific literature. Specifically, the number of studies, the size of each study, the active ingredient, target pest species, location, elimination success, and time to elimination were recorded from each study to consider the scientific merits of the published research, and to find patterns over time.

Method

We search for peer-reviewed, scientific literature on termite baiting. We considered only field studies because we wanted to know the results from studies that had whole colonies, because one of the aims of baiting was colony elimination. We did not consider laboratory studies because they do not use whole colonies, the experimental groups rarely contain reproductives and young, and are typically from dozens to hundreds of individuals in size; this represents perhaps as little as 0.1% of the colony population. (Laboratory studies are useful, especially for screening toxicity, repellency and so forth, but are not useful in a whole of colony context.)

We found 55 papers that tested termite baits in the field. We defined a study as one active ingredient used against one termite species in one location (usually within a country, except when locations in large countries were climatically different enough to justify separate consideration). We distinguished 92 studies using this definition. There were 62 studies that targeted termite colonies (some in urban areas, others in natural habitats; see Table 1), another 26 that targeted structures (and did not attempt to determine colonies in the structures; see Table 2), with five studies that covered large areas with many structures (not shown).

We categorised information from each study for active ingredient, termite species and location. We tabulated the number of studies, the number with experimental controls, the number of colonies receiving treated baits (i.e. with the active ingredient), the proportion of colonies eliminated, the time to elimination, and the author and institutional affiliation of the study. Some studies used termite colony as the replicate whereas others used a building or other structure as the replicate. These studies were treated separately.

Most of the published studies considered 'elimination' to be the absence of termites in the baiting and monitoring stations, whether the study targeted the termite colony or a built structure. This definition was used in this review. Few studies measured the actual effect on the colony by examining the nest for termites, especially reproductives. These few were all in Australia and SE Asia against mound building species. Four studies used DNA fingerprinting to determine the genetic identify of the termites before and after baiting, which although does not measure effects on the nest, is likely to be accurate.

Results

Number of studies

There were a total of 15 active ingredients used in baiting studies. These belonged to three classes of insecticide: neurotoxin, metabolic inhibitor and chiton synthesis inhibitor.

There were a total of 22 species used in baiting studies. These included one species in the Mastotermitidae, *Mastotermes darwiniensis*; 17 species in the Rhinotermitidae, with eight species in *Reticulitermes*, two species in *Heterotermes*, and seven species in *Coptotermes*; and there were four species in the Termitidae, with one species each in *Macrotermites*, *Odontotermes*, *Globtermes* and *Microcerotermes*.

Table 1. The active ingredients, species and locations of termite baiting studies that targeted termite colonies. nb, A9248 is a type of diiodomethyl para-tolyl sulfone. For number of studies: Σ = total number and C = those with untreated controls. For species: *C* = *Coptotermes*, *G* = *Globitermes*, *H* = *Heterotermes*, *Mac* = *Macrotermes*, *Mas* = *Mastotermes*, *O* = *Odontotermes*, *R* = *Reticulitermes*; sp = species unknown.

Active ingredient	**# Studies**	**Species**	**Country**
	Σ / UC		
Neurotoxin			
Mirex	2 / 2	*C. formosanus*, *Mas. darwiniensis*	Aust, USA
Deltamethrin	1 / 1	*C. formosanus*	USA
Abamectin	3 / 1	*C. formosanus*, *R. flavipes*, *R. virginicus*	USA
Avermectin	1 / 1	*C. formosanus*	USA
Fipronil	3 / 3	*O. formosanus*, *R. hageni*, *R. flavipes*	USA, China
Metabolic Inhibitor			
A9248	1 / 1	*C. formosanus*	USA
Sulfluramid	2 / 1	*C. formosanus*	USA
Hydramethylnon	2 / 0	*C. formosanus*, *R. speratus*	Japan
Zinc-Borate	1 / 0	*R. flavipes*, *R. virginicus*	USA
Chitin Synthesis Inhibitor			

Hexaflumuron	30 / 6	*C. curvignathus*, *C. formosanus*, *C. gestroi*, *C. travians*, *H.* sp, *R. flavipes*, *R. lucifugus*, *R. speratus*, *R.* sp, *R. virginicus*	Cayman Is, Italy, Japan, Malaysia, Puerto Rico, USA
Noviflumuron	7 / 0	*C. formosanus*, *H. aureus*, *R. flavipes*, *R. hageni*, *R. hesperus*, *R. virginicus*	USA
Chlorfluazuron	6 / 2	*C. acinaciformis*, *Mac. gilvus*, *G. sulphureus*	Aust, Philippines, Thailand
Lufenuron	1 / 1	*R. hesperus*	USA
bistrifluron	2 / 2	*G. sulphureus*, *C. acinaciformis*	Aust, Malaysia

The baiting studies were performed in 15 countries and territories. The majority of locations and studies were in the USA, across 13 states: Arizona, California, Florida, Georgia, Hawaii, Kentucky, Louisiana, Mississippi, New York, North Carolina, Ohio, Texas and Virginia. There were three locations in the Caribbean Sea: Cayman Islands, US Virgin Islands and Puerto Rico, and one in South America in Chile. There were two locations in Europe, in the UK (England) and Italy. There were two locations in Australia (Queensland and the Northern Territory). Finally, there were eight locations in Asia, in Indonesia, Malaysia, Thailand, Philippines, Taiwan, China (two provinces: Wuhan and Zhejiang), and Japan.

Table 2. The active ingredients, species and locations of termite baiting studies that targeted built structures. Abbreviations as for Table 1, plus *Mic* = *Microcerotermes*.

Chemical	**# studies**	**Species list**	**Country**
	Σ / UC		
Neurotoxin			
Mirex	2 / 1	*R.* sp	USA
Ivermectin	2 / 0	*C. formosanus*, *O. formosanus*	China
Metabolic Inhibitor			
sulfluramid	3 / 1	*R. flavipes*	Chile, USA
Chitin Synthesis Inhibitor			
Hexaflumuron	14 / 1	*C. formosanus*, *C. travians*, *H. aureus*, *H.* sp, *R. flavipes*, *R. grassei*, *R. lucifugus*, *R. separatus*, *R.* sp	Chile, Italy, UK, Malaysia, Taiwan, USA, US Virgin Is
Noviflumuron	2 / 0	*C. gestroi*, *C. formosanus*	Malaysia, USA
Chlorfluazuron	3 / 2	*C. curvignathus*, *C. vastator*, *Mic. losbanosensis*	Indonesia, Philippines

The average numbers of colonies in studies were generally low (Table 3), with averages typically five replicate colonies or fewer for 11 of the 15 active ingredients. Only noviflumuron and bistrifluron had appreciably higher averages.

The percentage of colonies eliminated varied from zero to one hundred (Table 3). Three neurotoxins (deltamethrin, abamectin and avermectin) and two metabolic inhibitors (A9248 and Zinc-Borate) had zero rate of colony elimination, where all chitin synthesis inhibitors reported colony elimination, with averages of greater than 90%.

The time to elimination of colonies varied between active ingredients (Table 3). Mirex had the lowest average of less than four weeks. The next lowest average at about two months was lufenuron, followed by fipronil and bistrifluron with averages of about three months, then by sulfluramid and chlorfluazuron with averages approaching four months. Noviflumuron averaged about five months, hexaflumuron averaged nearly six months, and hydramethylnon averaged about nine months. Some studies of sulfluramid and hexaflumuron used additional spot treatments in buildings to help control infestations; the relative value of these spot treatments is unknown.

The ranges of time to elimination of colonies were highly variable (Table 3), with the fastest reported time of seven days for Mirex against *Mastotermes darwiniensis* in Australia, and the slowest reported time of 15 months for hexaflumuron against *Heterotermes* sp. in Puerto Rico.

Table 3. The active ingredients, species and locations of termite baiting studies that targeted termite colonies. Abbreviations as for Table 1, nb the number of colonies baited = with active ingredient (non-treated controls, if used, not included).

Active ingredient	**# Colonies baited**		**% Colony elimination**		**Time to elimination (days)**		**Reference**
	mean	**min-max**	**mean**	**min-max**	**mean**	**min-max**	
Neurotoxin							
Mirex	4	2-6	100	100	24.5	7-73	20, 27
Deltamethrin	2	2	0	0			20
Abamectin	2.7	1-4	0	0			12, 20
Avermectin	3	3	0	0			20
Fipronil	2.3	2-3	55.6	50-67	92.3	71-150	10, 21
Metabolic Inhibitor							
A9248	3	3	0	0			42
Sulfluramid	6	3-9	38.9	0-78	101	49-153	20, 38
Hydramethylnon	1	1	50	0-100	268	268	23
Zinc-Borate	2	1-3	0	0			12
Chitin Synthesis Inhibitor							
Hexaflumuron	3.8	1-35	90.3	0-100	173.3	25-450	9, 11, 15, 18, 20, 22, 23, 24, 30, 32, 36, 39, 40, 41, 43, 44, 45, 48, 50, 51, 55
Noviflumuron	18	4-72	100	100	143.9	20-342	3, 5
Chlorfluazuron	5.3	2-13	97.4	85-100	105.5	56-126	4, 14, 28, 29
Lufenuron	5	5	100	100	65	37-93	19
Bistrifluron	9	6-12	91.7	83-100	88	56-120	8, 26

The percentage of infestations eliminated from structures varied from zero to one hundred (Table 4). Only mirex had a zero rate of colony elimination, whereas all chitin synthesis inhibitors reported infestation elimination of up 100%.
The average numbers of replicated built structures were generally higher (Table 4) than replicated colonies, although three of the six active ingredients tested this way had averages of around five replicated structures, the same as colony targeted studies.

The time to elimination of infestations from built structures varied between active ingredients in a more-or-less similar fashion, albeit with longer times reported (Table 4). The quickest average

eliminations of infestations in built structures were for chlorfluazuron and sulfluramid with times of three to four months. Next quickest average at a little over four months was ivermectin, followed by hexaflumuron with an average of approaching seven months, then by noviflumuron with an average of about 11 months. However, some of the studies with hexaflumuron and noviflumuron were in large structures, and it is likely that many colonies were baited over this time.

The ranges of time to elimination of colonies were highly variable, with the fastest reported time of 27 days for sulfluramid and hexaflumuron against *Reticulitermes flavipes* in Texas, USA, and the slowest reported time of 1170 days for hexaflumuron against *Heterotermes* sp. in the US Virgin Islands.

Table 4. The active ingredients, species and locations of termite baiting studies that targeted built structures. Abbreviations as for Tables 1 and 3.

Chemical	**# Structures / plots baited**		**% Infestations elimination**		**Time to elimination (days)**		**Reference**
	mean	min-max	mean	min-max	mean	min-max	
Neurotoxin							
Mirex	9	6-12	0	0			6, 7
Ivermectin	4.5	3-6	100	100	126	37-302	25, 53
Metabolic Inhibitor							
Sulfluramid	17.3	2-25	54.7	0-84	109.5	27-196	17, 31
Chitin Synthesis Inhibitor							
Hexaflumuron	9.5	1-29	96.8	80-100	204.6	27-1170	1, 13, 17, 30, 31, 33, 37, 46, 47, 52, 54, 55
Noviflumuron	5	5-5	100	100	340	34-905	2, 34
Chlorfluazuron	5	4-6	100	100	100.3	42-231	14, 49

Trends over time

Active ingredients. The earliest of the 'modern' studies with mirex occurred in the 1960s and 1970s (Figure 1). A variety of neurotoxins and metabolic inhibitors were trialed from the mid-1980s to the mid-1990s. The chitin synthesis inhibitors, especially hexaflumuron received the most attention from the mid-1990s to the early 2000s, after which other CSIs received more attention, but had fewer trials than hexaflumuron (see Figuire 1).

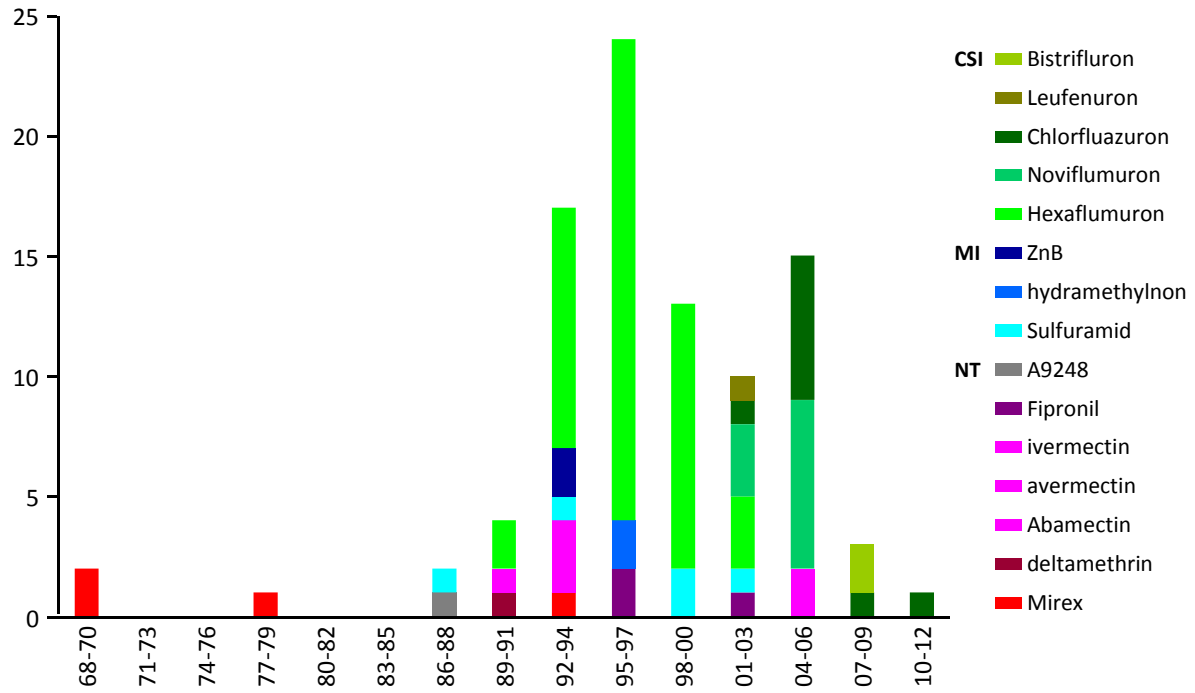

Figure 1. The number of termite baiting studies over time. nb, time has been separated in to three year segments. CSI= chitin synthesis inhibitor (in shades of green); MI = metabolic inhibitor (in shades of blue); NT = neurotoxin (in shades of red and pink).

Termite species. The majority of studies have been on *Reticulitermes* species, followed by *Coptotermes* species. Species in the 'higher termite' Family Termitidae were not considered until 2001, which is when studies of the Rhinotermitidae were declining (see Figure 2).

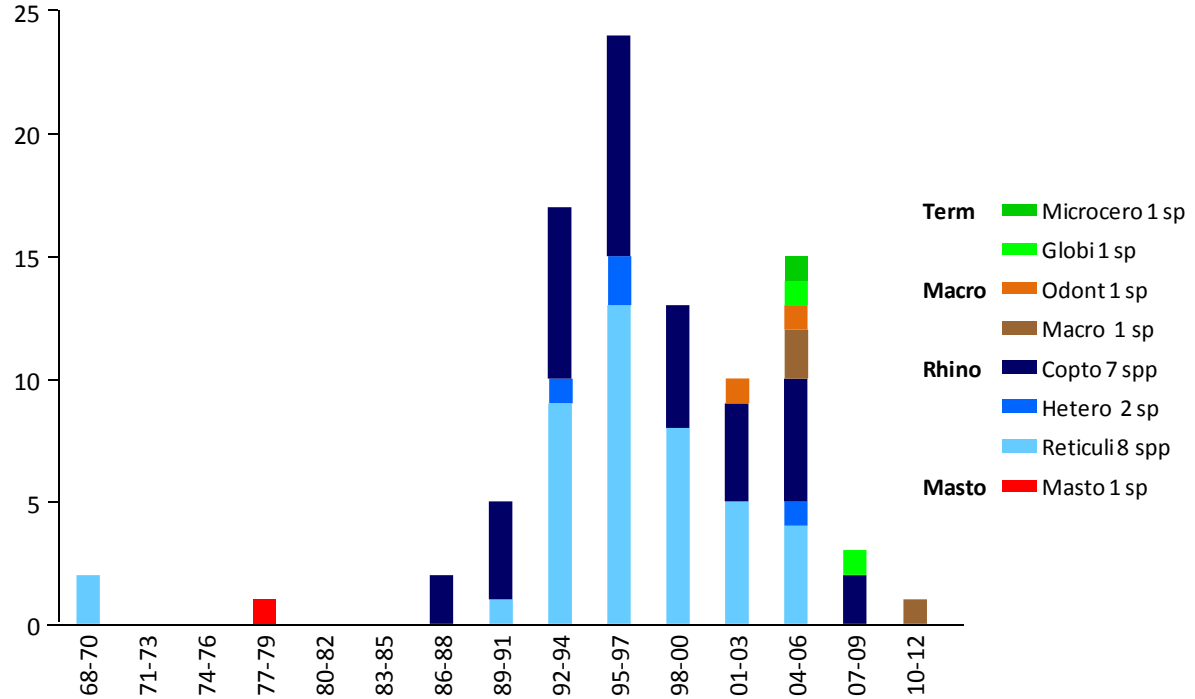

Figure 2. The species trialed in termite baiting studies over time. nb, abbreviations for (sub) Family Term = Termitinae in Termitidae; Macro = Macrotermitinae in Termitidae; Rhino = Rhinotermitidae; Masto = Mastotermitidae. nb, abbreviations for genera simply lack 'termes'; also the number of species follow each genus.

Location. The majority of studies have been in in USA, in fact almost all reported studies were in the USA from 1968 until 1995; the one exception was in Australia. From 1995 the number of studies in Asia has increased, and now dominate, albeit at a lower (and declining) level (see Figure 3).

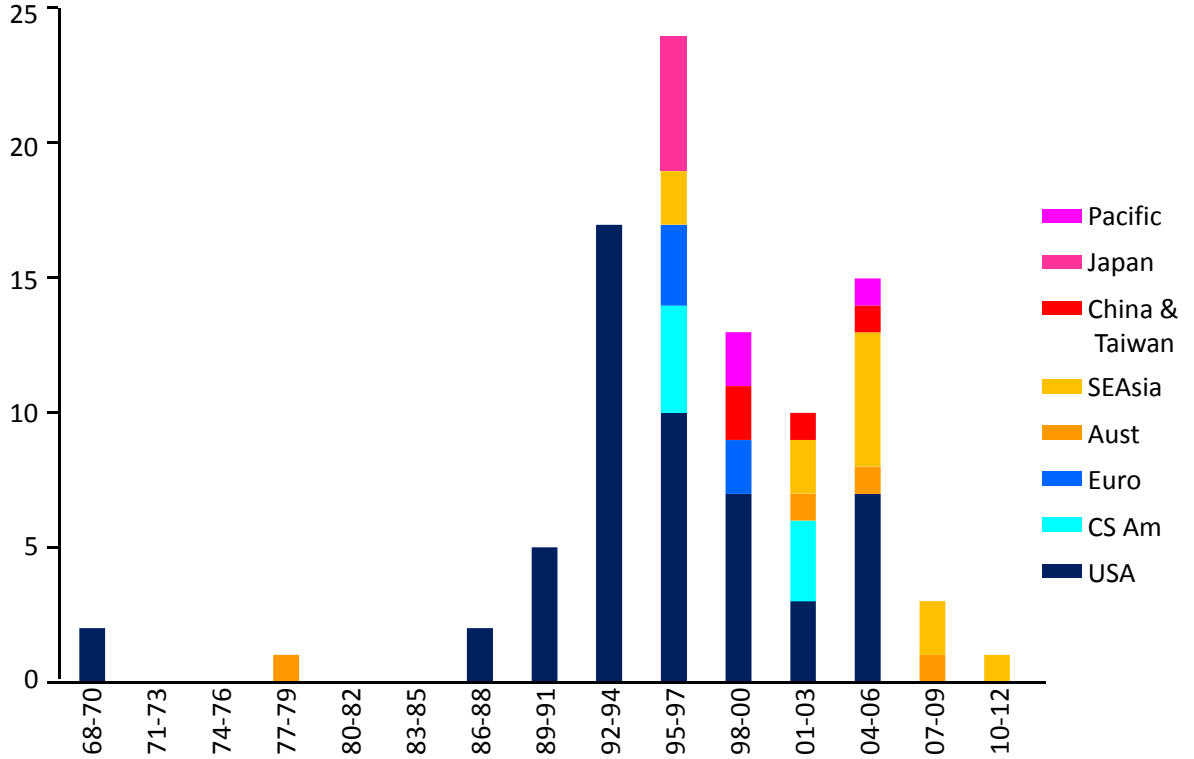

Figure 3. The location of termite baiting studies over time. nb, Pacific = Hawaii plus other US territories, SEAsia = Indonesia, Malaysia, Thailand, Philippines, Euro = Italy and UK, CS Am = Central and South America including the Caribbean Islands; Aust = Australia.

Conclusion

About half of all termite baiting studies have been on one active ingredient (the chitin synthesis inhibitor hexaflumuron), against one genus (*Reticulitermes*) in one country (USA). The outcomes in this scenario are positive, with a high average percentage of colonies eliminated / infestations in structures eliminated, although the length of time to control could be long (a norm of about six to seven months). These results are similar for *Coptotermes*, which is a close relative of *Reticulitermes*, both genera are in the Family Rhinotermitidae.

These results are not ubiquitous for all termites. There is increasing evidence that higher termites in the Family Termitidae do not respond to chitin synthesis inhibitors as well as species in the Family Rhinotermitidae. This is likely due to two reasons. The first is that the chitin synthesis inhibitors developed for the Rhinotermitidae do not disrupt the chitin synthesis enzymes in the Termitidae, as they are too distantly related. The second reason is that most species in the Termitidae moult fewer times than species in the Rhinotermitidae, thus decreasing their vulnerability to this mode of action.

The low success with baiting species in the Termitidae has encouraged experimentation with alternative active ingredients, especially neurotoxins. These active ingredients were considered to be too fast acting for baiting 20 years ago, however if they are delivered in bait matrices at very low

doses, then they appear to have some success. There are only 10 studies using neurotoxins, across a broad range of species, thus patterns remain unclear; expect more studies in this area.

It is not coincidence that most of the studies with neurotoxins have occurred in Asia; this is because there are a higher number of pest species in the Termitidae in this region, compared with the relatively cooler regions of the USA and Europe. The lack of success with chitin synthesis inhibitors, combined with a growing environmental awareness and increasing wealth, has prompted more research into alternatives in Asia. It seems likely similar patterns will emerge in South America, especially Brazil, which has a strong tradition of termite research. It is possible that this work may start in Africa too, with African researchers trained with a PhD in China, returning home.

This research may not be restricted to the species in the Termitidae. A consequence of "slow-acting" active ingredients was baiting has proved to be comparatively slow, typically three to seven months. "The biggest complaint, common to all the current baiting systems, is that it is slow, time-consuming and tedious" according to Prof. Mike Potter of the University of Kentucky in the USA. This is especially true compared with soil based insecticides, which may stop infestations in structures in very short periods, days or less. If the use of neurotoxins as bait active ingredients is successful for the species in the Termitidae, and if the neurotoxins eliminate colonies faster than the chitin synthesis inhibitors, then they are likely to be trialled against species in the Rhinotermitidae.

It should be noted that this review of baiting studies in the peer-reviewed scientific literature has not captured all baiting studies. There are some studies published without peer-review, in conference proceedings or trade journals. Many studies were completed without being published, including many by CSIRO in Australia. In addition, most studies were funded or performed, at least in part, by people or organisations with a financial interest in the product. This raises conflict of interest concerns about objectivity.

Even those studies in the peer-reviewed scientific literature, which ought to have the highest standards, there were issues. Firstly, most studies lack untreated controls, which affects the interpretation of results. Secondly, the lack of any measurement of baiting on the colony, since the vast majority of studies simply recorded presence of termite in bait stations. It is difficult, usually impossible, to examine the nest of a cryptic underground nesting species, such as those in *Reticulitermes*. Although it is possible, even probable, that a long absence of termites from bait stations is due to the elimination of the colony it is not the only interpretation. For example, termites are known to abandon bait stations that are inspected too frequently as they avoid disturbance, or even for no apparent reason. The use of DNA tools and other more accurate measurements to monitor colony identify is likely to increase.

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