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Development of Commercial Wood Preservatives

Efficacy, Environmental, and Health Issues

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ACS Books Department

Chapter 15

Termite Control from the Perspective of the Termite: A 21st Century Approach

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Termites, although essential recyclers of carbon in tropical ecosystems, are serious structural pests in urban environments. Traditional termite management was based largely on the use of biocides, which did not require an intimate knowledge of the organism. However, recent legal and socioeconomic pressures have forced many of the toxicants out of the marketplace. We present a review of the current and cutting-edge developments in termite management that are based upon a greater understanding of termite behavior and ecology.

Introduction

The termites (Order Isoptera) are an important insect group comprising approximately 2300 species (*1*). One could easily argue that termites are principally a beneficial group of insects owing to the fact that only 10% of these species are pests (*2*). Termites are the chief decomposers of cellulosic debris (trees and other plants) in the tropics, contributing to the development of humus, as well as bringing lower-level nutrients to the soil's surface (*3*). Their food can be a standing, dead tree, an old stump, buried wood, or your home. Although consuming dead wood is generally a beneficial function in nature, it puts termites in direct conflict with humans in our urban environment.

Individually, termites are blind, helpless insects. However, collectively they are unaffected by many environmental and manmade hazards. Some researchers have suggested that social insect colonies, such as those of termites (as well as ants, wasps, and bees) act not as collections of individuals, but as "superorganisms" (*3*). Like the many specialized cells within our own bodies, the different castes (workers, soldiers, reproductives), and even specialized groups within each caste, conduct specialized activities: foraging, temperature regulation, feeding, defense, reproduction, and brood care. Thus, when relieved of the necessity to perform other tasks a single termite queen can produce thousands of eggs per day. Because of this specialization, colonies of some subterranean termite species can exceed 1,000,000 workers (*4, 5*). Members of the colony are linked by a complex communication network that involves chemical (pheromone) and tactile (vibratory) stimuli. Communication facilitates the rapid recruitment of the colony to food sources, repellence of invaders and defense from pathogens and toxins.

Subterranean termites (Family Rhinotermitidae), as their name suggests, live beneath the soil surface. A colony can literally exist anywhere in the landscape totally hidden from view, while maintaining numerous foraging galleries, each leading to a separate food source. Foragers of some species can cover distances in excess of 100 meters (*4*) and can occupy an area as large as 3000m^2 (*6*). The cryptic and diffuse nature of termite colonies makes control a challenging proposition.

Although drywood termites are more common overall in structures than subterranean termites (*7*), the damage they cause is relatively minor when compared to the rapid and severe damage caused by large subterranean termite colonies. Su (*8*) estimated that 80% of the economic damage is due to subterranean termites. The most important subterranean termite species in the United States are *Coptotermes formosanus* in Hawaii and along the Gulf coast (*9*), *Heterotermes aureus* in the southwest, *Reticulitermes hesperus* in California, and *Reticulitermes flavipes* from the southeastern states north into southeastern Canada (*10*).

Economic estimates of damage from subterranean termites are problematic as they involve many different segments of the economy, including not only the pest control and construction industries, but real estate, insurance and legal as well. It would generally be agreed that damage in the United States easily exceeds $1.5 billion (*8*). In the state of Hawaii, a paradise for termites as well as humans, the Formosan subterranean termite costs the state at least $100 million annually (*11*); a 15-year-old estimate that can easily be doubled given the recent real estate boom.

Due to its sheer size, a subterranean termite colony needs to consume large quantities of biomass to maintain itself. While the total worker mass of a colony of *R. flavipes* can range from 7 to 10 kg (*5*), the foraging population of a *Coptotermes* colony can be as large as 34 kg (*4*). Grace (*6*) suggested that a large subterranean termite colony can be thought of as a moderately sized herbivore (an invisible, giant rodent gnawing on your home), consuming on the order of 1 kg (2.2 lb) of cellulose per day.

The potential damage wrought by these insects dictates requisite efforts to protect property. Control of subterranean termites in buildings has traditionally involved the use of persistent, broad-spectrum insecticides applied to the soil beneath structures. This persistence was once necessary to provide a barrier, which either killed termites attempting to cross it or repelled them from the structure. The organochlorine soil insecticides chlordane and dieldrin, for example, could keep termites out of structures for many decades (*12*). However the same features that made these treatments so effective, their persistence and broad-spectrum activity, also created environmental problems and a sociopolitical backlash that can still be felt throughout the pest control industry. Due to these environmental concerns these persistent insecticides have been removed from the market and other more environmentally-benign methods and materials have taken their place.

Chemical Barriers

The earlier practice of applying environmentally-persistent termiticides (organochlorines) was very effective and provided multiple decades of protection. Ideally, this traditional preventative strategy was implemented prior to construction, when termiticide could be thoroughly applied directly to the soil. Less persistent termiticides have now taken the place of the persistent materials, however. Thus, the overall approach to termite prevention has had to be modified because modern soil termiticides do not remain effective as long as the incredibly persistent chlordane.

Insecticides used as "barriers" around structures can be repellent (e.g., pyrethroids such as permethrin, cypermethrin, and bifenthrin), non-repellent and causing rapid mortality (e.g., chlordane and chlorpyrifos), or non-repellent with a delayed action (e.g., imidacloprid and fipronil). Su et al. (*13*) referred to these categories as Type I, II, or III toxicants, respectively. Chlordane and its immediate successor in the marketplace, chlorpyrifos, were not repellent; however, the accumulation of dead termites at the treatment boundary appears to cause a secondary repellency in the form of necrophobia (*13*). Repellent pyrethroid insecticides protect the structure by preventing penetration of the treated soil, while leaving the termite population largely intact. The non-repellent, delayed toxicants, such as imidacloprid and fipronil, are the latest tools for soil treatment. These newer insecticides appear to protect the structure primarily by killing a large portion of the termite population, rather than by any sort of direct or indirect repellent action.

Repellent toxicants are generally pyrethroids. Since they are overtly repellent to termites and probably do not actually kill many foragers, the barrier effect can be rather profound. The first generation pyrethroid permethrin is particularly persistent and has remained effective for over 10 years at some locations in field tests in Hawaii (*14*). Later generation pyrethroids, such as bifenthrin, are more biologically active than permethrin but are also less persistent, most likely due to their application at much lower concentrations.

Delayed toxicants, such as imidacloprid and fipronil, are toxic to termites at low concentrations. Unlike the traditional rapid toxicants these materials may require days or even weeks to kill. Thus, the paradox of using these delayed action termiticides is the fact that termites can readily penetrate the treated soil (*15*). Notwithstanding, several studies have indicated that termite penetration is actually more limited than is generally thought (*16*, *17*). Yet, the ultimate role of these materials may not be in the traditional sense as barriers, but rather their effect in reducing the overall termite population.

A population-level effect could reduce termite pressure on structures and possibly even resemble the effects of a termite bait application, as discussed later. Transfer of these materials from exposed donors to unexposed recipients in laboratory studies (*18*, *19*) suggests that they may reduce termite populations beyond the treated area, although Shelton and Grace (*18*) suggested that the transfer effect is likely limited in scope. The mechanism of transfer is unknown, but it is probably the result of grooming and/or trophyllaxis. Su (*20*) investigated the horizontal transfer of the delayed toxicants fipronil and thiamethoxam as compared with a typical bait toxicant, noviflumuron, in a linear, 50-m foraging arena. He found that while the bait toxicant had a universal impact throughout the arenas, termite mortality with the delayed toxicants was limited to a range of less than 5m from the site of application.

A recent development in termite control is the use of polymer sheets impregnated with repellent insecticides. In building construction, the polymer sheeting can act both as a moisture barrier and as a barrier to termites. The polymer may be either "leaky" or "non-leaky." A leaky barrier functions much as a slow-release insecticide formulation and slowly emits a small quantity of termiticide into the surrounding soil. This effect can extend the residual efficacy of insecticides, such as deltametrin, that would otherwise degrade in the moist soil environment (*21*). In the United States, a similar type of material containing lambda-cyhalothrin proved effective (*22*). However, concerns over handling and pesticide residues led to further development as a non-leaky barrier, in which the insecticide-impregnated plastic layer is sandwiched between two impermeable plastic layers. Tests with this three-layer barrier have shown that termite penetration of the plastic barrier ceases immediately when the middle layer is reached. Theoretically, these materials may be able to provide the level of long-term protection once conferred by the persistent organochlorine termiticides.

Physical Barriers

The loss of persistent, broad-spectrum termiticides also facilitated the development of various physical alternatives, each of which act as an obstacle between the termites' subterranean environment and manmade wooden structures. While physical barriers are certainly longer-lasting than insecticides applied to the soil, because they are not toxic or repellent termites will readily probe the surface of these materials in search of entry points. This means that these materials must be flawlessly installed to the extent that termites must venture into an area visible to inspection. Thus, barriers also may aid in termite detection, as the termites' cryptic nature is their greatest asset in avoiding control strategies. Conventional monolithic slab construction alone does not provide a significant barrier to termites, as they can come through plumbing and utility penetrations, or through cold joints and cracks that inevitably form in concrete slabs. Both wire mesh and particle barriers have been developed and commercialized to protect these common entry points.

Sand or gravel particle barriers take advantage of the relative size and strength of termite workers. This concept was first presented using silica sand (*23*), and later developed using crushed, basaltic rock in Hawaii (*24*). The commercial product now widely available in Hawaii is called Basaltic Termite Barrier, or BTB (Ameron HC&D, Honolulu). Tamashiro et al. (*24*) found that Formosan subterranean termites would not penetrate a layer of gravel particles with a size range of 2-2.5mm when the thickness was at least 10 cm thick. From the perspective of the termite, a larger particle size leaves large gaps that they can penetrate, while a smaller particle size can be manipulated with the mouthparts and thus excavated. Within the critical size range, the gaps between particles are too small to penetrate and the particles too large to be grasped and moved. BTB can be applied in the same way as normal gravel fill before a concrete slab is poured, and has been accepted into the building codes in Hawaii as a preconstruction termite treatment (*25*). Elsewhere in North America where the basalt matrix is not readily available, similar gravel barriers have been investigated but have not been commercialized. In Australia, however, a similar barrier of crushed granite was developed and is used commercially against *Coptotermes* species (*26*).

Perhaps the simplest barrier is a durable metal screen with a mesh size small enough to exclude termites. TermiMesh (TermiMesh Hawaii, Honolulu) is a marine-grade stainless steel mesh that can be used instead of chemical barriers. Field studies with this material have demonstrated that it can prevent termite foraging or penetration for extended periods (*25*, *27*). However, this is a relatively high-cost material, and cannot be used in large-scale installations under concrete slabs in the same manner as the particle barriers. Instead, the mesh is generally inserted only in critical areas, such as around plumbing penetrations, in cold joints and along retaining walls, all areas that are difficult to treat with insecticides.

Biological Control

Biological control is a process whereby natural parasites or predators are introduced or augmented to reduce or eliminate insect populations. Many successful biological control agents have been developed for insects other than termites, thus there has been a great deal of interest in their use against termites. A number of recent reviews of termite biological control have been conducted (28-32). Given the cryptic nature of termites, control is inherently difficult. Thus, it has been hypothesized that a biological agent introduced into a termite colony might be able to penetrate the inner sanctum and kill colonies that would otherwise be impossible to control. Unfortunately, a number of studies have demonstrated that termites, which live in an environment rich with all manner of pathogens, are adept at detecting these agents and responding defensively.

Lack of success with biological control has not been due to a paucity of potential agents. In a recent review, Myles (*32*) listed 2 viruses, 5 bacteria, 17 fungi, 5 nematodes and 4 mites that are potentially detrimental to termites. Specifically, Zoberi and Grace (*33*) identified a unique pathogenic fungi associated with *R. flavipes*, while 15 bacteria and one fungus have been associated with *C. formosanus* in Louisiana (*34*). The most plausible and potentially effective biological control agents to date have been either fungi or nematodes.

The most promising fungal pathogens are those that are endoparasitic, including the two common insect parasitic species *Metarhizium anisopliae* and *Beauvaria bassiana*. Numerous studies have shown that these fungal species readily kill termites under laboratory conditions, but field studies have not been as favorable (*29*). Laboratory studies in Hawaii (*35*, *36*) indicated that even small doses of conidia applied for durations of less than one hour were lethal to termites. The goal of using these fungi was to treat a small portion of the foraging population which would then become infected and spread the infection to the remainder of the colony. The principle difficulty with these fungal species, however, was that they did not sporulate readily within dark termite galleries, and infection was limited to only those individuals immediately treated. While it seems evident that epizootics could be generated in the field, the concentrations of conidia required and the numbers of termites that would have to be exposed simply may not be practical under typical commercial field conditions.

Nematodes in the genera *Heterorhabditis* and *Steinernema* have shown promise as pathogens against termites. Wang et al. (*37*) investigated a number of nematode species against *R. flavipes* and *C. formosanus* in laboratory studies and found high levels of virulence for some nematode species at concentrations exceeding 200 nematodes per termite. *Heterorhabditis* spp. nematodes have been used to control residual populations of *Coptotermes* spp., however high nest temperatures (30°C) preclude their use against entire colonies (*31*). Additionally, Mankowski et al. (*38*) recently reported that termite workers of

Coptotermes species readily removed the nematodes *Heterorhabditis indica* and *Steinernema carpocapsae* by mutual grooming. These authors concluded that the dosages required for control in the field were not practical. As with some fungal applications, these high nematode concentrations may also be hampered by the fact that they are repellent to termites (*37*).

Limited field efficacy of biological control agents against subterranean termites is more the rule than the exception. Termites have a number of social, sanitary behaviors, and also physiological mechanisms, that allow them to avoid epizootic infections. Termites may avoid contact with fungal spores and toxin-contaminated surfaces by vacating contaminated gallery systems (*39*). Dampwood termites, *Zootermopsis* spp., have been reported to exhibit an immune response to pathogens (*40*) in a manner analogous to the immune response of a human to a bacterial or viral infection. Once a pathogen is detected, workers rapidly communicate alarm via head-banging (an acoustic signal) or other behaviors. Head-banging has been observed by *Z. angusticollis* in the presence of spores of *M. anisopliae* (*41*), and this vibratory activity causes unexposed individuals to rapidly flee the infected area. For those individuals already exposed, allogrooming (*42*, *38*); i.e., termites grooming each other, may also reduce the pathogenicity of agents that need to germinate on, or penetrate, the cuticular surface. Termite workers not only can detect pathogens but will also isolate or bury sick individuals away from the rest of the colony (*43*). There is also evidence that termites may be able to produce antibiotics and fungistatic compounds, such as naphthalene (*44*).

Although these biological agents have had limited efficacy in the field, success with biological control may not be with the agents alone but in combination with other strategies. As concluded by Culliney and Grace (*29*), biological control agents may come to "supplement" but not "supplant" established control strategies. Lenz (*31*) concluded that pathogens are more effective when the colony is weakened by age or insecticide application. Sublethal doses of imidacloprid have been linked to high rates of fungal infection, synergistically causing faster colony collapse than either agent alone (*45*). These combined strategies have yet to be developed into commercially viable products, however. A final strategy for successful microbial control may be to engineer more effective pathogens, as suggested by Grace (*30*) and discussed below.

Physical Control

All insects are poikilothermic; i.e., they are at the mercy of environmental extremes, as their body temperature closely follows that of their surroundings. A number of free-living insect species are adapted for living in extreme environments, such as desert-inhabiting tenebrionid beetles, or arctic chironomid midges. Unlike ants, which often forage in the open, termites must carry their cool, moist microclimate with them wherever they go. Termites, as individuals, are extremely sensitive to minor variations in the physical environment. It is only as members of a colony that can they modify their environment to maintain homeostasis.

Temperature extremes have been investigated in a number of studies as a means of control. Woodrow and Grace (*46*) found that termites are generally susceptible to high temperatures: 90-minute exposures of 42°C for subterranean termites and 45°C for drywood termites are fatal. Additionally, termites are not able to acclimate to rapidly-rising temperatures, as has been observed with many free-living insect species (*47*). Heat has been used successfully to control drywood termites in a commercial setting, as they are captives of the structure which they infest (*48*). However, thermal structural treatments are not effective for the control of subterranean termites because they have no effect on those individuals that are not present in the structure; i.e. the remainder of the colony, at the time of treatment.

Extreme low temperatures (achieved with liquid nitrogen) have also been investigated for control of drywood termites under simulated field conditions (*49*). Lewis and Haverty (*49*) determined that excessively high rates of liquid nitrogen (>200kg/m^3) were required to achieve 99% mortality. Additionally, there are numerous safety concerns that go along with the use of large quantities of a frozen, compressed gas. In commercial applications of liquid nitrogen, depletion of the oxygen in confined spaces, such as attics, is a recognized danger for applicators. As with high temperatures, it is difficult to conceive of a way to use this technology to control soil-inhabiting termite species.

Termite Bait Technologies

Modern baiting technologies are the ultimate example of use of the biology of termites against them. As discussed previously, one of the most confounding aspects of subterranean termite biology is the fact that colonies are cryptically located, making direct control all but impossible. Knowledge of foraging behavior has given rise to baiting strategies, because it has allowed us to utilize the foraging worker population as a means of introducing a toxicant to the colony at large. The goal of this technology is to reduce or eliminate termite populations around structures, and thus reduce the possibility of infestation. To understand the technology, it is important to understand the historical context.

Early research indicated that termites transfer food and other materials to their nestmates via a process called trophyllaxis. For the sake of this discussion, this transfer is particularly profound between foragers and nestmates, as only a portion of a social insect colony actually leaves the nest or visits any particular foraging site. While typical materials transferred include food, symbionts and hormones, this social sharing behavior is an inherent weakness that baiting can exploit. Termite foraging studies were advanced by the use of mark, release and recapture (MRR) methods (*50*). MRR is a process where a large number of foraging termites are captured in the field and brought back to the laboratory, where they are counted and fed a persistent dye marker, and then returned to the field site where they were initially captured. After releasing the marked termites, sampling is then again undertaken at subsequent intervals. The termite samples will contain a proportion of marked and unmarked individuals, and when compared to the original released quantity and location can be used to estimate the foraging range and size of the foraging population. Various studies established that the foraging territories of subterranean termites can exceed 3000m^2 meters, with foraging populations often in excess if 1,000,000 individuals (*4*, *5*,). This technique was also essential in the development of baits in another way: it established the efficacy of toxicants in the field; termite activity was monitored within the pre-established foraging range in non-baited monitors after applying a bait toxicant to ascertain a decline in the termite population or activity (*51*, *52*).

In addition to basic discoveries about termite foraging, an essential requirement for a baiting protocol was the discovery of an effective toxicant. It was reported in the 1970s that the organochlorine insecticide mirex could reduce foraging populations of subterranean termites (*53*). However, this insecticide was subsequently deregistered in the United States. The search for another viable toxicant took over a decade, leading one researcher to draw an analogy to the search for the Holy Grail (*54*) given the various obstacles to bait development.

A number of criteria must be met for a toxicant to be effective in a baiting scenario. Toxicants must first be slow-acting; i.e., toxicity must be delayed long enough for the material to be transferred to the remainder of the colony from foragers. Also, delayed toxicity will assure that there is no association between the toxicant and any subsequent mortality (*13*). Secondly, the material must not be repellent to foragers or it must be undetectable at toxic concentrations. Thirdly, the material must be stable enough in the termite's body as to be transferred between individuals and persist sufficiently long for toxicity to be expressed. Lastly, the toxicant must be effective at low concentrations, as one cannot reasonably expect foragers to consume large quantities of a bait in the field, given competing natural food sources.

Various materials have been investigated for use in baits, including fungi (*55*) and various chemical toxicants: sulfluramid (*56*), borates (*57*), hydromethylnon (*13*), abamectin (*58*), imidacloprid (*59*), and fenoxycarb (*60*); all with somewhat limited success, although several of these have in fact emerged as viable commercial products. The one class of insecticides that has emerged as most effective in termite baiting is the chitin synthesis inhibitors. Specifically, the benzoylphenyl ureas hexaflumeron, novaflumeron, diflubenzeron and lufenuron have been shown to be potentially effective, and are currently in use as commercial bait toxicants (*61*). These materials are true delayed toxicants, since mortality largely occurs only during molting, or other cuticle forming periods of the termite life cycle. As such, these insecticides, once consumed, are like time bombs that kill arbitrarily at a later time, with no association to the original source of exposure.

Subterranean termite baiting often involves two distinct processes: monitoring (first to detect termites, and second to establish efficacy of the treatment) and toxicant baiting. Commonly, the first step in a baiting protocol is to establish termite foraging activity in a monitoring station. This involves installing monitoring stations around structures, with some portion of the stations below ground, into which some form of cellulose food is placed. Periodic checks of the monitors are made to determine whether termites are present and actively feeding. Once termites are observed in the monitor, a toxic bait matrix is placed into the station in place of the edible cellulose. A number of variations of the process can be found among commercial systems. Some systems do not differentiate between monitoring and baiting, placing baits into inactive stations either with or without wooden attractants around the perimeter of the station.

The apparent efficacy of subterranean termite baiting systems has been accompanied by a certain degree of controversy due to the difficulty of directly observing colony mortality as a result of bait toxicant consumption. However, this does not mean that baiting is not effective, just that it is extremely difficult to establish the absence of an exceedingly cryptic organism. In a recent review, Su and Scheffrahn (*62*) reported that among 16 published field studies of the Sentricon Colony Elimination System (Dow AgroSciences, Indianapolis), total cessation of activity was reported in 89% of 53 colonies representing eight termite species. However, of necessity these claims about colony elimination/ mortality are based largely on termite foraging activity in monitoring/bait stations. Some longer-term studies have observed reinvasion of monitors (*63*), which would be expected over time, as new colonies move into a given area. This underscores the importance of continued monitoring following bait treatments.

The controversy over how to best define the efficacy of baiting systems has led to a great deal of recent, productive research into termite tunneling and foraging behavior. For example, Campora and Grace (*64*) demonstrated that subterranean termites would continue to forage outward for new food sites from sites that they had recently discovered. This work reinforced the likelihood of foraging termites finding bait stations placed in the field, even though the colony was also feeding on natural food sites, and possibly manmade structures as well, at that location.

Baiting technology is typically applied on a single-structure basis. However, one house in a neighborhood with a baiting system could theoretically control termites that are also feeding on neighboring houses. Thus, there has been interest in using these systems to control populations over larger areas. Government-funded, area-wide projects in Mississippi and Louisiana have certainly decreased termite incidence (*65*, *66*), although long-term results are not conclusive given that each area, where treatment has been applied, is surrounded by neighborhoods with extensive termite populations and activity. Baiting was also used successfully to eliminate subterranean termites from a large area in Florida, although social and political factors impinged on the effort (*67*).

The successful commercial implementation of termite baiting has led many to seek improvements to the existing paradigm, both to augment existing baiting systems and to establish unique new products. The first augmentation that we will discuss relates to decreasing the time and/or increasing the probability of termite discovery of in-ground monitoring stations. This is especially significant given the results of Puche and Su (*68*), who found that subterranean termites were unable to detect sound wood even within a distance as small as 2.5mm; i.e., termites have to tunnel directly to bait stations to locate them. So, if foraging workers cannot detect a piece of sound wood in close proximity, what can be done to the area around the monitoring or bait station to improve the odds and reduce the time until discovery?

One way to improve discovery might be to modify the soil around the monitor with a chemical that could cause termites to tunnel more readily in that area. One possibility is the use of an analog of termite trail following pheromone, 2-phenoxyethanol, isolated and identified from ball-point pen ink (*69*). Compounds associated with brown-rot fungi may also be attractive to termites. In laboratory studies, Cornelius et al. (*70*) recently confirmed that subterranean termite foragers will aggregate in the presence of brown-rot fungi-degraded wood when given the choice of sound or decayed wood. Su (*71*) further demonstrated that foraging subterranean termites will orient towards extracts of brown-rot fungi in the field, suggesting, as did Grace et al. (*72*) with trail pheromone, that these chemicals could be applied to the soil to direct termite foraging toward monitoring or bait stations. Practical difficulties in the application of such an approach to bait enhancement may be the stability of the extracted chemicals (*73*), and habituation by the termite foragers to their presence (*74*). It has also been demonstrated that subterranean termites tunnel more readily in damp sand as compared to low-moisture conditions (*75*). Carbon dioxide has also been suggested as a means of attracting termites to monitors (*76*).

Other possibilities to shorten discovery time involve modifying the physical environment around a monitor. For example, Ettershank et al. (*77*) found that *Gnathamitermes tubiformans* and *Amitermes wheeleri* discovered food items on the soil surface in desert environments far more readily than similar buried items, because termites seemed to detect the thermal shadow produced by items on the surface. More recently, Swoboda and Miller (*78*) found that *R. flavipes* aggregated in thermal shadows (cooler areas at 20°C) as compared to warm areas (25°C).

Other physical aspects of the subterranean environment that may be used to direct termite foraging are guidelines; termites naturally follow solid surfaces in the soil environment. Laboratory assays with various guidelines demonstrated that *Reticulitermes* spp. workers followed wood and wood thermoplastic composites in preference to plastic alone (*79*). Monitors connected with these materials were more likely to be encountered by termites than unconnected monitoring stations. However, bait consumption did not increase in connected monitors, presumably because termites initially fed upon the guideline materials themselves rather than the contents of the monitors.

Once termites are active in monitoring or bait stations, the next important parameter is feeding on the bait. If foragers do not feed on the bait, or it is not preferred, they may not accumulate a toxic dose. Various researchers are interested in chemicals that could be added to bait matrices to increase palatability and thus increase feeding. Chen and Henderson (*80*) investigated the feeding responses of termites to various amino acid additives. A number of these patented materials were also investigated by Cornelius (*81*), and only ergosterol proved to be a significant feeding stimulant. Various carbohydrates have also been investigated as termite phagostimulants, and papers treated with 1-3% glucose or sucrose have been identified as preferred in various studies (*82*, *83*). Other identified preferred sugars include fructose, rafinose, galactose and trehalose (*82*), and xylose (*83*). However, Cornelius (*84*) investigated the effect of a sports drink (Gatorade®) containing various carbohydrates on discovery times of *C. formosanus*, and did not find a significant effect over non-treated controls. In the same study (*84*), however, termites did appear to orient their tunnels towards an extract of a commercial bait enhancement product (Summon, FMC Corporation). Swoboda et al. (*82*) also observed that papers containing low concentrations of uric acid were preferred over untreated paper.

The Cutting Edge

As discussed previously, pathogens have been investigated with little success in developing a viable biological control agent for subterranean termites, due to their ability to detect and respond behaviorally or physiologically to these threats. Also discussed previously, baiting strategies have proven to be effective in the commercial setting. Researchers are currently investigating a novel hybrid of these two strategies. In this scenario, a bacterial "Trojan Horse" would be introduced into a termite colony via conventional "toxicant" baiting (*85*). The advantage of this variation is that the bacterial species is a naturally occurring termite symbiont, that would not be rejected by foragers. This bacterial species would carry within its genome a gene which would express a lethal toxin that could be turned-on (expressed) via some environmental or introduced factor. This might seem to be outside of the realm of possibility, if not for the fact that the tools for its implementation have already been developed.

Husseneder et al. (*86*) successfully introduced a model bacterium, *Escherichia coli*, transformed with a fluorescent marker, into groups of termites and demonstrated that the bacteria were rapidly spread throughout the group through trophallaxis. However, the transformed bacteria did not persist more than a week in a termite colony without constant feeding. Husseneder et al. (*87*) then isolated a termite gut bacterium, *Enterobacter cloacae,* and transformed it, as had been done with *E. coli.* These transformed bacteria were quickly established in the laboratory colony and persisted for at least 11 weeks, unlike the *E. coli* model. To assuage concerns about releasing a genetically transformed organism into the environment, the transformed bacterium was also introduced into soil, with no evidence that it persisted or that the marker genes were transferred into other soil bacteria. Clearly, more research is needed to develop this concept to commercial fruition, but the use of such genetically modified microbial control agents may represent the future of termite baiting technology.

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