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United States Department of Agriculture — Agriculture Research Service research on targeted management of the Formosan subterranean termite *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae)[†‡]

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Abstract: The Formosan subterranean termite, *Coptotermes formosanus* Shiraki is currently one of the most destructive pests in the USA. It is estimated to cost consumers over US $1 billion annually for preventative and remedial treatment and to repair damage caused by this insect. The mission of the Formosan Subterranean Termite Research Unit of the Agricultural Research Service is to demonstrate the most effective existing termite management technologies, integrate them into effective management systems, and provide fundamental problem-solving research for long-term, safe, effective and environmentally friendly new technologies. This article describes the epidemiology of the pest and highlights the research accomplished by the Agricultural Research Service on area-wide management of the termite and fundamental research on its biology that might provide the basis for future management technologies. Fundamental areas that are receiving attention are termite detection, termite colony development, nutrition and foraging, and the search for biological control agents. Other fertile areas include understanding termite symbionts that may provide an additional target for control. Area-wide management of the termite by using population suppression rather than protection of individual structures has been successful; however, much remains to be done to provide long-term sustainable population control. An educational component of the program has provided reliable information to homeowners and pest-control operators that should help slow the spread of this organism and allow rapid intervention in those areas which it infests.
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1 INTRODUCTION

Of the Agricultural Research Service's programs highlighted in this issue, targeted management of the Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae) is among the newest. The program was established through Congressional mandate in Fiscal Year 1998 in response to increasing damage to historic and other structures in New Orleans' French Quarter and in the other south-eastern states and Hawaii where the Formosan subterranean termite has become established. Where it occurs, the Formosan termite is among the most destructive insects in terms of damage and control costs. New Orleans is believed to have the densest populations of *C formosanus* in North America and perhaps throughout the world. Devastation caused by this insect throughout North America has been estimated to be hundreds of millions of dollars yearly.[1] It is estimated to cost consumers in New Orleans alone over US $300 million annually. These figures represent costs for prevention of infestation, treatments of infested structures and costs of repairing damaged homes. These estimates, however, do not include the aesthetic losses due to the damage of trees and landscape hardwoods that the termite infests. Over 50 species of living plant have

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been reported to be infested by the termite, including New Orleans' majestic live oaks.[2-4] Significantly, *C formosanus* is also known to damage non-cellulosic materials, chewing through the insulation on buried electrical and telephone cables and causing short circuits.[5] This termite most likely was introduced into the USA in the thousands of tons of wooden military cargo such as crates, pallets and dunnage shipped back from the Asian theater following World War II.[6,7] New Orleans, Louisiana was one of the most active ports of entry. Populations of *C formosanus* have flourished in the warm, humid climate of New Orleans, virtually blanketing the city over the last half century. *Coptotermes formosanus* is native to East Asia and was first discovered in New Orleans and Lake Charles, LA, in 1966. Sites where it was first found in the USA are as follows: Houston, TX, in 1965, Galveston, TX in 1966 and Charleston, SC about 1967. In California, it was discovered in San Diego in 1992, apparently having been introduced in wooden household goods transported from Hawaii 10 years previously.[8] Introduction of the pest into Hawaii is believed to have occurred much earlier through the sandalwood trade from the Far East. Since its introduction to the US mainland, populations have grown explosively. In the New Orleans area alone the number of alates captured in 1999 was 35 times larger than in 1989, indicating a growing threat to the rest of the USA if *C formosanus* populations continue to grow unchecked.[8]

Property owners in heavily infested areas reached a state of despair over the difficulties encountered by pest-control professionals to control *C formosanus*. Chemical barrier treatments have been circumvented often by the pest. Its foragers frequently discover gaps in chemical coverage and can bridge over or through some treated zones. Physical disruption of chemical barriers through gardening or construction practices often provides entry points for a foraging colony into a structure. In Florida, anecdotal reports of liquid treatments having failure rates up to 70% after only 3 years has led to much speculation about the causes of such failures. Surveys indicate that the range of the termite is expanding along the Gulf coast and inland. Long-distance spread is believed to occur primarily through human commerce in wood products such as railroad ties used for landscaping. While the termite is subtropical, the climatic factors that may limit its range are largely unknown.[8]

With the growing threat to structures and the landscapes caused by this and other species of subterranean termite, a critical need for the development of new methods and new approaches for termite detection and control to relieve economic and aesthetic losses caused by termite damage became apparent. Over the past two decades, the two predominant classes of chemical barriers (organochlorines and organophosphates) for control of *C formosanus* and other subterranean termite species have been removed from the market because of environmental or human health concerns.[1] It is critical that new and innovative strategies are developed that are not only effective for termite population management but are also environmentally friendly. The development of new baiting strategies and slow-acting non-repellent chemistries that potentially allow whole colony suppression has provided new opportunities for termite management through area-wide management approaches. These developments provide the basis for the shift in termite control from one of establishing a defensive barrier around an individual structure to one whose emphasis is on elimination of the colony and thus protection through reduced termite population levels. The Agricultural Research Service (ARS) has embraced this principal, which forms the basis for ongoing research in New Orleans' French Quarter.

The mission of the ARS within the Formosan Subterranean Termite Research Unit is to examine various aspects of the biology, ecology, behavior, chemical ecology and pathogens of *C formosanus* in order to provide creative technologies and approaches for area-wide, population-based management of this pest. Research results will allow exploitation of vulnerable sites in the life cycle of the termite for integrated control approaches through exclusion, improvements to baiting technology and deployment, and development of biological control strategies. Activities in each of these arenas have been initiated; their possible application to overall integrated management of the termite will be discussed herein. Research required to develop such approaches includes understanding the termite's nutritional needs and the semiochemicals and pheromones used by the termite for communication and maintenance of colony structure. Discovering and understanding chemical and hormonal regulators governing the termite's reproduction represent new means of population management. Novel toxicants from natural products and microbial fermentations are being sought to provide both efficacy and environmental safety. The biology and manipulation of the gut microflora responsible for cellulose digestion will also be explored.

2 THE BIOLOGY OF THE ORGANISM

2.1 The colony

A Formosan subterranean termite colony is a complex society comprised of various societal classes (castes) that are interdependent for continued success of the colony. The founding members of the colony are the king and queen whose primary responsibility is reproduction.[9-11] Colonies are believed to begin with a single primary queen which, when mature, may produce as many as 2000 eggs per day.[8] Supplementary reproductive individuals may also develop from nymphs, although the regulation of this development still unknown. In addition to the reproductive caste, the colony is comprised of approximately 10% soldiers whose responsibility is to defend the colony. Workers comprise the third caste whose responsibility is construction of the nest, foraging for food and water, grooming of nest mates and colony maintenance activities. A colony may contain millions of individuals with a mature Formosan termite colony typically containing ten times the number of individuals compared with a native subterranean termite colony.[12] The larger colony size and greater foraging aggression primarily account for the greater damage associated with *C formosanus* compared with other subterranean termite species, although individual *C formosanus* workers are roughly the same size and consume approximately the same amount of cellulose per unit time as native subterranean species. The percentage composition of the castes and communication between individuals is regulated via chemical signals known as semiochemicals; however, very little is known with respect to the nature or identity of these signals.[9] Identification and use of these compounds represent potential target sites for disruption of the colony or its development and will be discussed separately below. Understanding the hormonal regulation of caste development opens new possibilities for biologically based control of the colony, and is being pursued aggressively.

2.2 Nutrition of the termite and bait matrices

A major factor affecting the efficacy of termite baits is the amount of the bait consumed.[13,14] The earliest bait matrices consisted of wood blocks dusted with arsenic[15] or other toxins,[16–18] but more recent commercially available bait products consist of cardboard or paper impregnated with a slow acting termiticide.[19–24] We postulated that such baits could be improved by making them more palatable to the termites based upon termite food preferences.[25] As a first approximation of the food preferences of *C formosanus*, the most preferred wood species of selected commercially available woods were determined using multiple choice test chambers.[26,27] Interestingly, a complex interaction is noted when termites are permitted a choice from among numerous species and when they are presented only a single food choice. Morales-Ramos and Rojas[26] determined that river birch (*Betula allegheniensis* Britton), red gum (*Liquidambar styraciflua* L), Parana pine (*Arucaria angustifolia* (Bert)) sugar maple (*Acer saccharum* Marsh), pecan (*Carya illinoensis* Wangenh) and red oak (*Quercus rubra* L) were significantly preferred species compared with other wood species, including southern yellow pine. By contrast, in no-choice experiments *C formosanus* consumed significantly greater quantities of southern yellow pine (*Pinus palustris* Mill) than birch, indicating a complex pattern of food preferences, as demonstrated in earlier studies.[26]

The nutrition of *C formosanus* is a complex system since it involves the host plant, together with a series of different factors such as protozoa, bacteria, other insects, semiochemicals, toxic secondary metabolites and the environment. Detailed studies on the nutritional requirements and the different interactions that the termites use for wood digestion are important for the development of an effective bait matrix for this termite.[25,26] It is known that *C formosanus* prefers some types of woods to others as a source of food, but the preference mechanisms and interactions among them have not been shown clearly. Information obtained by the food preference study described above has been used to correlate wood preferences with chemical composition of woods.[27] Because of the high variability of wood consumption, numerous replications were performed to delineate preferred wood species.[26] Several species, primarily of hardwoods, appeared more preferable in these choice tests than southern yellow pine, and that may make these woods more useful in monitoring for the presence of termites in a monitoring/baiting program.[25] Such a choice test also provides information on woods that are clearly not preferred by the termite and could form the basis for increased commercial use of those woods for construction in heavily infested areas.[26] One of the woods, Alaska yellow cedar (*Chamaecyparis nootkatensis* (Lamb) Spach) is significantly less preferred than currently used commercial woods. It caused feeding deterrence and significantly increased mortality compared with southern yellow pine when presented with no choice. Significantly this wood is commercially available and suitable for construction, while many other naturally resistant wood species are either too costly or generally unacceptable for construction.[26]

Chemical analysis of several of the preferred woods partially degraded by the termitophilic fungus, *Curvularia lunata* Boed, was performed to develop a chemically defined matrix closely matching the chemistries of those woods that the termites preferred.[25] In choice tests the termites significantly preferred a matrix comprising the chemical composition of preferred woods to that of intact southern yellow pine or other cellulosic substrates.[25] Supplementing a purified cellulose powder with levels of sugars, free fatty acids, amino acids and sterols found in blocks of the five preferred wood species which had been partially degraded by fungi resulted in a bait matrix which was significantly preferred and consumed compared with southern yellow pine.[25–27] This matrix has been patented and is currently being field tested for efficacy against subterranean termite species.[28] No inhibition of consumption of the matrix was noted when it was supplemented with known chitin synthesis inhibitors.[25–27] This contrasts with earlier work in which some chitin synthesis inhibitors caused apparent feeding deterrence when applied to wood blocks themselves.[14] It was concluded that the feeding preference for the bait matrix masked any feeding deterrence caused by the inhibitors and indicates that the matrix may be used as an improved delivery vehicle for slow-acting toxicants employed in a baiting control strategy. Increased preference and consumption of this matrix may allow the use of an active ingredient that may have some innate repellency that is overcome by the matrix. Alternatively, the increased consumption of the matrix compared with other forms of cellulose may allow the use of lower concentrations of active ingredient while still ensuring delivery of sufficient material to the colony to achieve colony level control.[25–27]

2.3 Relation of micro-organisms to nutrition of the termite

2.3.1 Wood decay

Wood decayed by fungi has long been thought to make up the primary diet of subterranean termites.[14] It has been suggested that fungus-decayed woods may be favored by termites for numerous reasons, most importantly enhanced nutrient content, decreased wood density, and probable reduction of toxic allelochemicals present in the wood.[29] Determining the relationships between fungi and termite infestation and nutrition may serve as a viable route for developing improved control options for this pest.[25,26]

Termites have been shown to react differently to woods infected with brown- or white-rot fungi. Differences in attraction to the wood, as well as feeding stimulation or inhibition of feeding are possible depending on the infection source. Researchers have found wood decayed by the brown-rot fungus *Gloeophyllum trabeum* (Pers ex Fr) Murr to contain substances that acted as an attractant of *Reticulitermes flavipes* Koll, *R virginicus* Banks and *Nasutitermes columbicus* (Holmgren).[15,30] Termite attractant activity similar to that of *G trabeum* was also reported for *Serpula lacrymans* (Wulfen ex Fr). *Serepula lacrymans* and *G trabeum* are both known to stimulate feeding and trail-following activity in *C formosanus*. *Gloeophyllum trabeum* has been used successfully in bait block trials to increase the effectiveness of the slow acting toxin mirex (a mixture of dodecachloropentacyclodecanes).[16]

Cornelius *et al*,[31,32] working with partially decayed sawdusts, showed that the products of decay by the white-rot fungus *Phanerochaete chrysosporium* Burdsall or the litter rot fungus *Marasmiellus troyanus* (Murr) Sing were preferred more than that partially decomposed by *G trabeum*. None of the fungi grown on artificial media were by themselves attractive to the termites, but apparently produce attractants or arrestants when decomposing sawdust. Moreover, methanol extracts of the sawdust decomposed by each of the species tested increased tunneling activity of termites in sand treated with the extracts.[32] It is not currently known whether the termites consume more wood decomposed by these fungi or whether they are simply more attracted to it. Interestingly, laboratory tests with these same fungi and purified cellulose or lignin indicated greater termite foraging with degraded lignin, suggesting that a breakdown component(s) of the lignin may be responsible for the attraction.[33] Determining the factor(s) making the fungus-degraded lignin more attractive for foraging may provide a means of improving bait finding or consumption to improve effectiveness of baiting systems.

2.3.2 Intestinal microflora

The Formosan subterranean termite, like other lower termites, relies upon intestinal microflora for digestion of cellulose. Little is known of the biology or physiology of these intestinal symbionts or of regulation of the production of the cellulolytic enzymes which might be exploited for control of the termite. Manipulation of the normal gut microflora or disruption of cellulose catabolism through chemical or biological means could provide effective long-term control. Research efforts have begun which focus on the interaction of not only the gut protozoan fauna, but also on the interactions of these organisms with numerous other micro-organisms in the termite gut to specifically target these essential components of the digestive process.

3 CURRENT STRATEGIES FOR CONTROL OF THE FORMOSAN SUBTERRANEAN TERMITE

3.1 Chemical control

Manufacturers have evaluated a plethora of compounds for possible use as termiticides, yet relatively few qualify for commercial use. Limitations are due to stringent performance, environmental and safety requirements. The method of choice for termite control for over 40 years had been the organochlorine pesticides, most notably chlordane and heptachlor.[1] These chemicals were highly effective, having residual lives in excess of 25 years and, because of relatively high vapor pressures, would move sufficiently in the soil to ensure adequate soil distribution even under less than ideal application conditions. Manufacturers of these products voluntarily withdrew their application for re-registration to EPA for their use in 1988 because of various environmental and health concerns with respect to their active ingredients. However, these termiticides, where available, are still often the preferred choice for termite control world-wide.

The availability in the past of these inexpensive, effective chemical termiticides contributed, at least partly, to a lack of fundamental research to develop new and improved control strategies. Environmental concerns and withdrawal of organochlorine and organophosphate termiticides, as well as the desire to move to a population-control strategy rather than defending an individual structure have resulted in the development of new products. Over the past several years, monitoring baiting technologies have been developed and evaluated for subterranean termite population control.[13,14,19–21,34–36] Su and Scheffrahn[35] reviewed some alternative control methods including non-repellent slow-acting termiticides and bait technology. These new products do not repel termites, and are easily transferable in or on termite bodies, enabling transfer from foraging workers to non-foraging members of the termite colony.[22] The slow-acting nature of these compounds allows dosing throughout the colony prior to exerting their toxic effects.

Currently, synthetic pyrethroids, pyrroles (fipronil) and chloronicotinyls (imidacloprid) make up the 12 or so EPA-registered soil barrier termiticides used within the USA. These EPA registrations are not based upon direct testing against *C formosanus*. The latter is known to be more tolerant of several of the registered termiticides and, frequently, higher rates of application are recommended in areas infested by *C formosanus*.[37,38] Low mammalian toxicity and low environmental hazard are added advantages of the current group of soil barrier termiticides. Pyrethroids are highly repellent to termites, which invokes low mortality within a termite population, whereas organophosphates are non-repellent and cause high, localized mortality and secondary repellency caused by the presence of the dead termites within the treated zone. Pyrethroid-based soil barrier termiticides are much more useful in high temperature, low moisture environments than organophosphate-based soil barrier termiticides because they do not degrade as rapidly in this environment.[33,39] The chloronicotinyls, of which imidacloprid is the most active compound, are not readily detectable by termites. The dose-dependent modes of action involve attachment to specific binding sites at nerve endings of termites, resulting in discontinued feeding, disorientation and, eventually, death.[1] Failures of liquid termiticides applied to the soil prior to construction or after post-construction treatment for subterranean termites are well documented and have led to investigations of the pest control industry the attorneys general of several states. Osbrink and Lax[40] found that trees treated with imidacloprid suppressed (about 6 months) but did not eliminate *C formosanus* from adjacent independent monitors. The failure of pesticides to control structural infestations has been attributed to: (1) incomplete or improper application of the pesticide during treatment, (2) improper concentration of termiticide applied, (3) small gaps in the chemical barrier because of soil properties, (4) degradation of the pesticide, (5) physical disruption of the barrier and (6) bridging over or through the chemical barrier by gardening or mulching activities. In areas in which the *C formosanus* is a major pest, many pest-management professionals have chosen to use a combination of baiting and liquid barrier treatments to provide maximum structural protection. This integrated population management approach forms the basis for the area-wide management program in New Orleans' French Quarter and will be discussed separately below.

3.2 Resistance of termites to chemical controls

It is not known whether tolerance to particular pesticides or groups of pesticides has developed in subterranean termites. However, *C formosanus* is known to be more tolerant of soil termiticides than native termite species and the recommended rate of application of these products is frequently greater when applied for *C formosanus* control. Neither detoxification of the pesticides by the termites themselves, nor the mechanisms responsible for this tolerance have been fully investigated. Recent reports indicate tolerance of some colonies of both *R flavipes* and *C formosanus* to various classes of traditional termite control chemistries.[37,41] The selection of resistant individuals in a colony that can molt into secondary reproductives could lead to the development of colonies resistant to some insecticides.[41] Valles *et al*[42–45] reported the presence of several oxidases present in native subterranean termites that may be responsible for detoxification of and resistance to such pesticides, and further work is needed to determine the exact mechanism of such tolerance and the biological consequences of sub-lethal exposure of entire colonies to these pesticides. Osbrink and Lax[38] found that insecticide tolerance had an effect on the ability of termites to penetrate treated soils in the laboratory. Recent work confirmed different tolerance levels to several commonly used termiticides among colonies collected from different sites within New Orleans' City Park.[46] Because these termites were collected from a park area it is unlikely that they would have been previously exposed to commercial termiticides, and there may be no selection pressure for the development of resistance. While there were substantial differences in the levels of various detoxification enzymes such as cytochrome P450 oxidase, cytosolic esterases and microsomal esterases, there was no direct correlation between the levels of enzyme activity observed and the levels of insecticide tolerance noted.[46] This is interesting, given that microsomal esterases have been demonstrated to be important in detoxification of pyrethroids in *Reticulitermes* species.[43–45] To clarify this potential trend, additional studies should be conducted to include termites that have not been exposed to termiticides and termites which have persisted near structures in the continued presence of the termiticide.

3.3 Termite monitoring and baiting systems

Over the past several years, monitoring and baiting technologies have been developed for suppression of subterranean termite populations.[19–21] These termite monitoring and baiting systems have received more emphasis concerning suppression or elimination of termite colonies and less emphasis on the use of traditional exclusionary barrier treatments which have had little direct effect on termite populations. In most baiting systems cellulose materials are placed at regular intervals in the soil, allowing termites to discover and initiate foraging. Termite presence is examined on a regular basis and substrate laced with active ingredient is supplied when termite activity is present. Application of toxin only when termites are present makes baiting systems an environmentally friendly approach. Several such systems are commercially available for both in- and above-ground use. Monitoring/baiting technologies generally act more slowly than chemical spot or soil treatments and specifically utilize slow-acting toxins so that foraging termites are able to spread the toxin throughout the colony and thus have maximum effect on the entire population.[20,22] The development of these baiting systems and the development of non-repellent chemistries was in part responsible for the development of the area-wide pest management concept in New Orleans' French Quarter.

Because these systems rely upon their discovery and consumption by termites, understanding the underlying foraging behaviors of termites could improve the effective placement of monitoring stations.[32,47–49] Such information could provide new and improved placement of baits to optimize their discovery by the termites, or in the development of trail-following chemicals that could be applied to attract termite foraging in baited areas. Optimization of the placement of the baits around a structure through precision targeting or the use of improved baits would improve the control effectiveness and rate of control. Identifying the chemical factors that influence termite foraging behavior could have profound implications for improving bait technology by leading termites to the bait stations. Foraging patterns and the fidelity with which *Coptotermes* feeds on a food source once discovered make it imperative that species consideration be given when designing a baiting system for termite control. *Reticulitermes* species are more likely to discover and subsequently abandon a feeding site (bait station) than *Coptotermes*.[48] Because of the need to deliver significant amounts of toxin to an entire colony for a baiting system to be effective, differing patterns of monitoring/baiting station placement may be required to deliver an effective dose when dealing with these different subterranean termite species.[47,48]

In tests designed to discover trail-following substances with a view to improving bait discovery, it was determined that, within five minutes, both species deposited chemical constituents on glass tubes that elicited trail following behaviors of both species.[49] The substance produced by *C formosanus* was more long lived. Over a 14-day period, *C formosanus* deposited chemical markers which persisted for at least 8 days in the absence of termites.[49] Identification of the active components of these markers may lead to technologies that will lead termites into baiting arenas or away from structures to be protected. Work is ongoing to isolate and identify the active fractions for inclusion into laboratory scale foraging experiments.

3.4 Area-wide termite management

Since the initial discovery of *C formosanus* in the USA, populations of the termite have continued to grow despite the use of traditional liquid barrier-type treatments. Failure of the liquid termiticides to achieve population control has been attributed in part to improper or incomplete treatments of the structures by the pest-control operators and in part to human activities that disrupted the barrier. However, a major cause of the failure to control the termite population was the strategy of protecting individual structures without regard for controlling the termite populations themselves. Unlike native subterranean termites, whose colonies often contain hundreds of thousands of individuals, a *C formosanus* colony often contains millions of individuals. These colonies have been demonstrated to have foraging territories that may range up to 300 feet from the primary nest.[50] *Coptotermes formosanus* is also much more likely than the native termite species to attack and nest in living trees.[2,11] Thus while the barrier approach may have killed numerous termites, it is much more likely that the termites were simply redirected to foraging at a neighboring untreated home or into an unprotected tree, allowing continued growth of the population of that colony. Among the first objectives of the ARS research program was to establish an area-wide treatment program following the concepts of Knipling.[51] This management paradigm was made possible, in part, because of the availability of new termite control technologies including monitoring/baiting technology and non-repellent termiticides designed to reduce or eliminate termite colonies rather than simply repelling them. Area-wide tests were established in a fifteen-block area of New Orleans' French Quarter under the auspices of Operation Full Stop in which the homeowners, in cooperation with a licensed pest-control operator, selected from among the population reducing products. Over 99% of the properties within the designated zone were treated.[52,53] Approximately 40% of the properties outside the treatment zone also received treatments independently of the Operation Full Stop program.[52,53] Significantly, greater than 50% reduction in alates captured within the treatment zone has been measured using sticky traps attached to street lights at intersections within the French Quarter as a result of Operation Full Stop. A slight reduction of alates captured outside the treatment zone is attributed to the imposition of termite control treatments by homeowners outside of the treatment zone.[53]

Other area-wide tests were established in the USDA-ARS-SRRC campus and in southern Mississippi. In these tests, different insect growth regulators were incorporated into the ARS nutritionally based bait matrix and provided in underground stations when termites were present and active. Stations are being monitored monthly for activity and bait consumption and determination of population management.[54]

3.5 Detection

Detection of termite infestations remains a critical issue for pest control operators and homeowners alike. As cryptic organisms, subterranean termite infestations remain hidden below ground, within trees, and within walls or structural lumber of a building. The only predictably visible stages of *C formosanus* are the alates that typically emerge on warm, humid, calm evenings in the spring. Seeing these swarmers is often the first indication to a property owner that an infestation exists in or near the property. By the time a colony has reached sufficient maturity and numbers for swarming, substantial structural damage to the building (or tree) has occurred. Visual inspection by pest-control operators using flashlights and probing tools to discover structural damage or signs of termite infestation is the first line of defense in structural protection. However, inaccessible areas of a home may represent as much as 45% of the structure, making visual inspection impossible and necessitating the development of new means of termite detection.[55] Thus improved detection technologies are critical to provide early detection and intervention prior to significant structural damage.

Since 1929, means of detecting termites using alternative methods such as sound amplification has been attempted but with limited success.[56] Acoustic emissions detectors for termites have been widely studied in the laboratory and field to assess their potential for detection of termite colonies and for quantification of their activities.[57–61] Various frequencies of acoustic emission are detectable, although the signal strength and distance from the source that can be detected are dependent upon the numbers of termites present. Mankin *et al*[61] have recently reported the development of an acoustic device that can detect both native and Formosan subterranean termite species in infested trees and soil that should improve the targeting of tree treatments and determination of the effectiveness of those treatments. At the present time, acoustic detection devices are effective only at short distances from the termite activity.[61] Efforts have begun to improve the effectiveness of a device to detect small colonies within trees and structures to allow early intervention and control before significant damage can occur. Such an acoustic device should also assist in locating termites within a structure and the monitoring of the effectiveness of treatments using either spot chemical treatments or baiting programs.

Other detectors that have been studied for detection of termites include odor detection using electronic devices, although statistically significant detection was not achieved.[55] Odor detection using dogs was significantly better when larger numbers of termites were presented; however, dogs incorrectly identified a large percentage of control wood blocks as having termite infestations. Resistograph technology has also been used as 'smart drills' to detect termite galleries and determine the extent of damage in trees.[2,62]

Another technology that is being developed is the use of an infrared camera which can detect the presence of moisture and subtle temperature differences on the interior of structural components within walls that result from termite activity. Such temperature differences result in an anomaly in the image obtained by the camera which may indicate the presence of termites.[63] The use of this technology may allow a rapid initial survey followed by more specific confirmatory techniques. Combinations of these and other developing technologies, including devices that detect the presence of gases associated with termites, are certain to become more widely used as research confirms their utility in the pest-management industry. It is hoped that other sensitive electronic devices will be developed to provide more rapid and sensitive detection of incipient termite infestations. ARS is conducting substantial research to improve and integrate detection technologies to supplement visual inspections.

3.6 Wood resistant to termites

Concerns about the use of chlorinated hydrocarbons for termite control resulted in research into extracts of woods resistant to termites. Woods naturally resistant to termite infestation are very important due to their possible usefulness in areas where termites are problematic.[64–70] Reasons for such resistance are usually chemically related, as the chemical constituents in the wood may be repellent, toxic, injurious or distasteful to termites. In addition, the extracts of such woods may be useful for applications involving protection of susceptible lumber from termite attack.[1,26] New formulations derived from the chemical study of woods may lead to effective, environmentally safe chemicals for termite control.[71,72] Various tropical and American woods have been intensively screened for termite resistance, with tropical woods studied more extensively.[33,64,66,69] Several durable termite-resistant American woods such as California redwood, red cypress, and red and yellow cedars have been studied over the past two decades for susceptibility to attack by *C formosanus*.[25,71,72] In many cases, these naturally durable woods compare favorably with preservative-treated woods in their resistance to termite attack. Although there are several reports concerning the various levels of susceptibility of many woods, very few of the antitermitic components have been identified chemically. Some volatile, water-insoluble terpenoids have been identified in several North American coniferous woods as the prominent antitermitic substances.[25,71–75] Research on woods containing substances that attract termites is still in its infancy. It has been reported that steaming of Japanese larch and beech heartwoods may produce attractants and/or degrade, modify, or remove larch wood constituents that may suppress termite attack. These attractants may then be removed by hot water extraction.[76,77]

Many studies have reported differences in feeding rates and survival of subterranean termite workers in non-choice or force-feeding tests with different species of wood. Smythe and Carter[78] reported that *Reticulitermes flavipes* (Kollar) consumed significantly lower quantities of redwood (*Sequoia sempervirens* (Mierb) Endl) or bald cypress (*Taxodium distichum* (L) Rich) than nine other wood species. The preference for some woods change when termites are presented with choices.[25,79,80] Hardness and specific gravity of hardwood species are inversely correlated to preference by *R flavipes*. Softer woods were consumed at higher rates by *R flavipes* even in single wood species tests.[81,82]

Allelochemicals such as terpenoids, quinones, phenolics and flavenoids have been associated with termite-resistant woods, and research continues in this area to find useful new termite control products to replace other, more toxic, wood preservatives.[26,27,75]

3.7 Biological control agents

No specific pathogens of Formosan subterranean termite are known, although several entomopathogenic fungi are known which will kill the termite under laboratory conditions.[83,84] Field tests with these isolates have not proven successful in *C formosanus* control.[84] Identification of co-evolved pathogens of *C formosanus* or strain selection of more broadly entomopathogenic fungi, bacteria or viruses could provide potential biological control agents for further evaluation.[85–87] Exploration in Formosan subterranean termite centers of origin should be conducted to discover co-evolved microbes.[88] Field resistance, believed to result from grooming behavior or isolation of diseased individuals, may be altered to allow development of epizootics. Nematodes represent another potential biological control alternative that has not been effectively exploited.[89]

Antifungal volatile compounds have been identified in *C formosanus* nests that may contribute to the inability of the potential biological control fungi to propagate within the colony.[90] One strategy to overcome some of the obstacles to success with field control using fungal pathogens was to select for fungi resistant to the antifungal compounds. Recent studies using fungal strains selected to be resistant to several of these antifungal volatiles have shown an apparent loss of pathogenicity compared to the strain from which they were derived.[87] Longevity of *Metarhizium anisopliae* (Metsch) Sorokin conidia in the soil has been established but not in the presence of chemicals which predominate in termite nests such as naphthalene and fenchone.[91,92] Thus, further work is required to select for appropriate strains to overcome that source of resistance to fungal pathogens.

In addition to selection of superior strains of known entomopathogens of termites, substantial effort has been initiated to discover potential biological control agents in the areas of origin of the Formosan subterranean termite. Numerous collaborators have begun surveys in China, Taiwan, and Hong Kong for nests of the termite and collections of termites from these areas have yielded significant numbers of bacteria such as *Bacillus* sp, *Serratia* and *Pseudomonas* sp. Fungi collected include *Metarhizium*, *Beauveria* and *Paecillomyces* species isolates.[88]

The nematodes *Heterorhabditis* and *Steinernema* have been collected and evaluated in the laboratory for their activity against *C formosanus* as well as *Reticulitermes* sp. *Heterorhabditis indica* was more virulent than *Steinernema* sp at all rates of infective juveniles applied to laboratory cultures; however, 2000 or 5000 infective juveniles per termite must be applied to achieve near complete mortality in the laboratory within 8 days.[89]

Biological control has the potential to succeed as a primary technology for termite colony suppression or elimination. The use of naturally occurring pathogens of termites, principally fungi, bacteria, viruses and nematodes, offers unique advantages over chemically based termiticides. Chief among them are ease of registration, environmental responsibility and safety to non-target organisms. Biocontrol should be considered as a long-range research goal rather than an immediate solution. There is only one biocontrol product on the market, BioBlast™ (EcoScience, New Brunswick, NJ), which contains the fungus, *M anisopliae*, as the active ingredient. There is a small, but growing, body of literature on termite biocontrol from which new research approaches can spring. Grace[84] recently reviewed termite biocontrol. ARS scientists are actively searching for potential biological control agents in areas where the termite is endemic.

Other research has demonstrated an association of several fungal species with termites themselves as well as with carton material and infested wood. *Aspergillus fumigatus* Fres, *Curvularia lunata* Boed and *Aspergillus nomius* Kurtz were consistently found associated with *C formosanus* from six locations within the New Orleans, LA area.[93] Consistent associations of these fungi with numerous locations of *C formosanus* infestation suggest a possible nutritional role, although further research is needed to confirm this postulated role and to determine if these organisms may be useful in a biological control program.

Because of the failures of past attempts to control *C formosanus* in the field using known entomopathogens, we have also begun to explore methods to improve the infection of termites and thus effect colony control using these microbes; these include immune system suppression and selection of more viable strains.[86,87]

Other micro-organisms consistently isolated from moribund termites kept in the laboratory after field capture include *Serratia marcescens* Bizio, *Enterobacter*, *Klebsiella*, *Acinetobacter* and *Corynebacter* species.[85] While many of these genera contain species that are known human pathogens, or cause infections in immune-compromised individuals, there are isolates of *S marcescens* that are believed not to cause human disease. When strains of these microbes that had been isolated from termite cadavers, or the vermiculite in which they were foraging, were tested for pathogenicity, at least three of the *Serratia* isolates induced greater than 85% mortality within 19 days in Petri dish tests.[85]

Fungi exhibit qualities which can make them ideal for this application, including a slow-acting nature similar to that of successful chemicals, the ability to self-replicate, and the ability of fungal spores to be spread by termite social behavior.[94] In addition, their viability and virulence are favored by the warm, humid conditions found in termite nests. In Ontario, Canada, 21 fungal species were cultured from living termites.[95] Three fungi are most often cited as potentially useful pathogens in the termite biocontrol literature. They are *Beauveria bassiana* (Balsamo) Vuillemin, *Metarhizium anisopliae* (Metschnikoff), and *Conidiobolus coronatus* (Costantin) Batko. Isolates of *B bassiana* from soil were as effective as biocontrol agents for *Heterotermes tenuis* Snyder as those isolated directly from insect hosts.[96] Germ tubes of *B bassiana* penetrated the integument of *Reticulitermes flavipes* (Kollar) as early as 16 h after application. Important factors were the amount of inoculum, virulence of the strain, and condition of the host.[97] Formosan termite workers dusted with conidia of *B bassiana* or *M anisopliae* transmitted the pathogen to other colony members.[87] One isolate of *B bassiana* and one of *M anisopliae* that were originally isolated from termites were virulent against *C formosanus* and grew well on cadavers.[98]

An isolate of *M anisopliae* was effective against large colonies of *C acinaciformis* (Froggat) in Australia when conidia were blown into the center of their mounds.[99] Pure spores of *M anisopliae* are sometimes repellent to termites but the repellency can be overcome by formulating with clay and surfactant. Agar-coated baits containing *M anisopliae* or *B bassiana* killed foraging Formosan termites.[100] As few as two or three conidia of *C coronatus* attached to each *C formosanus* worker killed them within 9 days.

Bacterial termite pathogens have not been studied as much as fungal pathogens, but deserve attention as potential biocontrol agents because they can cause deadly epizootics.[101] Most bacterial research on termites has concentrated on *Bacillus thuringensis* Berliner. Recombinant expressed delta-endotoxin of *Bt* in the bacterium *Pseudomonas fluorescens* Migula when applied to *C formosanus* had no effect.[102] However, delta-endotoxin of *Bt ssp amagiensis* caused death of the termite *Anacanthotermes ahngerianus* (Jacobson).[103] Clearly substantially more fundamental research is needed to establish pathogenic bacteria as biological control agents.

Entomopathogenic nematodes such as *Steinernema feltiae* Filipjev can parasitize and kill Formosan termites.[104] However, field tests using only nematodes as the agent have not yet been fully successful.[105] A moist environment and sandy soil are conducive to the success of parasitic nematodes. When large numbers of individuals of *C formosanus* were infested with *S feltiae* and were then returned to their respective colonies they were not completely eliminated, perhaps because infected individuals were removed into isolation.[106] Similar results have been obtained with *Neoaplectana carpocapsae* Weiser and *C formosanus*.[107]

Continued surveys in the areas of origin of *C formosanus* are under way to determine whether co-evolved natural enemies that limit their colonies can be discovered. Suppression of colony fitness by such organisms could contribute to an integrated area-wide management program.

4 DISTRIBUTION AND MOVEMENT OF THE FORMOSAN SUBTERRANEAN TERMITE

Extensive surveys must be conducted to monitor the movement of *C formosanus* from the heavily infested Gulf Coast to other areas of the southeastern USA. Monitoring the presence of *C formosanus* in forests is critical to documenting its spread, since this pest has not yet been detected in forests north of I-10 in South Mississippi. In North and South Mississippi, as well as other states, surveys are being conducted to establish the presence and extent of infestation by this species. Termites play important roles in forest systems, especially in tropical rain forests which have enormous termite populations.[108–110] They promote organic matter decomposition, alter soil physical and chemical properties, and provide food for other animals.[111]

Although their ecological importance is well known, they have rarely been studied quantitatively in forests of the USA.[112] Perhaps this has mostly been due to their lower significance, in economic terms, in forests than in residential areas. Like other insects, abundance of termites is influenced by the distribution and quality of suitable food, but there is very little information regarding the relationship between termites and size or distribution of wood materials.[113] In Mississippi, *R flavipes* and *R virginicus* appear to be the dominant termite species in forest as well as in residential areas, but surveys are vital to document spread and to ascertain the extent of infestation in live trees of aesthetic, economic or ecological value.[114] Early detection of infestation through surveys will also provide the opportunity for early intervention by the pest-control industry to prevent or minimize establishment of infestations.

4.1 Distribution of the Formosan subterranean termite

Presence of the Formosan subterranean termite was first reported almost simultaneously in the mid-1960s in four locations: New Orleans and Lake Charles, Louisiana; Houston/Galveston, Texas; Charleston, South Carolina. As of 2001, the termite is known to have infested 94 counties/parishes in eleven states, although it is believed to no longer exist in several of the areas in which it was once established.[8,12] The primary means of long-distance spread is through man's movement of infested materials, such as infested salvaged building materials or landscape timbers. Natural spread of the termites over short distances is through construction of subterranean galleries or through the dispersal flights of the winged reproductives. The known US range of the termite is north to North Carolina and west to California.[8] Climatic factors that are expected to limit the range of the termite are annual mean temperatures greater than 14.3 °C and relative humidity greater than 62%.[115]

Understanding the factors that contribute to the continued distribution of *C formosanus* will allow more vigilance in susceptible areas and intervention before the termite can become firmly established. Such early intervention and the location of the infestations on the periphery of the range of the termites may have contributed to the apparent demise of infestations in Tennessee and North Carolina. As with all subterranean termite species, temperature and moisture are probably the major limiting factors with respect to the local distribution. *Coptotermes formosanus* infests virtually the entire New Orleans metropolitan area. Attempts to correlate the termite population with various plant species or soil types in New Orleans City Park did not reveal any particular preference for a food source or substrate type. It can be expected that the Formosan subterranean termite's range will continue to expand with long-distance spread mediated primarily through man's commercial activities. Left unchecked, local populations can be expected to grow rapidly in suitable climates. We expect that improved awareness of the problem by homeowners and increased education of pest-control operators will help to identify infestations in previously unoccupied areas and that improved area-wide intervention will limit this spread. Citizens in infested areas are updated through newsletters and regular public meetings to increase their awareness of the termite and current strategies to control the pest.

5 CONCLUSIONS

ARS has a strong commitment to elimination of the Formosan subterranean termite as an economic pest in the USA. The establishment of the Formosan Subterranean Termite Research Unit at the Southern Regional Research Center is the centerpiece of this effort and is supplemented by collaborations with other ARS laboratories and with numerous University cooperators. The emphasis of this program is the demonstration of effective subterranean termite control technologies when applied in an integrated area-wide pest-management program as exemplified in New Orleans' French Quarter. Our success to date in reducing the populations of termites in this extensively infested area suggests that the area-wide approach will be useful in managing this pest. Further improvements to current control technologies include improvements to detection technologies and fundamental research concerning the termites' biology that may provide keys to new approaches for control of this economically important species.

The shift in control paradigm from one of defensively protecting an individual structure to that of an aggressive, offensive strategy designed to eliminate or significantly reduce populations of the termites has shown considerable success and promises to be useful in areas where *C formosanus* has become established. Furthermore, extensive surveys to determine areas with newly established infestations along with education of homeowners and pest-control operators throughout the expected range of the termite are expected to result in aggressive intervention that should limit the degree to which the termites become established. Fundamental research has resulted in development of a nutritionally based bait matrix that has potential to more effectively distribute selected control agents within the termite colony, and in new micro-organisms that might be exploited in an area-wide population suppression approach. Further understanding of foraging behaviors and chemicals could lead to improved monitoring and baiting technologies. Similarly, understanding the reproduction and development of the termite colony is expected to lead to novel approaches to colony-based control. Discovery of new biological agents can be expected through active discovery and may form the basis for long-lived control technologies. The active ARS program on understanding basic termite biology should also lead to new specific approaches to subterranean termite control.

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