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A review of subterranean termite control practices and prospects for integrated pest management programmes

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Soil insecticide barriers have been the single most important tool for subterranean termite control in the last half century, but limitations with current soil termiticides have provided the impetus to look for alternatives in recent years. One such alternative is the monitoring–baiting programme. Monitoring stations to detect termites are placed in the soil surrounding a structure. Once termites are found in the stations, monitoring devices are replaced with slow-acting baits such as the chitin synthesis inhibitor, hexaflumuron. Field studies have indicated that termite colonies were eliminated using less than 1 g of hexaflumuron. After the elimination, monitoring resumes and bait is applied if new termite activity is detected. The monitoring and baiting procedure form the basis for an ongoing programme to protect structures from subterranean termite infestation. Although the cost–benefit model developed for agricultural integrated pest management cannot be applied directly to termite control, the underlying concept for using a cost-effective approach remains the same. The benefits of the monitoring–baiting programme over conventional soil treatment are a reduction in pesticide applied per unit and the elimination of termite populations near structures, resulting in the reduction of liability and damage potential. It is expected that the data management system when used in conjunction with the monitoring–baiting programme will provide a database to improve its cost-effectiveness continuously.

Keywords: Isoptera; subterranean termite control; monitoring–baiting programme.

Introduction

Of the over 2300 termite species in the world, 183 species are known to damage buildings and 83 species cause significant damage (Edwards and Mill, 1986). Subterranean termites, including mound building and arboreal species, account for 80% (or 147 species) of the economically important species and the genus *Coptotermes* (Rhinotermitidae) contains the largest number of economically important subterranean termites (28 species). Unlike drywood termites that are easily transported from region to region, most subterranean species are restricted in their distribution. Of the 147 economically important subterranean termite species, only two, *Coptotermes formosanus* Shiraki and *Coptotermes havilandi* Holmgren, have been introduced in more than five regions worldwide (Edwards and Mill, 1986).

Economic impact, economic threshold, tolerance or action threshold

An organized service industry providing termite control is scarce throughout much of the tropics and subtropics where the majority of destructive subterranean termite species are found. Although the tolerance or action threshold for many urban pests (equivalent to the economic threshold for agricultural pests) is considered low or even absent in developed countries (Robinson, 1996), control action against termites may not be economically feasible in many countries where these destructive pests are most abundant. In rural areas of many developing countries, for example, severe termite damage to structures is often tolerated because the control cost may exceed the replacement of damaged lumber or reconstruction costs. On the other hand, in the USA, the presence of a single destructive species such as the Formosan subterranean termite, *C. formosanus*, can sustain a multimillion-dollar termite control industry. It is probably true, therefore, that the tolerance threshold for termites is near zero in countries with a relatively high standard of living. The control cost, although high compared to those for other household pests, is considered relatively small in comparison with the value of a house and the damage potential by termites.

In recent years, factors such as building costs and expanding urbanization have contributed to the substantial increase in monetary expenditure due to termite damage and control in the USA (Su and Scheffrahn, 1990). Edwards and Mill (1986), who extrapolated the data of Pinto (1981), estimated a $1.02 billion economic impact by termites in the USA. Based on sales figures for liquid termiticides, Su (1994) suggested the control cost alone might exceed $1.5 billion. Subterranean termites account for an 80% share or $1.2 billion. This figure may increase substantially when repair costs are included.

Control objectives and options

The objective for the control of subterranean termites is to protect a structure and its contents. The current control options include soil barrier treatments, wood treatments and population control using baits. The damage potential of subterranean termites, however, is often impossible to predict accurately, due in part to their cryptic habit and unpredictable foraging pattern. Consequently, the pre-construction treatment of subslab soil using liquid termiticides is mandated by building codes or required by financial institutions in many areas of the USA. Regardless of the presence of subterranean termite populations near structures, 5–10 kg of insecticide are typically used in pre-construction treatments for a single-family home of ~185 m^2.

Barrier treatment

Soil termiticide barriers. Ground treatments have been widely used by commercial termite control firms for subterranean termite control since the beginning of this century (Randall and Doody, 1934). Early on, ground treatments were apparently thought to 'eradicate' subterranean termites from soil, but such treatments were later found to serve only as foraging barriers between sources of infestations and the structures to be protected (Randall and Doody, 1934). The insecticides used for ground treatments during the 1930s–1950s included sodium arsenite, trichlorobenzene, DDT, pentachlorophenol, creosote and ethylene dibromide (US Department of Agriculture, 1951). Following a 5 year efficacy test in southern Mississippi, chlordane was marketed as a soil termiticide in 1952. Other cyclodienes, such as heptachlor, aldrin and dieldrin, soon followed and dominated the termite control industry as the main treatment for subterranean termites until the mid-1980s. These inexpensive insecticides provided persistent soil barriers for excluding soil-borne termites from structures and were the single most important treatment tool for the termite control industry for the last half-century. Environmental persistence and public health concerns over cyclodienes, however, led to their withdrawal from the market in the mid-1980s. Currently, one organophosphate (chlorpyrifos), four pyrethroids (permethrin, cypermethrin, bifenthrin and fenvalerate) and one nicotinoid (imidacloprid) are the compounds marketed as soil termiticides for the pest control industry in the USA. The current termiticides are more expensive and less persistent than the cyclodienes. Because of the cost factor, some pest control firms are tempted to use lower volumes or rates to reduce operating expenses (Mampe, 1994). This, in conjunction with reduced soil longevity, has apparently resulted in the failure of some termiticide barriers in recent years. Even applied at the label rates, the continuous barrier provided by the pre-construction application of these biodegradable termiticides eventually wanes. In areas of high subterranean termite populations, the failure of such barriers can result in structural infestation.

Despite these shortcomings, soil termiticide applications will continue because of their mandatory use in the pre-construction market. Liquid termiticides will also continue to play a vital role in remedial treatments, where their application has an immediate effect in mitigating termite activity.

Physical barriers. Two physical barrier types, uniform-sized particles and stainless steel screening, have been employed as non-chemical controls in recent years. Originally discovered by Ebeling and Pence (1957), barriers composed of soil particles that are too large for termites to displace with their mandibles, yet are too small for termites to pass between, are known to stop termite penetration. This observation was later rediscovered by Tamashiro *et al.* (1987) and confirmed by others (Smith and Rust, 1990; Su *et al.*, 1991b; Su and Scheffrahn, 1992; Lewis *et al.*, 1996). Currently, the gravel barrier (BTB, basaltic termite barrier) is accepted in Hawaii as a pre-construction treatment option (Grace *et al.*, 1996a). Field studies have demonstrated that stainless steel mesh barriers (TERMI-MESH®) withstand the intensive foraging activities of several termite species under field conditions (Lenz and Runko, 1994; Grace *et al.*, 1996a). These physical barriers can be used most effectively as continuous horizontal barriers during pre-construction installation. The role of physical barriers in the future of subterranean termite control may depend on their acceptance by the construction industry and willingness of buyers to absorb the cost.

Population management

Before the advent of soil barrier treatments using organic insecticides, slow-acting toxicants such as arsenic dust were applied into foraging tubes in an attempt to impact on colony populations (Van Zwaluwenberg, 1916; Wolcott, 1924). The population management approach was not rigorously pursued in the past because of the enormous success of the cyclodiene barriers used by the pest control industry. Esenther and Gray (1968) suggested that dechlorane (mirex), a slow-acting toxicant, could be used to eliminate isolated populations of the eastern subterranean termite, *Reticulitermes flavipes* (Kollar) in Canada. Subsequent studies using mirex bait blocks indicated that the continuous placement of toxic baits might have suppressed foraging activity of *Reticulitermes* species (Beard, 1974; Esenther and Beal, 1974, 1978; Ostaff and Gray, 1975), but the effects of baiting on colony populations were not assessed. The lack of information on the foraging populations of subterranean termites, in particular on the site fidelity between baited sites and evaluation sites, hindered such assessment (Su and Scheffrahn, 1996a).

Lai (1977) was the first to realize the importance of defining colony foraging territory when he attempted population control of *C. formosanus* using entomopathogenic fungi. The mark–recapture technique using the dye marker Sudan Red 7B, as described by Lai (1977), is probably the single most important development for the field evaluation of population management techniques against subterranean termites. As with the radioisotope ^{140}La used by Paton and Miller (1980), dye markers such as Sudan Red 7B (Lai, 1977; Su and Scheffrahn, 1988a; Grace *et al*., 1989; Grace, 1990a; Jones, 1990) and Nile Blue A (Su *et al*., 1991a, 1993; Sornnuwat *et al*., 1996) have been used to delineate the foraging territories of subterranean termite colonies. The presence of marked termites was used to confirm the interconnection of monitoring stations and the area encompassing the interconnecting stations was considered part of a colony's foraging territory. When a control method such as a slow-acting bait was applied within the colony's foraging territory, its efficacy against the colony population could be evaluated objectively by measuring the changes in foraging activity from untreated stations located within the foraging territory of the target colony (Su and Scheffrahn, 1996a).

In a practical sense, therefore, a subterranean termite colony is defined as 'a group of termites sharing interconnected foraging sites'. This pragmatic definition precludes the complication due to colony budding, namely that the budded population is considered an independent 'colony' once foraging sites have been separated. Thus, population control at the colony level only targets an interconnected foraging group. We disagree with Myles' (1996) assertion that a population control measure has to 'kill all the genealogically related members of the colony'. A foraging group that shares the foraging galleries of termite populations in or near a structure can pose a potential threat to the structure. A population that is not near a structure and is disconnected from a structure-infesting population, regardless of its genealogical relationship to the other populations, poses no such immediate threat.

To impact on the population of a subterranean termite colony that may contain 100 000 to >1 000 000 foragers with foraging territories extending up to 100 m (Su and Scheffrahn, 1988a; Grace *et al*., 1989; Su *et al*., 1993), the active ingredient for incorporation into a bait must be slow acting and non-repellent (Su *et al*., 1982). There are three groups of candidates that may satisfy these criteria: some biological control agents, metabolic inhibitors and insect growth regulators.

Biological control agents The above-ambient humidity and temperature in the foraging galleries of subterranean termites are suited for the growth of biological agents. Laboratory studies have consistently demonstrated the pathogenicity of biological agents such as the entomopathogenic nematode *Neoaplectana carpocapsae* Weiser (Fujii, 1975) or the fungi *Metarhizium anisopliae* Sorokin and *Beauveria bassiana* (Balsamo) Vullemin (Lai *et al*., 1982). Field trials using these biological agents, however, have been generally unsuccessful (Lai, 1977; Mauldin and Beal, 1989). To date, only Hänel (1983) was able to trigger successfully an *M. anisopliae* epizootic in colonies of an Australian mound-building termite, *Nasutitermes exitiosus* (Hill). Because termites are known to be repelled by pathogenic microbes, the discovery of non-repellent strains of some fungi species may be the key to the successful control of the vast populations of subterranean termite colonies (Staples and Milner, 1996).

Metabolic inhibitors. The metabolic inhibitors which have been used in baits include borates (Grace, 1990b; Jones, 1991; Forschler, 1996), dechlorane (mirex) (Beard, 1974), hydramethylnon (Su *et al*., 1982; Pawson and Gold, 1996), A-9248 (diiodomethyl para-tolyl sulphone) (Su and Scheffrahn, 1988b) and sulphluramid (Su and Scheffrahn, 1988c, 1991; Henderson and Forschler, 1996). Early on, mirex was used for the population control of field colonies of subterranean termites (Esenther and Gray, 1968; Esenther and Beal, 1974, 1978; Ostaff and Gray, 1975; Paton and Miller, 1980). Of the field trials with mirex, only Paton and Miller (1980), who used a radioisotope to establish the foraging territory of target colonies, were able to demonstrate the elimination of field colonies of the Australian subterranean termite *Mastotermes darwiniensis* (Frogg). In field evaluation studies using other metabolic inhibitors such as A-9248 (Su *et al*., 1991c) or sulphluramid (Su *et al*., 1995a), the populations of target colonies were reduced but not eliminated following monthly baiting for 1 year. A recent field study using hydramethylnon by Pawson and Gold (1996) also indicated population suppression of *C. formosanus* and *R. flavipes*, that is the foraging activity of baited colonies was reduced but not totally eliminated. Sulphluramid baits, however, were successfully used to eliminate spatially restricted populations of *C. formosanus* colonies confined to standing bald cypress (*Taxodium distichum* (L.) Rich) boles (Henderson and Forschler, 1996).

When applied to ground-based colonies of subterranean termites, edible baits incorporating metabolic inhibitors generally reduced termite populations or activity, but some foraging activity remained. The inability of metabolic inhibitors to eliminate the populations or foraging activity of target colonies is probably due to their dose-dependent lethal time (Su *et al*., 1995a). The concentrations of the toxicants in baits can be adjusted so that baits are accepted by termites, but the total amount of bait ingested by the termites cannot be manipulated. Consequently, within days to weeks of bait placement, a colony population may contain termites that ingested toxicants at various doses (wt [a.i.]/wt termite), i.e. a lethal dose, sublethal dose or no ingestion. Because the lethal time for metabolic inhibitors is dose dependent, termites ingesting higher doses may be killed relatively quickly, thus negating the slow-acting charcteristic required for effective bait transfer and assimilation (Su and Scheffrahn, 1996c).

One alternative for a metabolic inhibitor to be successfully delivered to the majority of the target population may be to collect a large number of foragers and dust (French, 1991) or coat (Myles *et al*., 1994; Myles, 1996) them with toxicant before releasing them back to the colony. This trap–treat–release approach depends on the grooming behaviour of the termites to distribute the toxicant among nest mates, thus minimizing the problems associated with the dose-dependent lethal time of metabolic inhibitors. A higher concentration of toxicant can be incorporated in groomable coatings than in edible baits without eliciting repellency (Myles, 1996). Using the trap–treat–release approach with sulphluramid, colonly populations of *R. flavipes* were significantly suppressed in city blocks of Toronto (Myles, 1996).

Insect growth regulators. Two classes of insect growth regulators (IGRs), juvenoids (juvenile hormone analogues or JHAs and juvenile hormone mimics or JHMs) and chitin synthesis inhibitors (CSIs), have been tested on termites. The gradual and cumulative mode of IGRs' action makes them promising candidates for incorporation in baits.

Unlike most insect species in which juvenile hormones (JH) is responsible for retaining the immature forms, the effect of JH in termites is unique. Lüscher (1958) first suggested that JH regulated soldier formation in termites. This hypothesis was later confirmed by *corpora allata* implantation (Lüscher and Springhetti, 1960; Lebrun, 1967) and by injection of a JHA (Lüscher, 1969). Because the soldier caste is dependent on workers for feeding, it was suggested that JHAs' potential to induce excessive soldier formation may lead to the nutritional collapse of the entire termite colony (Hrdy and Krecek, 1972; Hrdy, 1973; Haverty, 1977). A literature review (Su and Scheffrahn, 1990) showed that JHAs were more likely to induce significant soldier formation for termite species that contained lower natural soldier proportions (e.g. 1–2% for *Reticulitermes* spp.) than for species with higher proportions (e.g. 10–20% for *Coptotermes* spp.), a view suggested earlier by Lenz (1976). Indeed, field trials using JHAs such as methoprene and hydroprene against *Prorhinotermes simplex* (Hagen) (6.9–22.2% soldier proportion; Haverty, 1977) failed to yield an increase in soldiers or a colony decline (Hrdy *et al*., 1979). When another JHA, fenoxycarb, was used against field colonies of *Reticulitermes* species, Jones (1989) observed an increase in pre-soldiers and soldiers and a subsequent decline in their foraging activity.

Derivatives of benzoylphenyl ureas are known to inhibit the chitin synthesis of insects, other arthropods and fungi (Hajjar and Casida, 1978). Doppelreiter and Korioth (1981) were the first to demonstrate ecdysis inhibition by diflubenzuron (Dimilin) against *Heterotermes indicola* (Wasmann) and *R. flavipes*. Subsequent testing with diflubenzuron on field colonies of *Microcerotermes* species, however, provided inconclusive results (Faragalla *et al*., 1985). Laboratory studies have indicated that CSIs such as diflubenzuron (Su and Scheffrahn, 1993) or lufenuron (Su and Scheffrahn, 1996b) inhibited the ecdysis of *R. flavipes*, but caused virtually no effect on *C. formosanus*. To date, only one CSI, hexaflumuron, is known to cause significant ecdysis inhibition of a wide range of economically important subterranean termites species, including *Reticulitermes, Coptotermes* and *Heterotermes* species (Su and Scheffrahn, 1993, 1996b). Pawson and Gold (1996) indicated that hexaflumuron baits were successful in only two of seven field trials against *Reticulitermes* species in Texas. However, the majority of field studies using baits containing hexaflumuron confirmed its efficacy against field colonies of *C. formasanus, Reticulitermes* species (Su, 1994; DeMark *et al*., 1995; Su *et al*., 1995b, 1997; Forschler and Ryder, 1996; Grace *et al*., 1996b) and *C. havilandi* (N.-Y. Su, unpublished data).

Other control options

Other options for subterranean termite control include wood treatments and cultural control such as the removal of wood debris and avoiding the accumulation of water (leaky roofs, plumbing, etc.) in and around structures. Building codes typically dictate the use of pressure-treated wood (creosote, pentachlorophenol, inorganic salts such as chromated copper arsenate, etc.) at the point of wood–soil interfaces, primarily to prevent fungi decay. If present, subterranean termites are capable of bypassing the treated wood and infesting untreated wood in structures. In recent years, the use of borates for the surface spraying of wood in service has become a popular practice for remedial control of subterranean termites. Grace and Yamamoto (1994), however, showed that the surface treatment of borate solution, even at the label rate, did not protect wood beneath the treated surface from field populations of *C. formosanus*.

Other construction practices can also have an important impact on subterranean termite control. The use of rigid board insulation by the building industry in recent years has made some houses vulnerable to subterranean termites because it provides a cryptic point of entry (Smith and Zungoli, 1995). In the St Johns County of Florida, for example, building codes were changed to prohibit such building practices, but an effort for a statewide change did not materialize because of opposition by the construction industry (Holt, 1996).

Will there be an integrated pest management programme for termite control?

Many parties may become involved in termite control considerations, for example consumers (property owners), real estate developers, building contractors, financial institutions that issue home mortgages, pest control applicators, manufacturers of control measures and researchers and extension agents. Each party has its own set of priorities. The priority for a homeowner whose house is currently infested by termites is the immediate remedy of the problem, namely the cessation of infestation and protection of property. Buyers of new houses, who ultimately pay the cost of pre-construction treatment of termite inspection, are usually unaware of potential termite problems. For real estate developers and building contractors, the certificate of pre-treatment or termite inspection is often more important than the real or perceived termite problem. Financial institutions, which mandate termite proofing, are usually unfamiliar with the mechanics of termite control. Most consumers are also unaware of the potential problem of subterranean termites until an active infestation is found.

As pointed out by Walton (1995), integrated pest management (IPM) represents a philosophy (Dent, 1992) rather than a specific control measure. Because of the different priorities of the parties involved, there are many definitions of IPM in termite control. For researchers who place a priority on environmental issues, the development of safer control measures dominates their perception of IPM (Robinson, 1996). For a manufacturer whose product alone cannot remedy the problem, IPM is the employment of all other control measures to supplement its product to achieve an acceptable performance (Ballard, 1997). For a pest control firm whose respective control measures such as soil termiticide injection, trenching or spot treatments fail to remedy termite problems, cultural control measures, such as the removal of wooden debris in soil or correction of excessive moisture problems in or around structures, become the major components of an IPM programme. These measures are often renamed using IPM as a preferred suffix for marketing purposes (Robinson, 1996).

IPM was devised to address the problems associated with agricultural intensification during the 1990s, namely pesticide resistance, secondary pest outbreaks, host plant resistance breakdown and environmental pollution and hazards (Dent, 1995). It was recognized that a pest control treatment is justified only when 'the density of the pest at which the loss through damage exceeds the cost of control' (Mumford and Norton, 1984). When resistance development renders an insecticide treatment less effective or when the potential risk of environmental pollution increases, the treatment cost outweighs the benefit.

Pesticide resistance, however, has never been recorded from social insects such as termites. When the chlorinated hydrocarbons were widely used for soil barrier treatment, little attention was given to IPM by the termite control industry. The relatively inexpensive and persistent cyclodiene insecticides were used in large quantities to protect structures from soil-borne termites. There was no need for the termite control industry to look for alternatives until the mid-1980s when chlordane was withdrawn from the market due to its potential risk to health and the environment. The potential risk posed by chlordane was apparently considered too costly for its benefit. Moreover, there was concern (La Fage, 1986) over the pesticide use rate for subterranean termite control ($390\,\mathrm{kg\,ha^{-1}}$) in comparison with the agricultural rate ($2.17\,\mathrm{kg\,ha^{-1}}$). With few alternatives, however, the termite control industry quickly switched to other liquid insecticides such as organophosphates (OPs) and pyrethroids. Because the currently available soil termiticides are less persistent yet more expensive than chlordane, the shortcomings of soil termiticide barriers to protect structures soon became apparent. Once the continuous horizontal barrier (pre-construction treatment) degrades, a post-construction drill and inject treatment cannot completely re-establish this subslab barrier. The limitations of current liquid termiticides have motivated the pest control industry to look for other alternatives.

Monitoring–Baiting programme

Following the pioneering works in the 1960s and 1970s (Esenther and Gray, 1968; Beard, 1974; Esenther and Beal, 1974, 1978; Ostaff and Gray, 1975; Lai, 1977; Paton and Miller, 1980), studies continued in search of alternative slow-acting agents for population control of subterranean termites (Su *et al*., 1982, 1985; Jones, 1984, 1991; Su and Scheffrahn, 1988b,c, 1991; Haverty *et al*., 1989; Grace, 1990b). In the early 1990s, Su and Scheffrahn (1993) discovered that a CSI, hexaflumuron, exhibited an extreme slow-acting characteristic against the two economically important termite species in the USA, *C. formosanus* and *R. flavipes*.

Following a field study using hexaflumuron (Su, 1994), a commercial prototype monitoring–baiting station was designed for further field evaluation (Su *et al*., 1995b). These studies led to the development of the first bait product for subterranean termite, the Sentricon® Colony Elimination System (DowElanco, Indianapolis, IN). Other bait products using metabolic inhibitors such as sulphluramid (FirstLine®, FMC, Princeton, NJ) or hydramethylnon (Subterfuge®, American Cyanamid, Parsippany, NJ) are also currently commercially available to the pest control industry in the USA.

Efficacy: elimination versus suppression. Field trials using hexaflumuron baits repeatedly demonstrated that baited colonies of subterranean termites were suppressed to the point of inactivity or, at least, 'functionally' eliminated (Su, 1994; DeMark *et al*., 1995; Su *et al*., 1995b, 1997; Forschler and Ryder, 1996; Grace *et al*., 1996b). Before bait applications, the termite activity of these field colonies was monitored for from several months to years using independent (i.e. no bait treatment) stations. The foraging activity and territory of a subterranean termite colony may fluctuate over time, but persists within a given site (Fig. 1A and C) (Su and Scheffrahn, 1996c). The interconnection of monitoring stations was confirmed using the triple mark–recapture technique to delineate the minimum boundary of the foraging territory of a colony. Following the application of hexaflumuron baits, activity generally declined to the point where no termite activity could be detected from the monitoring stations or survey stakes (Fig. 1B and C). This state of inactivity may last for months or years (Su and Scheffrahn, 1996c). Direct observation to confirm the death of all termites in a subterranean colony is difficult to accomplish. However, the prolonged absence of termite activity in soil previously occupied by a persistent presence of foraging population(s) (Fig. 1C) presents a strong evidence that the baited populations or colonies were probably eliminated. Colony elimination is probably the more plausible explanation for the total cessation of termite activity in various field studies (Su, 1994; DeMark *et al*., 1995; Su *et al*., 1995b, 1997; Forschler and Ryder, 1996; Grace *et al*., 1996b).

Aerial colonies of *C. formosanus* have no connection to the ground. Because of the high traffic in occupied buildings, occupants usually notice signs of an aerial infestation such as swarming alates, foraging tubes or damaged wood. When an above-ground baiting system incorporating hexaflumuron was applied into chronic infestations of aerial colonies in high rise buildings, the activity was reduced to zero and remained inactive for years (Su *et al*., 1997). Because there is no ground connection and because the residents of these high-occupany buildings should have detected any remaining population, the absence of aerial colony activity following

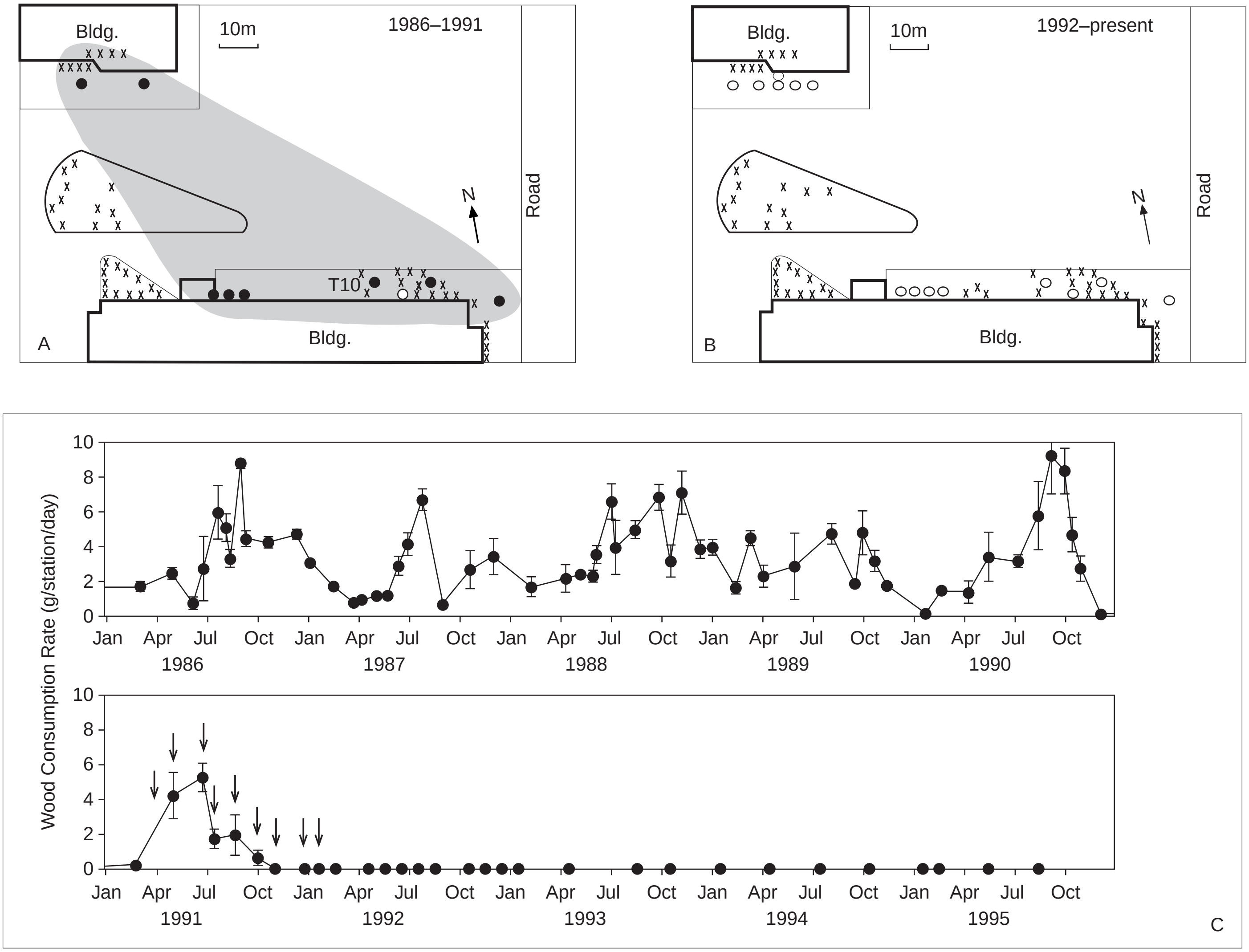

Fig. 1. (A) The foraging territory (shaded area) and (C) activity of a *C. formosanus* colony may fluctuate over time (1986–1991), but persisted in a site. Following the application of hexaflumuron baits between (C) March 1991 and February 1992 (arrows), the colony declined to the point of inactivity (B and C). No termites have been found in this site since March 1992. Each cross denotes a survey stake and circles denote the underground monitoring stations. Solid symbols denote the termite activity and open symbols indicate no termite activity.

the bait application is further evidence of colony elimination by hexaflumuron baits.

Direct evidence of colony elimination was recently provided by Lenz *et al*. (1996) who reported the demise of a colony of Australian mound-building termites following hexaflumuron bait application. The excavation of a *C. formosanus* colony in Japan also confirmed the underground nest was littered with dead and decomposing termites after baits containing hexaflumuron were applied within the colony foraging territory (K. Yamauchi, personal communication).

Colony elimination (or a state of prolonged inactivity of termite population) by hexaflumuron baits usually creates a zone of termite-free soil that lasts for months or years, while colonies that are partially suppressed by metabolic inhibitors usually recover and cause additional damage (Su and Scheffrahn, 1996c). Consequently, baits containing hexaflumuron, such as Sentricon®, are marketed as monitoring–baiting systems that do not require additional pesticide use, while baits containing metabolic inhibitors, such as sulphluramid (FirstLine®) or hydramethylnon (Subterfuge®), are recommended for use in conjunction with other treatment methods such as liquid termiticides (Potter, 1997). Because other treatment methods are needed to supplement sulphluramid baits, FirstLine® is promoted as a tool for termite IPM (Ballard, 1997). Grace *et al*. (1996b), however, questioned the value of a bait application when other supplemental measures must be used to minimize the damage potential of partially suppressed populations. The significance of bait toxicants for subterranean termite control is the radical reduction of pesticide use (La Fage, 1986). The application of supplemental liquid termiticide, if always required, does not relieve the industry from the burden of potential risk posed by these traditional control measures. The potential of reinfestation by the surviving population also renders the pest control firm liable.

Socioeconomics of termite control

The overall objective of an IPM programme should be the protection of a structure from subterranean termite populations using the most cost-effective method(s). Cost does not only include labour, equipment and materials, but also the inherent risk of liability and actual health and environmental risk (Table 1). The liabilities are supposedly incorporated as a part of the operation cost (e.g. insurance) for a pest control firm. For a consumer to justify the cost of subterranean termite control, the potential damage by termites (D) has to exceed the fee (F), thus $D > F$ (Table 1). The total operation costs for a pest control firm (T) include labour (l), materials (m), equipment (e), liability (b) and overheads (o), thus $T = l + m + e + b + o$. The total operation cost (T) is passed on to the consumer along with the net profit (P), thus $F = T + P$ and $D > T + P$ or $D > l + m + e + b + o + P$. Two variables, the potential termite damage (D), which includes actual damage and perceived damage (or psychological cost) and the liability cost (b), are probably the most difficult to predict. Because termite individuals and colonies live longer than most insects, the damage potential by termites is usually considered open-ended, namely the presence of termites near a structure is likely to cause an ongoing threat of damage. This notion, be it true or not, thus increases the consumers' perception of termite damage potential to such an extent that most of the control cost F $(= T + P)$ is almost always perceived justifiable or $D > T + P$ (Table 1). The liability cost (b) includes environmental and health hazards due to insecticide use and additional damage from reinfestation. For a pest control firm that performed treatments, the presence of termites near structures may lead to reinfestation and liability.

Because agroecosystems are relatively homogeneous monocultures, the costs and benefits of control measures are more predictable. An IPM programme based on sophisticated prediction models is not unusual for crop protection. Houses and their surrounding environments, however, may differ substantially from each other. Because of this heterogeneous environment, a termite control operator who is contracted to protect a house from subterranean termites needs to weigh the costs and benefits of all possible control options on a case-by-case basis. Most termite control companies, however, are not equipped to or cannot afford to formulate such a programme. It is generally assumed that the termite damage potential (D) is so big that action to control it is always justified. For example, regardless of the extent of infestation, a large quantity of liquid insecticide is applied to soil when termites are found in the structures. In the pre-construction treatment, a similar application is adopted even in the absence of termites.

Table 1. General categories of costs and benefits for a consumer who demands subterranean termite control and for a pest control firm who performs the treatment[a]

Party	Cost	Benefit
Consumer	Fee (F)	Prevention of potential damage by termites (D)
Pest control firm	Labour (l), materials (m), equipment (e), overheads (o) and liability (b)	Profit (P)

[a] Total control cost $(T) = l + m + e + b + o$ and $T + P = F$. Treatment is justified when $D > F$.

Monitoring–Baiting programme and IPM. When hexaflumuron was evaluated against field populations of subterranean termites (Su, 1994), a monitoring phase was incorporated as an integral part of the operation so that this monitoring–baiting procedure could become one element of a system approach to protect structures from subterranean termites. Because of the cryptic nature of subterranean termites, the detection of even a small foraging group may indicate the presence of a colony containing several million foragers for species such as *C. formosanus* (Fig. 2). The conventional soil treatment technique depends on insecticide barriers to exclude existing subterranean termites and to prevent future invasion. The monitoring–baiting programme (Su *et al.*, 1995b), on the other hand, depends on a periodic inspection by pest control professionals for detecting a potential termite infestation (Fig. 3). To track effectively the location and status of monitoring–baiting stations in many commercial sites, a computer software system, Prolinx® Information Management System (DowElanco) was developed for use in conjunction with the Sentricon® system (Thoms and Sprenkel, 1996). A hand-held scanner is used to identify the unique bar-code for each station in the field and to record its status. The information is then downloaded to a computer to generate a report for the homeowner and aid the pest control firm in managing the monitoring–baiting programme at each site.

At present, the monitoring–baiting system is used mostly when active infestations are found in structures. For such remedial control cases, the damage potential (*D*) is present and real. Because of the present damage potential and because of the liability, bait application by pest control firms is almost always justified. Unlike the agriculture IPM programme, where information gathered from the monitoring phase (number of insects per trap, etc.) is used to determine whether an action (pesticide sprays, etc.) is justified, the detection of termites in monitoring stations mainly serves to identify the points of bait application. The cost of taking control action such as aerial sprays of insecticides is usually so high in crop protection that a careful evaluation of the cost–benefit of such action should be taken. Because the labour costs for the monitoring outweigh the material costs to apply baits for a monitoring–baiting programme and because the potential damage and liability is large, there is little incentive not to apply baits when termites are found in the monitoring stations.

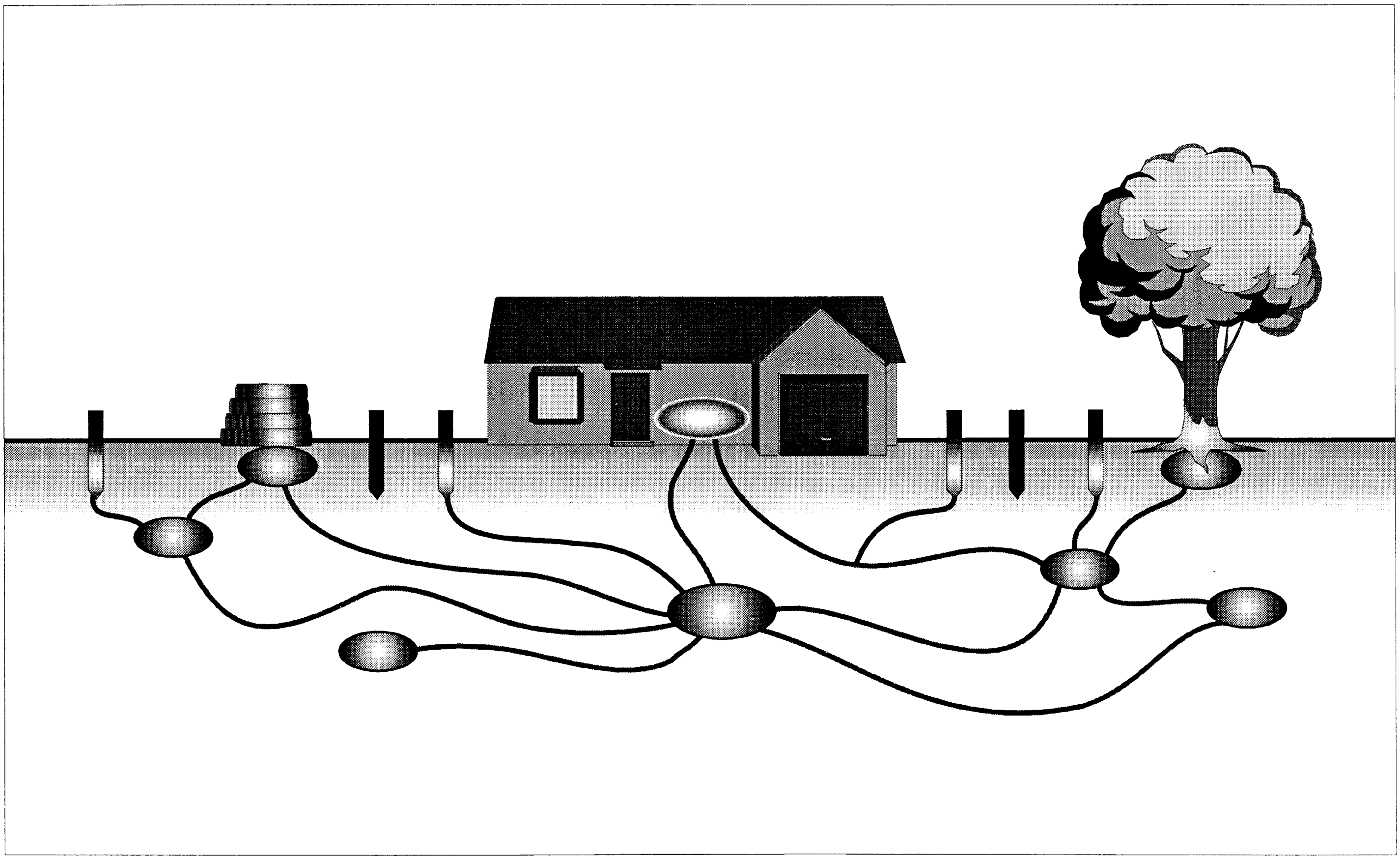

Fig. 2. Because of the cryptic nature of subterranean termites, the detection of a small foraging group from the survey stakes may indicate the presence of a colony containing 100 000–1 000 000 termites.

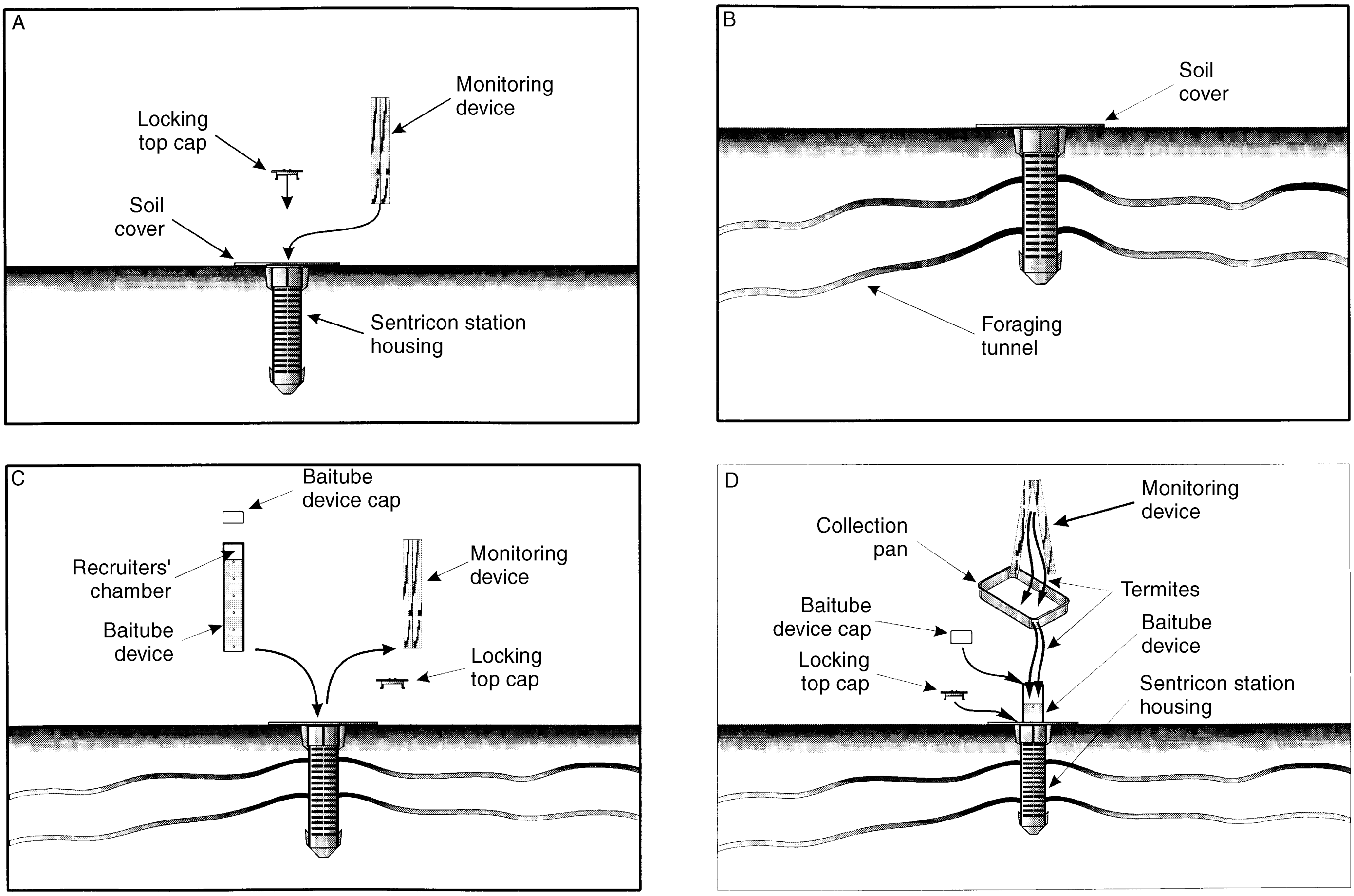

Fig. 3. The installation and operating procedure for the Sentricon* system. (A) The station containing the monitoring device is first installed in soil surrounding a home. (B) When termites are found in the station, (C) the monitoring device is replaced with a tube containing bait laced with hexaflumuron. (D) Termites collected from the monitoring device are dislodged into an empty space on the top of the tube, called the 'recruiter's chamber'.

It is probably unrealistic to apply the cost–benefit model developed for agriculture IPM directly to an urban pest management programme because of the vast difference in the perceptions of damage potential and the tolerance threshold between these two environments. The underlying concept of IPM to use a cost-effective approach to solve pest problems however, is the same. An IPM programme for subterranean termites is not just a mixture of individually ineffective tools (Ballard, 1997); it needs to provide cost-effective protection of a homeowner's property.

The monitoring–baiting system uses a target-specific insect growth regulator at a lower rate (less than 1 g hexaflumuron) than conventional soil treatment (5–10 kg of termiticides). As predicted by La Fage (1986), the cost burden due to health and environmental risk by baiting is drastically reduced. Eliminating termite colony(s) near a structure also reduces the liability of further structural damage. The major benefit of adopting the monitoring–baiting system for a pest control firm is the reduction of the liability (b) factor in the total operation cost $T = l + m + e + b + o + P$ (Table 1). For a homeowner, the absence of termite populations near a structure diminishes the damage potential (D).

The future of subterranean termite control

Safer and more effective barrier techniques such as physical barriers (Lewis *et al.*, 1996) or pyrethroid-impregnated polymer barriers (N.-Y. Su, unpublished data) may replace the current liquid insecticides for soil treatment in the future. These barriers may be installed before building construction to supplement the monitoring–baiting programme and further reduce termites' damage potential. Because manual monitoring is the major component of the current monitoring–baiting system and because the industry is uncertain how to pass on this labour cost to the consumers, the system is currently more expensive than conventional soil treatments. As the industry becomes more aware of the financial benefit of colony elimination (*b*) and becomes more familiar with the operation (*l*), the costs should decrease. Technological development, such as the acoustic emission device (Scheffrahn *et al*., 1993, 1997; Imamura and Fujii, 1995; Fujii *et al*., 1997), will further increase monitoring efficacy and reduce costs. Aboveground bait stations, which are to be placed directly over the active termite infestation found in the structures, will provide another tool for the introduction of bait into termite colonies (Su *et al*., 1997). Studies on feeding stimulants (Chen and Henderson, 1996) and semiochemicals associated with foraging behaviour (Rust *et al*., 1996) and food-searching behaviour (Robson *et al*., 1996; Reinhard *et al*., 1997) will improve the efficacy of baiting techniques. To manage subterranean termite populations better, however, the factors affecting the population dynamics of these cryptic and poorly understood insects need to be studied.

A monitoring–baiting programme (both in-ground and above-ground) incorporating a computerized data management system such as Prolinx® may become a focal point for future IPM for subterranean termites. Optionally, other control tools, such as barriers, the localized application of liquid or foam termiticides, building modifications, cultural practices, etc., may be integrated into the programme as needed. The information collected from the data management system can be used to dictate station placement, improve monitoring efficiency, predict bait requirement or to suggest other optional control tools at different regions and under various environmental conditions. Using feedback from the database, the integrated programmes may became a self-improving system that continuously enhances its cost-effectiveness.

IPM is still in its infancy for the termite control industry. Various definitions of termite IPM are mushrooming from every corner of the industry and reflect a state of confusion on this subject. An IPM programme for subterranean termites needs to provide cost-effective protection of a homeowner's property. The pest control industry and neutral parties, such as the extension service or building inspectors, need to be better trained so that accurate information can be disseminated to homeowners. The final decision for a proper control programme needs to be made by educated consumers. If consumers are fully aware of their options and the costs and benefits of each option, the grass-root demand should shape an IPM programme for the termite control industry.

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