Persistence of Organochlorine Insecticides for Formosan Subterranean Termite (Isoptera: Rhinotermitidae) Control in Hawaii

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ABSTRACT In a long-term field test, five organochlorine soil insecticides were applied at two concentrations to crushed coral, Catano sandy loam, or Waimanalo silty clay. The treated soils were weathered in exposed field plots in Waimanalo on the island of Oahu, Hawaii, and tested periodically for efficacy against the Formosan subterranean termite, *Coptotermes formosanus* Shiraki. We report the toxicity of aldrin, chlordane, DDT, dieldrin, and heptachlor to *C. formosanus* 17, 20, 24, 28, and 33 yr after treatment. The degree of penetration of the treated soils by *C. formosanus* was also measured in laboratory bioassays. After 28 yr, termites tunneled significantly less in soils treated with 0.5% aldrin (in coral and clay), 0.3% dieldrin (in clay), 1.0% heptachlor (in sandy loam), and 2.0% DDT (in coral). None of the insecticides prevented termite penetration 33 yr after application. At label-recommended concentrations, all pesticides except DDT (8.0%) caused high termite mortality up to 28 yr after application. Only 0.5% aldrin, 0.3% dieldrin, and 1.0% heptachlor caused significant mortality after 33 yr. Results of this study should be of value in estimating the risks of termite reinfestation of structures in the tropics and Pacific islands where organochlorine insecticides have been used.

KEY WORDS *Coptotermes formosanus*, termite control, organochlorine pesticide

SUBTERRANEAN TERMITE PREVENTION and control are largely dependent upon the application of residual insecticides to the soil. These insecticides are applied beneath and to the perimeter of structures at risk from termite infestation. The toxic or repellent (or both) chemical barrier prevents termites from tunneling into the structure, although termites may still continue to forage actively in the untreated soil beyond the barrier (Su & Scheffrahn 1988, Grace et al. 1989). Thus, a long residual life is advantageous in termiticide application.

A limited number of long-term termiticide field studies have been performed. In the United States, data demonstrating that termites have not penetrated treated soil for at least 5 yr at three or more of the USDA Forest Service termiticide test sites are usually supplied by pesticide manufacturers to the Environmental Protection Agency to facilitate registration of new termiticides (Beal 1986, Kard et al. 1989). At present, all but two of these test plots are within the continental United States, and these data are not necessarily transferable to tropical or Pacific island regions, with distinctly different termite species and environmental conditions. Since 1943, the USDA Forest Service has tested termiticides at several sites in the Republic of Panama (Beal 1981). Unfortunately, these sites suffered extensive damage in recent military actions. Studies were also initiated on Sand Island of Midway Atoll in 1981 (Mauldin et al. 1987, Kard et al. 1989). The Formosan subterranean termite, *Coptotermes formosanus* Shiraki, is thought to have been introduced to Midway in soil transported from either Hawaii or Guam (Mauldin et al. 1987).

In 1958, a termiticide field study was initiated at the University of Hawaii Waimanalo Experiment Station on the island of Oahu (Bess et al. 1966). As on Midway, *C. formosanus* is the only subterranean termite species known to be established in Hawaii; this species is an extremely serious structural pest (Tamashiro et al. 1987). The Formosan subterranean termite has a patchy distribution in urban areas of Hawaii and appears to have been distributed largely by the transport of infested wood (Tamashiro et al. 1987). Because termites were not found in rural Waimanalo, the field study combined weathering of the termiticides in exposed plots with periodic soil sampling and laboratory bioassays to determine the toxicity of the materials to *C. formosanus*. This approach was a departure from previous termite field-testing procedures and was well-suited to *C. formosanus*. The sporadic and variable feeding reported on control stakes in field plots infested by *C. formosanus* (Mauldin et al. 1987, Kard et al. 1989, Tamashiro et al. 1991) indicates that foraging by this termite species does not occur in a homogenous fashion throughout these plots, although a homogenous distribution is generally assumed to occur when the results of termiticide field evaluations are interpreted.

The seven insecticides included in the Hawaiian field study were all recommended for application to the soil to control subterranean termites. Bioassays performed 9 yr after installation (1967) indicated that the termiticidal activity of lindane and sodium arsenite had declined drastically (Bess & Hylin 1970). The other five organochlorine insecticides (aldrin, dieldrin, DDT, chlordane, and heptachlor) in the study continued to show termiticidal activity, although toxicity was somewhat reduced with the DDT, chlordane, and heptachlor treatments (Bess et al. 1966, Bess & Hylin 1970).

Although none of these organochlorine insecticides is currently used in the United States for termite control, they are available on the world market and remain the principal tools for termite control in many countries (e.g., Grace 1990, Lenz et al. 1990, Wood & Pearce 1991). Moreover, even where organochlorine insecticide use has been curtailed, past termiticide applications to the soil continue to provide protection for many buildings. Knowledge of the longevity of these materials under different environmental conditions is necessary to estimate the risk of termite reinfestation of previously treated structures and to determine whether additional applications of organophosphate or pyrethroid termiticides are warranted. Such information may also be useful in determining the degree of environmental contamination resulting from past soil insecticide use at certain sites. Although longevity is considered an asset in termiticide applications, misuse and persistence of pesticides in the environment may also lead to adverse effects on other aspects of the ecosystem (Wood & Pearce 1991).

Here, we describe the termiticidal efficacy of aldrin, chlordane, DDT, dieldrin, and heptachlor 17, 20, 24, 28, and 33 yr after application to crushed coral, clay, or sandy loam at the Waimanalo test plot. Soil samples were bioassayed both for residual toxicity to *C. formosanus* and for resistance to termite penetration.

Materials and Methods

Field Plots. As described by Bess et al. (1966) and Bess & Hylin (1970), the field plots were established in 1958 on ≈0.2 ha at the Waimanalo Experiment Station, on the windward side of Oahu. This site is at 25 m elevation, with approximate annual rainfall of 122 cm, and a mean temperature of about 24°C (Tamashiro et al. 1990). The field was divided into five blocks. Each block contained 51 holes, each 51 cm diameter by 30.5 cm deep, spaced 2.7 m apart. Each hole was filled with soil treated in a cement mixer with an aqueous solution of formulated insecticide. Three soil types were included in the test: crushed coral (≥90% calcium carbonate, pH 8.3), Catano sandy loam (a coastal coral sand, pH 7.6), and Waimanalo silty clay (a monmorillonite type composed of clays that are moderately sticky and plastic, pH 7.2) (Bess & Hylin 1970).

Seven insecticides—aldrin, chlordane, DDT, dieldrin, heptachlor, lindane, and sodium arsenite—were included in the original field test. Aqueous emulsions of these formulated insecticides were mixed with soil in a cement mixer (53.5 liters emulsion per cubic meter of soil) at label concentrations to approximate the manufacturers' recommended rates in 1958 for termite control in "critical areas," and at one-quarter of that concentration. Because of a misunderstanding, heptachlor was actually applied at twice the recommended concentration (1.0 rather than 0.5% solution) (Bess et al. 1966).

Because of the decreased toxicity of lindane and sodium arsenite noted by Bess & Hylin (1970), sampling of these plots was curtailed 9 yr after the original treatment. As a result of the decreased termiticidal activity noted in three other treatment–soil combinations (0.25% chlordane in crushed coral and clay, 0.25% heptachlor in coral) at the 20-yr sampling in 1978, these plots were not sampled in 1982, but were sampled again in 1986 and 1991. Although each treatment was originally replicated five times, difficulties in locating some of the sample plots after 24–33 yr resulted in bioassay of three to five replicates per treatment.

Bioassays. Plots were sampled by scraping away about 3 cm of topsoil, then removing ≈197 cm^3 soil with an unused steel can. The soil was placed in a plastic bag and sealed loosely in the laboratory for several days to permit air-drying. Following the protocol of earlier bioassays (Bess et al. 1966, Bess & Hylin 1970), in 1975 (17 yr after treatment) and 1978 (20 yr) a subsample of soil from each plot was placed 2 mm deep over a damp filter-paper disk in a petri dish, and two short lengths of wooden tongue depressor (1.5 by 2.5 cm) were placed on the surface. The substrate and wood were lightly dampened, and 20 (1975) or 25 (1978) *C. formosanus* workers were placed on the soil. The plates were covered with plastic wrap (with several small perforations) to retain moisture and incubated under laboratory conditions. Termite mortality was recorded after 5 d exposure.

A different bioassay procedure was used in 1982 (24 yr), 1986 (28 yr), and 1991 (33 yr), to measure termite penetration of the treated soil as

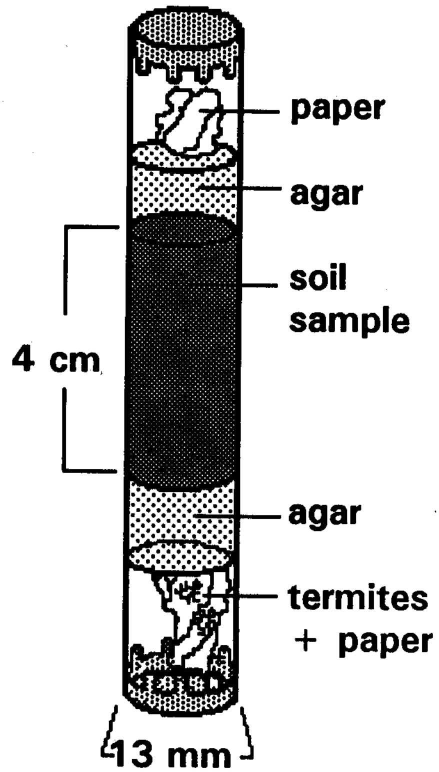

Fig. 1. Bioassay for measuring termite penetration of pesticide-treated soil. Termite mortality and distance penetrated through 4-cm soil sample were recorded after 4 d exposure.

well as termite mortality. In this test (Fig. 1), 4 cm of the test substrate was sandwiched between two plugs of 8% agar in a 13-mm-diameter glass tube. Crumpled paper toweling was provided at either end of the tube as food, 150 termites (131 workers and 19 soldiers) were placed in the bottom of the tube (Tamashiro et al. 1989, 1990), and the ends of the tube were sealed with metal caps. Termite mortality and the total distance tunneled upward through the test substrate were recorded after 4 d incubation in an unlighted temperature cabinet at 29 ± 0.5°C.

Percentage mortality and penetration data were transformed by the arcsine of the square root and subjected to analysis of variance (ANOVA). Treatment means were tested for significance against the respective substrate controls by Dunnett's one-tailed t test at $\alpha \leq 0.05$ (SAS Institute 1987).

Results and Discussion

Seventeen and 20 years after installation of the field site, all of the five termiticides sampled were still toxic to Formosan subterranean termite workers (Table 1). At the lowest solution concentrations, 0.25% chlordane was less toxic

Table 1. Mortality of *C. formosanus* exposed to soils treated with pesticides in 1958 and weathered for 17–20 yr in Hawaii

Treatment	% concn	Substrate	% mortality[a] 17 yr (1975)	20 yr (1978)
Dieldrin	0.3	Coral	100*	100*
		Clay	100*	100*
		Sandy loam	100*	100*
	0.075	Coral	100*	100*
		Clay	100*	100*
		Sandy loam	100*	100*
Aldrin	0.5	Coral	100*	100*
		Clay	100*	100*
		Sandy loam	100*	100*
	0.125	Coral	100*	100*
		Clay	100*	100*
		Sandy loam	95 ± 11*	90 ± 23*
Chlordane	1.0	Coral	100*	100*
		Clay	82 ± 40*	89 ± 25*
		Sandy loam	100*	100*
	0.25	Coral	100*	33 ± 47*
		Clay	62 ± 49*	5 ± 5
		Sandy loam	91 ± 17*	57 ± 44*
Heptachlor	1.0	Coral	100*	100*
		Clay	80 ± 45*	94 ± 14*
		Sandy loam	100*	100*
	0.25	Coral	100*	25 ± 43
		Clay	55 ± 50*	70 ± 45*
		Sandy loam	100*	100*
DDT	8.0	Coral	100*	100*
		Clay	100*	100*
		Sandy loam	100*	100*
	2.0	Coral	100*	100*
		Clay	85 ± 34*	66 ± 46*
		Sandy loam	100*	100*
Water		Coral	3 ± 5	0
		Clay	2 ± 5	0
		Sandy loam	0	0

[a] Each mean (± SD) represents five replicates of 20 (1975) or 25 (1978) termite workers placed on the sample substrate in a petri dish for 5 d. Means followed by an asterisk (*) are significantly greater than the respective substrate water control (t = 2.532, df = 44, $p \leq 0.05$; Dunnett's one-tailed t test [SAS Institute 1987]).

in clay and 0.25% heptachlor was less toxic in crushed coral than DDT, aldrin, or dieldrin. However, 1.0% chlordane and 1.0% heptachlor were still very toxic in all substrates. Bess et al. (1966) noted some reduction in the toxicity of the chlordane, heptachlor, and DDT treatments 6 yr after installation. In clay soils in Panama, 0.25% chlordane resisted termite penetration for 8 yr, and 0.25% heptachlor was effective for 15 yr (Beal 1981).

In the indirect-exposure tunneling assay, all of the termiticide treatments except 8.0% DDT in sandy loam caused significant termite mortality 24 yr after application (Table 2). At the higher concentrations (AI) this toxicity persisted for 28 yr, again with the exception of 8.0% DDT in sandy loam. However, at the lower concentrations (AI), only 0.125% aldrin and 0.075% dieldrin caused significant mortality in all three substrates after 28 yr, with 0.25% chlordane also eliciting significant mortality in coral and sandy

Table 2. Mortality of *C. formosanus* exposed to pesticide-treated soils weathered for 24–33 yr in Hawaii

Treatment	% concn	Substrate	% mortality[a] 24 yr (1982)	28 yr (1986)	33 yr (1991)
Dieldrin	0.3	Coral	100*	100*	46 ± 47*
		Clay	93 ± 12*	100*	68 ± 53*
		Sandy loam	100*	100*	99 ± 2*
	0.075	Coral	100*	89 ± 18*	7 ± 6
		Clay	96 ± 8*	76 ± 42*	10 ± 3
		Sandy loam	100*	100*	10 ± 13
Aldrin	0.5	Coral	100*	100*	67 ± 27*
		Clay	100*	100*	55 ± 42*
		Sandy loam	100*	85 ± 27*	54 ± 48*
	0.125	Coral	95 ± 7*	94 ± 10*	8 ± 4
		Clay	99 ± 2*	80 ± 34*	9 ± 8
		Sandy loam	99 ± 1*	99 ± 2*	7 ± 5
Chlordane	1.0	Coral	88 ± 8*	83 ± 24*	7 ± 5
		Clay	94 ± 10*	54 ± 45*	9 ± 7
		Sandy loam	91 ± 14*	71 ± 50*	12 ± 6
	0.25	Coral	—[b]	45 ± 40*	2 ± 2
		Clay	—[b]	31 ± 22	5 ± 2
		Sandy loam	94 ± 8*	56 ± 27*	6 ± 4
Heptachlor	1.0	Coral	88 ± 8*	99 ± 2*	26 ± 41
		Clay	96 ± 6*	99 ± 2*	11 ± 6
		Sandy loam	99 ± 1*	100*	45 ± 39*
	0.25	Coral	—[b]	8 ± 7	7 ± 2
		Clay	87 ± 14*	32 ± 36	9 ± 2
		Sandy loam	95 ± 8*	52 ± 19	8 ± 3
DDT	8.0	Coral	92 ± 2*	69 ± 35*	27 ± 8
		Clay	95 ± 8*	89 ± 5*	15 ± 2
		Sandy loam	34 ± 12	21 ± 7	14 ± 1
	2.0	Coral	46 ± 8*	35 ± 26	18 ± 9
		Clay	52 ± 7*	27 ± 9	10 ± 4
		Sandy loam	61 ± 23*	44 ± 44	15 ± 13
Water Control		Coral	7 ± 4	2 ± 1	3 ± 1
		Clay	15 ± 7	3 ± 2	6 ± 4
		Sandy loam	11 ± 3	2 ± 1	6 ± 3

[a] Each mean (± SD) represents three to five replicates of 150 termites (131 workers + 19 soldiers) allowed to tunnel through the treated substrate for 4 d in an indirect-exposure tunneling assay. Means followed by an asterisk (*) are significantly greater than the respective substrate water control (ANOVA of transformed percentages, $P \leq 0.05$; Dunnett's one-tailed t test [SAS Institute 1987]; 1982 coral, $F = 102.86$, df = 8, $P = 0.0001$; 1982 clay, $F = 12.63$, df = 9, $P = 0.0001$; 1982 sandy loam, $F = 24.31$, df = 10, $P = 0.0001$; 1986 coral, $F = 11.10$, df = 10, $P = 0.0001$; 1986 clay, $F = 6.22$, df = 10, $P = 0.0002$; 1986 sandy loam, $F = 7.55$, df = 10, $P = 0.0001$; 1991 coral, $F = 4.04$, df = 10, $P = 0.0009$; 1991 clay, $F = 4.56$, df = 10, $P = 0.0003$; 1991 sandy loam, $F = 9.42$, df = 10, $P = 0.0001$).

[b] Not sampled.

loam but not in clay. Only the higher concentrations of aldrin (0.5%), dieldrin (0.3%), and heptachlor (1.0%, in sandy loam) continued to cause significant, although variable, mortality 33 yr after treatment.

Penetration of the treated substrates, as well as termite mortality, was evaluated in the indirect-exposure tunneling assay used in the 24-yr and subsequent samplings. Toxicity of the substrate, particularily in a rather lengthy 5-d exposure, is a measure of the activity of the insecticide. However, the degree to which the treatment prevents penetration of the substrate is a more realistic measure of termiticide efficacy. Applications of 0.5% aldrin in crushed coral and 0.3% dieldrin in coral and sandy loam resisted termite penetration 24 yr after application (Table 3). At the 28-yr sample period, 0.5% aldrin (in coral and clay), 0.3% dieldrin (in clay), 1.0% heptachlor (in sandy loam), and 2.0% DDT (in coral) resulted in significantly less termite penetration, although there we observed a great deal of variation among replicates. Such variation among replicates and variation from one sample period to the next is not uncommon in field studies. However, after 33 yr, none of the treatments offered any resistance to penetration by *C. formosanus*.

None of the substrates treated with the lowest concentrations (one-quarter label recommendation, except heptachlor) of termiticide solutions caused significant termite mortality or resisted penetration 33 yr after application. The toxicity of 1.0% chlordane, one of the most widely used organochlorine termiticides, was significant in clay and sandy loam, but decreased to a level equivalent to that of the water controls in coral after 28 yr (Table 2). After 33 yr, none of the substrates treated with 1.0% chlordane differed in toxicity from the respective controls. Thus, at concentrations and application rates approximating normal termite control applications, after 33 yr of exposure only 0.5% aldrin and 0.3% diel-

Table 3. Penetration by *C. formosanus* of pesticide-treated soils weathered for 24–33 yr in Hawaii

Treatment	% concn	Substrate	% penetration[a] 24 yr (1982)	% penetration[a] 28 yr (1986)	% penetration[a] 33 yr (1991)
Dieldrin	0.3	Coral	25 ± 0*	100	100
		Clay	100	58 ± 36*	100
		Sandy loam	63 ± 22*	92 ± 13	100
	0.075	Coral	75 ± 43	100	100
		Clay	100	100	100
		Sandy loam	100	100	100
Aldrin	0.5	Coral	54 ± 32*	71 ± 27*	100
		Clay	100	67 ± 21*	100
		Sandy loam	96 ± 7	79 ± 32	100
	0.125	Coral	100	100	100
		Clay	100	100	100
		Sandy loam	100	100	100
Chlordane	1.0	Coral	75 ± 43	100	100
		Clay	96 ± 7	93 ± 13	100
		Sandy loam	100	100	100
	0.25	Coral	—[b]	100	100
		Clay	—[b]	100	100
		Sandy loam	100	100	100
Heptachlor	1.0	Coral	79 ± 26	80 ± 35	100
		Clay	96 ± 7	95 ± 9	100
		Sandy loam	83 ± 29	68 ± 33*	100
	0.25	Coral	—[b]	100	100
		Clay	100	100	100
		Sandy loam	100	100	100
DDT	8.0	Coral	83 ± 29	83 ± 14	100
		Clay	100	100	100
		Sandy loam	100	100	100
	2.0	Coral	100	78 ± 9*	100
		Clay	100	100	100
		Sandy loam	100	100	100
Water Control		Coral	100	100	100
		Clay	100	100	100
		Sandy loam	100	100	100

[a] Each mean (± SD) represents three to five replicates of 150 termites (131 workers + 19 soldiers) allowed to tunnel through 4 cm (=100% penetration) of treated substrate for 4 d in an indirect-exposure tunneling assay. Means followed by an asterisk (*) are significantly less than the respective substrate water control (ANOVA of transformed percentages, $P \leq 0.05$; Dunnett's one-tailed t test [SAS Institute 1987]; 1982 coral, $F = 4.45$, df = 8, $P = 0.0041$; 1982 clay, $F = 1.00$, df = 9, $P = 0.4711$; 1982 sandy loam, $F = 4.29$, df = 10, $P = 0.0021$; 1986 coral, $F = 2.63$, df = 10, $P = 0.0282$; 1986 clay, $F = 4.11$, df = 10, $P = 0.0027$; 1986 sandy loam, $F = 2.07$, df = 10, $P = 0.0739$).

[b] Not sampled.

drin remained termiticidal in all substrates, and 1.0% heptachlor (twice the recommended label concentration) remained toxic in sandy loam. However, these treatments were not sufficiently toxic nor repellent to prevent termite penetration.

Although differences in climate, soil type, application techniques, and evaluation methods make it difficult to compare the results of various field studies, 1.0% dieldrin, applied at 5.06 liters/m^2, was reported to be 100% effective (that is, none of 10 boards placed on treated soil were attacked) after 27 yr in Panama (Beal 1981). At the same application rate, 0.25% heptachlor was 100% effective for 15 yr, and 0.25% aldrin and 1.0% chlordane were 100% effective in a 16-yr test (Beal 1981).

To date, the longevity of organochlorine soil insecticides evaluated under tropical conditions exceeds that of organophospate and pyrethroid termiticides (Kard et al. 1989, Tamashiro et al. 1990). Our long-term study illustrates the gradual degradation of organochlorine termiticides in Hawaiian soils. These results are useful in estimating the longevity of commerical termiticide applications in the tropics and may also be of value in land management decisions where remediation of pesticide-treated soils is an issue.

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References Cited

Beal, R. H. 1981. Termite control studies in Panama. U.S. For. Serv. Res. Note SO-280: 1–6.

1986. Field testing of soil insecticides as termiticides. International Research Group on Wood Preservation, Stockholm, Sweden. Document No. IRG/WP/1294: 1- 9.

Bess, H. A. & J. W. Hylin. 1970. Persistence of pesticides in Hawaiian soils. J. Econ. Entomol. 63: 633–638.

Bess, H. A., A. K. Ota & C. Kawanishi. 1966. Persistence of soil insecticides for control of subterranean termites. J. Econ. Entomol. 59: 911–915.

Grace, J. K. 1990. Termites in eastern Canada: an updated review and bibliography. International Research Group on Wood Preservation, Stockholm, Sweden. Document No. IRG/WP/1431: 1–6.

Grace, J. K., A. Abdallay & K. R. Farr. 1989. Eastern subterranean termite (Isoptera: Rhinotermitidae) foraging territories and populations in Toronto. Can. Entomol. 121: 551–556.

Kard, B. M., J. K. Mauldin & S. C. Jones. 1989. Evaluation of soil termiticides for control of subterranean termites (Isoptera: Rhinotermitidae). Sociobiology 15: 285–297.

Lenz, M., J.A.L. Watson, R. A. Barrett & S. Runko. 1990. The effectiveness of soil barriers against subterranean termites in Australia. Sociobiology 17: 9–36.

Mauldin, J. K., S. C. Jones & R. H. Beal. 1987. Soil termiticides: a review of efficacy data from field tests. International Research Group on Wood Preservation, Stockholm, Sweden. Document No. IRG/WP/1323: 1–20.

SAS Institute. 1987. SAS/STAT guide for personal computers, version 6 ed. SAS Institute, Cary, NC.

Su, N.-Y. & R. H. Scheffrahn. 1988. Foraging population and territory of the Formosan subterranean termite (Isoptera: Rhinotermitidae) in the urban environment. Sociobiology 14: 353–359.

Tamashiro, M., J. R. Yates & R. H. Ebesu. 1987. The Formosan subterranean termite in Hawaii: problems and control, pp. 15–22. *In* M. Tamashiro & N.-Y. Su [eds.], Biology and control of the Formosan subterranean termite. Hawaii Institute of Tropical Agriculture and Human Resources Research Extension Series 083, University of Hawaii, Honolulu.

Tamashiro, M., J. R. Yates, R. H. Ebesu, R. T. Yamamoto, N.-Y. Su & J. N. Bean. 1989. Dursban TC insecticide as preventative treatment for Formosan subterranean termite in Hawaii. Down Earth 45(2): 1–5.

Tamashiro, M., J. R. Yates, R. H. Ebesu & R. T. Yamamoto. 1990. Effectiveness and longevity of termiticides in Hawaii. Hawaii Institute of Tropical Agriculture and Human Resources Research Extension Series 119, University of Hawaii, Honolulu.

Tamashiro, M., J. R. Yates, R. T. Yamamoto & R. H. Ebesu. 1991. Tunneling behavior of the Formosan subterranean termite and basalt barriers. Sociobiology 19: 163–170.

Wood, T. G. & M. J. Pearce. 1991. Termites in Africa: the environmental impact of control measures and damage to crops, trees, rangeland and rural buildings. Sociobiology 19: 221–234.

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