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Office of Pesticide Programs
Field Operations Division
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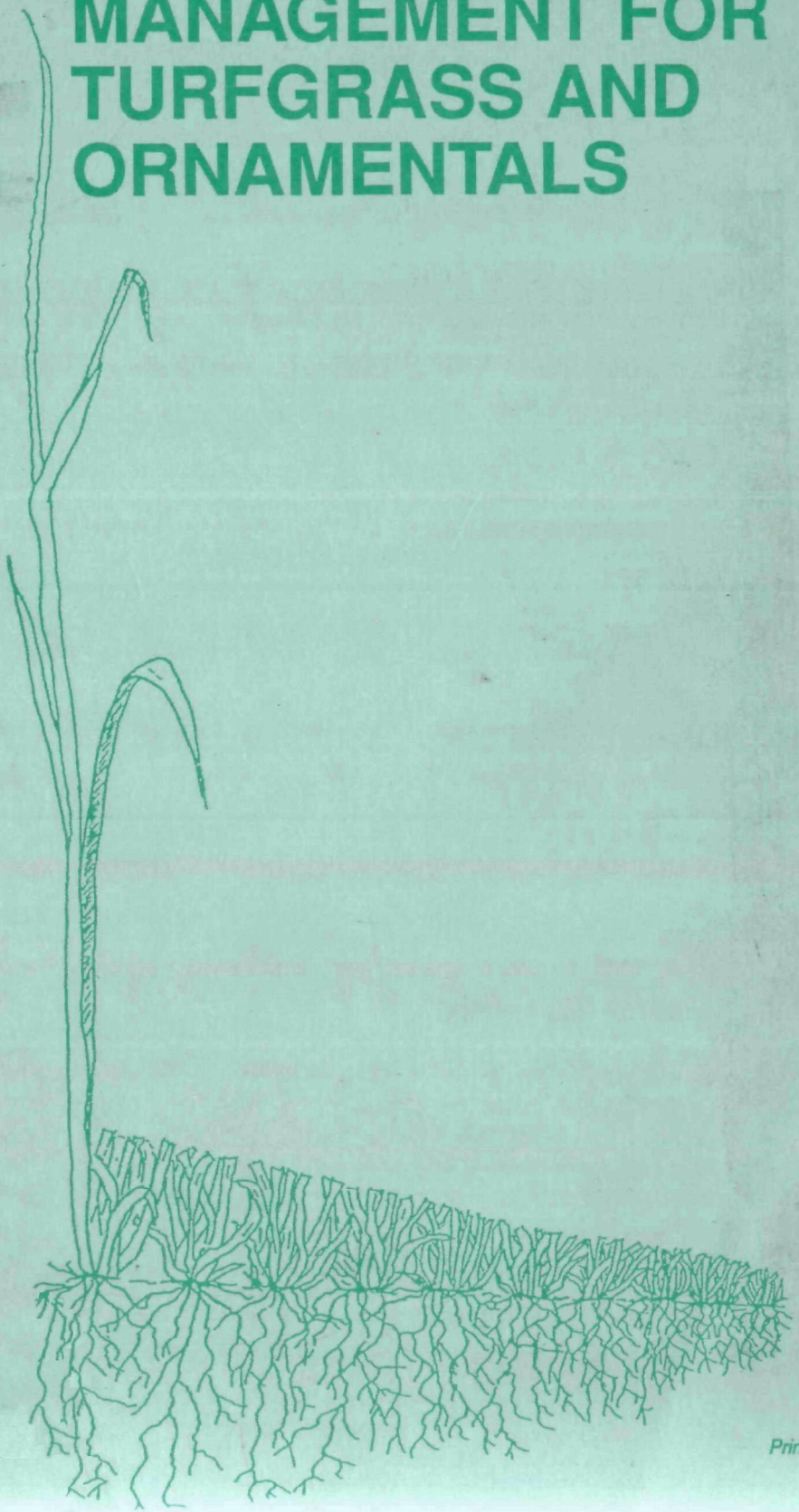
EPA

INTEGRATED PEST MANAGEMENT FOR TURFGRASS AND ORNAMENTALS



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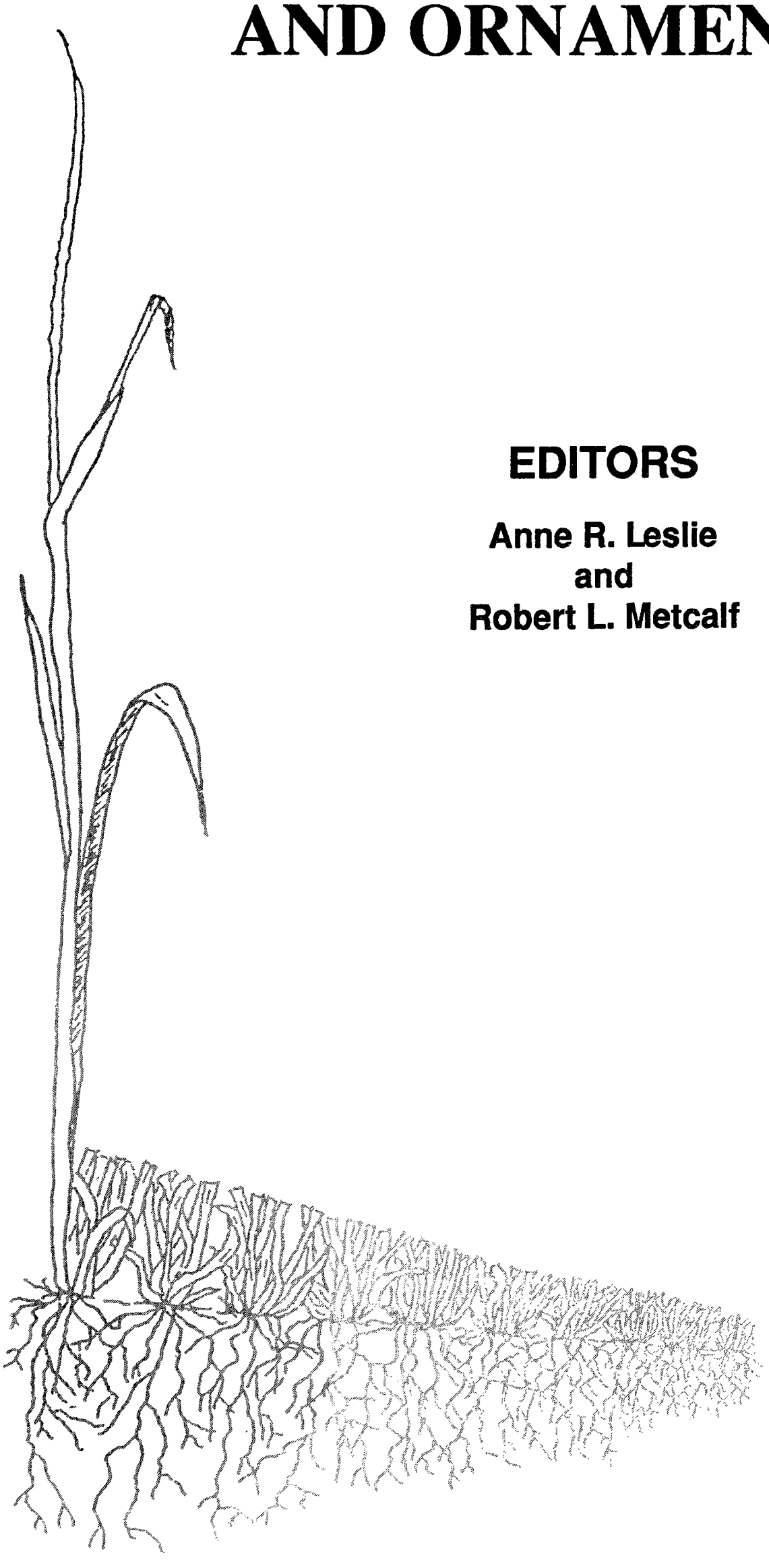

EDITORS

Anne R. Leslie
and
Robert L. Metcalf

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INTRODUCTION

Anne R. Leslie

U.S. Environmental Protection Agency
Office of Pesticide Programs
Field Operations Division (H7506C)
401 M Street SW
Washington, DC 20460

This book is the product of a symposium held during the 194th American Chemical Society meetings in New Orleans, Louisiana, in September 1987. Entitled "Urban Integrated Pest Management: An Environmental Mandate", the symposium was sponsored by the Division of Environmental Chemistry and co-listed by the Division of Chemical Health and Safety. The symposium was a project of the Integrated Pest Management Unit (IPM Unit) of the United States Environmental Protection Agency (EPA) to pull together the latest information on alternative controls for urban pests. An important part of the IPM Unit's mission within the Office of Pesticide Programs (OPP) has been development of demonstration projects and workshops for technology transfer to private sector managers. Most of the non-chemical alternatives presented addressed turfgrass and ornamentals, so this work focuses on turfgrass sites and includes relevant information on integrated pest management for ornamentals.

Concerns related to the current pesticide practices for turfgrass include:

- increasing problems with resistance to pesticides, which have been documented for insects, weeds and fungus diseases,
- attitudes of the general public about health effects to occupants when pesticides are applied to home lawns,
- downstream effects based on the appearance of pesticides in ground and surface water from agricultural uses.

It is time to evaluate these concerns; to state the evidence for adverse effects and the benefits of maintaining healthy turf; and to present the best possible alternatives. We believe an integrated pest management program can be devised that will promote a more sophisticated use of pesticides, control turf pests and still maintain highest turfgrass quality. Such a program will preserve the useful life of valuable pesticides, and provide cost savings for those who implement it.

A planned demonstration project based on this program should provide a comparison of the results of several management methods and information on the extent of movement of pesticides from turfgrass into groundwater and surface water. This information thus addresses EPA's concerns that people must reduce pollution of all kinds at the source. Based on sound ecological principles this program involves conservation of valuable resources.

Different sites will have different pest problems and different maintenance requirements. For example:

Home lawns: A healthy stand of the appropriate variety of grass, properly irrigated and fertilized, will rarely require fungicide treatment, will have minimal insect damage, and will have a weed population manageable without herbicides.

Golf courses: Because golfers' demands present special grass stress problems, superintendents need to use fungicide treatments for certain areas to lower disease pressure when weather conditions indicate potential problems. These chemicals must be applied before disease is expressed to control certain diseases effectively. The current practice is to apply fungicides to all vulnerable areas on a calendar basis,anticipating disease outbreaks at certain times of the year, dependent on weather conditions.

Groundskeepers have experienced difficulties with disease control under this system because of the toxic effects of fungicides on the turf and the buildup of resistance of disease organisms to fungicides. If a disease is misdiagnosed, repeated treatment with the wrong chemical can be disastrous to the turf.

An integrated pest management system advocates careful monitoring, and the chemical industry, interested in proper application of their products, has now developed diagnostic kits that are quick, simple to run and very accurate in predicting the outbreak of disease. Superintendents are finding that they can rely on such products to identify the disease organism and to avoid unnecessary treatments, thereby preserving the effectiveness of the chemicals. The savings in treatment costs more than compensates for the cost of the kits, and the chemical industry still benefits in the marketplace.

The public has expressed concerns about the emphasis placed on chemical control of turfgrass pests by the professional lawn care operators and about homeowner use of the non-restricted pesticides registered for turf. The Professional Lawn Care Association of America is concerned about new State regulations on posting. A number of companies now offer alternative service programs to their customers and give advice on proper cultural management. The acreage of urban turfgrass has increased greatly in the last ten years, and the acreage under treatment by lawn care companies has doubled (see the chapters by Raupp, Potter and Welterlen). We are encouraged that the industry is taking steps to alter its practices, as shown in the chapters by Jim Wilkinson and by Roger Funk.

Very few studies have been done to determine the downstream impact of the increased use of pesticides on the growing urban area. Studies such as those reported by Welterlen take several growing seasons to complete and can be very complex in design and costly to run. Research on the impact of urban pesticides on water resources should be considered an important part of the investigation carried out at land grant colleges as a part of their mission.

In summary, we believe that:

- the turfgrass industry in general can become more sophisticated in their pest control programs and
- integrated pest management programs are designed to maximize proper use of pesticides.

Unnecessary use of any chemical is of benefit to no one and is a waste of valuable resources. Our society can no longer afford to ignore such practices.

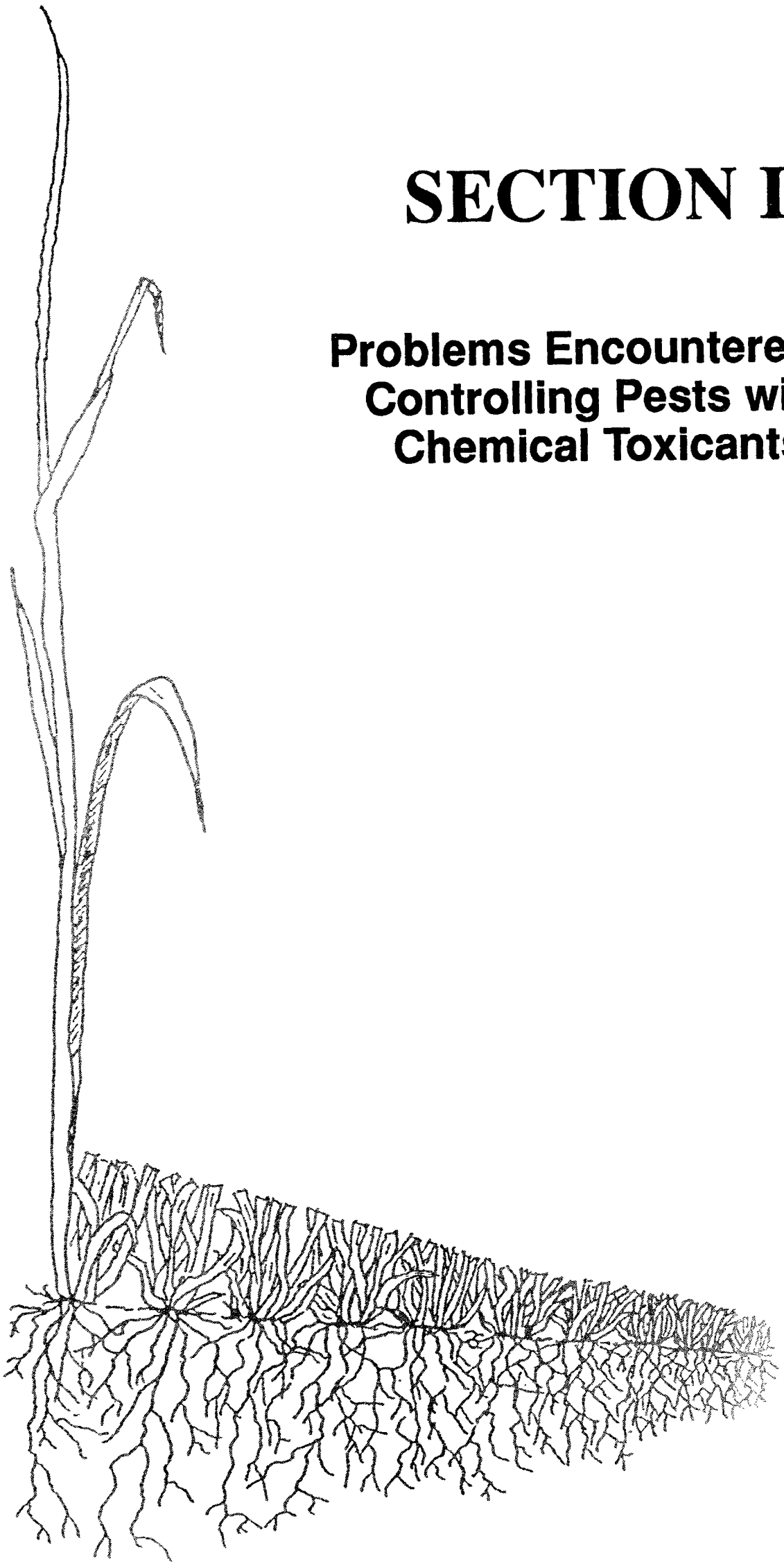
The monitoring methods, biological alternatives and cultural practices discussed in this book will greatly benefit the golf course industry as well as the growing lawn care service industry by providing information on a number of control methods and how to design the best program for their needs.

We hope that this book will contribute to a greater understanding of best management practices for turfgrass and will supplement turfgrass and landscape management courses. We hope that it serves as a comprehensive source of information for anyone from city managers to homeowners who wants to learn how to maintain healthy turf.

I acknowledge the gracious cooperation of my authors in providing their material under sometimes very short deadlines. Especially I would like to acknowledge the expert work of Randy Bacon, of EPA's print shop, who has made my work easy by his management of the text as it arrived.

Thanks are due to Charles Reese, Chief of the Certification and Training Office of OPP, who offered to provide funding for the project because he saw the need for material on integrated pest management in the training program.

I am especially indebted to Diana Horne, Chief of EPA's Integrated Pest Management Unit, who has enthusiastically supported this work through all the administrative travails of the project, and to Joyce Herbert, who has provided exceptional clerical and secretarial service from the time the symposium was first planned.



SECTION I

Problems Encountered in Controlling Pests with Chemical Toxicants

INSECT RESISTANCE TO INSECTICIDES

Robert L. Metcalf
Department of Entomology
University of Illinois
Urbana, IL 61801

BRIEF HISTORY OF INSECTICIDE RESISTANCE

That insect pests acquire resistance or tolerance to insecticide action has been known for 73 years, since the description of lime-sulfur resistance in the San Jose scale Quadraspidiotus perniciosus in California (Melander 1914). In 1916, resistance to hydrogen cyanide fumigant was reported in the California red scale Aonidiella aurantii and in the black scale Saissetia oleae (Quayle 1922). The number of scientifically validated cases of insecticide resistance increased gradually and by 1946 insecticide resistance was known in a total of 11 species including the codling moth Cydia pomonella and the peach twig borer Anarsia lineatella to lead arsenate, the citricola scale Coccus pseudomagnoliarum to hydrogen cyanide, the citrus thrips Scirtothrips citri to potassium antimonyl tartrate (tartar emetic), the walnut husk fly Rhagoletis completa to cryolite, and the cattle ticks Boophilus microplus and B. decoloratus to sodium arsenite dip (Metcalf 1955). This evidence suggested that the prognosis of the chemical control of insects was poor. However, little scientific attention was given to insecticide resistance which is nothing more than accelerated microevolution. Insecticide resistance began to receive the scientific attention that it deserved following the introduction of DDT after World War II when resistant strains of the housefly Musca domestica appeared almost simultaneously in Sweden and Denmark in 1946; of the mosquitoes Culex pipiens in Italy and Aedes solicitans in Florida in 1947, of the bedbug Cimex lectularius in Hawaii in 1947, and of the human body louse Pediculus humanus in Korea and Japan in 1951 (Brown and Pal 1971).

With the steady proliferation of new insecticides and their increasing use in insect control programs, the number of scientifically documented cases of insecticide resistance has increased at an exponential rate, encompassing 224 species in 1970, 364 in 1975, and 447 in 1984 (Table 1, Georghiou 1986). Although most early examples of insecticide resistance were found in insect vectors of human diseases because of the very widespread use of DDT, lindane and dieldrin in

vector control programs, by 1970 insecticide resistance was demonstrated in 118 pests of crop, forest, and stored products as compared with 166 pests of humans or animals (Brown 1971). By 1980, resistance was established in 260 agricultural pests compared to 168 pests of humans and animals (Georghiou, 1981). These figures probably understate the severity of the resistance problem worldwide because the susceptibility of many insect pests species has not been studied, is incompletely characterized, or is not reported adequately in the scientific literature.

Insecticide resistance has been documented in 16 orders of Arthropoda with the distribution recorded by Georghiou (1981) as: Acarina, 53 (12.4%); Anoplura, 6 (1.4%); Coleoptera, 64 (14.9%); Dermaptera 1 (0.2%); Diptera, 153 (36.7%); Ephemeroptera, 2 (0.5%); Hemiptera, 20 (4.7%); Homoptera, 42 (9.8%); Hymenoptera, 3 (0.7%); Lepidoptera, 64 (14.9%); Mallophaga, 2 (0.5%); Orthoptera, 3 (0.7%); Siphonaptera, 8 (1.9%); and Thysanoptera, 7 (1.6%). These data reflect the relative numbers of pest species in the individual orders and the amount of insecticide pressure placed upon them.

As each new class of insecticides was introduced and widely deployed against insect pests, the rate of development of resistant species has followed an almost identical pattern of essentially exponential growth until high-level resistance or legal restrictions slowed further usage. These curves are best characterized by the doubling times over the middle range. These can be approximated by the data in Table 2, as DDT/methoxychlor 6.3 years, lindane/cyclodienes 5.0 years, organophosphates 4.0 years, carbamates 2.5 years, and pyrethroids 2 years. Thus these data show that the doubling time for the development of numbers of resistant species has steadily decreased with the introduction of each new type of insecticide. This is corroborated by the decreasing spans of effectiveness of substitute insecticides to such pests as the Colorado potato beetle Leptinotarsa decemlineata (Forgash 1984), the Agromyzidae leaf miner Liriomyza trifolii (Parrella and Keil 1984), the citrus thrips (Morse and Brawner 1986) and the house fly (Keiding 1977) as illustrated in Tables 3 and 4. This accelerated development of multiple resistance is a product of the persistence of R genes in the species genome and of their interactions through a variety of resistance mechanisms that affect both the detoxication of and the target-site sensitivity to various insecticides.

RESISTANCE AS AN EVOLUTIONARY PHENOMENON

Insecticide resistance is dependent upon random mutation that establishes an R-allele in the natural population of the species. Widespread application of the insecticide propagates the R-allele through preferential survival and it is dispersed throughout the population. As the R-allele becomes sufficiently common, the effectiveness of the insecticide is reduced. Where the R-allele is partially dominant, RR homozygotes are rapidly selected that are completely resistant. With recessive alleles or combinations of genes each conferring low-level resistance, selection is much slower (Sutherst and Comins 1979).

There is surprisingly little data about the natural frequency of resistance alleles. These are thought to be present in typical insect populations at frequencies of 10^{-4} to 10^{-2} with RR homozygotes present at 10^{-8} to 10^{-4} (Georghiou and Taylor 1986). The most carefully studied example is that of Anopheles gambiae in West Africa (Hamon and Garrett-Jones 1963). In this vast region, dieldrin was used as the primary insecticide for WHO malaria eradication programs because of its persistence on the mud surfaces of dwellings. Initially dieldrin was very effective against A. gambiae adults with LC_{50} values as low as 0.02 -0.07% based on a 1 hour exposure to treated filter papers as producing 24-hour mortality (Armstrong 1958). The corresponding value for DDT was 0.6%.

Dieldrin spraying began in 1954 and dieldrin-resistance was first observed in the Sokoto Province of northern Nigeria that had been sprayed 3 times over 18 months. Within 2 months after spraying, large numbers of A. gambiae were observed resting, unaffected upon treated walls and the LC50 was 2.0% dieldrin (Armstrong et al. 1958). Laboratory colonization produced a RR strain that was unaffected by 4.0% dieldrin test papers and had resistance-ratios of 800 for dieldrin, 400 for aldrin, 140 for isodrin, 90 for endrin, and 26 for lindane, but no resistance to DDT (Brown and Pal, 1971). Crossing the R-Ambursa strain with a S-Lagos strain produced RS heterozygotes exactly intermediate in resistance and the RS, and RR alleles could be distinguished in field populations by exposure to standard WHO test papers, of 0.4% and 4.0% for 1 hour. By this technique, it was shown that resistant heterozygotes formed 0.04% of the wild unsprayed A. gambiae arabiensis population in Diggi and 6.0% in Sokoto (Armstrong et al. 1958). A single large scale treatment of lindane (HCH) produced a population of 86% RS and RR genotypes. In Upper Volta in an area near Bobo-Dioulasso which had been sprayed 4 times with dieldrin, there was 100% RR genotype. No mortality was produced by exposure to 4.0% dieldrin papers, as compared to an LC_{50} of 0.03%

in an unsprayed village 40 km. away (Brown and Pal 1971). Areas where A. gambiae had high frequencies of RS and RR genotypes have appeared in Ivory Coast, Ghana, Togo, Dahomey and Cameroon (Hamon and Garrett-Jones 1963). Surveys have shown 91-100% RR homozygotes in Liberia, Dahomey, Cameroon,and Republic of Congo. There is evidence that increases in the frequency of R alleles may be related to the heavy use of dieldrin and lindane on agricultural crops such as cotton and peanuts. The dieldrin resistant mosquitoes have sporozoite indices as high as neighboring susceptible populations and dieldrin resistant strains have been found to be larger, longer-lived, and more stress-resistant than susceptible strains (Davidson 1956, 1958; Hamon and Garrett-Jones 1963). Thus the failure of dieldrin residual spraying has always resulted in the resumption of malaria transmission.

RESISTANCE MECHANISMS

A. Cross Resistance. This is the most common form of insecticide resistance where a single detoxication process or an aberrant intoxication process reduces the susceptibility of resistant alleles of an insect pest species to a chemically related family of insecticides. Cross resistance has been demonstrated in naturally occurring arthropod populations to discrete groups of insecticides classified in order of historical appearances as I DDT/methoxychlor, II lindane/cyclodienes, III organophosphates, IV carbamates, and V pyrethroids. As shown in Table 1, many insect pest species have successively acquired resistance to these various classes of insecticides. In general, races of insects resistant to one insecticide in a class exhibit a spectrum of abnormal responses to all the other members of the class as dictated by their individual stereochemical peculiarities.

B. Multiple Resistance is defined as resistance extending to a variety of classes of pesticides, unrelated to one another chemically. The mechanisms typically involve target site insensitivity e.g., the kdr mechanism that shows reduced sensitivity of the nerve axon to DDT as well as to the chemically unrelated pyrethroids; and the altered acetylcholinesterase mechanism where both organophosphates and carbamates fail to react with the modified catalytic site of the enzyme due to a structural modification that restricts access of the chemical inhibitor. Multiple resistance is now present in at least 213 arthropod species from 10 orders and 44 families (Table 1). Thus almost half of all the documented cases of arthropod resistance to insecticides comprise resistance to several chemically unrelated classes of insecticides: I DDT/methoxychlor, II lindane/cyclodienes, III organophosphates, IV carbamates, and V pyrethroids. By 1987, at least 19 arthropod pest species are resistant to all 5 classes of insecticides as identified in Table 5.

This extensive and ever widening pool of species with multiple-resistant genes is the product of the historical replacement of insecticide as resistance developed, by insecticides of different chemical types and modes of action. Each new insecticide produces a selection for one or more mechanisms of resistance and each mechanism selected produces a spectrum of cross-resistance to closely related insecticides. Thus the sequential use of alternative compounds has led to widespread multiple resistance and the continued selection pressure favors the retention of resistant genes to discontinued insecticides. Therefore the presence of alleles for multiple resistance in a pest population reflects the past history of insecticide use and precludes a return to insecticides previously used. The devastating effects of cross-resistance and multiple resistance to control programs for the Colorado potato beetle attacking potatoes and the house fly in Denmark are shown by the sequences of resistance development portrayed in Tables 3 and 4. Similar portrayals of the development of multiple resistance have occurred with the serpentine leaf miner and the German cockroach (Section V-C).

The past history of selection for resistance may result in an accumulation of mechanisms for resistance that confer multiple resistance across the various classes of insecticides. For example, an esterase in the housefly (E.O. 33) selected by exposure to the organophosphate malathion and trichlorfon confers moderate resistance to the pyrethroids as well (Sawicki et al 1984). However, in houseflies with the kdr mechanism for resistance selected by exposure to DDT, subsequent exposure to the pyrethroids resulted in intensification of both the kdr and esterase mechanisms leading to total immunity to deltamethrin (LD_{50} greater than 20 ug per fly) (Sawicki et al 1986). Thus a history of sequential use of DDT followed by OP's produced a genetic history of multiple resistance that contributed to the rapid failure of a third group of insecticides, the pyrethroids. There is, therefore, valid concern that the effective lifetime of the pyrethroids may be shorter in developing countries where their use directly succeeded that of DDT than it will be in developed countries where the sequence after DDT involved several years of use of OP's and carbamates (Georghiou 1986).

C. Genetic and Biochemical Processes of Insecticide Resistance.

A number of increasingly more generalized mechanisms for insecticide resistance have been identified in terms of specific genetic control (Plapp 1986). Most of these studies have been made with the housefly but the types of resistance have been identified in many other insects and there is little reason to question their generality.

Metabolic resistance involves detoxication of the insecticides by a variety of enzymatic processes including esterases, mixed function oxidases, glutathione transferases, and epoxyhydrolases. Genes on chromosome II are the controlling factor and this may be a common codominant resistance gene controlling a variety of detoxifying enzymes (Plapp 1986). Metabolic resistance involves DDT, OP's, carbamates, and juvenoids and the specific detoxication enzymes are typically inhibited by synergists that may act to restore the effectiveness of the pesticide. Examples include (a) the DDT'ase inhibitor 1,1-bis-(p-chlorophenyl)-ethanol (chlorfenethol) for DDT; (b) O-ethyl, O-(p-nitrophenyl) phenylphosphonate (EPN-oxon) a carboxyesterase inhibitor for malathion, (c) S, S, S-tributyl phosphorotrithioate (DEF) for esterases hydrolyzing OP's; and (d) piperonyl butoxide for mixed function oxidases detoxifying carbamates and pyrethroids.

Kdr or knockdown resistance involves a modification of the target sites for DDT and the pyrethroids on the nerve axon and is controlled by a gene on chromosome III. The kdr resistance mechanism confers multiple resistance to all DDT analogues and pyrethroids. Both low level (kdr) and high level super kdr alleles have been studied.

Dld-r or dieldrin resistance involves another modification of the target site on the nerve axon and is controlled by an incompletely recessive gene on chromosome IV.

AChE-R or altered acetylcholinesterase involves a change in the biochemical action of the nerve synaptic regulator acetylcholinesterase that is the target site for OP's and carbamates. The codominant gene is located on chromosome II and confers multiple resistance to organophosphorus and carbamate insecticides.

Pen is a resistance mechanism involving decreased penetration of insecticides and is controlled by a recessive gene on chromosome III. This type of resistance can act in concert with other resistance genes to further increase resistance levels.

1. DDT'ase. Resistance resulting from the selection of alleles that produce high levels of a specific enzyme that catalyzes the dehydrochlorination of DDT to the non-insecticidal DDE was very intensively studied during the 1950's when the insect resistance picture was relatively unique and simplistic remedies were sought. The enzyme is DDT-dehydrochlorinase or "DDT'ase",and its

high titre produces DDT resistance in the housefly, in the yellow-fever mosquito Aedes aegypti, the pest mosquitos Culex fatigans, the malaria vectors Anopheles saccharovi, and A. subpictus, the human body louse Pediculus humanus, the triatomid bug Triatoma infestans, the Mexican bean beetle Epilachne varivestis, the red-banded leafroller Argyrotaenia velutinana, the pink bollworm Pectinophora gossypiella, and the cotton bollworm Heliothis virescens.

DDT'ase isolated from DDT-resistant flies (Sternburg et al 1954) appears to be a lipoprotein with a molecular weight of about 120,000 daltons and consists of 4 subunits. Glutathione is required as a cofactor for DDT'ase activity (Lipke and Kearns 1960; Dinamarca et al. 1969, 1971). DDT'ase activity is present in the susceptible (S) housefly to only about 0.03 to 0.3% of that in highly resistant strains (R), and the level of resistance in houseflies where this mechanisms is present is roughly correlated with the resistance ratio or RR ($LD_{50}R/LD_{50}S$) (Lipke and Kearns 1960; Oppenoorth and Welling 1976; Oppenoorth 1984).

DDT'ase functions by attacking the alpha-H of the DDT molecule in a manner similar to OH-catalyzed dehydrochlorination, producing an E_2-type elimination reaction and the expulsion of Cl-leading to the formation of DDE or 2,2-bis-(p-chlorophenyl)-1,1-dichloroethylene (Figure 1) (Metcalfand Fukuto 1968). The rates of reaction of various DDT analogues with DDT'ase are similar to the OH-catalyzed dehydrochlorination constants and are controlled by the relative availability of electrons at the H-C bond (alpha carbon) as determined by the polar effects of the p,p'-substituents on the aryl rings. Thus DDT'ase attacks methoxychlor with p,p'-CH_3O groups (electron-donating) at a rate only about 0.2 that of the attack on DDT with p,p'-Cl groups (electron-withdrawing) (Lipke and Kearns, 1960). The rates of dehydrochlorination by DDT'ase are also dependent upon the electronic properties of the substituents on the beta carbon, and 2,2-bis-(p-chlorophenyl)-1,1,1-tribromoethane is attacked about 4X more readily than DDT. The analogue DDD or 2,2-bis-(p-chlorophenyl)-2,2-dichloroethane is attacked about 3.8X more readily than DDT, and the dibromo-analogue of DDD or 2,2-bis(p-chlorophenyl)-2,2-dibromoethane about 4.6X more readily than DDD (Berger and Young 1962).

2. DDT'ase Inhibitors as DDT Synergists. Dramatic demonstration of the role of DDT'ase in DDT resistance has been provided by discovery that certain structural analogues of DDT, although insecticidally ineffective, could synergize the toxicity of DDT to highly resistant strains of houseflies. Chlorfenethol or 1,1-bis-(p-chlorophenol)-ethanol was found by Summerford et al. (1951) to have a synergistic ratio (SR) or LD_{50} DDT alone/LD_{50} DDT plus synergist of 60. Chlorfenethol was shown to inhibit the in vivo detoxication of DDT to DDE in R flies and when a range of 0.06 to 6.5^{ug}was applied topically together with a constant amount of 0.65^{ug} of DDT, the mortality was increased from 2 to 100%, the amount of DDT recovered internally was increased from 9.4 to 77%, and the amount of DDE formed was decreased from 63 to 12% (Perry et al 1953). Chlorfenethol proved to be an effective in vivo inhibitor of DDT'ase at a molar ratio of 0.001 that of DDT (Lipke and Kearns 1960).

Many other structural analogues of DDT are synergists for R flies, and synergistic ratios (SR values) determined for the R super pollard housefly are: 1,1-bis-(p-chlorophenyl)-ethane SR 100, bis-(p-chlorophenyl)-chloromethane SR 140, and 1,1-bis-(p-chlorophenyl)-2,2,2-trifluoroethanol SR 78-127 (March et al 1952; Metcalf, 1967). The high activity of p-chlorobenzenesulfon-p-chloroanilide SR 108 was described by Speroni (1952) and emphasized the structural similarity of such compounds to DDT. This led to the development of p-chlorobenzene-N,N-dibutylsulfonamide as an oil soluble synergist for DDT (Neeman et al. 1957).

These DDT-synergists clearly fit the active site of the DDT'ase enzyme and act as competitive or in some cases as irreversible inhibitors thus blocking the dehydrochlorination of DDT. The DDT synergists such as chlorfenethol, 1,1-bis-(p-chlorphenyl)-chloromethane, and 1,1-bis-(p-chlorophenyl)-ethane were used successfully in field experiments to control DDT-resistant houseflies (March et

al. 1952). However, the DDT-synergist combinations had only temporary effectiveness in housefly control and eventually treated populations developed "super resistance" to the DDT-synergist combination (March et al. 1952). The widespread development of an alternative DDT-resistance mechanism in the housefly, the kdr nerve axon insensitivity which was not responsive to synergistic action (Oppenoorth and Welling 1976), emphasized the inadequacy of the synergist approach.

3. "Resistance Proof" DDT Analogues. The relatively greater effectiveness of methoxychlor to DDT resistant houseflies with high DDT'ase activity and the spectrum of activity of DDT'ase toward a variety of DDT analogues suggested that analogues in which dehydrochlorination was hindered or blocked might be effective insecticides for DDT-resistant insects. This requirement posed a nice problem in finding DDT-analogues which had the proper stereochemical configuration to be active intoxicants but were not DDT'ase substrates. Four distinct mechanisms for "resistance proofing" of the DDT-type molecule have been identified (Metcalf and Fukuto 1968):

a. Changing the bond strength at the alpha-carbon to substitute alpha-D or alpha-F for alpha-H. The deuterium isotope effect in OH-catalyzed dehydro-chlorination is 6.8. The alpha-C-F bond cannot be attacked by DDT'ase.

b. Steric hinderance to interaction with DDT'ase by introduction of an ortho-group of proper size as in o-Cl-DDT. This reduces OH- catalyzed dehydrochlorination to 0.17.

c. Changing the bond character of the chloromethyl moiety as in 1,1-bis-(p-chlorophenyl)-2,2-dichlorocyclopropane.

d. Total replacement of aliphatic halogens by CH_3 as in the neopentanes or isobutanes or by CH_3 and NO_2 as in the nitropropanes (Coats et al 1977). Examples of the effects of these changes in the DDT molecule on toxicity to the susceptible and DDT-resistant housefly are shown in Fig. 1.

Several of these "resistance proof" DDT analogues have had serious consideration for practical use. DDT-resistant larvae disrupted the Aedes aegypti eradication program in the United States (Section VI-A). The DDT'ase of Aedes aegypti differs from that of the housefly in effectively dehydrochlorinating o-chloro-DDT but not alpha-deutero-DDT (Kimura and Brown 1964). Therefore the use of alpha-deutero-DDT which dehydrochlorinates at a rate of about 0.14 that of DDT was proposed as a substitute in the eradication program. The relative LC_{50} values for alpha-deutero DDT and DDT to S- and R- Aedes aegypti larvae were (Pilai et al. 1963):

	DDT	deutero-DDT
S	0.012 ppm	0.004 ppm
R	31.0 ppm	0.40 ppm

However, the substitution of alpha-deutero-DDT at $10 per lb. for DDT at $0.20 per lb. posed an unacceptable reduction in the cost effectiveness of the eradication program.

4. Kdr resistance factor. A totally different mechanism of DDT resistance,the knockdown resistance or kdr mechanism was first identified in the housefly in 1951 (Winteringham et al. 1951). The kdr mechanism is a target site insensitivity of the nerve axon and evidence for it is obtained largely by electrophysiological measurements of nerve physiology together with the absence of DDT'ase, the inactivity of DDT-synergists (Georghiou 1980) and kdr resistance to DDT analogs that cannot be dehydrochlorinated (Coats et al 1977). The development of kdr is controlled by a gene on CrIII and is recessive. Kdr is widespread in the housefly in northern Europe and was found in practically all populations in Denmark (Keiding 1977). Kdr has been identified in a variety of mosquito species: Culex fatigans, C. tarsalis, Aedes aegypti, Anopheles albimanus, A. gambiae, A. quadrimaculatus, A. saccharovi, A. stephensi, in the stable fly Stomoxys calcitrans, the horn fly Haemotobia irritans and the cattle tick B. microplus. Kdr is also found in a variety of armyworms and bollworms including Spodoptera exigua, S. frugiperda, S. littoralis, and Heliothis armigera(Miller et al. 1983).

The pyrethroids act at the same general target site in the insect nerve axon as DDT, and the introduction of residual pyrethroids in Denmark, Switzerland, Germany, and England was followed by development of high levels of pyrethroid resistance in the housefly within a few months (Keiding 1980; Keiding 1986; Chapman and Lloyd 1981). In contrast, kdr is rare in Japan and pyrethroid

resistance in the housefly did not develop until after 6 years of residual pyrethroid use (Motoyama 1984).

The influence of kdr on multiple resistance of DDT and pyrethroids was demonstrated by the very rapid emergence of pyrethroids resistance in the horn fly, Haematobia irritans, following the use of ear tags containing permethrin and fenvalerate on cattle throughout the U.S. DDT has been used extensively to control the horn fly during the 1950's and resistance appeared about 1960. The pyrethroid-containing ear tags were introduced in 1980 and within 2 to 3 years widespread resistance was evident (Quisenberry et al. 1984, Sparks et al. 1985). This resistance resulted from genetic selection for the kdr mechanism (Roush et al. 1986) that resulted in cross-resistance to cypermethrin, fenvalerate, permethrin, deltamethrin, and flucythrinate (Byford et al. 1985).

5. Altered AChE resistance factor. The enzyme acetylcholinesterase (AChE) is the target site of the entire groups of organophosphate and carbamate insecticides which number in the hundreds. Resistance to these insecticides resulting from a decreased sensitivity of AChE was first identified in the mite Tetranychus urticae (Smissaert 1964). The development of altered AChE is controlled by a gene on CrII that is codominant, and has been identified in the mites T. telarius, T. kanzawai, Typhlodromus pyri, Aphis citricola, the green rice leafhopper Nephotettix cincticeps, the housefly, the mosquitoes Anopheles albimanus and Culex pipiens, the cattle tick Boophilus microplus, and the cotton leafworm Spodoptera littoralis (Nolan et al. 1972; Yamamoto et al. 1983; Raymond et al. 1986). Kinetic analyses of the enzymes of S and R races have shown a decrease of about 200-fold in the bimolecular rate constant ki for the inhibition of housefly AChE by tetrachlorvinphos (Tripathi and O'Brien 1978) and of about 500-fold for the enzyme in the green rice leafhopper by m-sec-butylphenyl N-methylcarbamate (Yamamoto et al. 1983). The phosphorylation or carbamylation constants, k_2 were not appreciably altered but the affinity constants K_a were reduced by 300-500 fold; indicating structural alterations in the stereochemistry of the active sites of both fly and leafhopper AChE, hence the term "altered AChE." In contrast, for both altered enzymes there was only a 2-3 fold difference in the affinity of ACh for the altered enzyme (Yamamoto et al. 1983). The altered AChE resistance is particularly destructive to insecticide resources as its appearance results in wholesale loss of effectiveness of the large groups of OP and carbamate insecticides.

PERSISTENCE OF GENES FOR PESTICIDE RESISTANCE

Once selected for, resistance genes have very lengthy persistence in wild insect populations. Although gene frequency of a specific resistance allele may decrease upon removal of insecticide pressure, the persistence of an apparently changed background of residual inheritance in the genome causes the strain to regain its resistance as soon as the insecticide is reapplied (Brown 1977). Genes for DDT and cyclodiene resistance in Danish houseflies have persisted for more than 20 years; these insecticides again became ineffective within 2 months after reapplication of the insecticides. Genes for resistance to diazinon and dimethoate also have shown long persistence (Keiding 1977). The citrus thrips, Scirtothrips citri has retained its resistance to tartar emetic for more than 45 years and to DDT for more than 35 years (Morse and Brawner 1986). Multiple resistance in the cotton leafworm in Egypt showed no signs of regression over an 11-year period (El-Sebae 1977). There also appears to be no sign of regression of resistance in the multiple resistance patterns of the Colorado potato beetle (Table 3) and the house fly (Table 4) over periods of as much as 30 years.

These unpleasant consequences of the segregation of R-genes are predictable from the Hardy-Weinberg equilibrium which predicts that gene frequencies and genotype ratios in large biparental populations reach an equilibrium in one generation and remain constant thereafter unless disturbed by natural selection, new mutations, or genetic drift. This factor, therefore, prevents the successful long-term reuse of any insecticide in insect populations with resistance alleles, even though the initial resistance has apparently reverted to full susceptibility (Brown 1971; Georghiou and Taylor 1976; Keiding 1979).

IMPACT OF INSECT RESISTANCE TO INSECTICIDES UPON PEST CONTROL

The onslaught of cross and multiple resistance has greatly complicated the chemical control of individual insect pests (Georghiou, 1981) and jeopardized highly structured eradication programs. A few examples will suffice to illustrate the severity of the problems.

A. Colorado Potato Beetle, Leptinotarsa decemlineata. This native American insect is the key pest of the Irish potato and fed on buffalo burr, Solanum rostratum until about 1859 when it was found attacking the potato S. tuberosum in eastern Nebraska. The beetle rapidly accommodated to this new host and migrated eastward until it reached the Atlantic Coast in 1874 (Casagrande 1987). Paris green or copper acetoarsenite was found to control this insect in 1865 and was replaced by lead arsenate as the standard remedy until the introduction of DDT in 1946. Resistance to DDT developed in New York in 1949, North Dakota in 1952 and Minnesota in 1959. The beetle was introduced into Europe after World War I and has become a major pest of potatoes there and resistant genes are now ubiquitous. Subsequently resistance has developed to lindane and the cyclodienes, to a wide variety of OP's, carbamates, and pyrethroids. Since 1945, at least 12 insecticides have been used on Long Island to control this insect and, as shown in Table 3, all of them have failed due to the onset of multiple resistance (Forgash 1981). This accumulation of resistance genes has progressively decreased the interval of effectiveness so that since 1973 no insecticide has remained effective for more than 2 years. In the words of Forgash (1984) "the fact is we are rapidly running out of control materials for the Colorado potato beetle in certain areas of the Northeast....where do we go from here?"

B. Serpentine leaf miner, Liriomyza trifolii. This insect was a minor pest of ornamentals, vegetables, and cut flowers until the use of the broad spectrum insecticides chlordane and toxaphene in Florida destroyed its natural enemies and resulted in huge population resurgences, following the development of resistance about 1957. Since 1975, no insecticide has given effective control for more than 2-4 years and there is widespread multiple resistance to the cyclodienes, OP's, carbamates, and pyrethroids. Subsequently, the resistant race was imported into California (Parrella and Keil 1984), and pest control costs have risen to $6,000 per acre. By 1984, as all registered insecticides were ineffective, the leafminer problem "had become so serious that it has threatened the chrysanthemum industry throughout the United States and the celery industry in Florida" (Parrella and Keil, 1984).

C. German cockroach, Blattella germanica, is the most ubiquitous of urban pests and is responsible for the great majority of requests for the services of professional pest control operators (PCO's) as well as for the preponderance of insecticide applications to the interiors of urban and suburban structures (National Academy of Sciences 1980). Although other species of domestic

cockroaches are household pests including the oriental cockroach Blatta orientalis, the American cockroach Periplaneta americana, the smoky brown cockroach P. fuligenosa, the Australian cockroach P. australasiae and the brown banded cockroach Supella longipalpa; the enormous populations of the German cockroach and its almost universal exposure to insecticides have brought about the most acute problems of insecticide resistance.

The German cockroach was initially of only moderate susceptibility to DDT (topical LD_{50} ca 50 ug per g, Heal 1953). True DDT resistance was first demonstrated in Trinidad and Panama in 1959, and in Canada, Germany, France, and England in 1961 (Grayson 1966). Laboratory colonies have shown DDT resistance ratios (RR values) as high as 200X (Grayson 1953). Chlordane (topical LD_{50} ca 20 ug per g), (Heal et al. 1953), was substantially more effective than DDT and became the insecticide of choice for cockroach control from 1948-1952 (Kearns et al. 1948). However, a strain

of B. germanica collected in Corpus Christi, Texas in 1952, where control failures with chlordane had been experienced, was found to have RR values of 5-6 for DDT, 10-12 for lindane, and 100-200 for chlordane (Heal et al. 1953). By 1953, chlordane resistance had appeared generally in the Gulf States of the U.S. and sporadically elsewhere and diazinon and malathion were recommended as substitute insecticides. Cyclodiene resistance was demonstrated in Europe by 1961 and RR values of 5,000 to chlordane and 6,000 to dieldrin were reported (Green et al. 1961). Chlordane resistant B. germanica were cross resistant to heptachlor, aldrin, dieldrin, and lindane (Fisk and Isert 1953; Butts and Davidson 1955) and a strain collected from Hawaii showed RR value for females of chlordane 322X, dieldrin 194X, lindane 27X, DDT 6X, malathion 8X, naled 3X, and the carbamate propoxur 3X (Ishii and Sherman 1965).

Resistance to diazinon was demonstrated in roaches collected near Owensboro, Kentucky in 1959 (Grayson 1961) and resistance to malathion had apparently appeared by 1959-1960 and was conclusively demonstrated in 1962 (Johnston et al 1964). Cross resistance among diazinon, malathion, and fenthion was widespread in major Texas cities by 1964 (Grayson 1965).

Pyethrins resistance at RR levels up to 20-31X was found in a strain of B. germanica collected at Fort Rucker, Alabama in 1954 (Keller et al. 1956) and three strains collected in Texas in 1963 had RR values of 10-15X (Grayson 1966).

Resistance to the carbamate bendiocarb appeared in England in 1977 (Barson and McCleyne 1978) and the roaches were cross resistant to dioxacarb and showed resistance to diazinon, and malathion, with weak resistance to permethrin (Barson and Renn 1983). A strain of the German cockroach from Baltimore, Maryland was highly resistant to bendiocarb (RR 90X) and had cross resistance to propoxur (RR 13X) and resistance to diazinon (4X), malathion (6X), and chlordane (8X) (Nelson and Wood 1982). German roaches with kdr type resistance to DDT were found to have resistance to pyrethrins, allethrin, permethrin, fenvalerate, and marginal resistance to cypermethrin, but none to deltamethrin.

Chlordane resistance in B. germanica has been shown to be stable over 25 generations of non-exposure and malathion resistance for 13 generations (Grayson 1966). A major consequence of the widespread multiple resistance in this species has been the introduction of more acutely toxic OP compounds into human dwellings and the workplace, e.g., the replacement of malathion (rat oral LD_{50} 1250 mg per kg) by chlorpyrifos (rat LD_{50} 97) and propetamphos (rat LD_{50} 82).

IMPACT OF RESISTANCE ON VECTOR CONTROL AND ERADICATION PROGRAMS

The development of DDT and its successful initial uses in controlling the mosquito, louse, and flea vectors of such dreaded human diseases as malaria, yellow fever, typhus, and plague afforded remarkable visions of mass public health programs for the abatement and eventual eradication of these and other vector-borne diseases throughout the world. DDT was safe to humans even when applied in the intimacy of dwellings, inexpensive and highly persistent in its effectiveness in all sorts of environmental situations. Thus it was possible to secure financing for major public health programs that naively promised eradication of disease vectors by the domestic application of DDT over periods of only a few years. The projected costs of such programs although reckoned in tens to hundreds of millions of dollars, have proved in retrospect to have been grossly underestimated and the eventual magnitude of the operations was such that the original goals have been lost and "eradication" has quietly slipped into oblivion. Vector resistance to DDT and to subsequently

developed cheap and durable insecticides such as lindane and dieldrin has been the principal technical problem leading to steadily worsening control failures.

DDT resistance appeared in the housefly Musca domestica and in Culex molestus in Italy in 1947, in the human body louse Pediculus humanus in Korea and in Anopheles saccharovi in Greece in 1955, and in the oriental rat flea in India in 1959. The rapidly increasing number of vector species for which insecticide resistance was suspected as the cause of control failures are shown as (Quarterman and Schoof 1958).

1946	1947	1948	1949	1950	1951	1952	1953	1954	1955
1	3	6	12	19	23	26	29	33	37

However, these abundant warning signs were virtually ignored in planning and operating vector eradication programs with the result that monumental failures have resulted as shown in the following examples. The ultimate failures of these programs represent an enormous disaster to the cause of global public health and are the most extravagant economic tolls yet levied by insect resistance.

A. Aedes aegypti eradication. This domesticated mosquito, the urban vector of yellow fever and dengue fever, was introduced into the Americas from its native home in Africa before the 16th century. For hundreds of years, the presence of Ae. aegypti was responsible for devastating outbreaks of yellow fever in seaports throughout the Americas. By 1930, the mosquito was present in 19 countries and ranged from Oklahoma and Tennessee in the United States to Buenos Aires in Argentina and Tecopila in Chile (Gratz 1973). Ae. aegypti is the vector of the several serotypes of dengue fever virus and the number of reported cases in the Americas reached 503,000 in 1977 and 354,000 in 1982 (Tonn et al. 1982).

The concept of a hemispheric eradication program for Aedes aegypti was first proposed by the 11th Pan America Sanitary Conference in Rio de Janeiro in 1942, and by 1947, the Pan American Health Organization (PAHO) officially embarked in the eradication of the mosquito as the solution to the urban yellow fever problem. By 1960, the United States was the only country in the mainland Americas that had not initiated an Aedes aegypti eradication program. Strong political pressures resulted in a Congressional appropriation of $3 million in 1963 for operations the succeeding year. The major weapon relied upon was the "perifocal"application of DDT water dispersible suspension in and around all potential breeding places of the mosquito and to any adjacent wall surfaces within a radius of about one meter (Gratz 1973).

The eradication effort was thus essentially doomed because DDT-resistance had been characterized in Aedes aegypti in Trinidad as early as 1950 (Brown and Pal 1971), and a survey of the mosquitoes' susceptibility throughout 16 countries of the Americas had shown that by 1964 no populations could be found that were susceptible to either DDT or dieldrin (Kerr et al. 1964). Initial control failures in the U.S. demonstrated that it would be necessary to replace the relatively cheap organochlorines with more costly and less persistent organophosphorus insecticides and these economic dislocations resulted in the quiet demise of the eradication program in 1968 after the expenditure of $54 million. A PAHO report in 1970 estimated that it would cost an additional $250 million and require another 5 years to eradicate Ae. aegypti from the U.S (Gratz 1973).

Presently A. aegypti is known to have multiple resistance to DDT, cyclodienes, OP's and pyrethroids (Georghiou 1981), and it seems most unlikely that eradication can be accomplished by chemical applications.

B. Malaria Eradication. The onset of insecticide resistance has produced its most deleterious effects in the control of malaria. Malaria has long been called the king of diseases and before the advent of DDT annually caused about 300 million illnesses and 3 million deaths. During World War II, the persistence and efficiency of DDT residual sprays against a variety of mosquito species entering human habitations suggested that yearly spraying of all dwellings in malarious areas could eliminate the disease by killing female Anopheles mosquitoes over the 10-14 day period required for infective sporozoites to develop in the mosquito's body following the ingestion of male and female gametocytes from a human blood meal. Application of this control measure directed at the vector Anopheles labranchiae in Italy in 1944 reduced the number of primary cases of malaria from 4800 in 1946 to 81 in 1949 and malaria was considered eradicated in 1950 (Missiroli 1950). A similar program in Sardinia using DDT spraying at 2 g per m^2 on the interior walls of houses eradicated malaria in 1951 (Logan 1953). In India 3-4 years of DDT residual spraying against the vectors An. culicifacies and An. fluviatilis reduced the parasite rate to less than 0.05% of its former level and by 1954 at least 64 million inhabitants were under protection of DDT spraying. These and successes in other parts of the world set the stage for the 1955 World Health Organization's program for the global eradication of malaria to be accomplished by residual house spraying with DDT at 2g per m^2 or with dieldrin at 0.6 g per m^2. It was planned that 8 years of continuous operations would be required for eradication in each national program and the entire global eradication was estimated to cost $1.3 billion (Brown et al. 1976; Soper et al. 1961).

DDT resistance was first observed in An. saccharovi in Greece in 1950 and was followed by dieldrin resistance in 1954. The onset of resistance was marked by a deterioration in malaria control that has continued for more than 30 years, with sporadic epidemics of malaria (Brown and Pal 1971). Resistance in An. saccharovi is now found in Greece, Lebanon, Iran, and Turkey and multiple resistance to DDT, dieldrin, malathion, fenitrothion, propoxur, and permethrin has been demonstrated.

Pronounced DDT resistance appeared in An. stephensi in Iran and Iraq when full scale residual spraying operations were begun in 1957-58. Dieldrin resistance appeared three years later, followed by malathion resistance in 1975 after six years of use (World Health Organization 1976).

In Central America and the Caribbean, dieldrin spraying against An. albimanus was begun in 1956 and widespread resistance appeared in 1958. A return was made to DDT spraying, and resistance appeared in 1958 and was general by 1960. The effective carbamate propoxur was employed in Guatemala, El Salvador, Honduras, and Nicaragua in 1970-71, and pronounced resistance had developed by 1974. An. albumanus now shows multiple resistance to DDT, dieldrin, lindane, malathion, propoxur, and permethrin (World Health Organization 1981).

An. culicifacies is the principal vector of malaria in India, Pakistan, and Sri Lanka. This vector developed dieldrin resistance in India in 1958 and DDT resistance in 1959 after three years of spraying, but a widespread malaria eradication program was continued until 1965-66 when both DDT and BHC failed to control outbreaks of malaria in areas under consolidation and maintenance (Brown and Pal 1971). Malathion was substituted in 1968 with some success, but widespread epidemics of malaria were reported in 1975 with 4 million cases as compared to 125,000 in 1965. In Pakistan, the experience was similar with DDT resistance appearing in An. culicifacies in 1963. The importance of this resistance was not recognized until outbreaks of malaria began in 1969. Neither DDT nor lindane was effective. By 1975 malaria cases in Pakistan were reported to number

over 10 million as compared to 9,500 in 1961. Malathion resistance appeared in An. culicifacies in 1975.

The problems of the rapid development of BHC and dieldrin resistance in An. gambiae in Africa have been discussed in Section II.

Many other examples of insecticide resistance in Anopheles spp occurred throughout the world, and by 1981 multiple resistance was present in 52 of the 60 vectors of malaria as shown in Table 6 (World Health Organization 1981).

Malaria eradication through residual house spraying reached a high point in 1974 when the malaria was considered eradicated in 36 countries; the population in areas in the maintenance phase and essentially without risk had increased to 797 million or 41.2% of the population in the areas of endemic malaria (Brown et al. 1976). However, malaria eradication programs in Saudi Arabia, Somalia, Burma, Cambodia, and South Viet Nam had reverted to organized control programs

covering a population of 168 million. Parasite rates remained high in Africa, Southern Asia, and parts of Central America involving about 100 million people. Massive epidemics of malaria had occurred India and in Pakistan. Thus in the areas where multiple resistance in Anopheles vectors is widespread malaria eradication efforts have almost completely broken down with some countries recording 30-40 fold increases in the number of cases of malaria from 1968 to 1976 (Agarwal 1979). Bruce-Chwatt (1970) stated that "physiological resistance has become one of the major threats of the success of global malaria eradication", and as of 1976, WHO quietly abandoned the concept of global malaria eradication by residual house spraying (WHO 1978).

DEPLETION OF INSECTICIDE RESOURCES

The widening spread of cross and multiple resistance through the genomes of major pest insects has severely limited the armamentarium of insecticides effective for the control of insect pests. The chronology of control failures with the Colorado potato beetle (Table 3) and the house fly (Table 4) provide dramatic confirmatory evidence (see also Section V). The spread of resistance has resulted in the wholesale replacement of the organochlorines by organophosphates and these in turn are being replaced by carbamates and then by pyrethroids. The progressive substitution of newer and more sophisticated insecticidal molecules has caused escalating costs to the users of insecticides. On the average, lindane and the cyclodienes cost about 6 times more than DDT, organophosphates 11 times, carbamates 9 times, and pyrethroids 100 times more than DDT. To be sure there are substantial dosage differences, e.g. the pyrethroids are generally used at rates 0.05- 0.1 those for DDT. Nevertheless, the cost differential is a major factor for the farmer who is bound by essentially static farm prices, and it has been disastrous for public health programs such as the WHO malaria eradication scheme. Based on a cost factor of 1.0 for DDT residual house spraying at 2 g per m^2, replacement with dieldrin at 0.5g per m^2 costs 1.7 times more; with lindane at 0.5g, 5.2 times; with malathion at 2g, 5.3 times; with fenitrothion at 2g, 15.9 times; with propoxur at 2 g, 20.4 times (Metcalf 1983). With the synthetic pyrethroids costing $50-100 or more per lb. and used at 0.1 g per m^2; the costs become astronomical. These cost increases are completely beyond the resources of public health budgets.

During the past 40 years insecticide-resistant pests have been controlled by the simplistic process of changing to a new type of insecticide to which the pest is susceptible. The widening patterns of multiple resistance (Table 1) show that this is a dubious long term solution. Pesticide discovery and development have become increasingly rigorous and costly. In 1956, 1800 chemical compounds were screened per marketable new product; in 1965-3600; in 1969-5040; in 1970-8000;

in 1972-10,000; in 1977-12,000 and in 1984-22,000 (Johnson and Blair 1972, Menn 1980, Storck 1984). Over this same period, the total developmental costs for marketing a new pesticide in the United States have increased from about $1.2 million in 1956 to about $45 million in 1984 (Fig. 2).

Insecticide resistance has steadily decreased the marketable life of new insecticides and cross and multiple resistance prejudice the effectiveness of new products even before they are marketed. Thus cross resistance in An. albimanus in El Salvador initiated by the drift of carbaryl from cotton fields to aquatic breeding habitats of the mosquito, sharply reduced the effectiveness of the related carbamate propoxur developed as a replacement for DDT in malaria control by residual house spraying (Georghiou et al. 1973). Multiple resistance by the DDT-selected kdr mechanism predisposes insect pests to rapid development of high levels of pyrethroid resistance (Miller et al. 1983, Omer et al. 1980, Priester and Georghiou 1980, Georghiou 1986). There is substantial evidence that the accumulating genes regulating a variety of biochemical mechanisms for detoxication and target site insensitivity have progressively shortened the effective lifetimes of succeeding classes of new insecticides (Tables 1 and 2). Insecticide resistance, therefore, has played a major role in the precipitous decline in the discovery and development of new synthetic insecticides that has occurred since 1960 (Table 7).

TACTICS FOR MANAGING INSECT RESISTANCE TO INSECTICIDES

The methodology for insecticide use in agricultural and public health over the past 40 years has been largely that of endeavoring to suppress insect pest species to unrealistic levels, i.e. eradication. Pest species exposed to the massive applications of insecticides made to agricultural crops, to pest breeding sites, and to urban and suburban properties have been under intensive "natural selection" in the Darwinian sense. Species that survived such onslaughts were forced to change the nature of the genome by undergoing "accelerated microevolution". Naturally occurring mutations that favored survival in an insecticide laden environment rapidly become dominant as described in Section II. As shown in Tables 1 and 2, this process of resistance selection has occurred with disconcerting rapidity for almost all insect pest species. The persistence of resistance genes in the insect pest genome (Section IV), has made it impossible to reverse the historical loss of insecticide effectiveness as portrayed in Tables 3, 4, and 6.

Many tactics for resistance management have been proposed over the past 40 years but few specific methodologies have been put to practical use. The resistance problem has been addressed largely by toxicologists and entomologists who have proposed solutions directed solely at insecticide use, i.e., insecticide management (Leeper et al. 1986). Suggested solutions include (a) monitor insect pests so that primitive susceptibility levels are understood and early detection of specific resistance is possible, (b) avoid use of mixtures of insecticides, (c) extend the useful life of a satisfactory insecticide as long as possible, but monitor susceptibility and replace the insecticide before it fails, (d) choose a sequence of suitable alternative insecticides based on genetic considerations affecting cross and multiple resistance, and (e) exploit alternative treatments with insecticides devoid of common major R factors (Metcalf 1980). The frequently proposed remedy of incorporating synergists to restore insecticide effectiveness is unlikely to be productive in view of past experience (Section III-B). Resistance can rapidly develop to the combination of insecticide and synergist or through alternative pathways. The use of mixtures of chemicals is subject to disadvantageous registration and marketing considerations and to environmental quality problems.

However, resistance is a complex genetic, evolutionary, and ecological phenomenon and insecticide management is unlikely to produce other than temporary palliation. As we have seen (Section VII), the technological and economic requirements for successful insecticide management

are likely to exceed available resources. Resistance management tactics are more likely to succeed if they are directed at reducing the single-factored selection pressure that occurs with conventional chemical control. Obvious counter measures include (1) reduce frequency of insecticide treatments, (2) reduce extent of treatments, (3) avoid insecticides with prolonged environmental persistence and slow release formulations, (4) reduce the use of residual treatments, (5) avoid treatments that apply selection pressures on both larval and adult stages, (6) incorporate source reduction and non-chemical methods, such as biological and cultural controls in control programs (Metcalf 1980). National programs or policies incorporating these principles have been organized against the housefly in Denmark, and the cattle tick and the cotton bollworm Heliothis armigera in Australia (Keiding 1986).

The combination of these principles is essentially a blue-print for integrated pest management (IPM) that is a dynamic framework for insect control practice based around the observance of the economic threshold before initiating remedial practices, and that seeks to relegate the use of insecticides to emergency weapons to be applied as last resort. Within the IPM framework there is opportunity to consider resistance management tactics based on population genetics, i.e., relating to the frequency of resistant alleles, decreasing the dominance of resistant genes, and minimizing the fitness of resistant genotypes (Leeper et al. 1986). These proposals require manipulations of the agroecosystem such as the mass release of susceptible insects, the eradication of resistance foci, the application of insecticides at high rate to reduce dominance by heterozygotes, and reducing the fitness of resistant genotypes by preserving susceptible homozygotes (Georghiou and Taylor 1977). Whether such theoretically desirable schemes can be implemented within existing economic, social, and political constraints is an intriguing question. (Miranowski and Carlson 1986).

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TABLE 1

Development of Insect Pests with Multiple Resistance to Various Groups of Insecticides[1]

Year	Resistant	DDT Cyclodienes	DDT Cyclodienes Organophosphorus	DDT Cyclodienes Organophosphorus Carbamates	DDT Cyclodienes Organophosphorus Carbamates Pyrethroids	References
1938	7	0	0	0	0	Brown & Pal (1971)
1948	14	1	0	0	0	Brown & Pal (1971)
1954	25	18	3	0	0	Metcalf (1955)
1970	224	42	23	4	0	Brown (1971)
1975	364	70	44	22	7	Georghiou & Taylor (1981)
1980	428	105	53	25	14	Georghiou (1981)
1984	447	119	54	25	17	Georghiou (1986)

[1]From Metcalf, R.L. The ecology of insecticides and the chemical control of insects, pp. 251-297, in M. Kogan, ed. "Ecological Theory and Integrated Pest Management Practice", Wiley, N.Y. (1986)

TABLE 2

Approximate Rate of Development of Insecticide-Resistant Insect Species, Worldwide

Resistant pests (no.)	Year Resistance was Attained[1]				
	DDT/ methoxychlor	Lindane/ cyclodiens	Organophosphates	Carbamates	Pyrethroids
5	1951	1954	1959	1971	1976
10	1952	1955	1962	1972	1979
20	1955	1956	1964	1974	1980
40	1960	1959	1968	1977	
80	1968	1965	1972		1985
160	1974	1971	1976		
Average Doubling time -years	6.3	5.0	4.0	2.5	2.0

[1]Data from Brown & Pal (1971), Metcalf (1955), Brown (1971), Georghiou & Taylor (1977a), Georghiou (1981), and Farnham (1985).

TABLE 3

Development of Insecticide Resistance in the Colorado Potato Beetle Leptinotarsa decemlineata, Long Island[1]

Insecticide	Year Introduced	Year First Failure
Arsenicals	1880	1940
DDT	1945	1952
Dieldrin	1954	1957
Endrin	1957	1960
Carbaryl	1959	1963
Azinphos methyl	1959	1964
Monocrotophos	1973	1973
Phosmet	1973	1973
Phorate	1973	1974
Carbofuran	1974	1976
Oxamyl	1978	1978
Fenvalerate	1979	1981
Permethrin	1979	1981

[1]From Metcalf, R.L. The ecology of insecticides and the chemical control of insects, pp. 251-297, in M. Kogan, ed. "Ecological Theory and Integrated Pest Management Practice", Wiley, N.Y. (1986). Data from Forgash (1984).

TABLE 4

Rates of Development of Insecticide Resistance in the House Fly, Musca domestica, in Denmark.[1]

Insecticide	Year Introduced	Year First Failure
DDT	1945	1947
Lindane	1948	1950
Chlordane	1949	1951
Diazinon	1952	1955
Coumaphos	1955	1955
Malathion	1962	1963
Ronnel	1960	1961
Fenthion	1960	1964
Dimethoate	1963	1966
Fenitrothion	1967	1967
Dichlorvos	1968	1970
Bromophos	1969	1970
Tetrachlorvinphos	1969	1969
Iodofenphos	1969	1969
Bendiocarb	1976	1976
Dioxacarb	1976	1976
Decamethrin	1976	1976
Cypermethrin, permethrin	1977	1977
Fenvalerate	1977	1977

[1]Keiding 1977, 1978, 1979.

TABLE 5

Insect Pests with Multiple Resistance to Five Classes of Insecticides

Coleoptera

Colorado potato beetle, Leptinotarsa decemlineata

Granary weevil, Sitophilus granarius

Red Flour beetle, Tribolium castaneum

Diptera

House Fly, Musca domestica

House Mosquito, Culex pipiens

Horn Fly, Haematobia irritans

Leaf miner, Liriomyza trifolii

Malaria mosquitoes, Anopheles albimanus and An. sacharovi

Homoptera

Brown plant hopper, Niloparvata lugens

Green peach aphid, Myzus persicae

Pear psylla, Psylla pyricola

Lepidoptera

Armyworms, Spodoptera fruigiperda, S. littoralis

Cotton Bollworms, Heliothis armigera and H. virescens

Diamond back moth, Plutella xylostella

Orthoptera

German cockroach, Blattella germanica

Thysanoptera

Citrus thrips, Scirtothrips citri

TABLE 6

Spread of Insecticide Resistance in Anopheles Mosquito Vectors of Malaria[1]

Year	Number of Resistant Species	Number of Species Resistant to:				
		DDT	Dieldrin/ Lindane	Organophosphates	Carbamates	Pyrethroids
1951	1	1				
1957	8	4	6			
1959	24	7	23			
1962	35	12	34			
1969	39	15	37	1	1	
1976	43	24	43	6	2	
1980	51	34	47	10	4	2

[1]Data from Brown & Pal (1971), Georghiou (1981), World Health Organization (1976, 1980).

TABLE 7

Rate of Discovery and Development of New Broad-Spectrum Insecticides[1]

Years	Number Patented
1940-45	3
1945-50	6
1950-55	15
1955-60	19
1960-65	21
1965-70	17
1970-75	10
1975-80	8
1980-85	0

[1]From date of original patent (Merck Index 1983).

FIGURE 1

Action of DDT'ase in converting DDT to DDE, and relative toxicity of some "resistance proof" DDT analogues to susceptible (S) and DDT resistant (R) house flies. (Metcalf & Fukuto 1968).

Musca domestica

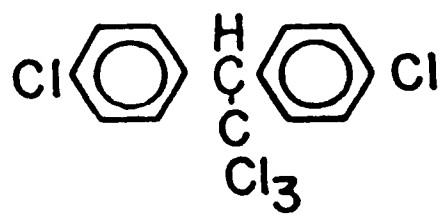
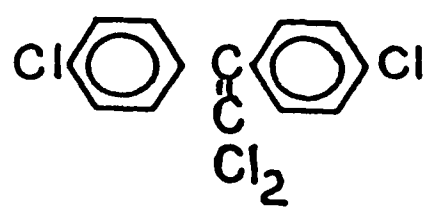
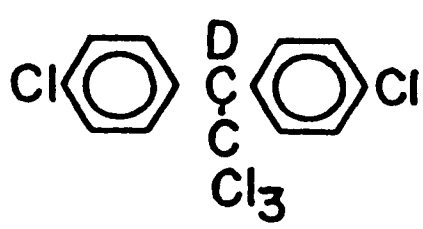
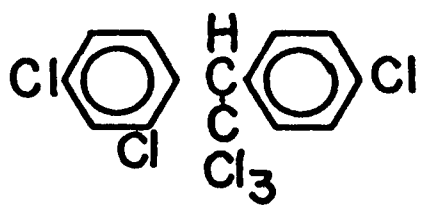
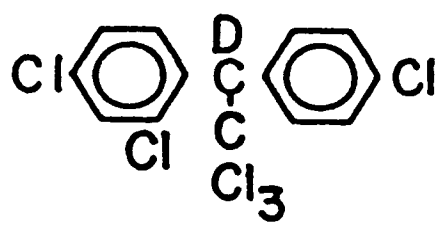
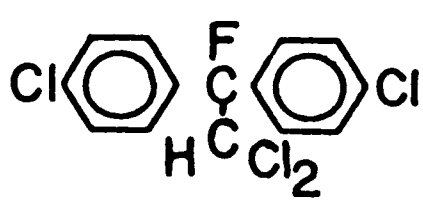
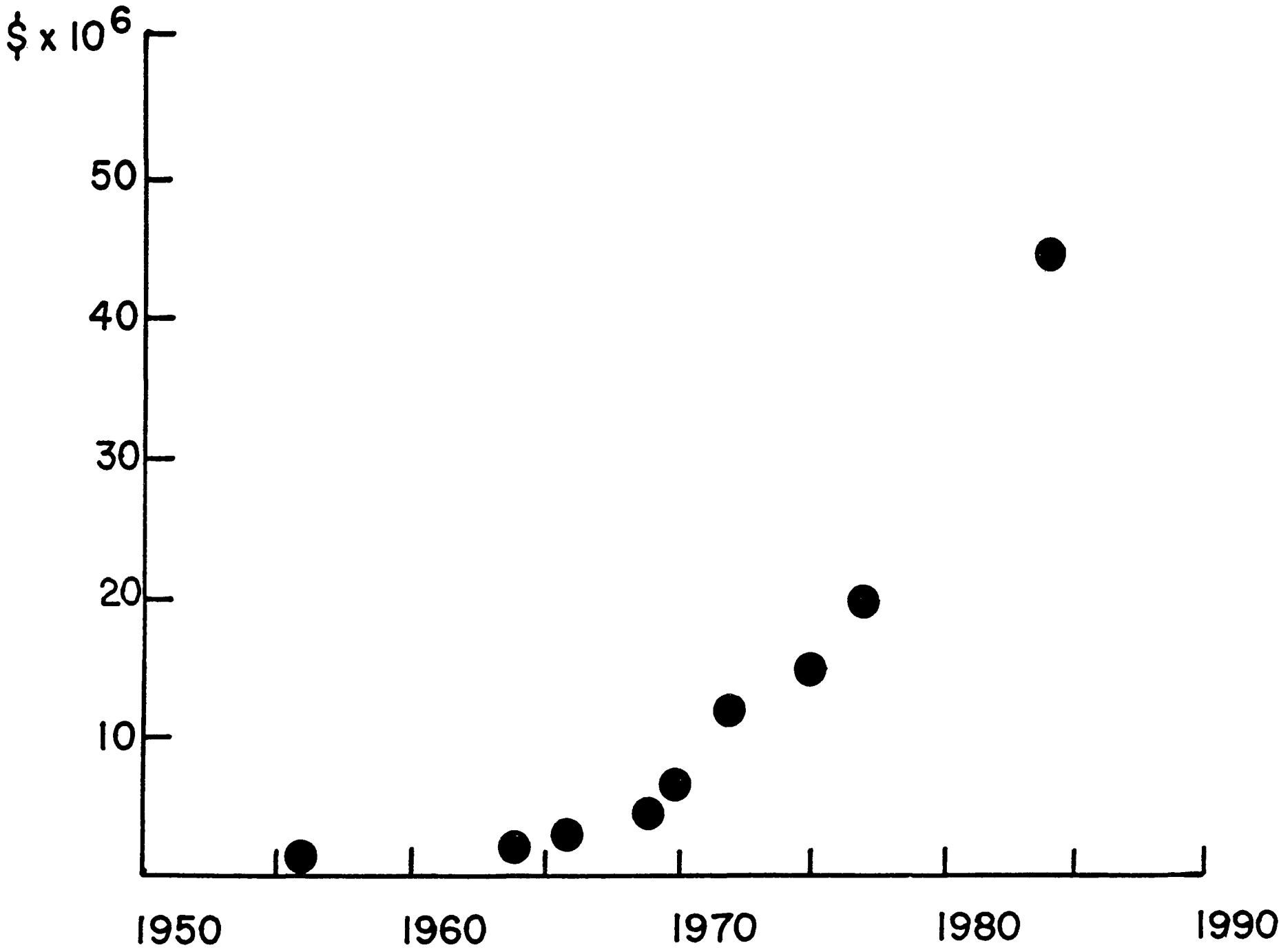
	LD_{50} µg per g	
	S	R
 *DDT*	2.0	>5000
 *DDE*		
	2.3	>500
	11.0	36
	9.5	22
	4.1	15.5

FIGURE 2

Increasing developmental costs for new pesticides. From Johnson & Blair (1972), Metcalf (1980), Menn (1980), and Storck (1984).



ECOLOGICAL SIDE EFFECTS OF PESTICIDE AND FERTILIZER USE ON TURFGRASS

Daniel A. Potter, Stephen D. Cockfield,
and
Terry Arnold Morris

Department of Entomology
University of Kentucky
Lexington, Kentucky 40546

Turfgrasses, which cover an estimated 8 to 10 million hectares in the United States (Kageyama 1982, Tashiro 1987), are typically the most intensively managed plantings in the urban landscape. Increasing public demand for dense, uniform, pest-free turf has resulted in a growing number of lawns, golf courses, and other turf areas being maintained with regular chemical applications (U.S. EPA 1979, National Research Council 1980, Anonymous 1984). Gross annual sales of the commercial lawn care industry increased at an average annual rate of 22% between 1977 and 1984, with ca. 13% of single-family households with incomes over $20,000 contracting for commercial lawn care in 1984 (Anonymous 1984). Total annual expenditures for turfgrass maintenance in the United States were estimated in 1983 to be about 15 billion dollars (Tashiro 1986), with much of this cost allocated to the purchase and application of insecticides, herbicides, fungicides, and fertilizers.

Pesticides and fertilizers are versatile and powerful tools of pest management, and there are many pest problems for which the use of chemicals currently provides the only practical solution (Metcalf 1975). However, use of chemicals may also have profound effects on the structure, stability, and resilience of agricultural systems (Pimentel and Edwards 1982). Because pesticides kill beneficial organisms as well as pests, their use may increase the risk of pest resurgences or secondary pest outbreaks (e.g. Luck and Dahlsten 1975, McClure 1977, Merritt et al 1983). Pesticides and fertilizers may also affect energy flow and nutrient recycling by altering primary production or by disrupting the activity of organisms important to decomposition processes (Edwards and Thompson 1973, Pimentel and Edwards 1982).

Like many cultivated crops, turfgrass lacks the complexity of natural grassland and forest systems, and so would be expected to be relatively susceptible to pesticide-induced perturbations. However, little information exists on the ecological side-effects of pesticide and fertilizer usage on turfgrass. The purpose of this chapter is to summarize recent research which has begun to clarify the effects of common turf management practices on populations of potentially beneficial invertebrates in turfgrass, and how this in turn may affect key processes such as thatch decomposition and natural regulation of pest populations.

THE TURFGRASS ECOSYSTEM

Turfgrass consists of the roots, stems, and leaves of grass plants, together with a tightly intermingled layer of dead and living roots, rhizomes, stolens, and organic debris commonly referred to as thatch (Beard 1973). This composite habitat supports a variety of plant-feeding insects and mites which inhabit the soil, thatch, and/or above-ground portions of the grass plants. These include a number of familiar pest species that cause injury by consuming roots (e.g., scarabaeid grubs; billbugs), devouring grass blades and stems (e.g., sod webworms, cutworms, armyworms) or by feeding upon plant sap and damaging vascular tissues (e.g., chinch bugs, greenbug, winter grain mite). Biology and host plant relationships of turfgrass insect pests were reviewed by Tashiro (1987).

Turfgrass also supports a diverse community of non-pest invertebrates. In one survey (Streu 1973), 11 taxa of nematodes, 83 arthropod taxa including numerous families of insects and mites, and numerous kinds of annelids, gastropods, and other invertebrates were collected from a bluegrass-red fescue turf in New Jersey. Pitfall trap surveys and Tullgren funnel extractions revealed a similarly rich fauna of free-living predators and soil and thatch inhabiting species from turfgrass areas in Kentucky. More than 40 species of Staphylinidae (rove beetles), 30 species of Carabidae (ground beetles), 10 species of Formicidae (ants), dozens of species of spiders and other predaceous arthropods, and large numbers of nematodes, earthworms, Collembola (springtails), oribatid mites, and other soil invertebrates have been collected from untreated Kentucky bluegrass and tall fescue turf (Cockfield and Potter 1984, 1985, Potter et al. 1985, Arnold and Potter 1987). These pest and non-pest invertebrates form a complex community which interacts with the living grass, thatch, and soil and contributes to the stability of the turfgrass habitat.

PESTICIDE EFFECTS ON NATURAL REGULATION OF PEST POPULATIONS

Pesticides that are applied for control of turfgrass pests are generally also toxic to predators and parasites. For example, a single, surface application of the organophosphate insecticides chlorpyrifos or isofenphos reduced populations of predatory mites, spiders, and insects in Kentucky bluegrass by as much as 60% (Cockfield and Potter 1983). Predator populations were still depressed more than six weeks after the application (Fig. 1). Given their sensitivity to insecticides, it is not surprising that predatory arthropods were found to be less abundant and less diverse in high maintenance Kentucky bluegrass sites (i.e., turfgrass that received scheduled applications of fertilizers and pesticides) than in sites that had been maintained without chemical applications (Cockfield and Potter 1985, Arnold and Potter 1987) (Table 1). Similarly, spider and ground beetle populations were found to be 20-30% lower in lawns receiving preventative insecticide treatments in Florida (Short et al. 1981).

Several authors (Streu and Cruz 1972, Streu and Gingrich 1972, Reinert 1978, Cockfield and Potter 1984) have cautioned that repeated pesticide treatments could reduce the stability of turfgrass communities and lead to increased pest problems. Nevertheless, documentation of pest resurgences or secondary pest outbreaks in turfgrass is somewhat limited. Reinert (1978) observed that southern chinch bug (Blissus insularis Barber) populations in Florida remained low in untreated St. Augustine grass lawns where predators and an egg parasite were abundant, while at the same time reaching outbreak densities on lawns that received repeated insecticidal treatments. Similarly, resurgence of hairy chinch bug populations following several years of chlordane treatment were attributed to reduced populations of predatory mites (Streu and Vasvary 1966, Streu 1969, Streu

and Cruz 1972), and possibly predatory hemipterans (Streu 1973). In New Jersey, carbaryl treatments over several years were accompanied by outbreaks of winter grain mite (Penthaleus major (Duges)) (Streu and Gingrich 1972). These authors suggested that carbaryl may have reduced populations of mite predators. In Kentucky, outbreaks of the greenbug (Schizaphis graminum (Rhondani)) appear to be more common on high maintenance lawns than on untreated turf (Potter 1982).

Short lists of natural enemies associated with various turfgrass pests have been published (e.g., Bohart 1947, Streu and Cruz 1972, Streu and Gingrich 1972, Tashiro 1973, Reinert 1978, Cockfield and Potter 1984). Nevertheless, the experimental evidence that predators or parasites are important in regulating pest densities in turfgrass is very limited. Reinert (1978) observed egg parasitism and predation upon southern chinch bugs in laboratory trials and in the field. He suggested that the combined predator-parasite complex may have contributed, at least in part, to an observed collapse in chinch bug populations in late summer. Cockfield and Potter (1984) collected sod webworm (Crambus and Pediasia spp.) eggs from field-collected females and exposed them to natural predation in Kentucky bluegrass. Predators, primarily ants, consumed or carried off up to 75% of the eggs within 48 hours. Treatment of half of the plots with a single surface application of chlorpyrifos to kill sod webworm larvae significantly reduced predator- induced mortality of the eggs for at least three weeks (Table 2), while simultaneously reducing the numbers of predators moving through the turf. To date, this study is the only experimental demonstration that natural enemies may be important in reducing pest populations in turfgrass, and that this process can be disrupted by pesticide applications.

THATCH ACCUMULATION AND DECOMPOSITION

The Greek philosopher and scientist Aristotle called earthworms "the intestines of the earth". Indeed, earthworms and other soil- inhabiting invertebrates including nematodes, millipedes, oribatid mites (Acari: Cryptostigmata), Diplura and Collembola are known to play a major role in plant litter decomposition and nutrient recycling in forest and pasture soils. These animals aid the decomposition process by fragmenting and conditioning plant debris in their guts before further breakdown by microorganisms (Lofty 1974, Harding and Stuttard 1974, Wallwork 1983). They also disseminate bacteria and fungi, enrich the soil with their excreta, and help to distribute organic matter throughout the topsoil layer (Satchell 1967, Lofty 1974). Plant litter decomposition is generally much faster with the combined influence of soil animals and microorganisms than with microorganisms alone (Ghilarov 1963). The burrowing action of earthworms and other soil invertebrates is also critical to air and water infiltration in turfgrass. Charles Darwin, considered an early authority on earthworms, wrote: "The plough is one of the most ancient and most valuable of man's inventions; but long before he existed, the land was in fact ploughed, and still continues to be thus ploughed by earth-worms" (Darwin 1907). This process is especially important in lawns, golf course fairways, and other turf areas which are "cultivated" mainly as a result of earthworm activity.

Excessive thatch results from an imbalance between vegetative production and decomposition at the soil surface (Beard 1973). Problems associated with thatch accumulation include restricted penetration of fertilizers (Cornman 1952, Nelson et al. 1980), binding of insecticides (Niemczyk et al. 1977, Niemczyk 1987), reduced water infiltration (Taylor and Blake 1982), and shallow root growth, with increased vulnerability to heat and drought stress (Beard 1973). Kentucky bluegrass lawns maintained with multiple applications of pesticides and high rates of fertilizer often develop

a thatch problem within 4 to 5 years (Engel and Alderfer 1967, Meinhold et al 1973, Shoulders and Hall 1983).

Excessive fertilization encourages thatch accumulation by increasing vegetative production, but may also indirectly contribute to the problem by affecting decomposition processes. Nitrogen fertilization commonly results in soil acidification (Pierre 1928) which may in turn inhibit microbial activity (Starkey 1953, Martin and Beard 1975, Bridges 1983). Furthermore, the repellent nature of NH4+ can reduce numbers of soil invertebrates, including microarthropods and nematodes, and earthworms (Marshall 1977, Edwards and Lofty 1977). Earthworms, in particular, are generally sparse in acidic pasture and forest soils (Satchell 1977, Edwards and Lofty 1977). Several studies (Starkey 1953, Engel and Alderfer 1967, Meinhold et al. 1973, Smith 1978, Potter et al. 1985) have indicated correlation between high rates of fertilization and thatch accumulation, although this may not always occur (Shearman et al. 1980). Potter et al. (1985) sampled earthworm and microarthropod populations in Kentucky bluegrass plots that had received varying rates of ammonium nitrate fertilizer (0 to 25 g N m-2) for seven years. Increasing the rate of fertilization resulted in a significant decrease in soil and thatch pH and in exchangeable Ca and K, and caused a significant increase in thatch. These changes were accompanied by a significant (33 to 66%) reduction in populations of earthworms and certain oribatid mites. Although thatch thickness was correlated with decreased earthworm density and biomass, it is probable that other factors such as increased plant growth and reduced microbial degradation also contributed to the relationship.

Use of pesticides can also contribute to thatch development. For example, treatment with certain fungicides may reduce soil pH, which can in turn impair the activity of microorganisms important to thatch degradation (Smiley and Craven 1978). Alternatively, fungicides may increase rates of root and rhizome production, further contributing to thatch accumulation (Smiley et al. 1985). Several investigators (Randell et al. 1972, Streu 1973, Turgeon et al. 1975) have reported correlation between increased thatch and reduction in earthworm populations following treatment with certain insecticides or herbicides. Many pesticides commonly applied to turfgrass, including benomyl, ethoprop, carbaryl, bendiocarb, and others, are toxic to earthworms (Ruppel and Laughlin 1977, Karnok 1980, Roberts and Dorough 1984, Potter, unpublished data).

It is generally observed that thatch is rarely excessive where earthworms are abundant, but until recently, the evidence that earthworms are important to thatch degradation has been largely correlative. If earthworms and other soil invertebrates are in fact critical to thatch degradation, then careful consideration should be given to any cultural practice that might reduce their activity. Experiments currently in progress (Potter and Powell, unpublished data) appear to verify the contribution of earthworms to thatch degradation in turf. Several hundred pre-weighed pieces of intact Kentucky bluegrass thatch (8 x 10 cm; ca. 18 mm thick) were sewn into nylon mesh bags having different sized openings (50 m, 1.2 mm, or 5 mm), and buried just under the surface of a Kentucky bluegrass turf. The small, medium, and large mesh sizes were intended, respectively, to exclude all decomposers except microorganisms, to selectively exclude earthworms while admitting smaller invertebrates, such as mites, or to admit all components of the soil fauna, including earthworms. In a companion experiment, thatch pieces in identical large mesh bags were buried in untreated plots, or in plots that had been treated with chlordane and carbofuran to eliminate earthworms. Thatch pieces from each experiment were disinterred every 3-4 months to compare rates of decomposition in the presence or absence of soil invertebrates. Pieces were re-weighed, analyzed for microbial activity and soil content, and extracted in Tullgren funnels to determine the invertebrate species present. Dramatic differences were apparent in both experiments after only 3 months. Without earthworms the structure and composition of the thatch remained nearly unchanged; however, the pieces were broken apart and dispersed when earthworms were present. The most striking effect of earthworm activity was a significant increase in the amount of soil

incorporated into the thatch (Fig. 2). The effect of this natural process is very similar to that achieved by core cultivation, a process by which soil is mechanically reincorporated back into the thatch layer, and which is considered the best method of managing thatch (Beard 1973, Danneberger 1982). Rates of microbial respiration and loss of organic matter were found to be much greater for thatch pieces that had been "worked" by earthworms than for those from which earthworms had been physically or chemically excluded. Details of these experiments will be reported elsewhere.

ADDITIONAL CONSIDERATIONS

Two other problems that may be encouraged by repeated pesticide usage in turfgrass are acquired resistance of pests to insecticides or fungicides, and enhanced microbial degradation of pesticide residues. Acquired resistance can become a problem when insecticides are applied repeatedly over a number of years. Acquired resistance has been documented for a number of turfgrass pests, including webworms, chinch bugs, billbugs, greenbugs, and several species of white grubs (Tashiro 1982, 1987; Reinert 1982). Judicious use of insecticides, and alternation of treatments with materials from different chemical classes (e.g., organophosphate followed by carbamate) will help to prevent or delay this phenomenon.

Enhanced microbial degradation occurs when pesticide residues are degraded more rapidly than usual by microorganisms. Enhanced biodegradation apparently occurs as a result of microorganisms becoming adapted to a pesticide to the point of being able to use it as an energy source (Forrest et al. 1981). This phenomenon has been documented in soil for several insecticides, including diazinon, carbofuran, fensulfothion, and isofenphos.

Recent experiments (Niemczyk and Chapman 1987) indicate that this alarming pattern may also occur in turf. When isofenphos was applied to golf course fairways that had a history of isofenphos treatments, more than 90% of the insecticide degraded within three days. In contrast, there was practically no degradation in previously untreated fairways. Enhanced microbial degradation of isofenphos residues in thatch appears to be the cause of at least some reported cases of poor residual control of white grubs (Niemczyk and Chapman 1987). Even more disturbing is the report that other insecticides, including diazinon, chlorpyrifos, carbaryl, and isazophos were rapidly degraded when applied to turfgrass that had been previously treated with isofenphos (Niemczyk and Filary 1987).

We choose not to here enter the debate concerning the potential acute and long-term chronic effects of pesticide exposure to humans, pets, and wildlife, or the fate of pesticide residues in the urban environment, as these are complex biological, social, and political issues that have been reviewed elsewhere (McEwen and Stephenson 1979, National Research Council 1980, McEwen and Madder 1986).

CONCLUSIONS

The intent of this chapter is not to support or condemn pesticide use on turfgrass. Rather, our goal has been to review some of the ways that chemical applications can affect interactions among turf- inhabiting invertebrates, and to speculate on how these changes may alter the stability and resilience of the turfgrass ecosystem. There are clearly certain situations in which the use of pesticides is essential to the maintenance of quality turf. However, like human medicines, pesticide applications can have some adverse side-effects, and these must be weighed against the overall benefits that the treatment provides. The available evidence suggests that turfgrass is a complex system with many buffers. However, we are only beginning to understand the roles of microorganisms, earthworms, predators, and other invertebrates in maintaining this natural balance. It does appear that pesticide or fertilizer applications can sometimes aggravate thatch or pest problems by interfering with the activities of beneficial organisms, or by encouraging the development of acquired resistance or enhanced microbial degradation. Awareness of these potential side-effects, together with additional research on basic interactions within the turfgrass ecosystem may facilitate development of more effective and more environmentally-sound turfgrass management programs.

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FIGURE 1

Impact of four turfgrass insecticides on spider populations in Kentucky bluegrass, based on relative numbers captured in pitfall traps in treated and control plots. Replicated plots were treated with surface sprays at label rates in late May. Similar reductions occurred for other taxa of predaceous arthropods, although not all groups were equally affected. Reproduced with permission from Cockfield and Potter (1983).

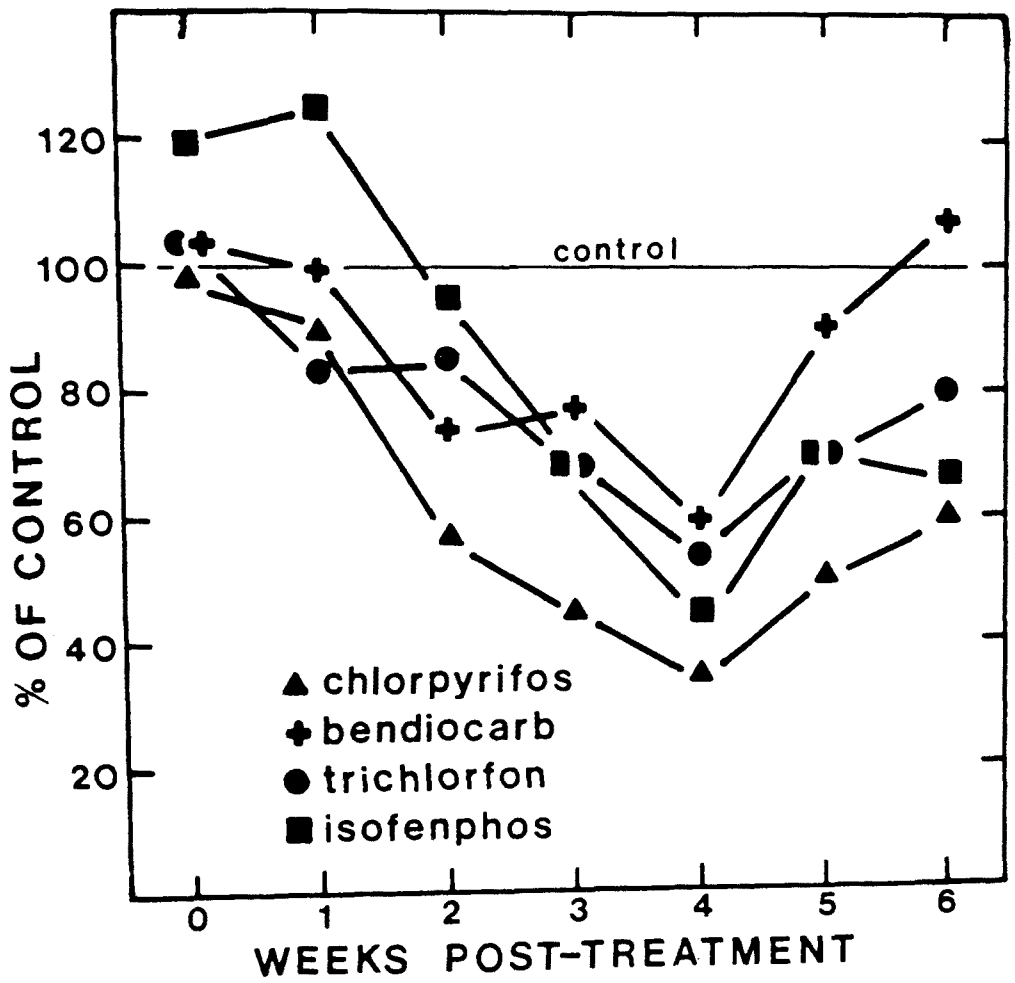

FIGURE 2

Change in the mineral content of thatch pieces buried under Kentucky bluegrass turf for 12 months. Samples depicted in upper graph had been buried in mesh bags having different sized openings to selectively admit or exclude certain components of the soil fauna (see text). Samples in lower graph were buried in identical large mesh bags in plots that were either untreated, or that had been treated with pesticides to eliminate earthworms. Data represent percentage of final sample weight remaining after incineration, and reflect mainly differences in the amount of soil incorporated into the samples by earthworms.

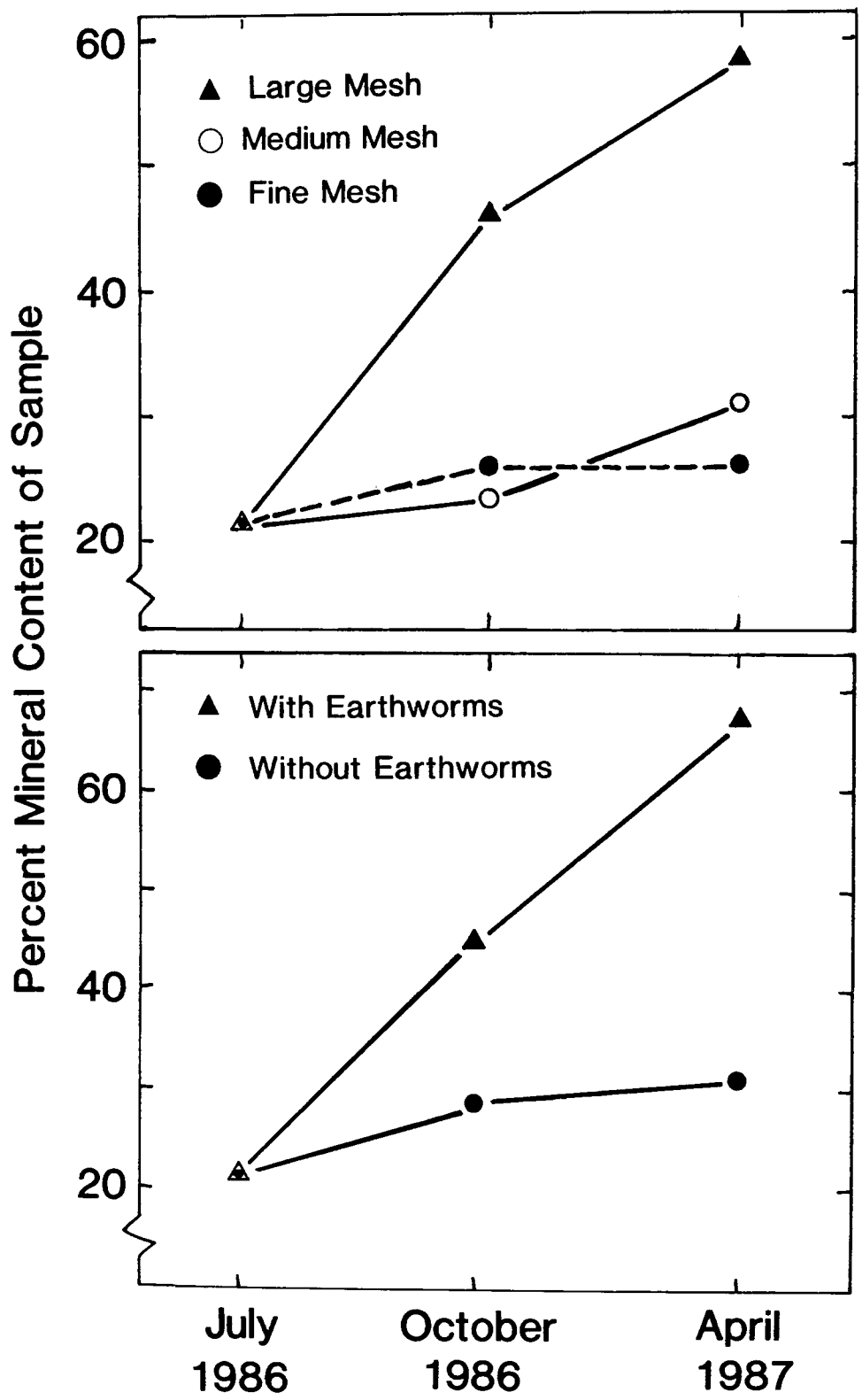

TABLE 1

Relative number of predatory arthropods captured in pitfall traps at Kentucky bluegrass sites maintained under a commercial lawn care program ("high maintenance") or under minimal care ("low maintenance"). Data are based on seasonal captures (22 March - 18 October) from 4 institutional lawns (1-4 ha each) of each type in Lexington, Kentucky. Adapted from Cockfield and Potter (1985).

Taxon	Mean number trapped per site: High Maintenance	Low Maintenance
Coleoptera		
Carabidae	24.8*	200.3
Staphylinidae	774.0	1172.5
Araneida		
Lycosidae	29.3	38.8
Erigonidae	394.0*	1017.8
Linyphiidae	60.3*	183.0

*Significantly lower than corresponding mean ($P < 0.05$).

TABLE 2

Mean percentage of sod webworm eggs eaten or carried off by predators in replicated plots of untreated Kentucky bluegrass compared to plots that had received a single surface application of chlorpyrifos at label rate. Based on cohorts of 500 total eggs placed in the field for 48 h at 1, 3, or 5 weeks after the insecticide treatment. Reprinted with permission from Cockfield and Potter (1984).

Weeks post-treatment	Percent missing from Untreated plots	Percent missing from Treated plots	P level[a]
1	37.7	0.9	$P < 0.001$
3	17.6	0.1	$P < 0.05$
5	75.4	61.3	$P < 0.08$

[a]Probability of a greater t statistic, one-sided paired t test.

CURRENT AND FUTURE REGULATORY CONCERNS FOR LAWN CARE OPERATORS

James F. Wilkinson, Ph.D.
Director of Regulatory and Environmental Affairs
Professional Lawn Care Association of America
101 Buena Vista Drive
North Kingston, RI 02852

Pesticide applicators, particularly those applying pesticides in the urban environment, such as lawn care operators (LCO's), today are confronted with a rapidly changing (and often adverse) environment. Public perception of pesticides and pesticide applicators is at an all time low. Federal, state and local regulation of pesticides increases almost daily. Environmental concerns from ground water contamination to endangered species will continue to generate regulations to be imposed on applicators for many years to come. And the non-agricultural user of pesticides, those applicators using pesticides in the urban setting (lawns, trees) or for vegetation management (utilities, rights-of-way) will face even stiffer rules and regulations. These uses have a perceived lack of "benefits".In addition, there is often the belief pesticides are not needed in the urban setting.

This paper first will present legislative and regulatory concerns for the LCO both today and in the future. The Professional Lawn Care Association of America (PLCAA) is currently involved with most of these issues since the issues will undoubtedly have a major impact on the way in which pesticides are used (or not used) in the future. Safety, health, certification and training issues will all play an increasing role and require increased attention from the LCO.

Next, the paper will review the need for LCO's to begin to help formulate reasoned pesticide public policy. This will involve cooperation with other pesticide applicator groups, decision makers (legislators and regulators), and environmental activists. LCO's will need to further incorporate IPM and other techniques into their operations to reduce pesticide use and use pesticides more safely. Otherwise, future regulations may jeopardize the very existence of the lawn care industry itself.

PERCEPTION OF PESTICIDES/MEDIA ATTENTION

The American public's perception of pesticides and toxic chemicals today, created generally by the media, environmental groups and a few, but highly effective antipesticide activists, is at an all time low. Here are the subjects of just a few of the stories which the public hears almost on a daily basis:

- pesticide residues on food
- groundwater contamination
- farm workers exposed to pesticides
- death of Navy Lt. Prior after playing golf
- 2,4-D, cancer and Kansas farmers
- data gaps, chronic effects of pesticides unknown
- allergies/sensitivities to pesticides
- dioxins, agent orange, Love Canal

It's no wonder that the public is concerned and feels the way it does about pesticides after a steady diet of such stories. These stories, especially when highly publicized by environmental groups such as the National Coalition Against the Misuse of Pesticides, Sierra Club, Audubon Society, National Wildlife Federation, and Environmental Defense Fund, strike a nerve with the public. Concern over pesticide use is heightened when pesticides are being used right in their own back yards for lawn care.

All of this has created a number of broadly defined issues facing the pesticide user industry in general, and the LCO in particular. These begin with the public demanding their right-to-know more about pesticide use and health and safety, and could end up with serious impairments to the way LCO's currently conduct their business.

RIGHT-TO-KNOW

The public's right-to-know has become an important issue among anti-pesticide groups and government officials. Communication of this right-to-know is taking many different forms as the issue arises in various locations around the country.

Prenotification of pesticide applications has been proposed in many areas and has already been adopted in some localities. Proposals often include notification of not only the LCO's customers, but neighbors as well. LCO's are strongly opposed to notification of everyone in the immediate areas of an application. They believe it is unjustified, and that it would add tremendously to their cost of doing business.

Some states (RI, MA, MD, NY) have adopted regulations requiring prenotification of lawn and tree pesticide applications as requested by customers and neighbors. This system seems to be working well, since only a small minority of people actually request prenotification so that it is not overly burdensome to the LCO.

Posting after lawn and tree care applications is required in at least half a dozen states, and more are sure to follow. In this case, strong industry input into the drafting of the regulations has so far led to the use of signs only at the time of application (as opposed to before the application). Many groups are in favor of "pre"posting (putting up signs one to two days before the application), and should this type of posting become law, applicator costs will significantly increase.

Central registries of pesticide sensitive or allergic individuals are gaining favor in some areas. Pennsylvania and Maryland, as well as some local communities, have established registries for individuals with medical evidence of an allergy or sensitivity to pesticides. The names of individuals on the registry are then shared with applicators to allow them to prenotify allergic individuals of impending applications. Industry's reaction to this system has been positive, with a high degree of compliance by individual companies. The actual number of people placing their names on the registry has thus far been low.

Health and safety information is frequently required to be passed along to customers, and this trend is expected to continue in more states. This information generally involves post application safety precautions, but in some cases labels and MSDS's must be made available.

The newly passed federal Community Right-to-Know Law will also require certain pesticide applicators to provide material information to local fire departments and other emergency personnel.

Local jurisdiction over pesticides is often an issue which arises out of local right-to-know concerns. Federal legislation as well as legislation in many states often prohibits political entities below the state level from regulating the use of pesticides. Numerous applicator alliances have

challenged the right of local governments to regulate pesticides (Wauconda, IL; Prince Georges County, MD), and in most cases courts have upheld the right of only the federal and state government to regulate pesticides. With over 88,000 political entities below state level in the U.S., LCO's clearly have a concern over the chaos which would be created if local governments were given authority to regulate pesticides.

PUBLIC HEALTH AND SAFETY

Public concern over the health effects of exposure to pesticides will continue to generate future regulations. Chronic risks from low levels of long term exposure, particularly in food residues and drinking water are a major concern. Dislodgeable residues resulting in potential human exposure to pesticides after lawn care applications is receiving considerable attention and has been one justification for requiring lawn care posting.

A recent GAO report alleging inadequate EPA testing of most pesticides will surely speed up the federal reregistration of many pesticides to bring them up to current registration standards. At the same time, some states have lost confidence in the EPA's ability to adequately regulate pesticides and protect the public. Thus, some states (CA, MA) will begin to require their own registration data. Both of these developments will surely lead to higher pesticide costs and product loss as manufacturers conclude that the economics of a product simply does not justify continued registration.

The public also is increasingly hearing the question of risk/benefit analysis on pesticides used non-agriculturally. Why, some ask, take any risk whatsoever simply to have a green lawn or to control vegetation that could be controlled mechanically? Non-agricultural users of pesticides have not done a good job of communicating the benefits of pesticides.

EMPLOYEE HEALTH AND SAFETY

The health and safety of applicators regularly using pesticides is receiving increasing attention. Proposed and enacted legislation and regulation in this area alone will add huge costs to LCO operations in the future. Consider the following examples:

- OSHA'S Hazard Communication Standard requiring health and safety information to be shared with employees;
- a newly proposed EPA worker protection standard requiring health monitoring and extensive personal protection equipment;
- strengthened certification and training requirements in most states and the adoption of federal minimum standards for certification and training;
- a narrowly defeated Senate bill which would have required extensive monitoring of the health of employees occupationally exposed to toxic chemicals;
- a newly implemented regulation requiring drivers carrying hazardous substances to carry commercial driver's licenses;
- proposed changes in pesticide labeling which should make them more readable for applicators, yet create labels which will contain more detailed information than ever.

Employee health issues will undoubtedly increase the cost of doing business, and at the same time make it increasingly difficult to find and train employees in an increasingly tight labor market.

ENVIRONMENTAL CONCERNS

Numerous concerns for the environment will place further scrutiny on all pesticide applicators, not just LCO's. Concern for the impact of pesticides on endangered species is leading to areas where specific pesticides simply will not be allowed. Wildlife concerns have recently led to the banning of diazinon on golf courses and sod farms. Problems with disposal of pesticide containers and wastes (RCRA, Superfund) have led to volumes of regulation.

The "granddaddy" environmental concern for the next decade, however, is groundwater contamination. As the EPA concludes its current survey of wells around the country, and more trace amounts of pesticides are found in wells, more and more public misunderstanding, fear, regulation and product loss and restriction are bound to impact pesticide applicators. LCO's can expect to encounter more questions and concerns about their use of pesticides around public and private sources of drinking water.

LEGAL ISSUES

Several legal issues are currently being debated as well. While some of these wouldn't seem to have an immediate impact on the LCO, their long term impacts could be immense:

- The 1988 amendments to FIFRA (FIFRA 88) significantly expand EPA's authority to regulate recall, storage, transportation, and disposal of pesticides. The Agency must exercise this authority by the study of all aspects of these issues, consultation with affected and interested parties, and issuing of requirements for storage, transportation, or disposal of a suspended or cancelled pesticide or its container, rinsates, or other materials which may be contaminated with such a pesticide. These findings must be submitted to Congress by December 1990. The new regulations will affect end users to the extent that they are subject to recall procedures. Details of reporting requirements will be announced in the Federal Register when they are developed.

- Under FIFRA 88 end users such as pesticide applicators will generally be indemnified against the costs of disposing of cancelled or suspended pesticides.

- Applicator liability on issues such as ground water contamination is another issue that was debated but not resolved in FIFRA 88. Farm groups are currently proposing that their members be exempt from liability should they be able to show they used a pesticide in accordance with all label directions. If this exemption is allowed, should it be extended to the non-agricultural user as well?

- Private right of action, or the ability of a citizen to bring suit against an applicator for pesticide misuse, another issue being debated, could change our thoughts on liability forever.

- Local regulation of pesticides continues to be debated at the federal level as well as within many states. Although applicators have won a few battles in the area, the war is far from over. All pesticide users should easily understand the chaos that would be created should the more than 88,000 local government entities in the United States be given the authority to regulate pesticides.

INDUSTRY/APPLICATOR RESPONSE

LCO's need to be more aware of the public's concerns over pesticides. Whether or not our use of pesticides creates a hazard is often not the issue. The issue sometimes becomes the fact that the public perceives a hazard! We must be willing to put ourselves in their shoes and imagine how we would feel if we believed pesticides were a threat.

Industry's response to many pesticide issues in the past has not been adequate. It is time industry becomes more proactive in terms of defending the legitimate and safe use of pesticides. The public must be made more aware of pesticides' benefits; regulators and extension people must be better educated on the professionalism which already exists within the lawn care industry; and all of us must work towards reasonable pesticide public policy. Increasing regulation is headed our way, and we must work hard to keep it reasonable.

The impact of lawn chemicals on ground water is a good example of where to start to educate decision makers and the media. Research underway at numerous universities is finding that lawn chemicals do NOT have the same potential to contaminate groundwater as pesticides applied agriculturally. It is important that decision makers understand this when developing groundwater protection strategies.

Alliances of pesticide users at the local, state and national levels need to be formed and to become actively involved in pesticide policy formation. A few state alliances, as well as the national Pesticide Public Policy Foundation, are already working toward this goal, but the job is immense and much more work is needed. The opposition, the anti-pesticide forces, are well organized and funded, and they network extremely well. Pesticide users need to rise up to face their challenge.

A major goal of the Pesticide Public Policy Foundation is to bring together an alliance of all national urban pesticide user groups (lawn, tree, pest control, landscape, golf, right-of-way) and to foster the formation and development of state-wide pesticide user alliances. Applicator alliances must be formed rapidly and in as many states as possible to allow applicators to be heard on the many important issues facing them today.

At the same time, LCO's need to do all they can to get their own house in order. Applicator training requires the highest priority, and operations must be run squeaky clean. Applicators also need to understand that they must adapt to many changes on the horizon such as IPM, new application equipment, and new products which will change forever the pesticide application business. LCO's definitely use less pesticide today than in the past, and this trend will continue.

The Professional Lawn Care Association of America is directing an increasing amount of its resources to regulatory and legislative concerns. PLCAA's goal is to protect the right of their members to apply pesticides safely, yet at the same time ensure adequate safeguards to protect employees, customers and the environment.

SOCIETAL PROBLEMS ASSOCIATED WITH PESTICIDE USE IN THE URBAN SECTOR

Anne R. Leslie
U.S. Environmental Protection Agency
Office of Pesticide Programs
Field Operations Division (H7506C)
401 M Street SW
Washington, DC 20460

The stage is set for spring in the Washington, D.C. metropolitan area. Rows of forsythia paint a golden backdrop to the ribbons of highway. The silhouettes of bare fruit tree branches glow with color and then disappear in soft clouds of pink or white blossoms. The birds and squirrels compete less for seeds around the feeder and more for each other's attention. Homeowners spend warm days pruning, raking, digging, planting and fertilizing, as they try to realize the fragile dream of a colorful flower garden framed by a deep green lawn.

Contained within these suburban gardens is a population of life forms which are indicted for their ability to interfere with the achievement of the dream. My neighbor's yard of wheat colored zoysia (whose golden color is prized in Japan) is punctuated with green clumps of wild garlic. This plant is not as obvious amid my lawn of mixed fescue and bluegrass, cool season grasses which green up earlier than zoysia or bermuda. Yesterday I dug some up to put in my salad as I pulled out unwanted honeysuckle that was moving from its firm foothold on an old wire fence to take over the yard, strangling a tree on the way.

In the lawn, a patch of bare earth piled up in mounds attests to activity of ants, and my neighbor worries at seeing a rat in his garage. The pest control company arrives to set out bait--the neighbor carries a contract with them to treat for termites, ants and roaches.

My yard has a patch of wild mustard, whose time of flowering is already past, and the seed heads float above the lawn. Henbit displays tiny purple flowers from a patch of soil the grass disdained to cover. Should we call a lawn care service, or visit the nursery or hardware store for some broad-leaf weed killer to clean up the lawn and get rid of these pests--or is there another way?

The appearance of all these life forms is part of the natural ecology. They have found a favorable niche to live in, and they are not concerned that it is the same niche we live in.

I would gladly pay for some sound advice on the alternatives for my half acre. Is a good lawn the best choice? Will the henbit and mustard retreat to form a meadow transition to the neighboring woods? I need to know what effort this will require.

What might I expect over a period of time if I just keep adding organic matter, adjusting the soil pH as needed, and overseeding with a grass variety that is adapted to my site? The beneficial spiders, earthworms and the bacteria in the grass thatch can then continue their roles in the system without the effects of pesticide. And if a damaging level of a pest such as the Japanese beetle appears, I might put my faith in introduction of their natural enemy, an entomophagous nematode.

Hand digging of unwanted plants may be enough to control a lot my size. But if my yard were larger, it would be prohibitively labor intensive. What if I let the grass grow to three inches instead of one and one-half? The dandelions will have their spring show and be choked out later by the healthy grass. Crabgrass is an annual. It has left its dead skeletons in patches where its seed can sprout anew. But I can tip the scales in favor of a chosen variety of grass that may grow vigorously and inhibit the crabgrass seedlings by shading them out.

The decisions I have to make are similar to those confronting many homeowners in the United States. Because some homeowners lack time to manage their own lawns and lack first-hand agronomic experience, choosing a lawn care service seems very attractive. Yet some sectors of society are objecting to the choices made by others, particularly when a contracted service impinges on a neighbor's property.

Problems Related to Pesticide Regulation

Environmental and citizen groups have collected information on pesticide use practices and combined that information with potential health and environmental hazards of individual pesticides. The public's concern over small amounts of chemicals in ground water is compounded by the lack of real data on long-term health effects of low level exposure. Detection is now better than ever because of the improved analytical methods developed by chemists in recent years. Testing for health effects lags far behind technically. It is an expensive and long-term project, and the regulatory process that requires and evaluates such studies is complicated and slow moving.

The federal government gives the states and local communities the ultimate responsibility to control the way registered pesticides are used. Local governments may decide to notify the public of pesticide use by posting areas being treated, and they draw up requirements for certification of applicators. However, there are limitations on what these controls can accomplish in the urban area, given the following facts:

- Most pesticides applied to home lawns are not restricted to use only by a certified applicator, and posting of private residences is not required.

- Large rural areas are being rapidly converted to urban land uses, which pose new problems that may require regulation. The regulatory agencies do not have the manpower for enforcement of proper pesticide use by private citizens.

- Turf is not considered an agricultural crop in some States, and, therefore, does not receive as much research funding to determine the effects of its management on the environment. However, it carries a definite economic value, which is used to justify the application of pesticides in its management, even though a dollar value for an aesthetic product is difficult to determine.

- The very real problem of resistance to pesticides is appearing in insects, as shown in the chapter by Metcalf; in weeds as detailed in a paper presented by LeBaron (ACS Symposium Series, in press, 1988), and in fungus as noted in the chapter by Dernoeden. Resistance buildup leads to use of increasing amounts of pesticide on turf, just as on agricultural crops.

Problems Related to Conflicts in Land Use

Conflict exists between people willing to pay for pesticides to achieve high quality turf on their lawns and people not wanting to have pesticides on their property, or even nearby. And conflicts exist over other kinds of land development.

Golf courses are a very visible expanse of highly managed turf. Projections of the increase in the golfing population by the National Golf Foundation (Golf Projections 2000, Golf Summit '86 Research Presentations, October, 1986) call for the opening of one new course per day until the year 2000. This represents a conservative 2% increase in this recreational land use. People who have experienced hypersensitivity to pesticides raise objections based on the potential for drift. Environmentalists fight the conversion of wilderness areas and impacts of land development on endangered species; cities blame the courses for pollution of their water supplies.

Studies on Water Pollution by Pesticides Used on Turf

For the most part, both sides argue from a minimal data base. Studies on groundwater pollution in natural watersheds, with one exception, have not been carried out. EPA's well water survey includes only agricultural land. The Cape Cod study carried out by EPA showed positive levels of nitrogen and traces of pesticides. No similar sampling studies have been run in less permeable soils than the sandy soil of the Cape. The studies by Gold and Sullivan, reported in chapter 13, include the most targeted and complete information we have seen to date on waterborne transfer of fertilizers on home lawns. Controlled studies on pesticides in runoff from turfgrass plots are reported by Welterlen in chapter 14. Studies by Watschke at Penn State University, Niemczyk at Ohio State University, and Petrovic at Cornell University substantiate the ability of thick turf to prevent or minimize pesticide transfer to water. These studies are cited in the above chapters.

More significantly, ground and surface water pollution from runoff of paved areas may be the largest urban source, since any chemical sprayed near or spilled on paving materials has great potential to be carried to the watershed. Although pesticides are not deliberately applied in these areas, they may arrive there carried by trucks, along with other chemicals such as gasoline, oil, dry cleaning fluids, disinfectants, and structural pesticides. In short, anything that is spilled during transport or accidental application. Many chemicals are not removed at most existing water treatment facilities.

Few published studies on water pollution via runoff from paved areas have been reported, although some companies are running determinations.

The greatest source of water pollution is application of chemicals to agricultural land. Concerns over contamination of groundwater by pesticides applied to turfgrass are usually based on the agricultural groundwater studies. Leaching through bare soil is much greater than through grass and thatch, as shown in the chapter by Welterlen. Agricultural use of pesticides and fertilizers is still much higher on a per acre basis than on golf courses, although limited areas of golf courses may use a higher rate. Agriculture employs restricted pesticides which are generally not used on urban turfgrass.

Direct Health Effects to Applicators and Residents

Pesticides registered for use on turfgrass and ornamentals carry labels indicating proper handling, protective clothing requirements and disposal instructions. These are based on studies required by EPA and carried out by the registrant. Restricted use pesticides are available only to

certified applicators, whether commercial or private. Certification is awarded on evidence that the applicator knows how to handle the material.

Although it is believed that current regulations adequately protect the applicator, such regulations may not protect a resident of the treated site. Because nonagricultural use of these pesticides has increased, EPA's Office of Pesticide Programs is re-examining current requirements for studies of dislodgeable residues. There is potential for exposure to residents "reentering" the lawn after treatment. These residents may include a highly vulnerable segment of the population--either directly, as with children playing on the lawn or indirectly with pets or applicator clothing coming into the household.

Landowners' Rights versus Society Benefits: Need for Land Use Planning

Health and environmental effects of turf pesticides are often cited in disputes over urban development. But the concerns have not always led to productive solutions. The societal issues are outside the scope of this book. However turfgrass managers who practice more sophisticated pesticide use through an IPM program will be making a positive step towards resolution.

Cities grappling with such issues need comparative data on the impact of all land development alternatives to decide on the land use of greatest benefit to society. All residents must keep in mind that urbanization is taking place regardless of individual preference, and wise planning needs to be done early to avoid the problems many cities now face.

Limitations of Pesticides and the Need for Realistic Goals

At the other end of the scale, homeowners are often led to expect they can obtain golf course quality turf solely through greater use of pesticides. And because they lack agronomic experience, they do not use cultural practices that can support reasonably high quality lawns. With increasing demands for perfect turf, the cost of chemical use and maintenance of a lawn escalates significantly.

Just as a cockroach inside the home incites much greater urge for chemical control than do most outdoor "bugs," a dandelion on a home lawn may incite a desire for pesticide use that would not be expressed for the same pest density in a park.

In a National Park Service project, stands of grass with different levels of weed infestation were to be evaluated by people to determine their perception of the grass quality. No satisfactory scale has yet been established.

Societal conflicts have evolved from urbanization of former agricultural land. Where development leads to increased pesticide use, land use planners need to consider long-term consequences. An IPM program can help greatly to reduce these potential consequences. Education of the public in basic agronomic practices and environmental fate of chemicals can contribute greatly to their intelligent decision-making for land use, management goals and conservation of resources. The remainder of this book is devoted to examining some of the best methods and putting them together in a concerted IPM program.

SECTION II

Benefits of an Integrated Pest Management Approach to Turfgrass and Ornamentals

URBAN INTEGRATED PEST MANAGEMENT EDUCATION AND IMPLEMENTATION: IMPLICATIONS FOR THE FUTURE

W. M. Brown, Jr.
and
W. Cranshaw
Colorado State University
Fort Collins, CO 80523
and
C. Rasmussen-Dykes
Jefferson County Cooperative Extension
Golden, CO 80401

Integrated pest management (IPM) programs are underway for many agricultural commodities. In contrast, few IPM programs are established in urban environments. The reasons for the lack of functional urban IPM programs vary, but two significant reasons emerge:

- the lack of technology and programs to address the wide variety of plants, cultural practices and pests encountered in the urban habitat;
- the lack of consistent research and development support for urban programs in pest management.

This is paradoxical, considering that in 1982 a national Extension Committee on Policy (ECOP) reported that 7.5% of the total pesticide used in the United States is used by homeowners. An additional 19.4% is used by urban government and industry (7). Thus, a total of almost 27% of the pesticides used in the United States are used in our densest population areas, and by predominantly untrained pesticide users. Concern over pesticide use has triggered right-to-know and pesticide posting ordinances in several communities in recent years. In Colorado, the city of Boulder recently voted to establish a pre- and post- pesticide posting ordinance covering lawn spraying. Frequently anti-pesticide advocates promote "IPM" as a blanket alternative to pesticide use without actually being fully aware of the lack of a research and implementation base in urban IPM. Therefore, a critical need exists for comprehensive national urban IPM education, research and program development. A pilot urban IPM educational and field program has been developed in Colorado and is described in the following pages.

DISEASE MANAGEMENT

Under good cultural practices, Colorado has few turf and ornamental disease problems. The problems encountered are frequently in stress situations resulting from unrealistic design, poor management, intensive use (i.e., golf courses with night watering and heavy traffic), home lawns with poor site preparation, high nitrogen and excessive pesticide applications or ornamentals planted in inappropriate sites.

An exception are the Pythium blight diseases caused by P. aphanidermatum, P. ultimum, P. myriotylum, and P. torulosum, all reported pathogens on turfgrass (15) that have been associated with disease outbreaks in Colorado (13,14).

Little work has been done on biological control of turf diseases. Trials using a known mycoparasite of Pythium spp., a benomyl tolerant mutant of Trichoderma harzianum (T95) (3,4,5) and a systemic fungicide specific for Pythiaceous fungi, metalaxyl, were carried out at Colorado State University and at field sites in Colorado. Tests were conducted on all the above Pythium spp. found associated with blighted turf in Colorado (13,14).

Each Pythium spp. was parasitized by T. harzianum in vitro in much the same manner as described by Chet et al. (6). Trichoderma hyphae coiled around Pythium hyphae and the latter collapsed (Fig. 1). Low concentrations (25-200 ppm) of metalaxyl significantly retarded mycelial growth of Pythium spp. (Fig. 2). Equal concentrations of metalaxyl did not affect mycelial growth and spore production of T. harzianum, although higher concentrations (275-2500 ppm) did (Figs. 3,4). Trichoderma spores produced on media at 750 ppm metalaxyl when streaked onto non-amended PDA media were viable.

Additional studies showed that other pesticides frequently used in turf disease management (benomyl, chloroneb, diazinon, Trimec, phenyl-mercuric acetate+thiram and iprodione) did not significantly affect the population of T. harzianum (Fig. 5)(13).

Work at Colorado State University by Ahmad and Baker (1) has demonstrated that rhizosphere competent mutants are more efficient in colonizing and subsequently protecting roots from infection. In addition to suppression of disease causing organisms, T95 also has demonstrated growth enhancement properties in bluegrass in the absence of known pathogenic organisms, Fig 6 (5,13,14,17). The mechanism responsible for growth enhancement by Trichoderma is not fully understood (17). The attraction of a biological control agent that is also compatible with fungicides and provides growth enhancement even in the absence of disease is exciting and more research must be initiated in this area.

A fluorescent pseudomonad, used as a biocontrol agent, was effective in control of take-all of Kentucky bluegrass, caused by Gaeumanoyces graminis. Figure 7 shows the effect on bluegrass growth in pots infested with the take-all fungus. Similar effects of fluorescent pseudomonads on wheat take-all organism, Gaumanomyces tritici have been reported by Baker, Cook and others (2, 18, 19).

While more work must be done to develop fully integrated Pythium blight or other turf disease control programs with combined chemical and biological components, the prospect is exciting. These components must now be field-tested using commercial turf management practices, and appropriate ways must be developed to deliver Trichoderma or other biocontrol organisms.

INSECT MANAGEMENT

Many of the insect and mite problems common in urban plantings in Colorado are unique to the region and have not been studied in depth. Lack of information on life history of these pests, their management and injury potential has significantly contributed to misunderstandings regarding appropriate controls and the damage assessments. This lack of information has resulted in excessive or inappropriate pesticide usage habits that are incompatible with IPM strategies. Consequently, a fundamental research effort at Colorado State University (C.S.U.) has been to improve our understanding of regional pest species biology and habits and to convey this information through Cooperative Extension outlets.

Concurrently, insect management research studies have been conducted to develop effective IPM technologies. Summaries of recent efforts and future needs are outlined below:

Turf.

Major emphasis has been to develop insect parasitic nematodes as biological control agents for thatch and soil infesting insect turf pests. White grubs in the genera Cyclocephala, Phyllophaga, and Polyphylla have been successfully controlled in our field trials at rates of control equivalent or sometimes superior to most standard insecticide treatments. In particular, the nematode genus Heterorhabditis (heliothidis, 'H.p. 88') has been effective in white grub control. Nematodes in the more commonly commercially available genera Neoaplectana (primarily N. carpocapsae) have been less effective for white grub control but have shown potential against other common turf pests such as sod webworms, cutworms, and billbugs (8).

Effectiveness of nematodes against soil insects has been shown by other researchers (8,16) to be influenced by factors such as soil type and moisture. In C.S.U. studies the importance of thatch as a barrier to nematode movement has been quantified. Of all the insect parasitic nematodes studied, only a small percentage of them (8-17%) were able to penetrate through a 1.5 cm thatch barrier layer. The ability of different strains and species to penetrate thatch varied; Heterorhabditis proved the species most inhibited by thatch. Trying to "flush"nematodes through thatch with varying water volumes was ineffective. It is obvious that thatch management will be important in effective use of insect parasitic nematodes as well as insecticides for soil insect control. Fortunately, insect parasitic nematodes do not adversely affect earthworms, the most important organisms involved in organic matter breakdown in turf. Impacts of nematodes on other non-target pest species are in progress.

Insect parasitic nematodes have also been screened for compatibility with various turfgrass management chemicals. Soaps and wetting agents appear fully compatible with nematode applications as are most fertilizers (16). Fungicides, with the notable exception of the mercurials, show no toxic effects to nematodes. However, mercurial fungicides are devastating to nematodes and prior use of these compounds may preclude adequate survival of insect parasitic nematodes at a turf site. Tested insecticides (11) show a range of effects on insect parasitic nematodes with the toxicity potential ranging chlorpyrifos, bendiocarb, carbaryl, diazinon. However, nematode species sensitivity to various compounds varies. For example chlorpyrifos is highly toxic to Heterorhabditis but only moderately toxic to Neoaplectana; carbaryl only showed toxic effects to Neoaplectana.

TABLE 1

Summarized results of white grub control with insect parasitic nematodes and Lawn Aerator Sandals in Colorado State University trials, 1986-1987.

Trial Location % Control	Target Pest	Treatment
Lamar, CO		
57	Phyllophage,	Diazinon 14G
55	Polyphylla	Lawn Aerator Sandals
48	H. heliothidis	
33	N. carpocapsae	
Pueblo, CO		
94	Cyclocephala	Oftanol 2
47	N. carpocapsae	
45	H. "H.P. 88"	
Grand Junction, CO		
0	Cyclocephala N. carpocapsae	

Simple cultural controls also appear to have potential in managing regional turf problems. A 1986 study evaluated the use of a spiked sandal, sold under the trade name "Lawn Aerator Sandal" for white grub control. Merely walking across plots with this product achieved a level of control (approximately 50%) comparable to that of the insecticide (diazinon) standard (Table 1). Other studies are demonstrating that adequate winter watering, a neglected turf maintenance procedure in the arid West, can greatly limit turf injury by clover mites and sod webworms.

Woody plants.

Spraying trees and shrubs has become a particularly visible and controversial use of insecticides in urban areas. Technologies to limit these treatments have proceeded along the following approaches.

Expanded trials developing the use of soil injected systemic insecticides was emphasized in 1987. These treatments involve the use of specialized equipment that rapidly injects the insecticides into the soil for subsequent root uptake, thus avoiding drift and many non-target problems. Oxydemetonmethyl (Metasystox-R) is fully labelled for this use and has shown promising levels of control against aphids, psyllids and mites (Table 2). Unfortunately control of leaf chewing insects (beetle larvae, tip moths, gall midges) with this product has been erratic. An alternative soil systemic treatment with great potential is dimethoate. Dimethoate is effective against a very wide spectrum of woody plant pests. Expanded use of this material is pending labelling developments.

TABLE 2

Summary of Colorado State University control trial results using soil applied systemic insecticides, 1984-1987.

Target Pest	Insecticide	Degree of Control
Honeylocust pod gall midge	Metasystox-R	Fair-Good
Honeylocust pod gall midge	DiSyston	Poor
Honeylocust spider mite	Metasystox-R	Excellent
Honeylocust plant bug	Metasystox-R	Poor
Honeylocust rust mite	Metasystox-R	Fair-Poor
Honeysuckle aphid	Metasystox-R	Excellent
	Cygon/Dimethoate	Excellent
Ash leaf curl aphid	Metasystox-R	Excellent
Pinyon spindle gall midge	Metasystox-R	Fair-Poor
	Cygon/Dimethoate	Excellent
Pinyon tip moth	Metasystox-R	Good
	Cygon/Dimethoate	Excellent
Hackberry nipple gall	Metasystox-R	Good
Hackberry bud gall	Metasystox-R	Poor
	Cygon/Dimethoate	Good
Elm leaf beetle	Metasystox-R	Poor

Various "soft"insecticide treatments also show potential for greatly expanded use in landscape plant care. Insecticidal soaps are routinely incorporated into CSU trials and have shown fair to good potential for control of spider mites, eriophyid mites, plant bugs, leafhoppers, and some aphids. More recently, interest has focused on the horticultural oils for summer foliage uses. These refined specialty oils appear to be greatly under-utilized at present. Researchers in other areas of the country have shown an exceptional level of effectiveness of these products against young scales and whiteflies in foliar applications. C.S.U. trials established efficacy against eriophyid mites and spider mites.

Elm leaf beetle treatment, the most common insecticide application made to trees in southern Colorado, demonstrates how several potential alternatives may be developed. Use of insecticide spot treatment to trunk bands was shown in 1984 studies to be highly effective at controlling larvae as they move to the tree base to pupate. A number of community spray programs have since successfully adopted area-wide trunk band applications with a dramatic reduction in insecticide usage and drift. In addition, new control products are in advanced development. The biological control Bacillus thuringiensis 'San Diego' shows activity against elm leaf beetle larvae and may be marketed in 1989. Summer spray oils also were effective in preliminary 1987 studies.

EDUCATION AND TRAINING

A major thrust of the Colorado urban IPM program is to expand information sources and delivery. This recognizes that lack of information on proper pest management methods leads to inappropriate pesticide use. Instruction in diagnosis, damage evaluation, timing of treatments, and effective pesticide alternatives can produce reductions in inappropriate preventive or "revenge" treatments. IPM education was especially given a high priority in the 1981 ECOP report on urban IPM (7). Additionally, increasing public awareness of ecological implications of pesticide use can promote more thoughtful considerations prior to and during urban pesticide applications.

Expanded IPM education is receiving major emphasis in the Colorado program. Colorado Cooperative Extension education activities are targeting three distinct audiences: turf and landscape maintenance professionals, homeowners, and youth.

Colorado State University IPM specialists carry on extensive workshops, field days and field experiment/demonstrations with parks and recreation, professional lawn care and golf course personnel. Over 1,000 turf professionals receive IPM training and updating each year. An additional 500-600 commercial landscapers, nurserymen, urban foresters and other urban pest management professionals also benefit from IPM training sessions. In addition to actual organized training, Colorado State entomologists and plant pathologists routinely offer informal on-site training through cooperative field trials, demonstrations, and visits.

A major emphasis has been made to update and develop new materials on regional urban insect management problems. In particular, publications outlining the proper use of insecticidal soaps, Bacillus thuringiensis, pheromones and spray oils for regional problems have been popular and distributed widely. Aides for identification of beneficial insect species and references in proper use of commercially available biological controls have also been well received.

For example, an atypical Extension publication drawing considerable interest from youth and adult audiences promotes "butterfly gardening". Implied in "butterfly gardening" is the careful use of pesticides, further assisting in improving pesticide use habits among urban audiences. By emphasizing and valuing an overlooked beneficial group of common insects this publication has directly assisted overall IPM efforts.

The Cooperative Extension Master Gardener program promotes appropriate IPM strategies for urban situations. Over 10,000 volunteer Master Gardeners have received IPM training and serve as Cooperative Extension paraprofessionals in Colorado urban communities (Fig. 8). For example, in 1986 in Boulder County, Master Gardeners fielded over 6,704 client queries. In Jefferson County (western Denver Metro area), 106 Master Gardener volunteers worked over 3,000 hours. Their impact in providing educational service to the wider community is outstanding (Table 3). Many of the Master Gardeners stay with the program and serve as volunteer leaders or in other, more advanced program capacities.

TABLE 3

Jefferson County* 1986 Master Gardener Accomplishments

Master Gardener's Trained/Used	106
Volunteer Hours Worked	3,000+
Plant Specimens Examined	1,082
Telephone Queries Answered	14,000+

* West Denver, CO, and adjacent foothill rural areas.

CSU IPM staff developed a special youth educational program, "THE BUG SHOW" using large insect and vegetable hand puppets (Fig 9). Use of large hand puppets have increased elementary school students attention and awareness (10). A pilot program consisting of a 15-minute skit followed by a question and answer period was begun in 1987. Advanced Master Gardeners (those who have received two or more years of in-depth Master Gardener training in horticulture and IPM) were trained as puppeteers. CSU Cooperative Extension staff and Master Gardeners have presented the pilot program to 350 youth (pre-school through third grade) in the Denver Metro area. This program gives youth an introduction to biology, biological control and pesticide safety. After the program, teachers and students use CSU prepared activity booklets as supplemental in-class or at-home study material. Under development is a follow-up video presenting selected information on biology, pesticide safety, and IPM; each teacher will be provided a copy for further class use and study.

Information dissemination systems using technical sheets, radio shows, weekly newsletters, and a special Cooperative Extension pre-recorded phone Teletips weekly Urban Pest Alert are all operational. The Teletips system uses three-minute pre-recorded tapes to provide current pest occurrence and management updates. Pest Alert tapes are updated weekly or more frequently if necessary.

FUTURE IMPLICATIONS

While there is a critical need for development and implementation of urban IPM, major problems exist.

There is very little plant pest research in urban IPM. Without a strong commodity support base, little financial support is available for urban IPM research. Minimal available funds are generally attached to chemical research. Thus, biological and cultural control approaches receive less attention.

There is a government trend to decrease Cooperative Extension in the cities. This is demonstrated in both federal budgets (i.e., Reagan Administration FY 87) and in many state budgets such as Colorado's 1987 and 1988, budgets in which decreases have specifically targeted urban programs. The critical nature of pest management education and research in urban IPM and its components must gain recognition, if environmentally sensitive urban programs are to be developed.

Present laws and confusion between various governmental agencies as to testing of biological control organisms in the environment must be clarified; provisions must be made for testing. Much

of the work to be accomplished in development of biological control is done and will be done by universities and public agencies. To date there is not enough public funding for this essential research and development.

CONCLUSION

Technology is available that can be adapted to urban IPM programs in turf and ornamentals. Much more is needed to provide a base for comprehensive urban IPM success. Without adequate funding, recognition and general education, successful implementation of IPM strategies to urban situations and the resultant use of pesticide alternatives will not be realized. This has long range, negative implications for both urban and farm populations.

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FIGURE 1

Trichoderma harzianum isolate T95 coiled around Pythium spp. showing the collapsed parasitized condition of the latter.

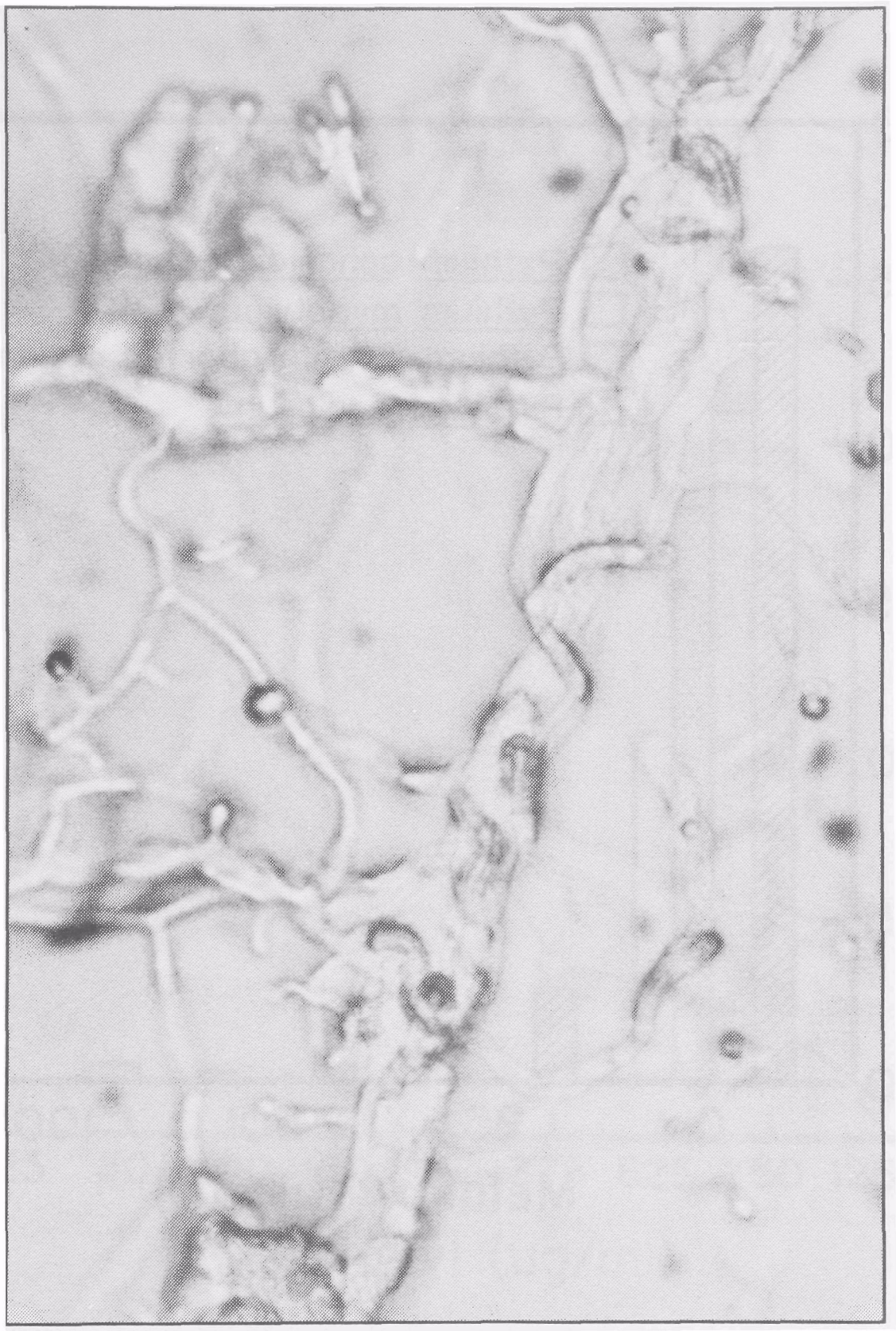
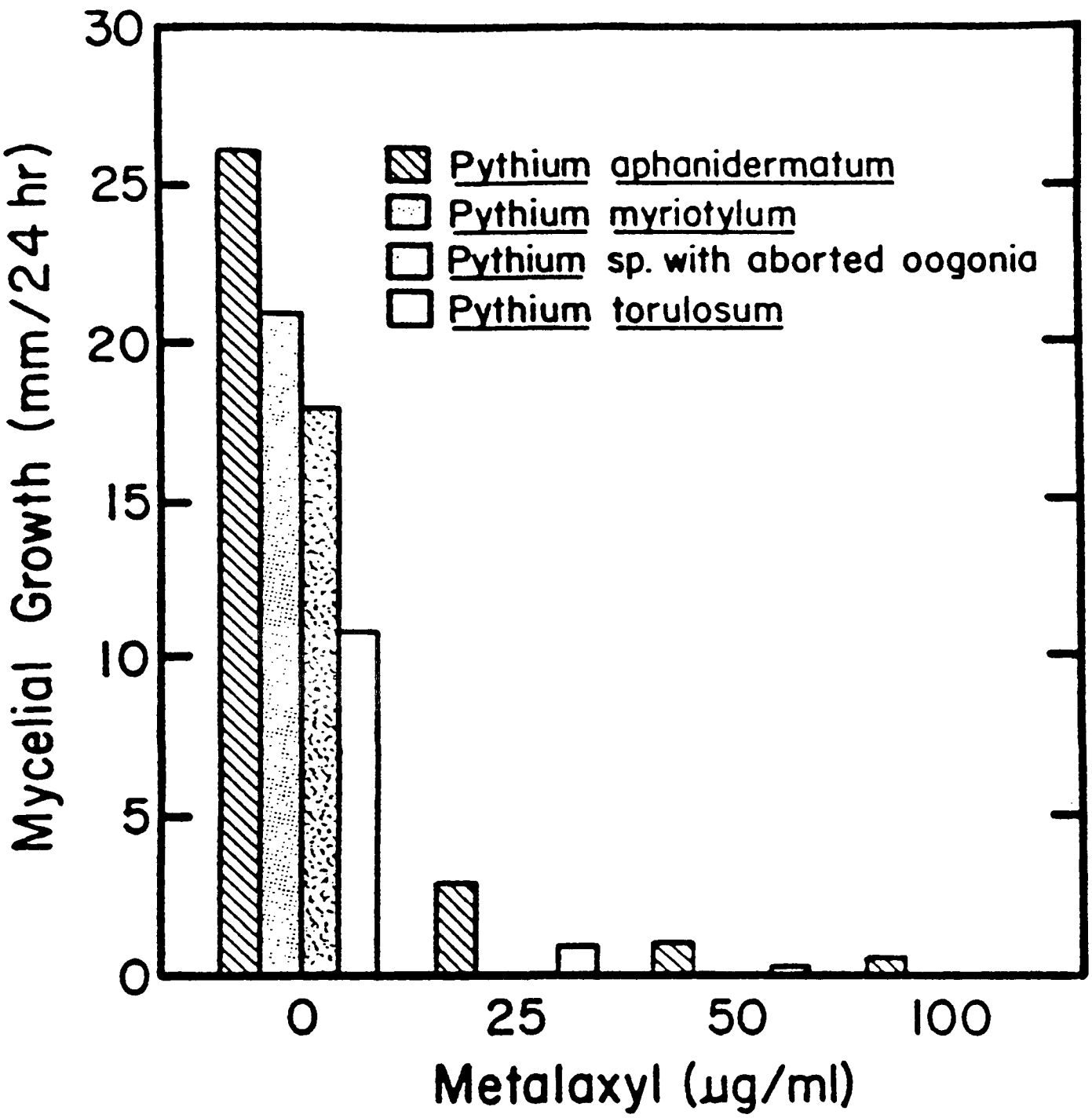


FIGURE 2

Effect of metalaxyl at varying concentrations on mycelial growth of Pythium spp.



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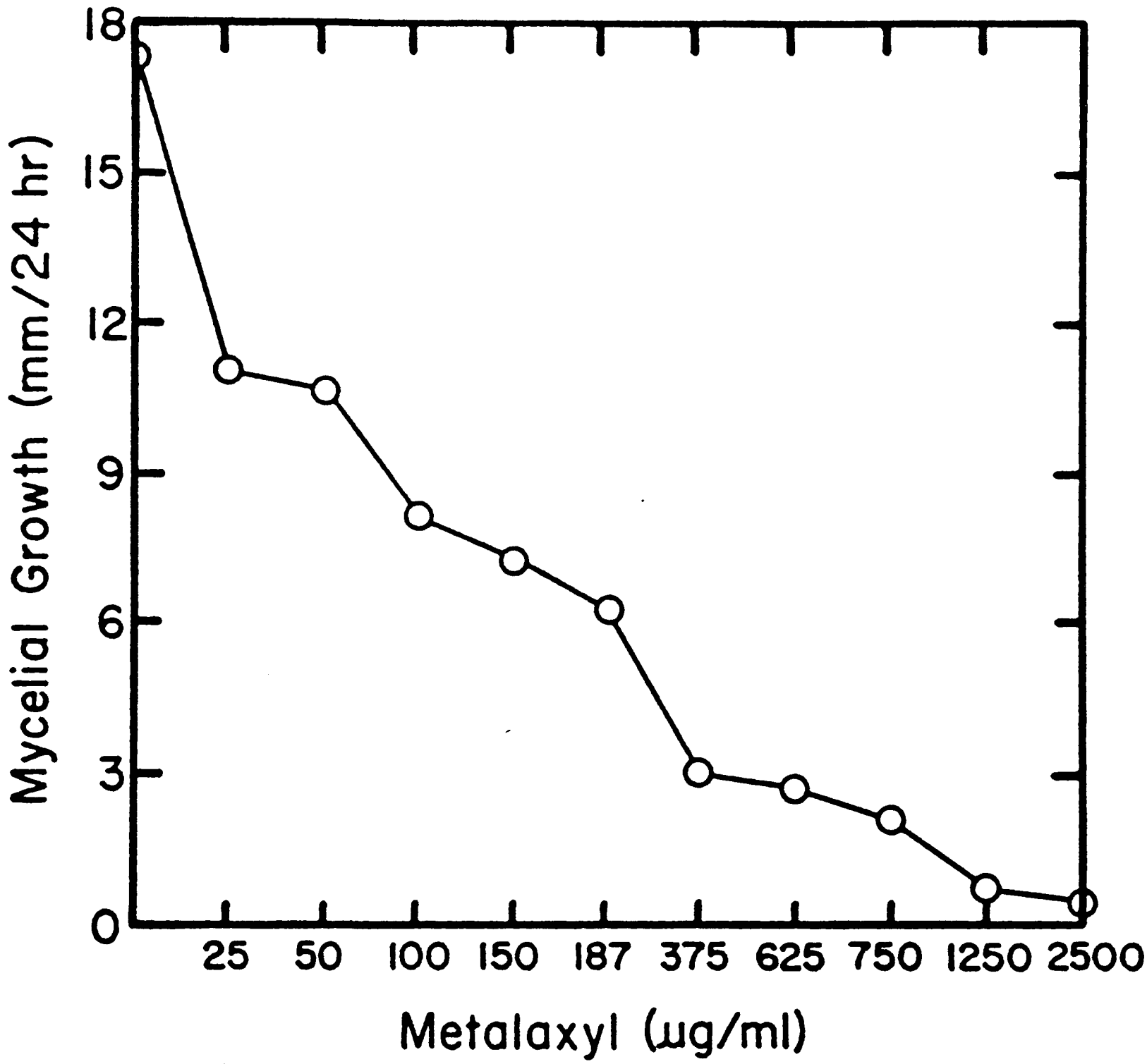

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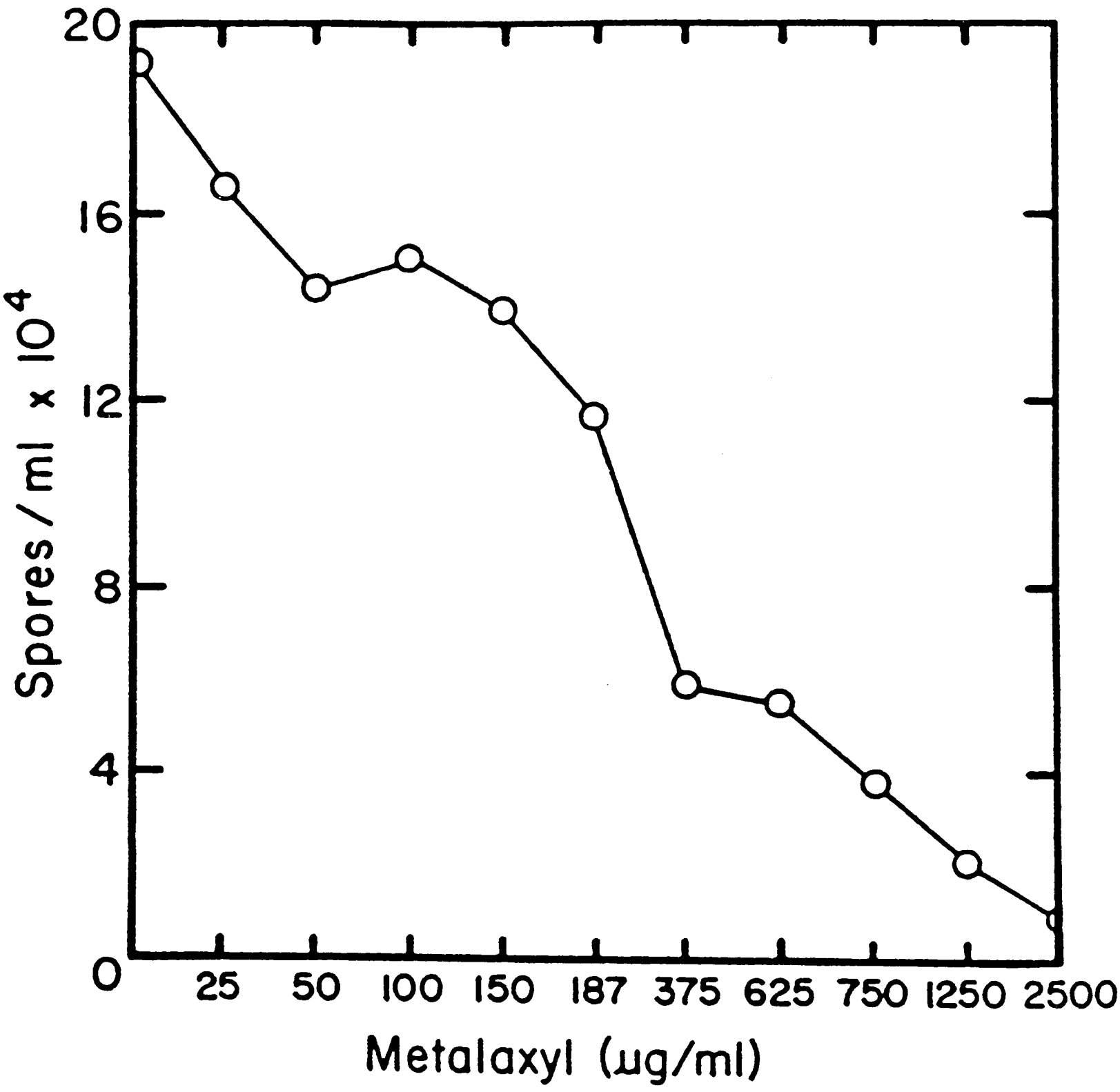

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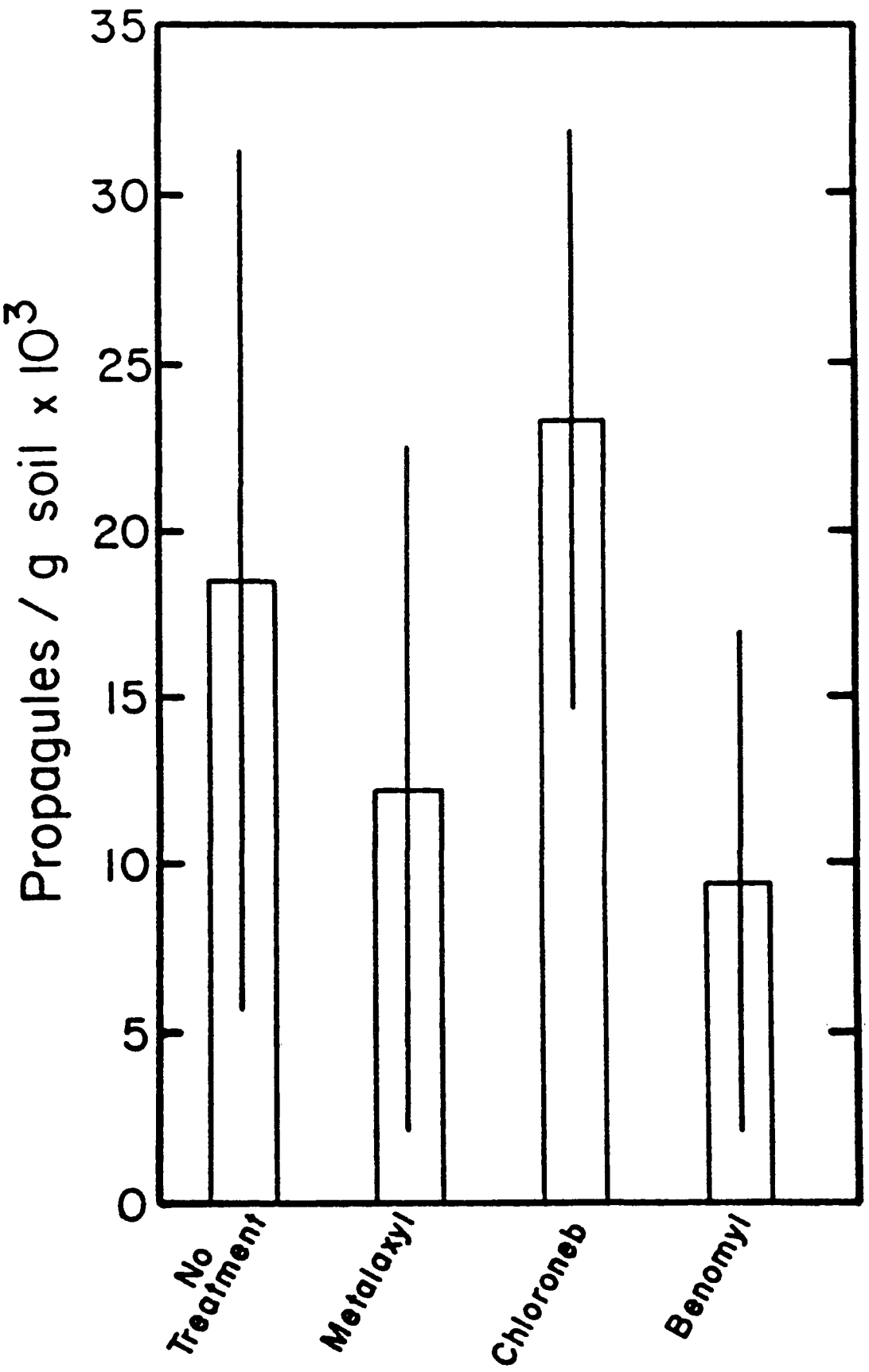

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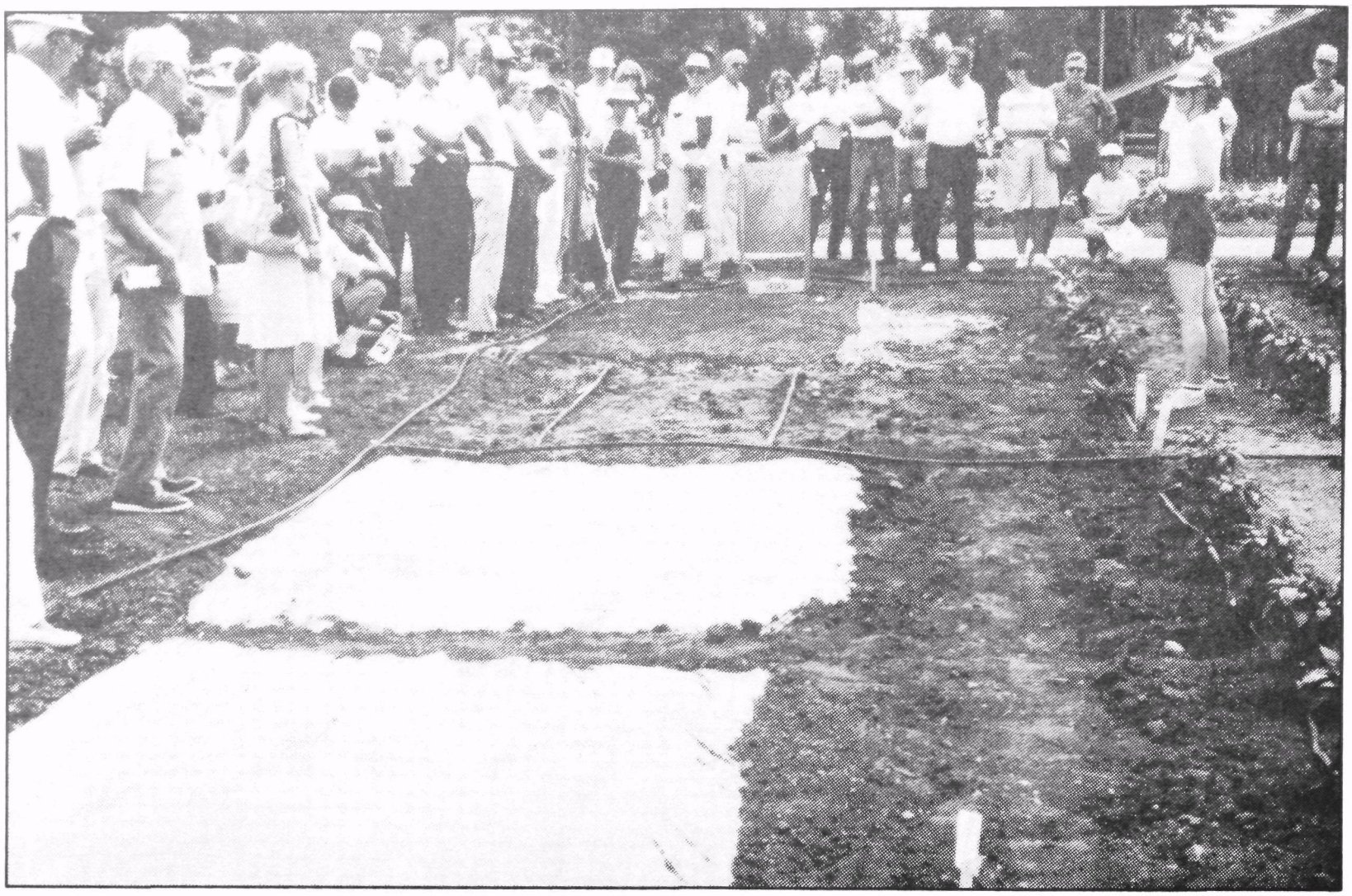

FIGURE 9

Cindy Rasmussen-Dykes with children and bug puppets used for childrens education IPM programs.

EDUCATIONAL, ENVIRONMENTAL, AND ECONOMIC IMPACTS OF INTEGRATED PEST MANAGEMENT PROGRAMS FOR LANDSCAPE PLANTS

by

Michael J. Raupp, Mildred F. Smith and John A. Davidson
Department of Entomology
University of Maryland
College Park, MD 20742

A landscape plant management pilot program was initiated in 1978 by extension specialists in the Department of Entomology, in cooperation with a county agent and a community of suburban Maryland homeowners. The objectives of the program were twofold. The first objective was to demonstrate the feasibility of the integrated pest management approach for managing landscape plants. As part of this approach, participating homeowners received regular monitoring of pest activity by a trained scout. The scout prepared a report that was reviewed by extension personnel. Management recommendations were sent to each cooperator via a weekly or biweekly newsletter. In addition to specific management recommendations, homeowners received timely extension literature on the life cycles and control of insects and diseases, cultural plant care, pest identification and proper pesticide use. As an educational program, the project provided homeowners with information that would allow them to deal with their plant problems more effectively. The second objective was to quantify changes in knowledge, attitudes, skills, and practices brought about by the program.

The program expanded from about 20 homeowners in the initial year (1978) to 100 homeowners in its final year (1982). At the conclusion of the 1982 program, a comprehensive evaluation was conducted. The program was evaluated by two methods, a survey of program participants and a group comparison between participants and their non-participating neighbors. Analyses were based on the 59 participants and 47 of their non-participating neighbors. Both survey techniques indicated substantial changes in knowledge, attitudes, skills, practices, and end results. Table 1 summarizes some of the changes detected by the survey of program participants.

TABLE 1
Changes Brought About by an IPM Program for Landscape Plants

Impact	Response (%)		
	Increase	No Change	Decrease
Identify ornamental plants	58	42	0
Inspect plants for problems	58	40	2
Recognize agents causing problems	75	25	0
Select the correct chemical control	75	25	0
Apply the chemical at the proper time	66	32	2
Use controls other than chemicals	53	47	0
Substitute alternatives for chemicals	45	52	3
Knowledge of cultural plant care	78	22	0
Deal effectively with plant problems	83	15	2

In addition to the changes summarized in Table 1, other changes were quantified. Ninety-seven percent of participants believed that the information received would be useful in future years and 81% thought this approach would save money on pest control in the long run (the average estimated savings was $53 per year). Furthermore, 93% felt the program was worthwhile and 98% believe it, or a similar one, should be conducted in the future. Program participants said that they followed extension recommendations about 71% of the time and were satisfied with their results 81% of the time.

In the area of pesticide application, participants and their non-participating neighbors were asked to select the best means of controlling aphids. Possible choices included insecticide, fungicide, miticide, and soapy water sprays and ladybird beetles. Responses of participants differed significantly from those of non-participants. The majority of non-participants selected insecticides as the control method of choice while cooperators selected insecticidal soaps most frequently. This difference undoubtedly resulted because participants were informed that insecticidal soaps provided good control of aphids and were an environmentally preferred alternative to insecticides. Homeowners were asked the same question regarding the control of mites. Non-participating homeowners chose insecticides as the preferred control tactic while participants selected insecticidal soaps and miticides most frequently. This difference is especially important because many insecticides provide little, or no, control of mites. An additional finding of interest was that 15% of the non-participants said that they had received helpful pest management information from neighbors who had participated in the program.

The final phase of homeowner program evaluation was conducted in 1985 when approximately 330 former program participants were sent a questionnaire through the mail. Ninety-eight homeowners returned the questionnaire. Of these, 71% indicated that they still used information from the program. This compares very favorably with other surveys of information sources used by homeowners. In 1979, Barrows et al. found that only 17% of gardeners surveyed used information from the local Cooperative Extension Service. A national survey of homeowners conducted by the Nursery Marketing Council (1983) revealed only about 16% using agents, universities, and

governments as a primary information source. Several uses of information are summarized in Table 2.

TABLE 2

Information Use by Former IPM Program Participants

Use	Continue to Use	Never Use
Recognize cause of problem	85%	15%
Decide if control is needed	84%	16%
Select proper control	84%	16%
Apply controls at proper time	84%	16%
Use pesticides safely	78%	22%

In addition to these results, 48% of those responding believed this information had helped prevent plants from dying.

Community managers and grounds maintenance supervisors face problems similar to those of homeowners with respect to the types of pests affecting their landscape plants. A demonstration project was conducted within a city of 27,000 people in 1983 and 1984. The demonstration project in 1983 placed 354 acres inhabited by 1,661 residents under IPM management. In 1984, the program was expanded to 476 acres, occupied by 3,844 people. Over the two years of the program, pesticide sprays were reduced by an average of 83% and the overall cost associated with pest management was reduced by 22% on the average. In 1985, the program was transferred to a private consultant employed by the city. The program expanded to seven communities. Environmental impact data is unavailable for the program conducted by the consultant; however, economic information indicates that costs continued to be reduced under the IPM approach (Table 3). The average total cost reduction resulting from the adoption of IPM ranged from $4.8 to 21.7/acre. The mean savings realized was $12.9/acre $\pm$ 3.99 (standard error).

TABLE 3

Economic Assessment of Traditional and IPM Programs in Three Communities

Community	Cost				Acres	Cost Reductions $/Acre		
	1982[a]	1983[b]	1984[b]	1985[c]		1983	1984	1985
1	2895	784	822	210	131	16.1	15.8	20.5
2	3750	1663	2986	420	56	37.3	13.6	59.5
3	1325	510	401	0	17	47.9	54.4	77.9
Pesticide Total	7970	2957	4209	630	204	24.6	18.4	36.0
Labor Total	0	2505	2779	2920				
Total	7970	5462	6988	3550		12.3	4.8	21.7

a. 1982 -- Traditional management program, including cover spray, no monitoring.
b. 1983, 1984 -- IPM management program conducted by Cooperative Extension Service as a demonstration.
c. 1985 -- IPM management program conducted by private consultant.

The success of the landscape plant management programs for homeowners and communities prompted extension specialists in entomology to undertake a demonstration project with a commercial arborist. The objective of this program was to demonstrate that an arborist could provide the same approach for managing pests as did the extension based IPM programs. This was a critical step in transferring technology to the commercial sector.

The program demonstrated the feasibility of the IPM approach conducted in the commercial sector. Furthermore, it demonstrated that an arborist could reduce unnecessary pesticide use by 94% while maintaining a high level of customer satisfaction with the program. Seventy-eight percent of the clients said they preferred the IPM approach to traditional cover sprays.

Part of the effort to continue the transfer of IPM technology to the commercial sector has been an intensive training program. One component of this training has been a technical conference held each winter at the University of Maryland. This interdisciplinary conference, called the Interstate Ornamental Plant Management Conference, features nationally recognized plant management experts from the disciplines of entomology, pathology, agronomy, weed science, botany, horticulture, and the green industry. In its first three years, this conference has provided training to more than 700 businessmen, government workers, and extension personnel. Ninety-six percent of the attendees at the 1985 conference rated the overall quality of the 20 presentations as satisfactory or excellent.

Other training activities include in-depth workshops conducted over several days during the winters of 1984 and 1985. These workshops focused on interdisciplinary approaches of pest management and were limited to approximately 30 participants each year. To determine how IPM information was being implemented by former workshop attendees, a telephone survey was conducted during the winter of 1986. The study group consisted of former program participants and a group of Maryland arborists selected at random. Both groups were asked questions designed to

reveal their pest management practices. One of the major impacts of the IPM approach is a reduction in unnecessary pesticide use. When asked if their pesticide spraying had declined in the last ten years, 83% of program participants were spraying less. Sixty-seven percent of non-participating arborists were also spraying less. Not only did program participants spray less, but the materials sprayed were more environmentally acceptable. Pesticides may be categorized according to toxicity and environmental persistence. Pesticides such as horticultural oils, insecticidal soaps, and the insect pathogen Bacillus thuringiensis (Bt) are considered biorational insecticides due to their low toxicity to vertebrates and short environmental persistance. Insecticides used by workshop attendees were compared to ones used by arborists that had not participated in workshops. Arborists that had received IPM training were significantly more likely to use biorational insecticides (Table 4). Furthermore, former program participants were the only ones to suggest non-chemical controls for pests.

TABLE 4

Control Tactics Used by Arborists for Controlling Insect Pests

Pest	Attended IPM Workshop	Control Method (%)		
		Non-chemical	Biorational	Synthetic Organic
Aphids	Yes	11	28	61
	No	0	6	94
Caterpillars	Yes	4	29	67
	No	0	7	93
Scales	Yes	0	78	22
	No	0	47	53
Spider Mites	Yes	6	35	59
	No	0	8	92

A second critical component of any IPM program for landscape plants is the regular inspection of the plants for problems caused by pests or improper culture. Eighty-five percent of the firms that attended workshops employed at least one person whose primary responsibility was plant inspection. This contrasts with arborists that had not attended workshops. Only half of these firms employed plant inspectors. To be effective, monitoring must be performed on a regular, short-term basis. This means a minimum of ten, or more, visits per growing season. A comparison of the frequency of inspections by program participants and non-participants revealed that 57% of the participating arborists conduct ten, or more, regular inspections compared to only 20% of the arborists that did not attend IPM workshops.

In summary, the demonstration programs have had the following results. First, they have conclusively demonstrated the feasibility of implementing IPM technologies in non-traditional settings, such as landscapes. Moreover, they have demonstrated that persons other than farmers, or farm consultants, can implement IPM programs. This group includes homeowners, grounds maintenance personnel, and commercial arborists. As educational activities, these programs have

succeeded in changing knowledge, attitudes, skills, and practices of information recipients. These changes have had the following economic and environmental impacts. They have reduced the cost of pest control. The documented savings in the community-based IPM programs averaged $12.9/acre. More important than the economic impacts are the environmental ones. Documented reductions in pesticide use in the arborist demonstration program averaged 73 gallons (dilute)/acre. These studies clearly indicate that IPM technologies have tremendous potential benefits for urban clientele.

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INTEGRATED PEST MANAGEMENT IN THE GOLF COURSE INDUSTRY: A CASE STUDY AND SOME GENERAL CONSIDERATIONS

Zachary Grant
Formerly Manager of Government Relations
Golf Course Superintendents Association of America
1617 St. Andrews Drive
Lawrence, KS 66046

Building a golf course in the late 1980's involves challenges beyond architecture, engineering, finances and the demands of the game. In many states, developers of a course must also overcome forbidding legal and regulatory barriers related to zoning, planning and environmental protection.

One of the most challenging of those regulatory obstacles is Vermont's Act 250 development law, which requires that proposed developments meet a series of ten separate tests to obtain a land use permit. These tests, administered by an independent environmental commission, range from effect on water quality to infrastructural demands to aesthetic value.

For the past four years, Act 250 compliance has been the aim of developers of the proposed Sherman Hollow golf course, planned for construction near Burlington, Vermont. Along the way, the Sherman Hollow management team has demonstrated exemplary concern for environmental interests, in spite of often burdensome and frustrating regulatory requirements.

Over the past four years, vocal opponents of the project repeatedly intervened to stall the progress of approval for Sherman Hollow. Using slogans such as "Keep Sherman Hollow", the protesters at one time appeared capable of bringing the development to a halt. Today, through a series of positive and progressive steps, much of the opposition to Sherman Hollow has subsided. However the Sherman Hollow permit was denied by the State Act 250 Commission. The Vermont Pesticide Advisory Council is now drawing up a comprehensive protocol for golf course permitting, and the Sherman Hollow case has been granted a new hearing.

A key component of the Sherman Hollow response to Act 250 inquiries was development of an integrated pest management (IPM) plan to govern the use of pesticides on the proposed golf course. Thought to be the first of its kind in the United States, it was hoped that this IPM plan could serve as a model for the golf industry in its efforts to contribute ever more effectively to the enhancement and protection of our natural environment. Meanwhile Cornell University Extension Service has been developing a detailed IPM manual for golf courses in the northeast that embodies all the concepts put forward in the Sherman Hollow plan. The manual should be available in the fall of 1989.

This essay explores the general nature and advantages of IPM to the golf course turf industry and outlines some of the specific features of the Sherman Hollow IPM plan.

WHAT IS INTEGRATED PEST MANAGEMENT?

Integrated pest management (IPM) has been defined in various ways by various authors, which has led to some confusion about the precise meaning of the term. From the perspective of golf course turf management, one enlightening definition was provided by Victor A. Gibeault and others of the University of California, Riverside.

They suggest that "IPM is defined as multiple tactics used in a compatible manner in order to maintain pest populations below levels that cause economic or unacceptable aesthetic injury without posing a hazard to humans, domestic animals, or other non-target life forms."

The decision-making process inherent within this definition involves setting up tolerance levels for pest populations, monitoring turf areas for pest incidence, maintaining accurate records of monitoring data and taking appropriate actions with regard to the information collected through monitoring.

An important point to note is that IPM is not itself a tactic for controlling pests, but rather it is a system for understanding various strategies and tactics of pest control. It serves to guide the pest manager in recognizing and selecting among various tactics. Further, it requires that such selections be hazard-efficient.

One of the objectives of IPM is to use chemicals less, but it is a misconception that IPM programs always replace chemical control. Rather, IPM encourages the pest manager to use chemicals more wisely, which can mean less often. In a study of tree care reported by Dr. Michael J. Raupp, an entomologist at the University of Maryland, pesticide use was reduced by more than 90% when IPM was utilized. Studies of household pest control have shown pesticide use reductions of 80% and more in controlling cockroaches.

To implement the IPM approach, superintendents must be prepared to establish thresholds for unacceptable economic or aesthetic injury based upon some reliable system of measurement. Before resorting to the use of any chemical pesticide, it should be established by actual monitoring of the turf that injury thresholds -- or action levels related to such thresholds -- will be exceeded unless chemicals are used. Until these thresholds are crossed, use of alternative methods should be attempted as feasible.

Because IPM is inherently site specific, explicit thresholds and the means of measuring injury cannot be standardized for the golf industry. However, this should not deter experienced professionals from drawing upon their best judgement in making such determinations.

Sheila Daar, IPM consultant and Executive Director of the Biointegral Resource Center, explains "golfers and superintendents at different courses will have different tolerance levels for turf injury. And differing maintenance regimes will result in different degrees of injury from the same number of pests. The setting of injury thresholds just isn't subject to uniform standards."

SHERMAN HOLLOW: THE SETTING

Sherman Hollow is in Huntington, Vermont, 18 miles southeast of Burlington, and 20 minutes from the Burlington International Airport. It is within 30 minutes of the Stowe, Sugarbush and Bolton Valley ski areas and 25 minutes from Lake Champlain.

Sherman Hollow occupies 1,200 acres of land in the foothills of the Green Mountains. The golf course is part of an overall development plan that will include a 70 room inn, conference facilities, indoor tennis courts, a complete sport fitness center, 72 luxury townhouses, a live theatre, a chapel, and 40 kilometers of cross-country ski trails.

The development will be arranged in a clustered "village" occupying only 20 acres. The golf course will be built on an adjacent 120 acres.

Sherman Hollow, Inc. President Paul Truax and his family have lived on Sherman Hollow land for many years. Paul and his wife Colleen purchased the core farm in 1961 with an eye toward

recreational development. Their residency is an important factor in the environmental sensitivity exhibited throughout the development.

"We've left a lot of land open, clustered the village and set a limit on the size of the project," noted Truax, "We want to make a profit, but life-style is important. After all, we live here."

The Golf Course

Sherman Hollow's golf course promises to be one of the finest in Vermont. Designed by architect Charles Ankrom and golfer Raymond Floyd, the par-72 layout will measure 6,849 yards.

Ankrom already has a number of fine layouts to his credit, including the TPC course at Monte Carlo and the Tower Club and Crane Creek in Martin Downs, Florida.

In designing Sherman Hollow, Ankrom recognized the need for a solid environmental design. Even with the natural plateaus and terracing of the property, the course drops vertically more than 300 feet from start to finish.

From a design standpoint, Ankrom indicated that his key environmental concerns included erosion control -- especially during clearing and construction --and good water management.

"We are doing a variety of things to control erosion," Ankrom said. "The layout parallels the natural terrain, creating terraces to reduce runoff. We've used birming, water retention areas, natural watersheds -- the works. We have no interest in soil leaving the property, so we've been very careful."

An extensive erosion control plan, detailing every square foot of the construction site, has been submitted to the Act 250 commission.

Ankrom also noted that good water management would play an essential role in pest management. An extensive irrigation and drainage system is planned to interface with a series of five lakes.

Floyd, who counts the 1986 U.S. Open crown among his five major tour victories, is consulting designer for the project. He will bring to the project his expertise as a well-travelled golf professional.

Commenting on the environmental effect of the project, Floyd referred favorably to the proposed IPM plan: "We play golf to enjoy and enhance our environment. If we can provide top quality playing conditions with reduced chemical applications, that is going to be good for the game. The specific pest control plan is outside my area of expertise but, as a player, I appreciate the philosophy behind it."

Pesticide Use Plan

The protracted battle for Act 250 approval has involved dozens of public hearings concerning the proposed golf course. The Sherman Hollow management team sought assistance from a variety of outside authorities, including a hydrogeologist, toxicologist, agronomist, environmental scientists and others.

Late in the spring of 1987, Sherman Hollow Superintendent Garry N. Crothers, CGCS, contacted GCSAA's office of government relations for assistance. Through GCSAA contacts, a working relationship between Sherman Hollow and the U.S. Environmental Protection Agency (EPA) was established.

Anne Leslie, of EPA's Integrated Pest Management Unit, and Unit Chief Diana Horne, had indicated to GCSAA representatives earlier that year that they were looking for golf courses to serve as IPM demonstration sites. Given Sherman Hollow's interests and needs, it was determined that a possible compromise could be arranged.

By early summer, discussions between Sherman Hollow and the EPA had solidified an agreement in principle to implement a comprehensive IPM plan. Leslie appeared at a local permit hearing in Vermont to discuss the proposal. Shortly there-after, the local Green Mountain Audubon Society withdrew its objections to the golf course plan, a move that "stunned opponents of the project", according to a report in the Burlington Free Press.

In a letter to Truax, Craig S. Sharf, chairman of the Green Mountain Audubon Conservation Committee, wrote that "the information you presented to us has satisfied our concerns and provided us with the assurance we felt is necessary."

Sharf said in a recent interview that some local Audubon members oppose any development whatsoever at Sherman Hollow. Others, including himself, see some form of development as inevitable. In that context, he sees the golf course as an "acceptable"alternative.

On July 29, Sherman Hollow representatives travelled to Washington, D.C., along with Kenneth E. Bannister of the Vermont Department of Health, to meet with EPA representatives, and observers from the staff of U.S. Senator Patrick Leahy, a Vermont Democrat and chairman of the Senate Committee on Agriculture, Nutrition and Forestry. This meeting produced a formal outline of the agreement to participate in an IPM demonstration project.

During the day long meeting, it was agreed that the overall goal of the IPM project was to reduce dependency on pesticides while maintaining a high quality golf course. The EPA supports the project to promote IPM for turfgrass and to demonstrate that good results can be achieved when the best IPM practices are put to use.

"We are pleased to be able to take a leadership role in protecting the future of the environment," Truax said. "We are particularly pleased to have the benefit of EPA's research and input in implementing this plan. GCSAA has been instrumental in securing our good relationship with EPA and other interested parties."

Leslie, of the EPA, pointed out that the Sherman Hollow IPM project is not expected to be an experiment per se, but rather a joining of the very best of various individual techniques to see how well they work within a comprehensive IPM approach.

"We will be looking for good preventive maintenance, such as selecting well adapted varieties of grass, proper irrigation, fertilization, aerification, mowing and so forth," Leslie said. "And we will recommend biological controls and other alternatives as advisable. Monitoring, record keeping and setting thresholds will be the key to chemical treatments."

IPM ADVANTAGES

A dedicated IPM program can help superintendents do a better job of managing turf pests and using various means of pest control -- including chemicals -- as widely as possible. For those who take IPM seriously, the rewards can be great. In the case of Sherman Hollow, IPM may spell the difference between having a golf course and none at all, if the opposition of environmentalists and concerns of regulators can thus be resolved.

Better Control

To individual superintendents, equally important advantages may result from adoption of an IPM approach. By encouraging the natural predators of turfgrass pests, for example, more effective control can be achieved. Further, the superintendent will not inherit the work of beneficial predators that might be killed off by the overuse of non-selective chemical pesticides.

Dr. Don Short, extension entomologist at the University of Florida, recently reported that, in a three year study in south and central Florida, spot treatment with pesticides and weekly monitoring of the turf resulted in good control of chinch bugs and webworms.

"This is primarily due to the fact that we are not killing off beneficial organisms that may be providing more control than pesticides," Short concluded.

Where overdependence on chemical controls has substantially reduced non-target beneficials, the stage is set for a dramatic resurgence of the unwanted pest. This is similar to the unchecked expansion of exotic pests in areas where they have no natural enemies, such as introduction of the mole cricket from South America in the early 1900's.

Avoiding Pest Resistance

Recent experience with various control failures illustrates the logical extension of this boom and bust cycle. Where dependency on chemical solutions is great, pest populations can develop resistance to pesticides.

Selection pressures are exerted by pesticide use, because genetically superior pests, which are less susceptible to the pesticide, will survive the application and pass their superiority to the next generation. With each successive treatment, greater resistance is encouraged. Eventually, the pesticide itself will no longer provide effective control.

James F. Moore, mid-continent director of the USGA Green Section, observed this same trend in a recent issue of the USGA Green Section Record.

"Combine excessive chemical use with improper turfgrass selection and superintendents find it necessary to make more and more pesticide applications a year," Moore noted. "On these courses, it is only a matter of time until resistant organisms develop or the turf overdoses on the chemicals."

Healthy Turf

Moore's use of the word "overdose" is well chosen. Similar to a person addicted to drugs, a golf course that is over-dependent on chemicals may be addicted to pesticides. In both cases, chemicals become necessary for short term survival but counterproductive to overall health.

Used wisely, both drugs and pesticides can have medicinal or therapeutic value. A seasoned physician addresses illness by adjusting diet, exercise, environment and various treatment interventions, including pharmaceuticals. Likewise, a good superintendent maintains healthy turf through appropriate cultural practices, fertilization, irrigation and various pest controls, including chemical pesticides.

Experienced superintendents realize that misuse of chemical pesticides can itself increase turf stress. Each additional application carries the small, but significant, risk of mishaps or misapplications that may radically degrade turf quality. These can include improper mixing or calibration, accidental use of the wrong chemical, spillage or equipment failure -- the list goes on.

USGA's Moore sums up the idea well by noting that chemicals "are not a substitute for good agronomics. By far the best chemical pest control programs are those that are as simple as possible."

Safety and Cost Factors

Minimizing hazards to humans, domestic animals and other non-target life forms is a part of IPM by definition. This does not universally translate into reduced use of chemicals, but often fewer applications do result.

For every application avoided, the associated human and environmental risks are avoided. Risks may also be reduced by use of chemicals that are more highly selective in attacking only the target pest, or by more selective applications, such as spot treatments.

The direct cost savings of reduced pesticide use also can be substantial when the price of single applications may be several thousand dollars.

The independence and judgement of individual superintendents considering an IPM alternative is essential in this respect. Because the use of pesticides is a cost factor in golf course maintenance, a superintendent has no monetary incentive to apply chemicals unnecessarily. Every treatment avoided is money in the bank.

The trade-off between resource intensive chemical controls and labor intensive alternatives may involve transitional costs. However, actual cost savings have been demonstrated in some pilot programs.

"Our experience has consistently shown the long term costs of IPM are less than with preventative chemical spray routines," says Daar.

Professionalism

One of the most important advantages of integrated pest management is that IPM recognizes the agronomic insight and management skill of the superintendent. The turf manager's judgement in balancing aesthetic, environmental, agricultural and human factors is the key to effective IPM. The level of responsibility and professionalism involved exceeds sheer dependency on chemical solutions.

Further, IPM is important from the perspective of good stewardship. Superintendents have a powerful interest in the long term viability of the land they manage. The challenge to do everything possible to preserve the integrity and productivity of the land logically includes a personal commitment to IPM.

"A superintendent with the vision to effectively administer such a system is obviously a very valuable asset to his employer," concludes GCSAA director William Roberts, CGCS. "It is, very simply, the smart way to manage pest problems."

A Word of Caution

Cultural techniques, such as proper aerification, thatch control, good drainage and careful irrigation have long been used by golf course superintendents to maintain healthy turf.

"We have been using IPM practices," notes Dr. Leon Lucas, Professor of Plant Pathology at North Carolina State University, "but many haven't called them 'IPM'".

Yet, there is a difference between the use of practices consistent with an IPM approach and actual adoption of IPM as a system of pest control.

Because of the positive public image associated with minimizing pesticide use, there is some temptation to appropriate the language and trappings of IPM prematurely, without a commitment to meaningful changes in behavior. Doing so reduces IPM to a hollow shell surrounding the same old methods of pest control.

"Even where essentially benign techniques are being used," Daar said, "if there is no monitoring program, no record keeping, no known tolerance level -- then there is no IPM."

The danger is that IPM will lose its credibility and appeal as an alternative to increasingly unpopular traditional methods. Where there is even the suspicion that IPM has been used to

whitewash continued overdependence on chemical pesticides, its value in resolving the emotional debate over environmental issues will be lost.

To preserve the genuine advantages of integrated pest management, it is important that the approach be understood and implemented with sincere appreciation for its intrinsic merit. In that vein, the work of progressive projects, such as Sherman Hollow, should be encouraged and supported.

The Bottom Line

Ultimately, the Sherman Hollow IPM plan represents a very creative and progressive response to an increasingly common -- and increasingly complex -- set of problems facing proposed golf course developments. By exhibiting an extraordinary level of professionalism and environmental concern, Sherman Hollow has set an important example for others in the golf industry.

As the Selectmen of the Town of Huntington testified during Act 250 hearings, issuing permits for Sherman Hollow would allow "flexibility in efforts to preserve the delicate balance between open spaces and developmental pressures."

As long as golf course construction and management continue to set a high standard for environmental awareness, the golf industry will remain a preferred development option.

SOCIETAL BENEFITS OF CONSERVATION ORIENTED MANAGEMENT OF TURFGRASS IN HOME LAWNS

Anne R. Leslie
U.S. Environmental Protection Agency
401 M Street SW
Washington, DC 20460

and

William Knoop
Texas A&M University
Research and Extension Center
17360 Coit Road
Dallas, TX 75252

This chapter shows how communities can benefit when homeowners choose an IPM approach to turfgrass management and city management is supportive through recycling programs. Although healthy grass is generally viewed as an aesthetic asset rather than a cash crop, evidence is accumulating for its positive health and environmental contributions. Balanced against all of this is the potential risk from the pesticides that may be applied. So an IPM program that emphasizes proper pesticide application without sacrificing turf quality is especially important. Reductions in air and water pollution can be realized through maintenance of this quality groundcover. Some recycling of urban solid waste is even possible, and as shown below, this can be an economic benefit to the community.

Healthy turf can act as a buffer to delay or prevent movement of chemicals and soil from agricultural sites to watersheds. Grass is used in orchards to absorb pesticides and minimize erosion. Grassland experiences 84 to 668 times less erosion than areas planted to wheat or corn. Studies show that an average golf course of 150 acres absorbs 12 million gallons of water during a three-inch rainfall, and thick, carefully managed turfgrass has 15 times less runoff than does a lower quality lawn (Watschke, personal communication). By comparison, parking lots, streets, and other paved residential areas load nearby waters with hazardous pollutants carried in runoff from road surfaces, gutters and catch basins.

Healthy turf can flourish with IPM techniques that also recycle sewage sludge, and detoxify air and water pollutants. Using recycled sewage sludge compost to fertilize golf courses helps mitigate groundwater pollution effects of waste disposal sites. Homeowners can purchase such materials to use on their lawns so long as they grow no food nearby. Some of these materials are discussed in the chapter by Vargas.

A healthy lawn can detoxify air pollutants. The capacity of grass is comparable to the same leaf surface area contained in trees. In addition, turf is an excellent groundcover to diminish loss of soil as dust, a significant air pollutant. Finally, a lawn can provide cooling to the home and lower the energy consumption for air conditioning in the summer.

Communities having limited landfill space have built incinerators to dispose of solid waste. In this technology the burning of organic matter such as lawn clippings, which have a high water and

nitrogen content, results in increased emission of the oxides of nitrogen. Reducing the quantity of garden plant material to this solid waste disposal stream will help reduce air pollution.

The Lawn Waste-Saver Program carried out in Plano, Texas addresses the problem of limited landfill space. William E. Knoop of Texas A&M University Research and Extension Center at Dallas, reports in Grounds Maintenance Magazine the only quantitative study of its kind that we are aware of. The plan has since been implemented in other communities, including Fort Worth, Texas. It was presented to the EPA Municipal Solid Waste Task Force in May 1988. This presentation included recent data from Wichita Falls, TX, and a report, "Turfgrass Management Practices and Their Influence on Pests," given by Philip F. Colbaugh of Texas A&M at the ACS symposium in New Orleans, August 1987. The latter report shows how this system is part of an IPM program that results in improved turf as well.

The original article by Knoop is reproduced here to show how the program was implemented by the City of Plano. (Reprinted with permission from the November 1982 issue of Grounds Maintenance 1982, Intertec Publishing Corp., Overland Park, KS 66212.)

WASTE-SAVER LAWN CARE PROGRAM

Landfill space is at a premium for most cities. It is expensive to obtain. It is also expensive to maintain. Cities surrounded by other cities often have used up all possible landfill space and must find land in other areas. Few residents are eager to allow any city to develop a landfill next to them. These considerations make it highly desirable to make the most out of the currently used landfill.

Plano, Texas, north of Dallas, is a bedroom community of about 80,000 people. To make the city government run as efficiently as possible, the management created a Productivity Department in the spring of 1980. It reviewed Plano's solid waste disposal system. During one week in mid-June 1980, productivity staff members rode each garbage truck on every route and recorded the number of garbage bags containing grass clippings and the number of bags containing other garbage.

The city officials found that 29.1 percent of all garbage bags picked up during the 1980 Plano sampling period were filled with grass clippings. A bag of grass clippings weighs approximately 40 pounds, so Plano homeowners were placing nearly 700 tons of grass in the landfill. Because bags of grass clippings weigh more than an average bag of other garbage, it was estimated that about 40 percent of the garbage truck's load (by weight) was grass clippings.

If analyzed on the basis of their dry weight, the 33,000 bags of grass clippings collected each week contain approxi-mately 2 1/2 tons of nitrogen, 1/2 ton of phosphorus, 1 ton of potassium and all the remaining essential plant nutrients. When placed in a landfill, their value has essentially ended; their only function is to possibly become a future source of ground-water pollution.

EDUCATIONAL PROGRAM

A cooperative public educational program between the city of Plano and the Texas Agricultural Extension Service was begun in April 1981 in an effort to reduce the amount of grass clippings reaching the landfill. This educational program used the local newspaper, area TV and radio, and a flyer that the city mailed to each of its nearly 19,000 homeowners. The goal of the program was to encourage proper fertilization, watering and--most importantly--proper mowing. Homeowners were advised that the management of golf courses (with the exception of greens), athletic fields and other high-quality turf areas does not include the process of picking up grass clippings.

The results of the program, summarized in the accompanying table, were encouraging. Although the number of bags of other garbage increased by 12 percent, the number of bags of grass clippings decreased by 11 percent, for a projected overall decrease of 23 percent. The percentage of bags containing grass clippings was reduced from 29.1 percent in 1980 to 24.7 percent in 1982. The total saving to the city was over $100,000. Perhaps more importantly, the burden on the landfill was reduced.

How unique is this problem? Plano is an upper middle-class city whose homeowners place very high aesthetic value on their homes. As word of the success of the program spread, mainly through city-government-oriented publications, more than 100 cities from 27 other states wrote asking for details of the Plano program. A director of public works from an Ohio city indicated that approximately 50 percent of the solid waste collection in summer was grass. He thought that 95 percent of homeowners bagged their grass clippings, indicating that the bagging of grass clippings may be a more universal problem than first considered. It might be hard to find a city without a landfill problem and grass clippings may be a part of that problem.

How did all this bagging of grass clippings get started? Perhaps we homeowners became more and more lazy about mowing practices. Instead of removing no more than one-third of the leaf surface area each mowing and letting the growth rate dictate the mowing frequency, we tended to let the calendar dictate mowing frequency. As a result, the heavy layer of clippings on the lawn presented a real management problem. Raking clippings certainly is not a pleasant task and mowers that collected the clippings in a container that could be emptied into a garbage can or plastic bag became highly desirable.

We homeowners may have compounded the problem by also placing such a great value on dark green lawns. Such lawns require fairly high applications of nitrogen, which tend to increase growth rates. Promoters have never emphasized turfgrass varieties that produce reasonable growth rates at low nitrogen rates.

HOMEOWNERS RECEPTIVE

Perhaps it is now time to provide homeowners with good, basic turfgrass management information that encourages such practices as proper mowing. The experience in Plano indicated that most people did not know they did not have to bag grass clippings. They assumed that, because the mower had a bagging attachment, there was no alternative. The program demonstrated to homeowners that if mowing frequency was increased to once every 5 days, then the need to bag was ended. Most homeowners felt this increase in mowing frequency was far more desirable than bagging clippings. The program also demonstrated the value of a 3-1-2 fertilizer ratio and the value of a slow-release nitrogen source in slowing growth rates without any sacrifice in lawn quality.

Mulching mowers can be expected to play an important part in a non-bagging lawn maintenance program. More research with mowers in controlled-management situations is needed.

Our energy as a turf industry has been concentrated in areas that benefit relatively few people. Now we must consider a larger issue, such as the bagging of grass clippings and its effect on landfills.

TABLE 1

SUMMARY OF THE PLANO, TEXAS WASTE-SAVER LAWN CARE PROGRAM

	YEAR		
	1980	1981	CHANGE
Number of homes	18,771	21,074	+12%
Number of stops for garbage	29,025	31,740	+ 9%
Number of stops that had bags of grass	9,894	9,133	- 8%
Number of bags of grass	33,625	30033	-11%
Number of bags of other garbage	81,852	91,462	+12%
Total bags of garbage	115,477	121,495	+ 5%
Truckloads of garbage	141	123	-13%

LAWN SERVICE INDUSTRY: TRANSITION IN SERVICES

Roger C. Funk

The Davey Tree Expert Company
1500 N. Mantua Street
Kent, Ohio 44240

The lawn care industry has experienced unprecedented growth in the last decade and the demand for our services is still growing.

The recent pesticide controversy has raised questions concerning the safety of pesticides and our current practices. It has also increased consumer awareness of our industry, expanding the market for quality-conscious lawn care operators. There has never been greater opportunity for those willing to accept the challenge.

Lawn care operators are developing an image problem. We are being perceived not as an industry that maintains the health of turfgrass but rather as an industry that applies pesticides. Of course we do apply pesticides but only as one of the many services that we provide.

Although several factors could contribute to the public's perception of our industry, the most important are media coverage, high market visibility and the overuse of pesticides. This perception can be changed only if we recognize that education is an integral part of the services we provide and that we must limit our use of pesticides through monitoring and selective applications and the use of alternative materials whenever possible.

One of the best methods of educating the public is through an educated media. Too often we take a combative or defensive attitude toward the media since they usually fail to present balancing viewpoint about lawn pesticides. It is their objective to report what they consider to be newsworthy. Unfortunately for us, the application of pesticides to millions of lawns without a single incident is not considered newsworthy. However, the perceived or alleged injury to just one person from those millions of applications is news and would be reported.

The high visibility of the lawn care industry has also contributed to our image as pesticide applicators. Because of the demand for our services, the lawn care industry has been highly successful. And because of our success, we're highly visible in the urban and suburban environment. There are estimates as high as 40-60% if the homeowners in any given market having a commercial applicator do their chemical lawn maintenance.

As success and visibility increase, questions and concerns about the effect of our applications on health and the environment also increase. Do-it-yourselfers use the same fertilizers and pesticides we use, but they maintain a lower visibility in the neighborhood.

The noticeable odor of pesticide applications is largely the result of the overuse of pesticides. Most lawn care operators apply pesticides to the entire lawn if pesticides are needed on any portion of the lawn. Some may apply the same granular or liquid formulation to all of the lawns serviced within a geographic area based on the predicted pests for that time of year. This practice leads to the unnecessary application of pesticides and contributes to the concern of pesticide exposure. In addition, "shot gun" applications are not an economically or agronomically sound practice since no

benefit is derived from a pesticide application if a pest is neither present nor anticipated within the residual period of the pesticide.

In order to change the public's perception of our industry, we must change the way we do business. Change is seldom easy, particularly for an established company with a growing market share. Change, however, is an integral part of any successful company. One definition of success is to find out what the public wants and then give it to them. When the lawn care industry first started, our customers wanted green, weed-free lawns. They still want the same thing but with less pesticides applied to achieve it.

Last year, insecticides and herbicides in Davey lawn care services in selected territories were effectively reduced 40% to 50%, respectively, through the use of the patented Davey Customizer.

The Customizer is specially designed for spot application of pesticides. Pesticides are not tank-mixed, but are secured in a separate reinforced tank and are injected in the fertilizer line only as needed. Another feature of the Customizer is its specially designed no-drift nozzle.

In a five-area representative sample of Davey lawn care operations (Akron, OH; Charlotte, NC; Minneapolis, MN; Rochester, NY; and Washington, DC), 1987 results show that 4,800 gallons of herbicide were used in 1985 compared to 2,260 gallons in 1987 with the use of the Customizer. (Fig 1). In addition, insecticide use was reduced from 1,020 gallons to 600 gallons. (Fig 2). This represents a 52.9% reduction in herbicides and a 41.1% reduction in insecticides.

Based on our field experience in the five test markets, we are projecting a company-wide reduction in lawn pesticide use in 1988 of almost 10,000 gallons--without any increase in insect or weed problems.

Petrochemical pesticide use can be reduced in other ways. Alternative materials such as soap and citric oil are being researched. Both materials are effective insecticides and currently are used in other industries. Biological controls may prove practical.

Milky spore disease has reportedly been reformulated and is more effective on Japanese beetles. Tests are under way for nematode control of grubs and fungal control of chinch bugs.

Electrostatic sprays may reduce drift of conventional pesticides by electrical attraction of spray particles to plant surfaces. This allows the rate of application to be reduced.

Micro-encapsulation of pesticides can potentially reduce the toxicity of pesticides while reducing odor.

Our industry should investigate alternative methods of pest management and discuss possible solutions with university personnel and material equipment manufacturers. We should not be committed to any material or method of application -- only to provide the quality of service the customer wants and has a right to expect.

In summary, the lawn care industry is partially responsible for the pesticide controversy due to our high visibility in residential areas and the overuse of pesticides. The news media has contributed by reporting only "newsworthy" items that sensationalize and distort the risks from pesticide exposure. We can, however, improve the quality of our service through education, and through alternative materials and methods of application. Controversy almost always results in change... and with change comes opportunity.

Editor's note: A more technical treatment of how the Davey Co. has responded to the need for change is presented in the following section dealing with ornamentals.

DAVEY'S PLANT HEALTH CARE

Pest management is an important service offered by Arborists to protect trees and shrubs in the landscape. Concerns for public health and the environment, however, have resulted in increased insurance costs and restrictions in the use of pesticides. Many tree care companies are weighing the benefits of a pest management service against the risks involved in the continued use of pesticides.

In January 1985, the Davey Company scheduled our first Plant Health Care (PHC) Seminar to discuss a comprehensive approach to improving tree health through proper selection, planting, and care. Since the concept of PHC emphasizes preventative maintenance, the health of the tree (not pest control) became the central focus of our service.

Neilsen (Reference #2) defines a similar concept and provides a framework for implementation in the November, 1986 issue of the Journal of Arboriculture.

One of the objectives of our PHC concept was to reduce the use of traditional pesticides. Horticultural oil was an obvious and underused alternative and we began testing its use for foliage-feeding insects. In addition, we began testing reduced rates of the registered insecticides in combination with soaps, horticultural oil, vegetable oils, and citric oils. More recently, we have begun testing Neem oil, diatomaceous earth, and detergents.

Our earliest successes were with soap plus reduced rates of insecticides. After two years of laboratory and field testing, we introduced the approved combinations in five test markets in 1987 and implemented the "program"through our U.S. market in 1988. We anticipate a 75% reduction in pesticide use this year with further reductions by 1990. Additional reductions are projected through the increased use of alternatives, selective spraying and improved methods of application.

EFFICACY TESTING

Preliminary research with Safer Insecticidal Soap indicated that soap alone would satisfactorily control most soft-bodied insects and mites, but provided no residual effect. Testing was begun on reduced rates of the petrochemical pesticides in combination with soap to determine efficacy for sucking as well as chewing insects and mites.

In most cases soap was found to enhance the control achieved with reduced rates of pesticides. This was particularly true with sucking insects and mites, but also with Japanese beetle. Tempo, a synthetic pyrethroid, was sprayed on linden leaves in the field. Leaves were also treated with Safer soap and Tempo plus soap. Foliage was collected one week later. During this period, rainfall was approximately 1-1/2 inches. Japanese beetles were introduced onto the foliage in the laboratory. After a feeding period of two days, mortality rates were recorded. The results are in the following chart:

Table 1.
Japanese Beetle on Linden

Insecticide	Rate/100 gal.	% Control (Residual)
Tempo	0.5 oz.	17
Soap	128 oz.	0
Tempo + Soap	0.5 oz. + 128 oz.	92

Tempo alone at 1/4 the recommended rate and soap alone at 1/2 the recommended rate did not control the beetles. The same rates of Tempo and soap when combined, however, provided 92% control.

In another experiment, Tempo and soap were tested for contact control of aphids. Rose of Sharon twigs infested with aphids were brought into the lab, placed in individual vials of water and sprayed. Results of this experiment are given in the chart below:

Table 2.
Aphids on Rose of Sharon

Insecticide	Rate/100 gal.	% Control (Contact)
Tempo	0.5 oz.	40
Soap	64 oz.	90
Tempo + Soap	0.5 oz. + 64 oz.	98

The combinations of Tempo plus soap again outperformed either component individually applied. The tests demonstrated that the rate of Tempo can be reduced significantly when combined with soap for the control of aphids and Japanese beetles. Tests with other insecticides, such as Dursban, Orthene, and Sevin, have shown similar results in combination with soap or horticultural oil, although the effective rates vary. In one test, Dursban at 1/16 the recommended rate in combination with horticultural oil (1 gal/100) provided mite control equal to Dursban at full rate.

COMPATIBILITY TESTING

The current soaps which are registered for ornamentals are strongly alkaline and may react differently with different insecticides or in different water sources. For example, in some of our markets, soap causes Sevin to deactivate within several hours of mixing and turn a brown to reddish-brown color -- which stains! In these situations, additives are necessary to combine soap with the insecticide. Davey researchers are working with soap manufacturers to alter the formulation of soaps so that additives may not be necessary in the future.

PHYTOTOXICITY TESTING

There are a number of plants listed as being injured by Safer's soap. (Reference #3) In addition, we have found that drought-stressed trees are more susceptible to injury from soap than standard pesticides and that, under certain conditions, the new growth of evergreens may be injured. In most cases, we did not find that the addition of a reduced rate of pesticide altered the occurrences or severity of the phytotoxicity. Although precautionary statements regarding phytotoxicity from horticultural oil persist, Johnson (Reference #1) has not observed injury when light, superior oil is applied to deciduous foliage, provided that the proper rate is applied and that the tree is not under moisture stress. Injury which we observed occurred only when oil was combined with Sevin and may have been related to drought stress and/or excessive heat and pressure.

SELECTIVE SPRAYING

Selective spraying involves monitoring to determine the presence and population levels of insects, and spraying only those trees and shrubs that have a pest problem. Pheromone traps are a useful tool in determining the most effective timing for control of clearwing moth borers. Traps have also been used successfully in identifying species of pine tip moth. This is particularly useful when first starting a monitoring program or when opening a new market.

Personnel training and resource information is essential to the success of our PHC programs since the person making the application normally determines which trees and shrubs will be sprayed. The Technical & Research staff developed pest/host timing charts for each of our field offices which are continuously being refined with the assistance of an on-site PHC trainer. (Figures 1 & 2) The charts provide guideline for anticipated insect and disease problems. In addition, the trainers attend week-long classes at our headquarters in Kent, Ohio, each year to enable them to train and monitor the effectiveness of the technician in the field. Extension courses developed in-house are part of the training supervised by the PHC trainer. The Technical staff also visits each territory each year to further train and motivate the field staff.

Educating clients is necessary, not only as a potential participant in the monitoring process, but also to accept the concept of selective spraying. Clients who have been on a program where all the trees and shrubs have been sprayed are often reluctant to accept selective sprays. Literature which explains Davey's approach to Plant Health Care is provided to clients as well as Fact Sheets which discuss any major problems on the property. Information is also available to help clients select the proper plants for site conditions and the proper transplant procedures and cultural requirements for those plants.

Application techniques can reduce the potential for drift and reduce the volume of pesticide used.

Davey researchers tested various pressures and disc sizes to determine the effect on drift. Trees should be sprayed with a large disc or nozzle and only sufficient pressure at the gun to reach the top of the tree. A ball valve or similar control at the spray gun will allow the technician to adjust the flow rate and pressure at the nozzle without returning to the truck.

Excess spray volume applied to trees and shrubs is a common problem, particularly with new technicians. Guidelines were developed by Davey researchers indicating the spray volume needed for coverage of different size canopies. For example, a tree 50-ft. high and 60-ft. wide would require 25 gallons of spray mix. This gives the technician and his manager a tool for comparing the actual with the estimated material usage.

A survey of all field managers was conducted in 1987 to estimate material savings from the improved application techniques. Although the actual material savings varied, depending upon the pest problem and the experience of the technician, the least savings reported was 5%.

In summary, Davey's Plant Health Care program enabled us to reduce our use of traditional pesticides by 75-80% in five test markets in 1987. Fifty percent of the savings was achieved through the use of alternative materials, 25% by selective spraying, and 5% by improved application techniques. Based on our findings we are projecting a reduction in use of over 20,000 gallons of pesticides in 1988 for our tree care markets--with no reduction in the quality of service to our customers.

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FIGURE 1

LAWN CARE

HERBICIDE REDUCTION IN FIVE-AREA REPRESENTATIVE SAMPLE OF DAVEY OPERATIONS

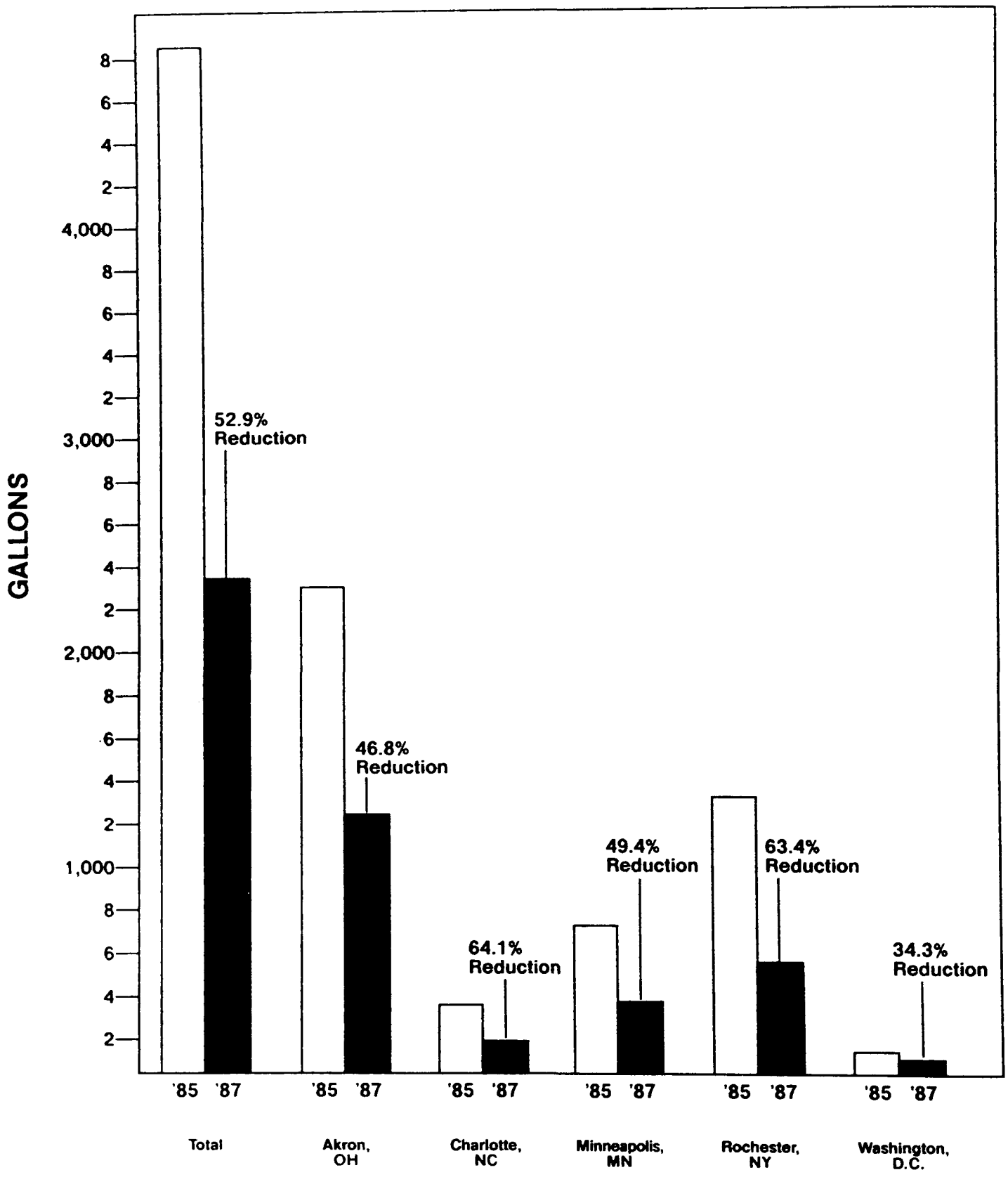
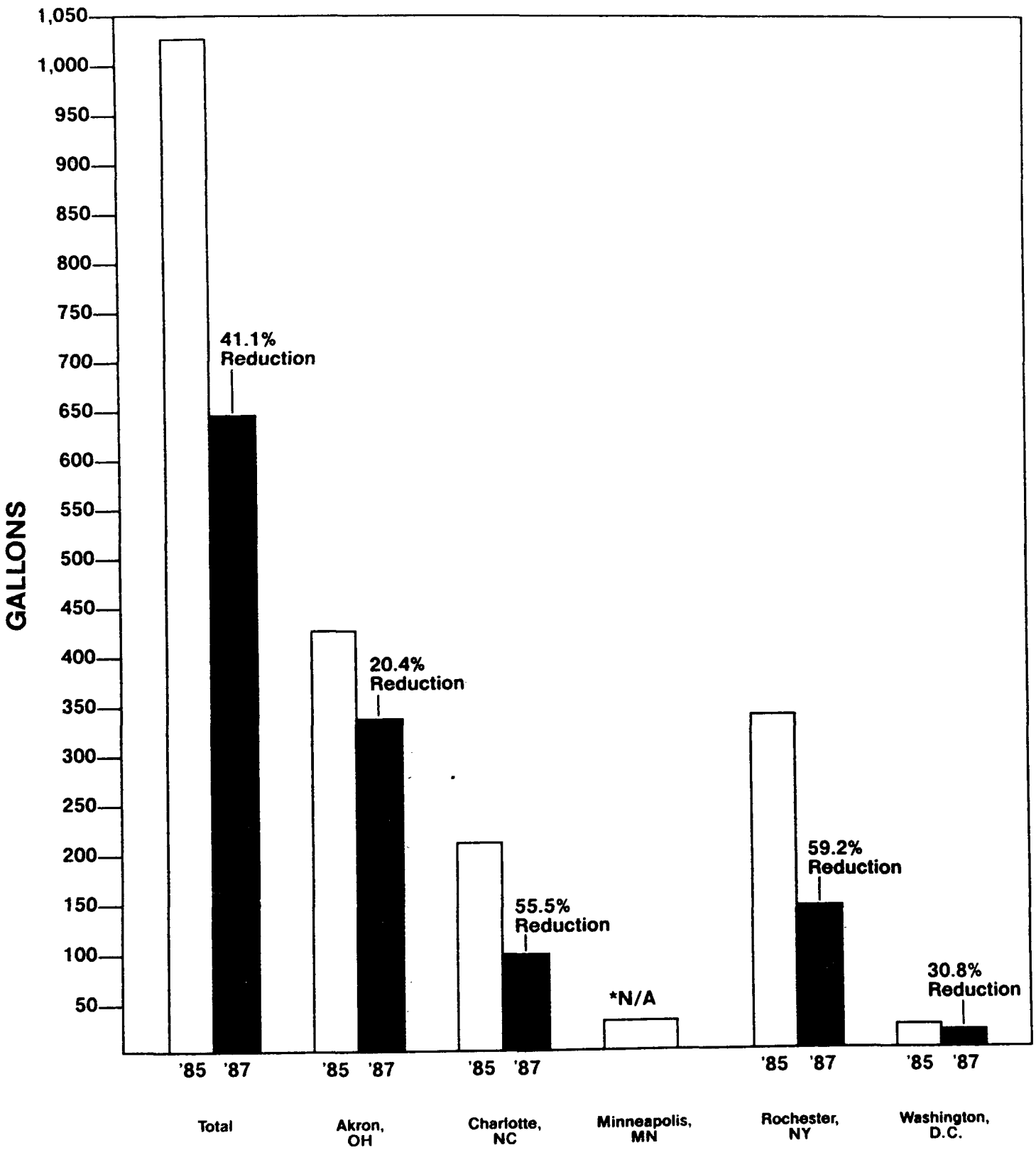


FIGURE 2

LAWN CARE

INSECTICIDE REDUCTION IN FIVE-AREA REPRESENTATIVE SAMPLE OF DAVEY OPERATIONS



*Minneapolis, MN does not have a high insect control problem.

SECTION III

Current Research Towards Understanding the Pest and the Site

DETECTION AND MONITORING OF TURFGRASS PATHOGENS BY IMMUNOASSAY

**S. A. Miller, G. D. Grothaus, F. P. Petersen,
J. H. Rittenburg, K. A. Plumley, and R. K. Lankow**

**Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077**

An integrated pest management (IPM) strategy for crop protection and production seeks to achieve maximum yields while minimizing crop damage, cost to the grower, and environmental hazards (1). For any crop, an effective IPM program must include the accurate and timely detection of pests and pathogens. For most plant diseases, few tools have been available to the grower or crop consultant for this crucial aspect of disease management, resulting in a reliance on symptomatology for disease diagnosis (11). However, symptom expression can be highly variable, depending on the crop variety, maturity, environmental conditions, and other factors. In addition, a number of pathogens may cause similar symptoms on the same plant variety. Reliance on symptoms usually precludes the early detection of pathogens, which may hinder the implementation of preventive management practices.

Recent advances in biotechnology are being applied to plant pathogen systems to provide diagnostic tests directly applicable to pathogen detection at the grower level (8,9). For broad acceptance among crop managers, these assays must be sensitive, specific, reliable and user-friendly. These criteria can be met by immunoassay-based diagnostic systems. Agri-Diagnostics Associates have developed immunoassays for the detection of three fungal pathogen complexes in turfgrass: Pythium Blight, Rhizoctonia Brown/Yellow Patch, and Dollar Spot. The basic concepts of immunoassay technology are described, focusing on the Pythium Blight assay and its effectiveness in detecting the disease in golf course turfgrass.

Immunoassays are tests in which antibodies are used as analytical chemistry reagents (7). To a large extent, the antibody is responsible for the specificity and sensitivity of the immunoassay, and two major types (polyclonal and monoclonal) are employed. Polyclonal antibodies are produced and secreted in experimental animals by a large number of B-cell clones which proliferate in response to recognition of chemical structures or determinants presented by the injected antigen. Polyclonal antisera can be produced in commercial quantities by immunizing large numbers of small animals or a few large animals such as sheep and goats in a relatively short time frame (3-6 months), and usually provide a robust antibody population due to the variety of immunoglobulin types in the sera. The generalized specificity of a polyclonal antiserum to a number of determinants on an antigen can be advantageous. If the target analyte is heterogeneous and somewhat variable in structure or the relative ratios of its various components, a polyclonal antiserum may provide a certain amount of "recognition buffering".

Monoclonal antibodies are now finding considerable application in immunoassay by providing a very high level of specificity as well as a potentially unlimited source of uniform antibody (4,5,6). Monoclonal antibodies are produced by fusing antibody-producing cells isolated from the spleen of

an immunized animal with "immortal"myeloma cells from tissue culture. The cells are transferred to a selective medium that will only support the growth of hybrid cells, called hybridomas. Individual hybridomas are subcloned and allowed to divide and produce antibody. Antibody secreted into the cell culture medium is then tested for desirable antigen-binding characteristics. Since each hybridoma cell line produces only one type of monoclonal antibody, it is possible to select antibodies with the specificity and sensitivity required for specific applications. Hybridomas may be stored frozen in liquid nitrogen and recovered at any time to continue reproducible production of the antibody.

For practical application of the unique properties of antibodies in a diagnostic assay, the user must be able to determine whether the antigen/antibody reaction has taken place. A variety of visualization and detection methods have been designed for this purpose. Enzyme immunoassay (EIA) is probably the immunoassay technology most widely applied today (7,9). One widely used EIA is the double antibody or "sandwich" immunoassay (2,3), in which an untagged or capture antibody is bound to a solid phase, such as beads, membranes or the wells of a microtiter plate. The test sample and enzyme labeled antibody are added sequentially, and unbound components are removed by washing after each incubation. Enzyme labeled antibody is detected by the addition of a color-producing substrate. The capture antibody is particularly useful when the test sample consists of a complex mixture of materials, such as a plant extract. The capture antibody binds the target antigen, while other components of the sample, which could interfere with subsequent steps in the immunoassay, are washed away.

One of the simplest immunoassay formats uses a dipstick as the solid phase (7). The dipstick is moved from one reagent to the next and the assay result is determined by examining the dipstick. Visualization of the bound enzyme-labeled antibody occurs when the enzyme converts the substrate to an insoluble colored product that binds to the dipstick. Quantitative results can be obtained through the use of an inexpensive field-adaptible reflectometer that measures the color intensity on the dipstick.

KIT CHARACTERISTICS

The Agri-Diagnostics turfgrass disease detection kits employ the dipstick format for performing a double antibody sandwich immunoassay. The assay requires no specialized equipment and can be completed in less than 4 hours.

The turfgrass sample is ground on an abrasive pad which is placed into the sample extraction buffer. The grinding homogenizes the sample, breaks up the fungi, and presents a controlled amount of sample (material trapped within the abrasive surface) into a fixed volume of extraction buffer. In the next step a fixed volume of enzyme-tagged antibody, specific for the pathogen, is added into the extraction solution. Then the dipstick, with antibody specific to the pathogen immobilized to its surface, is placed into the reaction mixture. During this step, the antibody on the dipstick captures any pathogen in the sample, and the enzyme-labelled antibody simultaneously tags the pathogen. After washing away any material not specifically bound, the dipstick is placed in a substrate solution which forms a colored precipitate in the presence of enzyme. The assay is quantitative, yielding a color endpoint, the density of which is directly related to the amount of pathogen in the turfgrass sample.

The graph in Figure 1 shows the dose response curve for the Pythium detection assay. The sensitivity limit based on fungal protein material is approximately 20 ng protein/ml. A reflectometer was used to quantitate the intensity of the reaction zone on the dipsticks.

The specificity of the immunoreagents used in the dipstick assay was determined using a "multiwell"EIA format. Dilutions of soluble extracts of isolates of fungi known to occur as pathogens or saprophytes on turfgrass were tested in a direct double-antibody EIA using standard protocols (3). The second ("tag") antibody was conjugated with horseradish peroxidase, and ABTS (2,2'-Azinobis(3-ethylbenzthiazolinesulfonic Acid) was the substrate used.

The reactivity of nine Pythium spp. associated with turfgrass as pathogens or saprophytes with the assay immunoreagents is shown in Table 1. All of the Pythium species associated with Pythium-induced disease, including P. aphanidermatum, P. ultimum, P. graminicola, P. aristosporum, P. arrhenomanes, and P. myriotylum are detected by the assay. Species described as weak pathogens or saprophytes of turfgrass, including P. torulosum, P. vanterpoolii, and P. rostratum are not detected. Other genera of turfgrass pathogens or saprophytic fungi associated with turfgrass also are not detected. Among the genera tested were Rhizoctonia, Sclerotinia, Fusarium, Drechslera, Bipolaris, Laetisaeria, Limonomyces, Curvularia, Rhizopus, Typhula, Trichoderma and Mortierella.

FIELD RESULTS

The Pythium detection assay was evaluated on a southern New Jersey golf course in 1986 and 1987. The 1986 test was of limited duration, carried out during an outbreak of Pythium blight on several of the course's fairways and greens in July of that year. Environmental conditions were conducive to Pythium blight for the duration of the testing period. The data resulting from tests on the green and fairway with the most severe disease are presented. The green that was studied (Green 4) contained bentgrass and a small percentage of annual bluegrass. Pythium blight occurred primarily on the collar, and samples were taken from this part of the green. The fairway studied (Fairway 7) consisted of perennial ryegrass, and was severely damaged by the disease. In order to determine the relative concentration of the pathogen at various stages of disease progression, samples were taken from the middle and edge of patches or streaks caused by Pythium spp., as well as from symptomless areas in proximity with the symptomatic areas. Samples of turfgrass from areas tested with the Pythium kit were also plated out on a selective medium for Pythium spp. isolation (10).

Pythium spp. were detected in both asymptomatic and symptomatic perennial ryegrass and bentgrass samples from the same green or fairway (Table 2). Pythium assay results were usually higher for symptomatic samples than for asymptomatic samples, as were Pythium spp. isolation frequencies. For all five of the asymptomatic samples shown in Table 2, Pythium spp. were detected by the immunoassay, although they were isolated from only three of the five samples. Since the samples were tested when environmental conditions were optimal for Pythium blight and prior to the application of Pythium control fungicides, Pythium spp. may have been present in the asymptomatic turfgrass samples at a high enough level to be detected but were not causing symptoms. Meter readings for Pythium assays of samples taken during conditions not conducive to Pythium blight development, or when the disease is well under control as a result of fungicide application, are usually in the 0-10 range (see Figure 4,5, below).

In general, the highest meter readings for blighted turf were obtained by sampling at the edge of patches or streaks (Figure 2). While Pythium spp. could usually be detected in dead grass in the center of a patch, high levels were detected more consistently at the leading edges.

Pythium spp. were detected on Fairway 7 and Green 4 throughout the testing period. A fungicide effective against Pythium spp. was applied on July 10, which was followed by a decrease in meter readings for samples taken from both the green and the fairway. Meter readings continued to decrease for samples taken from the green, while the readings for fairway samples increased to pre-fungicide application levels. These results reflect the amount of disease development on the green and fairway; Pythium blight damage was somewhat localized on the green, which had begun to recover by the end of the testing period. The damage on the fairway was extensive in the area that was tested, and the ryegrass turf did not recover quickly.

In 1987, a monitoring program was initiated on Green 4 and Fairway 7, beginning in late May and extending through the summer until termination at the end of August. Six subsamples were collected from the green and its collar, bulked separately, and thoroughly mixed. On the 7th Fairway, an area surrounded by trees and approximately 150 yards from the green was sampled. Six subsamples were taken from an area no larger than a green and bulked. Two dipstick assays were run for each bulked sample. Leaf blades were plated onto Pythium-selective medium as described above. Designated areas were sampled before mowing in the morning to maximize the amount of foliage that could be sampled, as well as to permit visual detection of pathogen signs (mycelium), if present.

As a result of the damage caused by Pythium blight to the greens and fairways during 1986, the golf course superintendent instituted a rigorous fungicide spray program in 1987. Beginning in late May, greens and fairways were sprayed on a weekly basis with three fungicides effective against Pythium spp. in rotation. As a result, no symptoms of Pythium blight were observed throughout the testing period, even during periods when the environment was highly conducive to disease development. Results of the monitoring program using the Pythium detection assay are presented in Figure 4. Conditions favorable for Pythium blight first occurred on May 29; low positive readings were observed for the sample from the collar of Green 4, which was taken from the area most severely affected in 1986. Results were negative for the samples from the Green 4 and from Fairway 7. The first fungicide application was made on May 29 after the sample was taken; all subsequent Pythium detection assay results were negative for Green 4 (including its collar) and Fairway 7. Thirty isolates of Pythium spp. were recovered during the testing period, five of which proved to be pathogenic in standard pathogenicity tests.

The negative results obtained with the Pythium detection assay were clearly correlated with the lack of symptoms of Pythium blight on the greens and fairway tested. With the exception of the low positive reading observed for the collar of Green 4 on May 29, Pythium spp. did not reach detectable levels at any time during the testing period. These results, especially when compared to the results of the 1986 trial, attest to the efficacy of currently available fungicides in controlling Pythium blight. However, the use of fungicides in this instance appears to have been excessive; our data (not shown) indicate that fungicide applications may not be required until meter readings reach 10-15, depending on the disease history of the turfgrass in question. By monitoring greens and fairways on a regular basis using the Pythium detection assay, increasing populations of Pythium spp. can be detected, and superintendents may more precisely time the application of fungicides.

CONCLUSIONS

The sensitivity and specificity of the dipstick assay system will make it possible for golf course superintendents and other turf managers to a) correctly diagnose turfgrass disease, b) detect pathogens at an early stage of disease, before symptoms appear, and c) monitor the development of pathogens in established turfgrass stands during periods of disease risk. An effective disease monitoring program will include a determination of the baseline readings for particular stands (i.e. greens, fairways, tees) during periods of low risk, followed by regular monitoring during the season. This capability will enhance the effectiveness of currently used disease control measures and promote an integrated approach to disease management in turfgrass.

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TABLE 1

Reactivity of isolates of Pythium species associated with turfgrass in a double antibody immunoassay using anti-Pythium aphanidermatum antibodies. Extracts of each isolate were standardized at a protein concentration of 1.0 ug/ml. Absorbance values (405 nm) are represented as the mean of all isolates tested.

Pythium species	Number of Isolates Tested	Mean Absorbance (405 nm) [1]
P. aphanidermatum	10	>2.00
P. graminicola	1	>2.00
P. ultimum	2	>2.00
P. myriotylum	2	>2.00
P. aristosporum	1	>2.00
P. arrhenomanes	4	>2.00
P. torulosum	2	0.12
P. vanterpoolii	1	0.00
P. rostratum	1	0.09

[1] Absorbance readings > 2.0 are off-scale.

TABLE 2

Detection of Pythium spp. in perennial ryegrass and bentgrass golf course turf by the Pythium detection assay and isolation from leaves using a selective medium. All samples were taken prior to application of fungicides for control of pythium blight.

Turfgrass Type	Symptoms[1]	Pythium Kit Meter Reading	Pythium Isolation Frequency[2]
Bentgrass	Pythium blight	37	5/8
Bentgrass	Pythium blight	25	0/8
Bentgrass	Pythium blight	43	3/8
Ryegrass	Pythium blight	28	3/8
Ryegrass	Pythium blight	36	3/8
Bentgrass	None	22	0/8
Bentgrass	None	20	1/8
Bentgrass	None	26	2/8
Ryegrass	None	22	1/8
Ryegrass	None	15	0/8

[1] Asymptomatic turfgrass samples were taken from areas within 10 ft of symptomatic turfgrass.

[2] Indicates the number of leaves/total plated on selective medium from which Pythium spp. were observed to grow out.

FIGURE 1

Dose response curve for the Pythium detection assay. The sensitivity limit of the assay, based on fungal protein of Pythium aphanidermatum, is approximately 20 ng protein/ml.

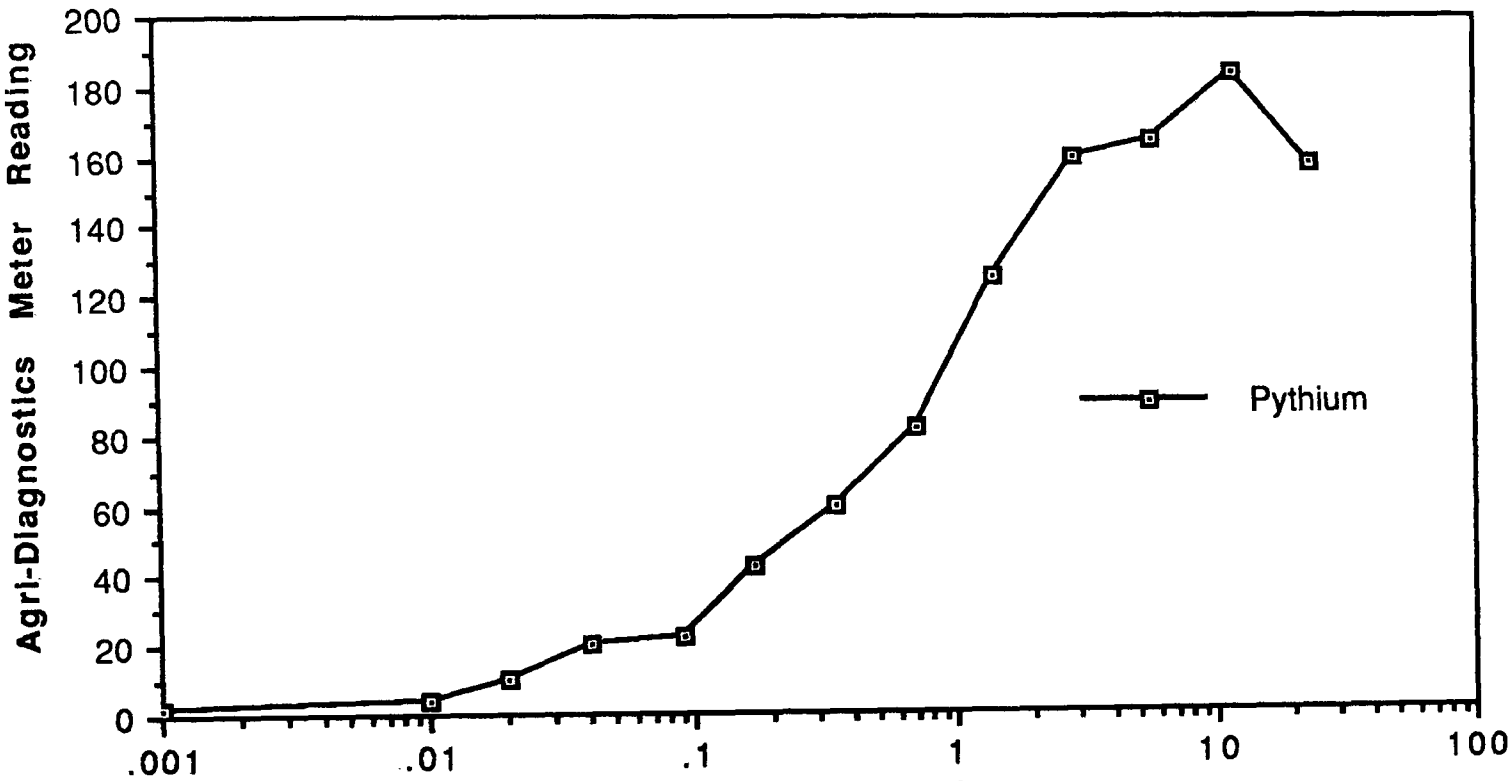


FIGURE 2

Prevalence of Pythium spp. in blighted patches and surrounding asymptomatic perennial ryegrass during a severe outbreak of Pythium blight, determined using the Pythium detection assay. In most cases, levels of Pythium spp. were highest at the edge of patches and lowest in the center of patches. Asymptomatic ryegrass samples taken from areas in close proximity to symptomatic areas also contained detectable levels of Pythium spp.

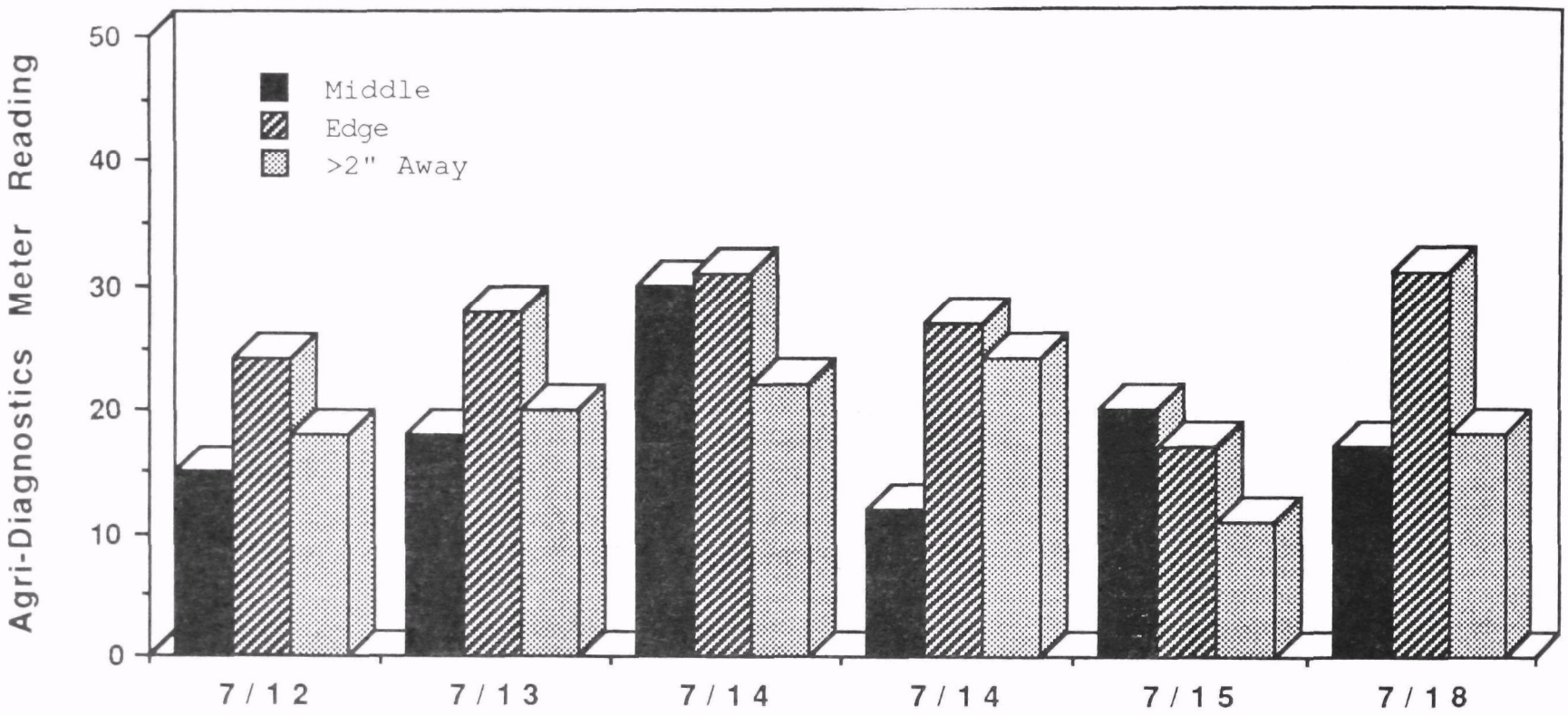


FIGURE 3

Detection of Pythium spp. in perennial ryegrass (Fairway 7) and bentgrass (Green 4) using the Pythium detection assay. Values represent the mean of two to four samples. Environmental condition remained highly favorable for Pythium blight development through the testing period. An application of a Pythium control fungicide was made on 7/10; Green 4 began to recover in the latter part of the testing period, but symptoms persisted on Fairway 7. The dotted line in the figure represents the threshold of positive detection for the assay.

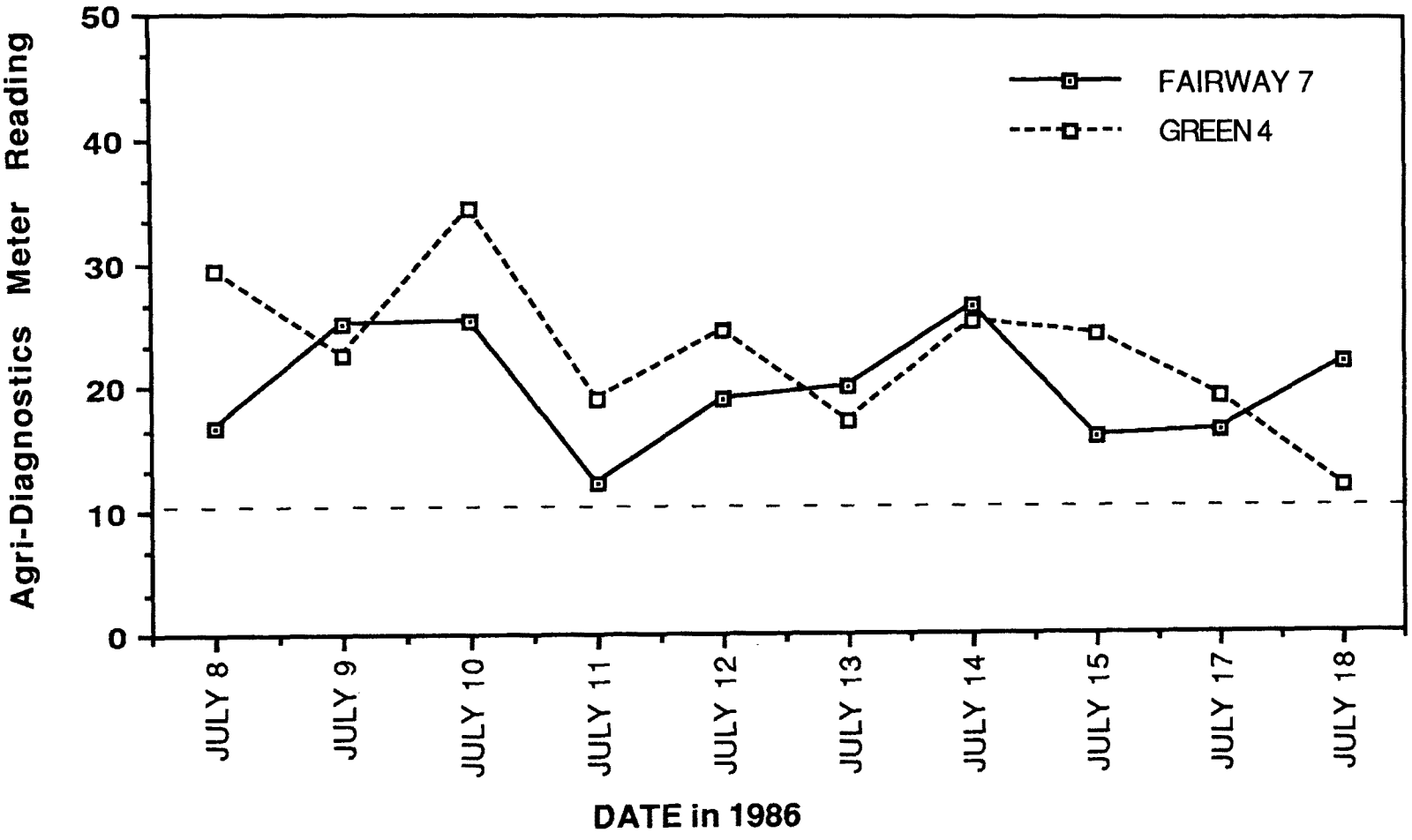
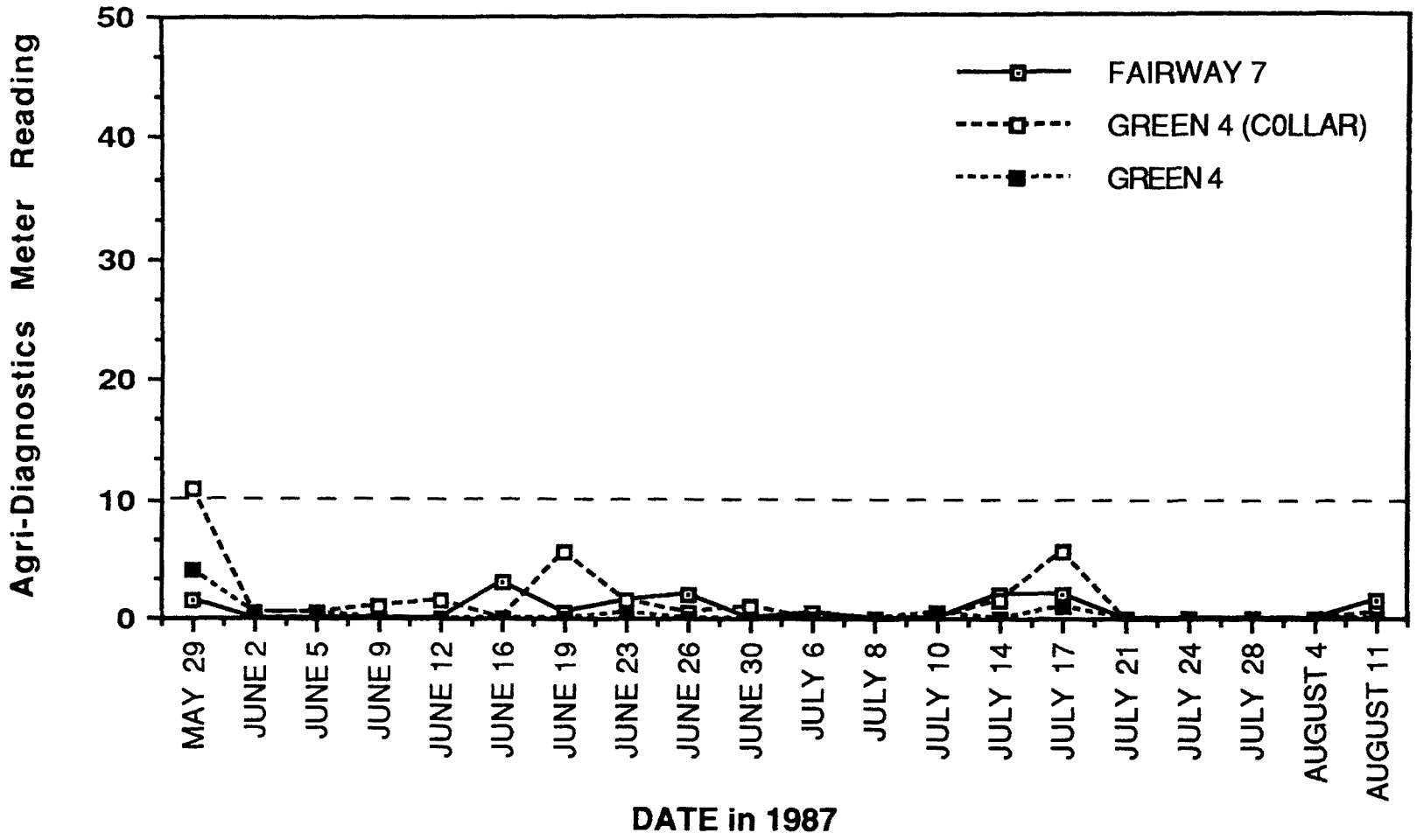


FIGURE 4

Results of a monitoring program for the detection of Pythium blight on Green 4 and Fairway 7 in 1987. Conditions favorable for Pythium blight occurred initially on May 29, and continued intermittently until late July. Pythium spp. were detected by the assay on the collar of Green 4 on May 29; however, regular application of Pythium control fungicides kept the pathogens at a non-detectable level. No symptoms of Pythium blight occurred during the testing period. The dotted line in the figure represents the threshold of positive detection for the assay.



BIOLOGICAL MANAGEMENT OF TURFGRASS PESTS AND THE USE OF PREDICTION MODELS FOR MORE ACCURATE PESTICIDE APPLICATIONS

J. M. Vargas, Jr.; D. Roberts; T. K. Danneberger;
M. Otto & R. Detweiler
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

Biological management of turfgrass pests, including some fungal diseases, insects, and weeds is now possible. These management tools consist of cultural practices to encourage natural predators as well as the direct application of beneficial organisms that are antagonistic to the fungal pathogens.

Necrotic ring spot (NRS), caused by Leptosphaeria korrae, is a serious disease of Kentucky bluegrass (Poa pratensis) in the northern areas of the cool season grass growing region. The disease was formerly referred to as Fusarium blight and mistakenly believed to be caused by either Fusarium roseum or Fusarium tricinctum. Koch's postulates were never completed for this disease with either F. roseum or F. tricinctum. as all attempts to produce patch or "frog eye" symptoms in the greenhouse or the field failed. Further investigation revealed a root pathogen associated with these disease symptoms which was eventually identified as L. korrae. Koch's postulates were completed in both greenhouse and field inoculation studies with L. korrae where actual patches and "frog eye" symptoms were produced, providing the final proof of the true cause of this patch disease on Kentucky bluegrass in the northern areas of the cool season grass growing region.

L. korrae is pathogenic to P. pratensis over a wide temperature range (15-28 degrees C.). L. korrae attacks the root systems of Kentucky bluegrass plants primarily during the cool weather of the spring and fall. The patches range in size from 7-8 cm up to 1 m in diameter. When the disease occurs in cool weather, red and straw colored blades are intermingled in the infected area of the patch. When the disease symptoms occur during the warm weather, the infected turf originally appears as wilted turf, later turning to straw color.

Necrotic ring spot is currently managed by high rates (compared to rates normally used to manage foliar turfgrass diseases like dollar spot or anthracnose) of the following fungicides: benomyl, thiophanate, thiophanate-methyl, iprodione, and fenarimol.

IRRIGATION AND BIOLOGICAL MANAGEMENT

Studies of the environmental conditions necessary for necrotic ring spot symptom development indicated low soil moisture was important. An irrigation study was established to determine the effects of irrigation on necrotic ring spot. The treatment included a daily irrigation treatment (1/10"/day), an 80% pan treatment (replacing 80% of the moisture lost from an evapro-pan twice a week), and a no supplemental irrigation treatment. Each replication included three sub-treatments: a muck sod, a mineral sod, and a seeded blend of three P. pratensis cultivars (Baron, Victa, Bristol).

In 1986 and 1987 necrotic ring spot symptoms developed in the muck and mineral sod 80% pan treatments and non-supplemental irrigation plots. No symptoms occurred in the daily irrigated plots. This is believed to be due to the increase in the beneficial microbial populations. There was an increase in the number of beneficial fungi, the number of actinomycetes (known producers of anti-fungal compounds) and beneficial bacteria. The effect of these various organisms on the development of necrotic ring spot is being investigated. Similar results have been observed in the reduction of melting-out, caused by Dreschlera poae and leaf spot, caused by Biopolaris sorokinianum in other irrigation studies. This disease reduction has been correlated to an increase in microbial populations. Two other pests that have been reported to be managed by irrigation are the chinch bug and bill bug. The possibility of managing five P. pratensis turfgrass pests biologically through the cultural practice of irrigation now appears feasible.

BIOLOGICAL MANAGEMENT PRODUCTS

In May 1984 a curative study was established on a heavily diseased P. pratensis sodded area in Novi, Michigan. The study was laid out with three replications of 1.83 x 2.44 m2 plots in a randomized block design. The condominium site at Novi was irrigated with an automatic irrigation system and in 1984 received, in addition to our treatments, the same four fertility and herbicide treatments as the rest of the complex, including a total of 180 kg N/ha. In 1985 and 1986 this area did not receive any additional fertilizer treatment other than those we applied. Green Magic and Soil Aid were applied using a CO2 small plot sprayer at a volume of 454.2 l/ha., equipped with a .914 m boom. Lawn Restore was applied by hand to individual plots. The results of Green Magic plus Soil Aid and Lawn Restore when compared to a nitrogen check can be seen in Table 1. They show complete recovery in the Green Magic plots when treatments were applied three times a year in May, July, and September at a 480 kg/ha rate. The amount of necrotic ring spot increased 303% during the same period of time.

TABLE 1

Mean percent reduction[a] in necrotic ring spot patches from 5/23/84 to 8/14/86 at Novi, Michigan.

Treatment	Month of Application	8/14/86 mean % red[b]	mean sep.[c]
Green Magic	MJO	100	a
Lawn Restore	MJS	100	a
Check (46)0)0)	AS	-303	b

[a] Calculated by subtracting number of patches per plot on 8/14/86 from the number on 5/23/84, dividing this by the number present on 5/23/84, and multiplying by 100.

[b] Percent disease reduction. Mean of three replications.

[c] Means followed by the same letter are not significantly different by LSD (.05).

Biological management of soil-borne disease through the use of microbes can act through two mechanisms. The first is competition for nutrients in the thatch and soil between the beneficial microorganisms and the pathogens. By utilizing available nutrients, they can deny the pathogens the nutrients needed to stimulate germination of resting structures (spores or sclerotia) and, after germination, they can deny them the nutrition needed to grow saprophytically to reach the root of the host plant for infection. The second feasible mechanism is the production by beneficial microorganisms of substances that are antagonistic to the germination and growth of soil-borne pathogens. The latter has been demonstrated under laboratory conditions with the microorganisms in Lawn Restore. Replicated studies conducted by Michigan State University over the past six years with Lawn Restore, Green Magic, and Strengthen and Renew have shown significant reduction in the amount of necrotic ring spot disease compared to the untreated controls.

There are two general categories of products involved in the biological management of necrotic ring spot. One category of products improves the thatch and soil environment to encourage higher levels of beneficial microbial activity and the other adds the beneficial microorganisms to the thatch and soil. Products developed by the Agro-Chem Corporation of Franklin Park, Illinois are in the first category. Soil Aid is designed to flush thatch and soil of substances that are toxic to sustaining high levels of microbial activity. It is an enzymatic type wetting agent. This treatment is followed by Green Magic or Strengthen and Renew, which are products that contain major and minor nutrients as well as plant and microorganism extractions. They have been shown to reduce the growth of L. korrae in laboratory culture work and increase natural microbial populations in the field. The use of Green Magic or Strengthen and Renew have been shown, under field conditions, to allow existing necrotic ring spot patches to recover and to prevent the development of new ones when used on a regular basis.

The Ringer Corporation, of Minneapolis, Minnesota, produces a product in the second category. It is an organic fertilizer consisting of bone meal, feather meal, soybean meal, and other

protein sources. This is supplemented with Actinomycete fungi and bacteria in the genus Bacillus. The product is called Lawn Restore. The microorganisms in Lawn Restore have been shown to produce substances in laboratory culture tests that are antagonistic to L. korrae. Lawn Restore has been shown to promote the recovery of necrotic ring spot patches and to prevent the development of new ones under field conditions when used on a regular basis.

Leptosphaeria korrae, the cause of necrotic ring spot in turfgrass, is a soil-borne pathogen that has been successfully managed by the use of beneficial microorganisms. It must be remembered that these products are not like fungicides that can be applied one time, halting the spread of the fungus and allowing the grass to recover. In order to be effective, Lawn Restore, Green Magic, and Strengthen and Renew must be applied on a regular basis, either monthly or bi-monthly, throughout the growing season to change the biological makeup of the thatch and soil environment.

POA ANNUA MANAGEMENT

Poa annua (annual bluegrass) is composed of two types: Poa annua c.v. annua, a true annual type, and Poa annua c.v. reptans, a perennial type. Both types are considered weeds in turfgrass stands. P. annua is the number one weed problem on golf courses in the northern United States. The annual type is managed mainly with pre-emergence herbicides, whereas the perennial type is primarily managed by post-emergence herbicides like the arsenicals. Neither chemical has been very successful in preventing the encroachment of P. annua into the species that were originally planted. In addition, the arsenicals are highly toxic compounds that present a hazard to both people and the environment. Xanthomonas campestris has been successfully tested under laboratory conditions for the management of P. annua. The bacterium infects the xylem tissue of the P. annua plant where it interferes with the uptake of water and nutrients. The infected plants wilt and die from the lack of water and nutrients. The bacterium is very specific for P. annua and all attempts to infect other grass species have been unsuccessful. The new biological control for the management of P. annua will certainly be safer for people to use, to play golf on after application, and safer for the environment. Hopefully, it will be more effective in managing P. annua than the pesticides that are currently being used.

ADVANCEMENT OF COMPUTER MODELS

More precise models for the prediction of disease development are being developed today because of advancements in computer technology and weather-gathering equipment. Most turfgrass diseases occur under certain environmental conditions, provided there is a susceptible host and a virulent pathogen present. The environmental parameters are: air temperature, soil temperature, soil moisture, leaf wetness, and relative humidity. Although not all of these environmental factors are involved in the development of every disease, at least two of them are involved in all disease development. Mathematical models to predict disease occurrence can be developed by measuring these factors, recording them over a period of time, and correlating them with disease outbreaks. These models can then be used to make more accurate fungicide applications based on environmental conditions, rather than applying them on a calendar or preventive basis.

Most golf course superintendents would like to apply fungicides at the most appropriate time to achieve maximum disease control for the least amount of money. This not only involves the money spent on fungicide, but labor cost to apply them, plus the wear and tear on the spray

equipment. Another consideration that has to be taken into account when applying pesticides is the environment. No one wants to put more pesticides into the environment than necessary.

COMPUTERIZED DISEASE MODELS

These disease models were developed by collecting hundreds of thousands of data points, analyzing them in various ways to determine which correlate best with disease development. This would be impossible to do without the use of a computer, which is one of the reasons effective disease prediction models have only recently been developed. Once the computer analyzes the data and it is determined which information is pertinent, a mathematical model is developed. This prediction model is first tested under controlled environmental conditions in the laboratory where appropriate adjustments are made. Then the prediction model is tested under field conditions for validity. It usually requires a minimum of two seasons, with three being preferred.

Once the model has been validated and any necessary corrections made, it is ready for the end user. This can be a time consuming process if the data must be collected from several different weather-measuring instruments, put into the formula and analyzed by the computer. However, if the model is placed in a microprocessor that can record all the weather and environmental data, analyze it and incorporate it into the model, then the task is much more quickly completed.

Although this sounds like science fiction from the 21st century, this technology is here today. Neogen Corporation's PestCaster has a Pythium blight model, an anthracnose model, and an annual bluegrass seedhead-emergence model. This microprocessor will collect the weather information, assimilate it into the models, and indicate when it is necessary to make a fungicide application.

ANTHRACNOSE DEVELOPMENT

Anthracnose, caused by Colletotrichum graminicola, is a devastating disease of annual bluegrass that can cause severe turf loss on golf course greens, tees, and fairways during the warm weather of July and August. To prevent this from occurring, golf courses normally treat their fairways three to four times a year on a preventive or calendar basis to prevent the disease from occurring. However, depending on location, anthracnose does not occur every year, nor do out-breaks occur all season long every year. Sometimes anthracnose outbreaks only occur once during a two to three month period in any summer. However, without a reliable system to predict the occurrence of anthracnose, the golf course superintendent has little choice but to treat the greens, tees, and fairways on a preventive or calendar basis. The same can be said about fungicide treatments for Pythium blight. It is too devastating a disease not to treat it on a preventive or calendar basis, unless one has access to an accurate predictive model. With these two models, fungicides can be applied only when needed, only when environmental conditions are present for disease development. This will result in more accurate treatment of these two diseases, more cost effective treatment of these diseases, and less fungicides being applied to the environment. This mathematical model was developed from over 150,000 individual data points. It has now been field tested for over six years. It has a 95% plus accuracy rate in predicting anthracnose outbreaks.

PYTHIUM BLIGHT MODEL

The second model is for Pythium blight, caused by Pythium aphanidermatium, which can be a devastating disease when it occurs. Pythium blight is a fast developing disease which can wipe out the majority of the turf on a golf course in a 24-hour period if environmental conditions for disease development are optimum. Because of this, most golf courses treat Pythium blight on a preventive basis. However, in many areas of the United States the disease does not occur every season. Even in areas where it does occur every season, it does not occur all season long. But, in an attempt to prevent Pythium blight from occurring and to maintain their jobs, often superintendents make unnecessary applications of fungicides. The use of the Pythium blight model can eliminate unnecessary fungicide application, reduce the cost of treating for Pythium blight, and reduce the amount of fungicides being applied to the environment. Other disease prediction models are being developed for other diseases, which will allow turf managers to apply fungicides only as needed for these problems as well. Hopefully, the day will come when all fungicides are applied based on disease models, which should reduce the cost of application by eliminating unnecessary treatments, while giving the desired level of disease control. This will also result in a significant reduction in the amount of fungicides being applied to the environment.

SUMMARY

Root pathogens like L. korrae and weeds like P. annua can now be managed biologically. Fungicides can be applied based on computer prediction models for diseases such as anthracnose and Pythium blight, which will reduce the amount of fungicides being put into the environment. The turfgrass area has already made great strides in reducing fungicide usage and, hopefully, this trend will continue in the future.

MANAGING THE SCARAB GRUB PEST COMPLEX IN TURFGRASS: SOME ECOLOGICAL CONSIDERATIONS

M. G. Villani and R. J. Wright
Department of Entomology
NYSAES/Cornell University
Geneva, New York 14456

INTRODUCTION

The scarab grub complex attacks a variety of crops in the Northeast including turf and grassy pastures, and woody ornamentals. The Japanese beetle, Popillia japonica Newman (JB), is the most abundant and widely distributed species of the group, but other important species include the European chafer, Rhizotrogus majalis (Razoumowsky) (EC), Oriental beetle, Anomala orientalis Waterhouse (OB), Asiatic garden beetle, Maladera castanea (Arrow) (AGB) and Northern masked chafer, Cyclocephala borealis Arrow (NMC). All species cause considerable damage as immatures and at least one, the Japanese beetle, causes heavy damage to a wide variety of agricultural and horticultural crops through adult feeding (41 and citations within). Historically, insecticides have been the major control tactic used against these insects, however, because many of the plants attacked by these grubs are grown in urban or suburban areas (golf courses, parks, home lawns and gardens, landscaping around commercial buildings) the potential for human exposure to insecticides through application or environmental contamination is great. Pesticide contamination of groundwater (from undetermined sources) has occurred in several areas of the Northeast (e.g., aldicarb, oxamyl and carbofuran on Long Island) and there have been instances of bird kills associated with use of diazinon on golf courses. Effective long-term control of the scarab grub complex was achieved with organochlorine and cyclodiene insecticides until their use was discontinued through insect resistance and government intervention; less consistent control has been achieved with organophosphate and carbamate insecticides (2, 45) and with a variety of biological agents (nematodes, fungi, bacteria and viruses) (27, 46, 49).

One reason for this inconsistency may be the lack of basic understanding in the interaction of the control tactic (chemical, biological or genetic), the cropping system, the target insect, and the soil physical and biotic environment (soil moisture, temperature, texture, compaction, and microbial flora etc). While each of these factors has been independently studied to varying degrees by basic and applied researchers, their interdependence has largely been ignored. If we assume that a combination of management tactics (IPM) will be required to effectively and safely manage scarab grubs in turfgrass in the future then the nature of specific interactions between target insect population(s), control agent(s) and the soil environment must be examined. In this chapter we will focus on the management of the scarab grub complex in turfgrass and discuss how 'ecological' approaches to this problem may help control scarab grubs more effectively.

SCARAB GRUB BEHAVIOR

C. R. Harris in reviewing the problems of controlling soil insects with insecticides in general (21) and soil insects in turf in particular (22) suggests:

> "During the past 20 years this problem (lack of efficacy of short residual insecticides in controlling soil insects) has received considerable attention and a number of factors have been shown to influence insecticide activity in the soil including: the physiochemical properties of the insecticide; soil and climactic factors; insect susceptibility to insecticides and insect behavior in the soil...a factor that has received little attention, other than in a very general sense, is the way insect behavior will influence the effectiveness of soil insecticides...for the immediate future, the most promising research possibilities are in the area of soil insect ecology. With greater comprehension of the factors influencing the behavior and development of soil insects, it would be possible to utilize insecticides far more effectively"

Much of the available literature on the impact of soil physical properties on the movement behavior of members of the scarab grub complex has recently been reviewed by Tashiro (41 and references within [1, 8, 11,12, 14, 15, 16, 17, 18, 19, 20, 24, 25, 35, 37 ,38, 43]) Although previous research has often been qualitative or anecdotal some interesting patterns do emerge. Briefly we would like to outline what is known about five species of scarab grubs (JB, EC, OB, NMC, AGB) which are of major economic importance in the Northeast and share similar life history patterns. All five species have somewhat similar seasonal patterns of vertical movement of grubs in response to gross temperature changes. After hatching, larvae feed at or near the soil surface from mid-summer to late fall. As surface temperatures cool grubs migrate down into the soil and overwinter as late instar larvae below the frost line. In the spring grubs migrate back to the surface again in response to temperature changes, complete feeding and move down again into the soil profile to pupate and eclose. Field observations indicate that EC grubs remain at the soil surface later in the fall and return to the soil surface earlier in the spring than do the other four grub species. Confounding this yearly temperature moderated movement pattern there may be more localized response to changes in soil moisture as well. Grubs have been reported to move deeper in the soil in response to decreasing soil moisture. Most of the observations concerning response to moisture are anecdotal. Even under 'favorable conditions' of soil moisture and temperature, field reports indicate that different grub species tend to be found at different soil levels; for example, EC and AGB tend to feed further below the soil surface than either JB or OB grubs. The differences in preferred feeding depths of different grub species have an effect on the types of plant tissues attacked. Grubs such as the EC, which feed for a longer period of time, have a greater potential effect per grub than do other grub species that leave the surface earlier in the fall and return later in the spring. AGB are normally less destructive than JB or OB grubs to turf, in part due to the tendency of these grubs to feed at greater depths which results in less damage (however due to their greater depth AGB may be much more difficult to manage with non-mobile chemical insecticides).

Information concerning the behavior of soil insects is anecdotal in most instances due to the difficulty in studying insect behavior under 'natural' conditions. There is a general perception that such research, if not impossible, is difficult, tedious, and cost ineffective when compared with similar studies of above ground insects. This attitude toward soil insect research has resulted in a situation where the soil ecosystem is treated as a 'black box' in which the consequences rather than the processes of insect behavior are measured. While there have been many studies looking at the movement of soil insects over long periods of time (3, 4, 5, 7, 10, 13, , 23, 29, 30, 31,) the studies

tend to lump the soil insects found in the top 5 cm as being at the surface layer. It is clear from insecticide movement studies in turfgrass systems that the details of grub movement within the top 5 cm over relatively short periods of time can have a profound effect on management.

Villani and Gould (44) have developed an x-ray technique that makes it possible to study soil insect movement and behavior within heterogeneous soil blocks.We have expanded this technique to include studies with several species of scarab grubs in larger arenas (up to 35 cm by 12 cm by 43 cm) and with field-collected soil blocks. Soil blocks retain their field characteristics (compaction, heterogeneity, endemic floral and faunal communities) and therefore allow for the careful monitoring and manipulation of the system for long periods of time. During the past year we have been gathering data from both simulated field soils (soil profiles created in the laboratory through the use of a variety of field soils) and actual field soil blocks extracted from turfgrass pasture plots (see 47 for details of experimental design and analysis for studies concerning radiographs outlined below).

Work in our laboratories with radiography indicates there is a species-specific response of scarab grub species to changes in moisture and temperature in the soil profile (47). These studies simulated the effects of irrigation and drought and temperature flux on populations of several scarab grub species. NMC, JB and OB and EC grubs all showed a strong trend for moving downward into the soil profile as soil moisture declined at the soil surface and turf root zone and movement back to the root zone when irrigated with the equivalent of 1 cm. of distilled water; EC grubs exhibited the least sensitivity to drying soil which may be related to their ability to rapidly escape from extreme conditions.

There were significant differences among grubs (EC, JB, and OB) in their responses to fluctuating temperatures. Shifts in soil temperature (decreasing from 20 to 5 C over 5 week period) had very little impact on the position of EC grubs. This relative unresponsiveness to temperature flux conforms to field observations (41, M. G. V. personal observations) which indicate that EC grubs are often found in the turf root zone well into early winter and early spring, and at times feeding in the root zone under snow if this zone is not frozen. In contrast, there was a marked response to shifting temperatures with the other two scarab species. JB grubs fed in the root zone in the stable temperature regime (constant 20 C) while in the shifting temperature regime grubs moved from the root zone downward with the onset of cooling soil (14 C) and returned to the surface as temperatures increased back up to 20 C. OB grubs appeared more variable but there was a clear population trend for grubs to remain at the root zone in the stable treatment (constant 20 C) and to respond to lower soil temperatures (8 C) by moving down into the soil profile . An increase in soil temperatures appeared to move a portion of the OB grub population back to the root zone while not affecting the median population value.

These studies demonstrate species-specific differences in scarab grub response to changing temperature and moisture conditions in simulated turf systems which conform to reported field reports. These differences involved both changes in the population median and the overall population distribution. Increased knowledge of species-specific movement patterns of scarab grubs in turfgrass in response to these and other soil environmental factors will have practical applications in developing more effective management systems for these soil insects in that they will help determine the probability of overlap of a specific grub species with a specific control agent in space and time, suggest depth to which sampling for grubs must occur in sampling and monitoring programs and indicate the 'hidden' population of grubs when sampling within the turfgrass root zone.

IMPACT OF IRRIGATION ON SCARAB GRUB BEHAVIOR AND INSECTICIDE MOVEMENT, PERSISTENCE, AND EFFICACY

Understanding the behavior of soil insects found in turfgrass is important considering the difficulty in moving soil insecticides down into the root zone of established turf. Physical factors that result in the movement of target insects as little as 1 cm into the soil profile may put these insects out of the effective active zone of chemical and biological control agents. Conversely, highly mobile soil insecticides will move beyond the root zone and will again be ineffective in controlling soil insect. Several studies (39, 28, 33) have shown that, unlike the cyclodiene soil insecticides, the less persistent organophosphate and carbamate insecticides degrade quickly, leaving little time for movement into the soil and roots. Diazinon applied to turf degrades so rapidly that < 1% of the original concentration is present in the root zone 14 days after treatment (39). Chlorpyrifos is considered one of the more persistent OP insecticides but Kuhr and Tashiro (28) found < 1% of the original concentration of this pesticide could be recovered from the thatch-root zone 56 days after application. These results indicate that there is a relatively narrow window in which turf insecticides can be applied to obtain consistent control. Niemczyk (32, also 33,34) reports that virtually no insecticide applied to turf for scarab grub control actually reaches the soil surface if appreciable levels of thatch are found at the surface. The generally low persistence, low solubility and high organic binding properties of soil insecticides labelled for turf insect control have led to a situation where soil insecticides may not be reaching the target population in the field.

It has been noted that soil insecticides are more effective in controlling scarab grubs in turfgrass when they are irrigated into the soil with at least 1 cm of water. It has been assumed that this irrigation helped move the active compound off the turfgrass and from the soil surface to the root zone where scarab grubs were feeding. Recent studies by Niemczyk (32) and Niemczyk et. al (34) suggest that little if any active material is moved into the soil through irrigation. A study (see 47 for detail on experimental design and analytic procedures) reviewed below, proposes an alternative hypothesis to explain increased insecticide efficacy with the use of irrigation: irrigation moves scarab grubs up to the surface rather than moving the insecticide down to the grubs in the soil profile.

Studies were conducted in plexiglass arenas (35 cm by 5 cm by 43 cm) filled with sieved loamy sand soil. Arenas were seeded with grass seed and ten third instar EC grubs were placed at the top of each arena; grubs which did not dig into the soil within 1 h were replaced. There were eight replications of each of the following treatments:

Treatment	Isofenphos (Oftanol 1.5G)	Amount of water added
1	2.24 kg (AI) per ha	50 ml (= 0.33 cm irrigation)
2	2.24 kg (AI) per ha	150 ml (= 1.0 cm irrigation)
3	none	50 ml
4	none	150 ml

Arenas were x-rayed at 0, 24, 96, 166, and 360 h posttreatment. Residue samples were taken at 24 h posttreatment from additional infested and treated arenas receiving treatments 1 and 2.

Grub condition (normal, moribund or dead) and location (depth below soil surface) was recorded at the end of the study (360 h posttreatment). Soil moisture was measured gravimetrically at this time by taking samples at intervals through the soil profile from all arenas. Residue samples were taken from the soil surface and at intervals through the soil profile of treated arenas and analyzed by standard analytic procedures.

The results indicate that there was little movement of insecticide past the 0-2.5 cm level of soil regardless of the irrigation applied (Table 1). There was a significant loss of active material (percent recovered) in the high moisture treatment after 360 h when compared with the dry condition. A significant portion of the insecticide recovered remained on the soil surface unavailable for insect control in both treatments. Percent control was identical in both treatments after 15 days. However, there was a higher proportion of morbid grubs in the higher moisture treatment; morbid grubs will die within 14 days in most cases (M. G. V., unpublished data). These results confirm that insecticides are not moving into the profile in response to simulated irrigation and suggest that grub mortality will be higher in high moisture plots despite lower total insecticide recovery.

Figure 1 shows the shift in the soil moisture profile for the high and low moisture treatments over the duration of the experiment. Twenty-four h after water was added to the low moisture arenas the percent moisture in the soil profile remained fairly uniform with a slight (but important) rise in the first 2.5 cm; the soil continued to dry up to 360 h when a strong moisture gradient was observed. Twenty-four h after moisture was added to the high moisture arenas there was a strong trend for decreased moisture with increased soil depth. Soil moisture remained uniformly high but there was a slight (but important) drop in the top 2.5 cm of soil. Data on grub position in each treatment (Fig. 2) were grouped at levels which are important with regards to the observed pesticide movement in the arenas (Table 1); 0-2.5 cm deep (high insecticide concentration), 2.5-5 cm and greater than 5 cm (no insecticide detected [< or equal to 045 ppm]). The following points can be made based on these data. First, addition of water brought grubs to the surface in all treatments (data at 24 h). Second, the activity of the insecticide (as indicated by the general lack of grub movement in response to changing soil factors when compared with non-treated boxes) becomes apparent in both moisture regimes between 96 and 166 h. There is a slight difference in grub population distribution within moisture regimes between control and treated arenas. Third, differences in grub population distribution between moisture levels in the control arenas begin to occur at 96 h ; i.e., grubs in low moisture control arenas begin to move down in the profile while those in high moisture regime remain near surface, potentially in contact with insecticide. And finally, grubs in high moisture control plots begin to respond to a slight decline in soil moisture at 166 h. Note that moisture levels at 360 h in these arenas are greatest in the greater than 5 cm level. Clearly soil moisture flux within the profile had a profound effect on both insecticide persistence and EC grub movement patterns in this study and these effects influenced the efficacy of isofenphos in the soil.

SPECIES-SPECIFIC SUSCEPTIBILITY OF SCARAB GRUBS TO TURFGRASS INSECTICIDES

Many factors, including soil pH, organic matter, moisture, thatch, insect behavior and microbial degradation of insecticides influence the efficacy of currently registered insecticides, (6, 21, 22, 28, 33, 36, 42, 47, 48). One factor contributing to the variable control of scarab grubs in the field is the presence of mixed-species populations of grubs, which may exhibit species-specific insecticide susceptibilities. Although field insecticide efficacy studies against mixed populations of scarab grubs have been reported (e.g.,9, 50), significant treatment effects can be demonstrated only for the most abundant grub species,because secondary species are often present at low densities and

their distribution is patchy. Previous work by Baker (2) has demonstrated among- and within-species variation in susceptibility of New York populations of Japanese and Oriental beetle larvae to chlorpyrifos, bendiocarb and isofenphos. Additional research in New York State (45) was done to provide more information on the susceptibility of three economically important scarab grub species to five currently labelled turf insecticides (diazinon, chlorpyrifos, isofenphos, bendiocarb and ethoprop). This laboratory study indicated that, in general, EC grubs are less susceptible to soil insecticides than the other two scarab grub species (Table 2). This finding agrees with reports from extension agents and turfgrass and sod producers in New York State. Several statistically significant interactions were found which indicated the need to study each species-insecticide combination separately. The most striking insecticide - scarab grub species interactions involved diazinon and chlorpyrifos. Diazinon provided good control of OB and EC grubs, but very poor control of JB larvae. However, chlorpyrifos provided good control of JB and OB, but very poor control of EC grubs. Since behavioral differences among grub species (i.e., their characteristic position in the soil profile in the field which may influence exposure to insecticides) have been eliminated in these studies, differential mortality of JB and EC grubs to diazinon and chlorpyrifos may reflect species-specific tolerances to these compounds (if testing of additional populations give similar results) or localized insecticide resistance. The relatively low level of mortality observed with all grub species in the isofenphos treatments may be attributed to a number of causes including: loss of activity of the compound through microbial degradation due to an 'activated' test soil, insufficient initial product, and insufficient time for mortality to be apparent; discrimination tests undertaken in future studies should be done with higher rates of this product. Ethoprop treatments induced uniformly high mortality with all scarab grub species tested indicating either similar tolerance to this material or application rates too high for discrimination among species.

The results of these studies indicate the need to develop species-specific insecticide recommendations for the scarab grub complex, and to encourage those responsible for insecticide use in turf to be aware of the scarab grub species present in their areas. Although single species infestations occur in some areas of New York, mixed populations of JB and EC grubs (western section of state) or JB and OB grubs (Long Island) and other scarab grub species are the rule rather than the exception. Our results suggest that, with some insecticides (e.g., diazinon and chlorpyrifos), intermediate levels of control of the overall scarab grub population may reflect high mortality of one species and little or no mortality of one or more co-existing species. Depending on the relative abundance of each species at a given site, percent control achieved with each insecticide may vary widely. Differences in insecticide susceptibility among species of the scarab grub complex need to be considered, as well as the possibility of insecticide resistance, microbial degradation, or inadequate application procedures, as a possible reason for control failures after use of turf insecticides.

BIOLOGICAL CONTROL OF SCARAB GRUBS: PATHOGEN/INSECT INTERACTIONS

Development of biological controls for soil insects such as scarab grubs would provide an alternative to the use of chemical insecticides and would alleviate many of the problems associated with insecticide use (development of insecticide-resistant pest strains, environmental pollution). We have found it useful to group pathogenic agents used to control soil insects in turf based on their mobility and their reproductive behavior. The first are agents that interact with the soil environment and the target species much like a soil insecticide, an example of this type of agent is Bacillus thuringiensis (Bt) toxin. The material is non-mobile (passive movement through profile only)

and non-replicating, therefore contact between toxic agent and target insect is determined by passive movement of the agent and activity of the target. The second class of control agents are those that are non-mobile but replicating (e.g. Bacillus popilliae, Beauveria bassiana and Metarrhizium anisopliae). Unlike soil insecticides and Bt, the behavior of the target insect is vitally important to the spread of the pathogen: infected grubs, which respond to environmental conditions and/or pathogen induced aberrant behavior, may move the control agent out of the range for effective control by moving the site of agent replication outside of the normal range of the target or the optimal range of agent replication. If for example scarab grubs infected with milky disease move down into the soil profile in response to environmental conditions and then die, this movement would effectively reduce milky disease spore levels from the upper soil profile. Since it is only in the upper profile that grubs would be actively ingesting spores (needed for infection) and where soil temperatures are sufficient for spore replication (see 41) this movement would effectively halt significant disease spread and insect control. Finally, there are those agents that are both mobile and replicating such as entomogenous nematodes (e. g. Steinernema feltiae) which have been discussed at length in previous chapters of this book (insect parasites and predators can be generally included in this third class of agent). These agents are interesting ecologically because infection and replication depend on the interaction of the soil environment on both agent and target. Initial infection and subsequent spread through the target population depends upon the overlap of agent and target in both space and time within the soil environment. We believe that this class of control agent has great potential for controlling soil insects when incorporation of control agent is not possible (47, 49).

CONCLUSIONS

The relative lack of success in predicting scarab grub damage in turfgrass and the costs involved in achieving satisfactory control dictates a more systematic and comprehensive research effort. Paramount to such an approach is the ability to monitor grub response to static and dynamic soil factors and to manipulate these factors to determine changes in insect response. Understanding the fundamental differences in behavioral response among the various grub species within the complex to a variety of typical soil factors will enhance our ability to predict the stress each species will inflict in turf and other horticultural plant species. An understanding of the interaction of the control agent (biological or chemical),with the target insect species and with the soil environment will lead to changes in current management practices which will allow for greater overlap in agent and target leading to a greater potential for effective management.

TABLE 1

Residue analysis and effect on EC larvae of surface applications of isofenphos (Oftanol 1.5G) under two different moisture regimes.

		Isofenphos residues				EC larvae	
Treatment	Time (h)	Depth (cm)	ppm	% Recovered	% on surface	% Control	% Normal
Dry	24	0-2.5	2.78	62.50			
		>2.5	ND[a/]				
Moist	24	0-2.5	1.92	74.00			
		>2.5	ND				
Dry	360	0-2.5	2.67	65.25	47.38	28.4	56.8
		>2.5	ND				
Moist	360	0-2.5	1.07	26.75	47.53	28.4	33.3
		>2.5	ND				

a/ ND = non-detectable (≤ 0.045 ppm).

Source:Villani and Wright (1988b)

TABLE 2

Efficacy of five turf insecticides against last stage larvae of three scarab grub species in a laboratory soil bioassay; insecticides were incorporated into soil at one-half labelled rates. Analysis of variance of percent control (angular transformed) of grubs after five weeks indicates significant differences among insecticides (df=4, F= 13.201, P < 0.001) and grub species (df=2, F=6.066, P < 0.01). There was also a small but significant insecticide by grub species interaction (df=8, F=3.255, P < 0.05).

Treatment	Percent Mortality		
	OB	JB	EC
Chlorpyrifos	74	91	21
Bendiocarb	75	70	37
Ethoprop	100	99	95
Diazinon	93	25	78
Isofenphos	26	38	11

Source: Villani et. al. 1988

FIGURE 1

Soil moisture profile for high and low moisture treatments at beginning and end of study of interaction of soil moisture and isofenphos persistence and efficacy against scarab grubs. Histogram bars indicate (left to right) % moisture at the 0-2.5, 2.5-5.0, 50.-7.5, 7.5-15.0, 15.0-22.5 and 22.5-30.0 cm soil depths.

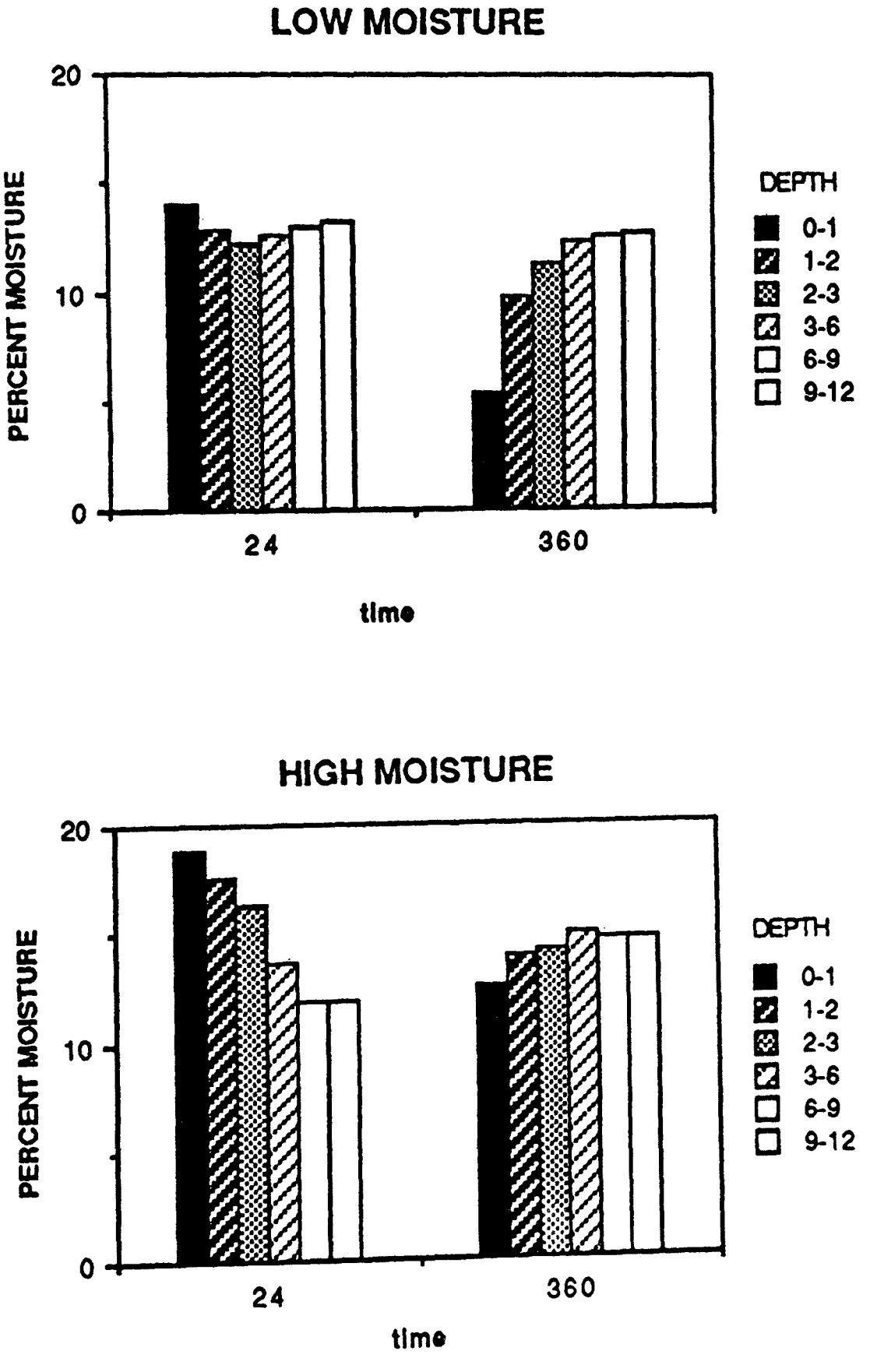
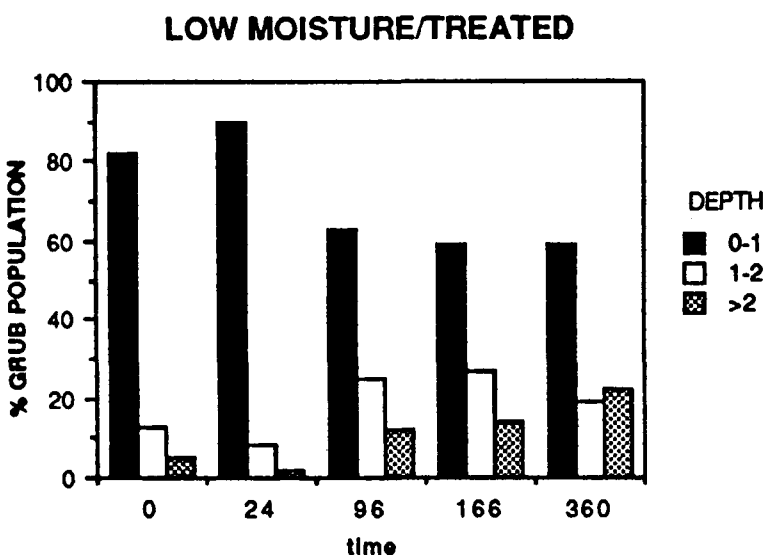
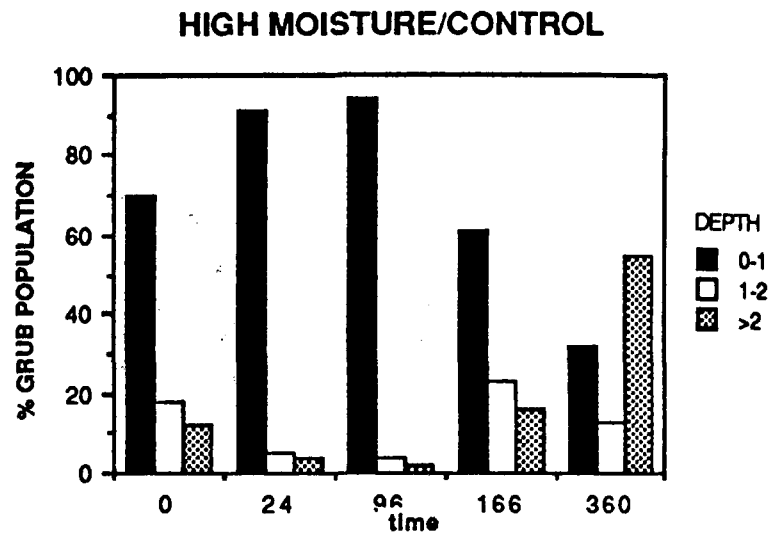
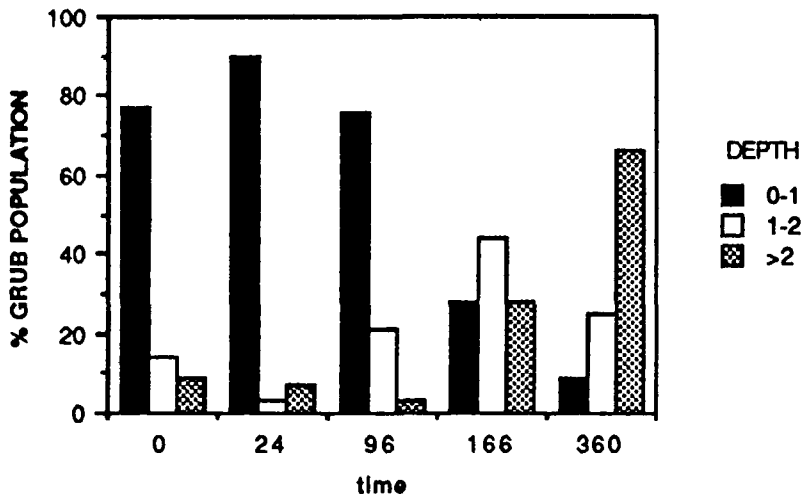


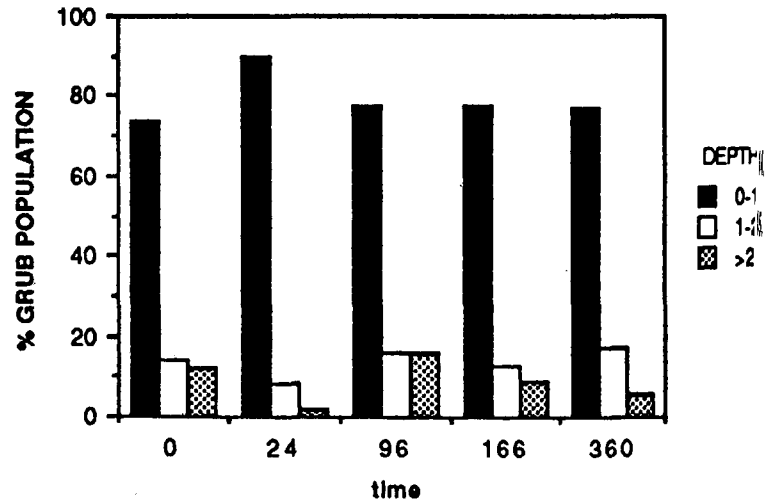
FIGURE 2

The distribution of EC grub populations in arenas maintained at high and low moisture levels with and without addition of isofenphos to the surface. Histogram bars indicate (left to right) percent of EC population at the 0-2.5, 2.5-5.0 and greater than 5.0 cm depth.









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INFLUENCE OF FERTILIZATION AND IRRIGATION PRACTICES ON WATERBORNE NITROGEN LOSSES FROM TURFGRASS

A.J. Gold, W.M. Sullivan, and R.J. Hull
Departments of Natural Resources Science and Plant Sciences
Contribution Number 2445 From the Rhode Island Agric. Exp. Sta.
University of Rhode Island
Kingston, RI 02881

INTRODUCTION

Nitrogen constitutes the largest chemical input routinely applied to well maintained turf. Nitrogen fertilizers are applied in a variety of forms, ranging from slow release types, such as methylene urea, to quick release formulations, such as ammonium nitrate. Regardless of the formulation applied, nitrogen not taken up by growing plants or soil microorganisms is readily transformed to nitrate-nitrogen. Figure 1 summarizes the nitrogen cycle in a turfgrass environment. Nitrate-nitrogen is a mobile anion that has the potential to move rapidly from the rootzone to the groundwater. Percolation of water from the rootzone is the major pathway for water discharged from turfgrass (Morton et al. 1988). Several researchers have found that selected fertilization and irrigation practices can generate substantial leaching of nitrate-N from the rootzone of turfgrass (Owen and Barraclough, 1983;Rieke and Ellis, 1974; Morton et al., 1988).

Nitrate-N is a drinking water contaminant with a U.S. Drinking Water Standard of 10 mg/L (USEPA, 1976). Nitrogen inputs to coastal bays and estuaries, such as the Chesapeake Bay, have been found to accelerate eutrophication. Water quality degradation can result from concentrations of nitrogen much less than the drinking water standard of 10 mg/L (Ryther and Dunstead, 1971).

Various turfgrass management strategies have been evaluated for their capacity to reduce nitrogen leaching losses from turfgrass. In this chapter, several options will be highlighted:

- Nitrification inhibitors to slow the formation of the mobile nitrate anion.
- Irrigation scheduling to reduce leaching to groundwater.
- Fertilizer source selection to minimize the pool of nitrate in the rootzone.
- Fertilizer application rate and timing to optimize plant uptake.

Our discussion will concentrate on practices typically used to manage home lawns or turf used for outdoor recreation.

NITRIFICATION INHIBITORS

Most nitrogen fertilizers and all natural processes of organic matter cycling introduce nitrogen into the soil solution in the ammonium form (Figure 1). This reduced cationic nitrogen is immobilized on cation exchange sites in the soil and readily absorbed by microorganisms and plant roots. Consequently, ammonium is not readily leached from the soil even when appreciable hydraulic flux

occurs. Hesketh (1986) generally found less than 1.0 mg/L of ammonium-nitrogen in the soil solution collected in suction lysimeters from the root zone (20 cm depth) of Kentucky bluegrass turf. At the same time, soil solution nitrate-nitrogen often exceeded 20 mg/L. It appears that if the transformation of fertilizer nitrogen to nitrate-N could be inhibited and nitrogen retained in the ammonium form, the potential for nitrogen loss through leaching would be minimized.

In field crop production, nitrification inhibitors have been used successfully to stabilize ammonium-nitrogen and increase nitrogen use efficiency (Huber et al. 1969; Prasard 1976; Warren et al. 1975). In these studies, the inhibiting compound was mechanically incorporated into the soil usually with the nitrogen fertilizer. Nitrification inhibitors used to improve the nitrogen use efficiency of turfgrass have yielded few positive results. Waddington et al. (1975) found no benefits from including the nitrification inhibitor nitrapyrin (2-chloro-6-(trichloromethyl) pyridine) with nitrogen fertilizers applied to turf. Hesketh (1986) evaluated nitrapyrin at two rates, terrazole (3-ethoxy-3-trichloromethyl-1,2,4-thiadiazole) and DCD (dicyandiamide) for their ability to enhance nitrogen use efficiency in urea-fertilized Kentucky bluegrass turf. Turf quality, clipping yield, clipping nitrogen content, and the nitrate and ammonium concentration in soil water were measured. No consistent evidence of improved nitrogen uptake was obtained when nitrification inhibitors were present.

In these studies, fertilizers and inhibitors were applied to the surface of turf and washed into the sod with irrigation water. No mechanical incorporation of the inhibitors into the soil was attempted nor has any practical way of accomplishing this in established turf been proposed. Because nitrogen leaching appears to be minimal on urea fertilized turf (Hesketh, 1986; Hull et al., 1987; Morton et al., 1988) nitrification inhibitors may not generate substantial effects. However, because there was no evidence of delayed nitrification when urea was applied with an inhibitor, Hesketh (1986) concluded that the inhibitors probably were adsorbed in the overlaying thatch and never reached the soil depths where nitrification was most active.

To determine if nitrification inhibitors can be effective in stabilizing ammonium-nitrogen when nitrogen fertilizers are applied at the time of turfgrass seeding, nitrapyrin and DCD were disked into the soil along with urea just prior to seeding Kentucky bluegrass (Hull et al. 1988). All parameters measured exhibited a beneficial response to DCD, applied alone or combined with nitrapyrin, but no response from nitrapyrin was noted. The nitrogen recovered in late season turfgrass clippings doubled in response to DCD incorporation but this constituted only 10 percent of the fertilizer nitrogen applied. It appears that the potential for nitrate leaching at the time of turfgrass seeding is significant. However, it can be reduced somewhat by incorporating a water soluble nitrification inhibitor.

IRRIGATION SCHEDULING

The potential for off-site nitrate-N losses depends on the concentration of nitrate in the rootzone and the frequency and quantity of water percolation through the soil profile. Irrigation has been shown to significantly increase nitrate-N leaching (Snyder et al., 1984; Endelman et al., 1974). Morton et al. (1988) found that overwatering increased nitrate nitrogen transport to the groundwater six fold from turfgrass, independent of fertilization rates. Home lawns are typically watered with little regard for soil moisture status or the water holding capacity of the soil. Where irrigation is automatically controlled with timers on permanently installed systems, rates are often selected to meet maximum evaporative demands, regardless of weekly rainfall and climatic conditions (Snyder et al., 1984). Excessive watering will increase antecedent soil moisture, thereby promoting additional leaching from natural storm events or from the supplemental water alone.

Supplemental water should be added judiciously in metered quantities to avoid drought stress and to reduce losses from the rootzone to the groundwater. Efficient scheduling of irrigation water requires an understanding of soils, plant physiology, and meteorology. Several approaches are used to determine when turfgrass is in need of irrigation:

- Direct measurement of soil moisture status,
- Direct measurement of plant water status, and
- Estimation of cumulative evaporative demand from evaporation pans or climatic data.

Soil moisture measurements can be obtained with inexpensive tensiometers placed 7 to 15 cm into the rootzone. In a given climate, plants have been found to exhibit drought stress at the same soil moisture tensions, regardless of soil texture. As soil dries the soil water tension increases. At a predetermined "critical tension" irrigation is initiated. Studies relating drought stress to soil moisture tensions have been performed on a range of turfgrass species. In a greenhouse experiment, Aronson, et al. (1987) found that fine-leaved fescues could maintain acceptable quality at tensions greater than 1 bar, while Kentucky bluegrass quality was found to decline markedly after the soil had reached 0.6 bars. To reduce unneeded irrigation and avoid drought injury, additional research is required to establish critical tensions for other turfgrass and grass mixtures.

Recently, Throssell et al. (1987) have suggested monitoring canopy temperature with an infrared thermometer to detect plant water stress. Several researchers have found that canopy temperature in turfgrass increased in response to drought stress. Other researchers have established the relationship between evapotranspiration from well watered turfgrass and moisture use predictions based on climatic measurements (Aronson et al. 1987; Pochop et al., 1977). Daily tabulation of the expected water loss along with soil moisture characteristics of a particular site can generate estimates of soil moisture status and critical tensions.

Determining the appropriate depth of irrigation is essential to avoid excess water draining from the rootzone. The proper application depth of water requires knowledge of the upper and lower limits of the available water in the soil and the depth of the rootzone. The lower limit of available water in the soil is the amount that can be extracted from the rootzone by turfgrass before drought stress occurs. Field capacity, the upper limit, is the soil water content that occurs after all gravitational water has drained from a previously saturated soil. Ideally, enough water should be applied to bring the entire rootzone to field capacity without promoting percolation. Since cultivated turf has a shallower rootzone than commonly irrigated field crops, drought stress may occur earlier in turf, while percolation from the rootzone could occur from the application depths used in field crop irrigation. Most of the data necessary to develop recommended application depths is available; however, the information needs to be evaluated and tailored to turfgrass.

FERTILIZER SOURCE SELECTION

Synthetic fertilizers, manures, animal and plant residues, by-products and a host of other materials can supply nitrogen to the turfgrass plant. The requirement for continued access and utilization of turf requires that turfgrass fertilizer products be easy to handle, of uniform quality, inconspicuous after application, readily effective, and impart no offensive odor. The general visual and functional expectations of modern turfgrass management practically eliminates use of non-processed fertilizer materials (Beard, 1973). The choice of one fertilizer over another traditionally has been based on turfgrass performance ratings (Waddington and Duich 1976; Wilkinson 1977; Nelson 1980). More recently, nitrogen loss to the environment has been considered (Snyder et al. 1981; Wesely et al. 1988)

Turfgrass management practices employ N fertilizer products that belong to three general classes. They are the synthetic inorganic, synthetic organic and natural organic nitrogen sources (Table 1). The differing properties of nitrogen containing fertilizers determine where and when the fertilizer N enters the soil nitrogen cycle (Figure 1).

Turfgrass fertilizer management ideally provides plant available nitrogen in the soil solution as plant demand arises. Turfgrasses absorb most nitrogen as nitrate, however ammonia which is less abundant in the soil solution is also absorbed. The three classes differ in the rate at which the applied N becomes available to the growing plant. The transformation of the fertilizer product to absorbed plant nutrient may involve only dissolving the fertilizer product in soil water or it may be dependent on exacting soil water, aeration, temperature and microbiological conditions (Hays and Haden, 1966).

The concept of nutrient release period refers to the rate with which the fertilizer increases the ammonium and nitrate concentration in the soil solution. The 'fast' or 'quick' release products are generally soluble salts and contain N in the ammonium or nitrate form at application.

The 'slow' or 'controlled' release fertilizer products require additional physical, chemical and/or biological processing after application for the nitrogen to reach the water soluble form required for plant utilization. These products range from urea and urea solutions to sulfur or resin coated urea to complex polymers of urea and formaldehyde. Barriers to solubilization and transformation are achieved through a number of different methodologies. Nitrogen release and transformation of these products will vary with the polymer length, coating thickness and integrity, and the environmental conditions into which they are placed. Sulfur coated urea and similar coated products such as OsmocoteR, have coatings of limited or reduced permeability that restrict the movement of water and nutrient from the granule. Methylene urea and urea formaldehyde are low molecular weight compounds that require microbiological activity to mineralize the nitrogen. IBDU (isobutylidene diurea) has controlled release properties due to its chemical structure and the particle size of the product used. These 'slow' release synthetic organics produce their metered solubility characteristics and reduced nitrification rates via different mechanisms. The methylene-ureas, IBDU and SCU products have solubility characteristics that are inversely proportionally to molecular weight and granule size (Hays and Haden, 1966; Hughes, 1976).

The major source of the natural organic fertilizer class is activated sewage sludge. The best known product comes from the Milwaukee municipal system and is called MilorganiteR. Milorganite and comparable materials contain the nitrogen in complex organic molecules. The rate of N release is dependent on the microbiological activity in the soil. The predominant factor influencing N release from this fertilizer class is soil temperature and aeration. The rate of N availability to the plant is regulated by soil temperature as it effects mineralization and subsequent nitrification by soil microbes.

The N in synthetic inorganic products, for example, ammonium nitrate, calcium nitrate, and ammonium sulfate, is water soluble, rapidly available to plants and highly susceptible to leaching. Synthetic inorganic N fertilizers have generated excessive N losses to the groundwater (Bredakis and Steckel, 1963; Brown et al. 1977; Snyder et al. 1981). Nitrate-N concentration up to 200 mg/L and total losses of over 15 percent of the applied fertilizer have been reported from turf fertilizers with synthetic inorganic N (Brown et al. 1977).

In contrast to synthetic inorganic fertilizers, the natural and synthetic organic products have been found to generate very low N losses to the groundwater. Bredakis and Steckel (1963), Snyder et al. (1981), Starr and DeRoo (1981) and Brown et al. (1982) all document limited release of nitrate-N from synthetic organic product used in the turfgrass environment. The highest nitrate-N

concentration leaving the turfgrass rootzone were 2 and 18 mg/L when ureaformaldehyde and activated sewage sludge were applied in a study conducted by Brown and colleagues (1977).

The most common nitrogen form now used for turfgrass fertilization are the synthetic organic products. Urea is the most common N source of the synthetic organic class. Turfgrass response is excellent and off site losses are low when urea is used as the N source. Mean annual nitrate-N concentration below the turfgrass rootzone following urea application never exceed 6 mg/L in studies conducted by Morton et al. (1988) or Wesely et al. (1988).

APPLICATION RATES AND TIMING OF FERTILIZER

Unlike field crops, annual fertilizer applications to turfgrass can be easily split and applied in small increments throughout the growing season. In the Northeast U.S., commercial lawn care companies almost exclusively use urea or urea formaldehyde as the nitrogen source. Applications may occur monthly, from late spring through late summer, with a final large application in late fall. Morton et al. (1988) found no evidence of increased nitrate-N leaching following late fall or late spring applications of urea/urea formaldehyde. In the late fall, the cool temperatures slow the enzymatic hydrolysis of urea to ammonium and the subsequent biological oxidation of ammonium to the mobile anion nitrate. Plant uptake may match the generation of ammonium and nitrate, reducing the pool of leachable N in the rootzone. More research is need to define the relationship between the rates of nitrate production and uptake by roots. The lack of nitrate-N in soil leachate following late spring applications of urea may result from the vigorous turf growth that occurs during this period. Plant uptake may be well suited for absorbing moderate nitrogen applications at this time of year. Again, we believe research on turfgrass nutrient budgets is essential to fully understand this situation.

Morton et al. (1988) observed high concentrations of nitrate-N in soil water leachate following late summer applications of urea. Cisar (1986), through analysis of leaf growth and N content of clippings, found that N uptake by Kentucky bluegrass declined in late summer. Applying nitrogen fertilizer when plant uptake is reduced could generate excessive amounts of soluble nitrogen in the rootzone and could increase the potential for waterborne nitrogen losses from the rootzone.

A dense turfgrass sod constitutes a substantial sink for topically applied synthetic organic nitrogen. This was dramatically demonstrated by Hull et al. (1987) when urea was applied as a single treatment at 288 kg N/ha to five turfgrass species during mid-May. Over the next four months, the nitrate-nitrogen content of soil water collected at a 60 cm depth never exceeded 1.0 mg/L. During the growing season, less than 0.4 kg N/ha leached from these plots while 58 percent of the applied nitrogen was recovered in clippings.

However, the soil water from Kentucky bluegrass plots which had received over 350 kg N/ha/year as urea for 14 years sometimes contained more than 10 mg N/L below the root zone and more than 50 mg N/L within the rootzone (Hesketh, 1986). At this high fertility level, approximately 22 kg N/ha were lost through leaching during the growing season which was equivalent to 6 percent of the nitrogen applied. It appears that the rate of nitrogen application may influence the quantity of nitrate leaching from turfgrass sod, but this is most likely to be a problem with turf that has been subjected to long term intensive fertilization rates.

CONCLUSIONS

Because no significant crop is removed from a turfgrass sod unless the clippings are collected, there is little mechanical or cultural nitrogen loss. If fertilizer nitrogen is repeatedly applied at elevated rates (greater than 200 kg/ha/year) the soil-plant system may become "nitrogen saturated" and generate substantial nitrate leaching. To reduce the potential for groundwater contamination, turf managers would be well advised to maintain their grass with less than 150 kg/N/ha/year, to utilize slow-release organic formulations, and to carefully control supplemental irrigation.

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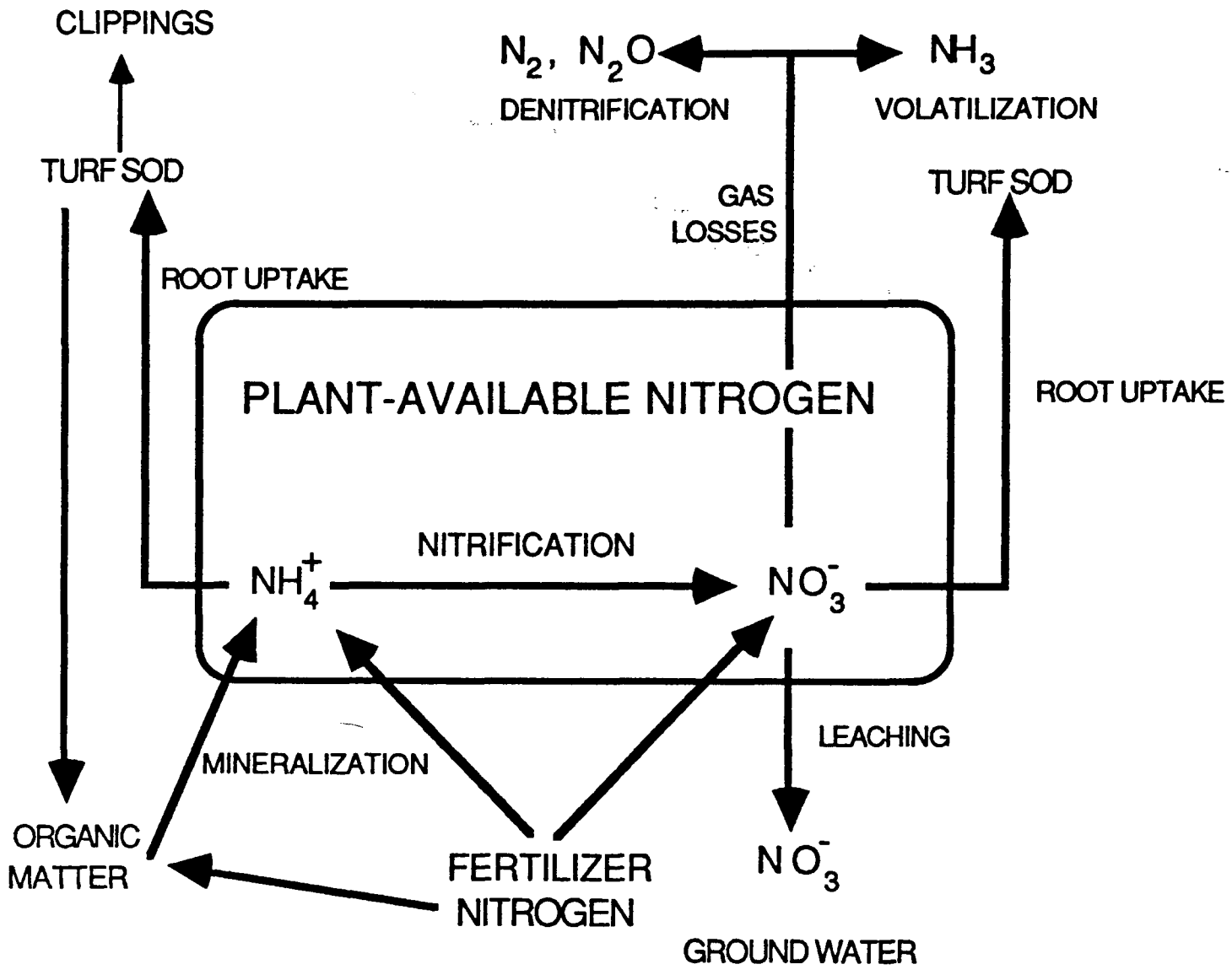
TABLE 1

Classification, burn potential, leaching potential, low temperature response and residual effect of common turfgrass nitrogen sources.

Fertilizer Source	N content %	Burn Potential	Leaching Potential	Low Temp Response	Residual Effect
Synthetic Inorganic					
Ammonium nitrate	34	High	High	Rapid	Short
Calcium nitrate	16	Very High	High	Rapid	Short
Ammonium sulfate	21	Very High	Mod. High	Rapid	Short
Synthetic Organic					
Urea	45	High	Mod. Low	Rapid	Short
Urea solutions	30	High	Mod. Low	Rapid	Short
Sulfur coated urea	35	Low	Low	Moderate	Moderate
Isobutylidene diurea	30	Low	Mod. Low	Moderate	Moderate
Methylene ureas	42	Low	Low	Low	M-Long
Ureaformaldehyde	30	Low	Low	Low	Long
Natural Organic					
Activated sewage sludge	6	Very Low	Very Low	Very Low	Long

FIGURE 1
Turfgrass Nitrogen Cycle



SURFACE RUNOFF FROM TURF

M. S. Welterlen
Grounds Maintenance Magazine
P.O. Box 12901
Overland Park, KS 66212
formerly, Dept. of Agronomy
University of Maryland
College Park, MD 20742

and

C.M. Gross, J.S. Angle, R.L. Hill
Department of Agronomy
University of Maryland
College Park, Maryland 20742

Nonpoint source pollution of waterways has received considerable attention in recent years as a result of a decline in water quality of these waterways and subsequent declines in desired resources derived from them. In assessing the impact of nonpoint source pollution of waterways the quality and quantity of surface and ground water emanating from various aspects of the watershed must be critically evaluated.

Sensitive areas such as the Chesapeake Bay, which is one of the most productive estuaries in the world, are particularly vulnerable to impacts by actions throughout their watersheds. Watersheds such as the Chesapeake Bay are comprised of various land uses such as forestation, urbanization and crop production. Surface characteristics as well as fertilizer and pesticide loading on these areas have been shown to affect the quality and quantity of water emanating from the watershed. Consequently, land use has been more critically reviewed in sensitive areas in recent years.

Urbanization with associated suburbanization has increased dramatically in the Northeast United States. Urbanization results in an increase in impervious surfaces which accelerate surface runoff from watersheds. In addition, an increase in the amount of turf acreage has also occurred with urbanization as residential lawns, parks, highway roadsides and other turf areas are established. Surveys conducted by the Maryland Department of Agriculture (1987) indicated an increase in Maryland turf acreage from 346,871 in 1979 to 614,024 in 1986. The increase in turf acreage has prompted public concern as to ecological impacts of turf management, since turf makes up a growing proportion of the watershed in urban areas.

This chapter will discuss research relating to the effects of turf on surface water movement. A discussion of the effects of turf on ground water quality is included elsewhere in this text.

PHYSICAL CHARACTERISTICS OF TURF

Turf is composed of many closely spaced individual plants that form a closed canopy over the soil surface. Turf density, leaf texture and turf canopy height are primary physical factors relating to dissipation of impact energy of rain droplets and resistance to surface movement of water over turf. Approximately 80 percent of the extensive fibrous root system of turfgrass is located in the

upper 5 cm of soil. The protective nature of both the turf canopy and the root system are responsible for the soil stabilizing effects of turf.

Turf density varies depending on inherent characteristics, environmental conditions and management. Creeping bentgrass (Agrostis palustris Huds.) which is used as an intensively managed turf, may exhibit density as high as 1,700 plants dm-2, whereas Kentucky bluegrass (Poa pratensis L.) density may be as low as 100 plants dm-2 and tall fescue (Festuca arundinacea Shreb.) less than 100 plants dm-2 (Beard, 1973). Cultural factors that increase shoot density include close mowing, adequate moisture and nitrogen fertility (Roberts, 1965).

Leaf texture refers to the width of turfgrass leaf blades and varies among turfgrass species and varieties (Table 1) as well as management and seeding rate (Table 2). In order to maintain turf uniformity, seeding mixtures are formulated with turfgrasses of compatible texture.

Optimum canopy height of maintained turf depends on the species and intended use. Residential lawns are typically maintained at heights ranging from 2 to 8 cm. Highway roadsides are generally maintained at 8 to 13 cm, and golf course fairways are mowed at 1.3 to 3.8 cm depending on the species.

RUNOFF CHARACTERISTICS OF TURF

Research conducted on the effects of grasses, in general, and turfgrass, in particular, on surface runoff has been documented, and more research is currently underway. Numerous studies have shown that grass buffer strips are quite effective in reducing runoff and the sediment and nutrients carried with it (Gross et al., 1987; Hayes et al., 1978; Tollner, et al.,1977; U.S. E.P.A., 1983a and 1983b; and Young et al., 1980). Most of the work conducted over the past 25 years pertaining to the pesticide content of surface waters draining from agricultural fields has been reviewed by Pionke and Chesters (1973) and Wauchope (1978). In cases where water quality has declined due to nutrient and pesticide movement in water or eroded sediment, the use of grassed buffer strips between treated fields and the receiving bodies of water have significantly reduced the problem. The Cooperative Extension Service in the Chesapeake Bay area currently recommends the planting of grass filter strips as well as natural vegetation filter areas for reducing runoff from field crops (Extension Services of the Chesapeake Basin, 1985). Doyle, et al. (1977) evaluated the effectiveness of forest and grass buffer strips in improving water quality of manure polluted runoff. The authors determined that both forest and grass buffer strips of approximately 4 meters were found to be effective in reducing levels of fecal bacteria from manure treated plots. Total soluble NH4-N, NO3-N, P and K levels were also reduced by the buffers.

Studies relating to surface runoff from turf are currently underway at the University of Maryland (Gross et al, 1988, unpublished data). Another study conducted on a Sassafras sandy loam with a slope of 8% at the University of Maryland (Gross et al, 1988, unpublished data), evaluated the effects of rainfall intensity and turfgrass seeding rate (density) on runoff initiation time, runoff rate and sediment loss. Three rainfall intensities (3.0 inches per hour, frequency of once every two years; 3.7 inches per hour, frequency of once in every 5 years and 4.7 inches per hour, frequency of once in every 20 years) were imposed with a rainfall simulator. Under a rainfall intensity of 4.7 inches per hour, runoff rate was reduced by 50% with tall fescue, seeded at 10 lb. per 1,000 sq. ft. one year prior to testing, in comparison to bare ground (Fig. 1). Runoff initiation time was positively correlated with rainfall intensity and seeding rate (Fig. 2). Under a rainfall intensity of 3.7 inches per hour, sediment loss was reduced from 1.1 g m-2 min-1 (bare ground) to 0.1 g m-2 min-1 (on turf originally seeded at 10 lb. seed per 1,000 ft.-2) (Fig. 3). Researchers in Pennsylvania (Harrison et al, 1988)

showed that only 5% of applied water (6 in./hr) ran off slopes with Kentucky bluegrass sod, whereas approximately 20% of applied water ran off slopes established by seeding. Consequently, by sodding critically-sloped areas during initial stages of construction, runoff can be further reduced. These studies indicate general trends in the effects of turf and rainfall intensity on surface water and sediment movement; however, it is important to note that specific values may vary depending on soil type, terrain, turfgrass species, turf quality and naturally occurring rainfall in the area.

Research conducted by the University of Maryland (Gross, et. al. 1987) at the Chesapeake Bay Foundation Research Farm in Upper Marlboro, Maryland showed that surface water runoff volume, sediment loss, total N movement and phosphate movement were dramatically lower in turf in comparison to conventional tobacco (Table 3) under natural rainfall. Under simulated rainfall intensities, turf was also shown to be superior to corn in terms of stabilizing soil (Table 4). With an intense rainfall occurrence of 4.7 inches per hour, turf was 133 times more effective in stabilizing soil in comparison to corn. These studies also indicated that annual runoff volume from tall fescue was five times less than from conventionally planted tobacco. Sediment loss was 4,730 kg ha-1 from tobacco versus 5.8 kg ha-1 from turf. Total N was 11.7 kg ha-1 from tobacco versus 0.11 kg ha-1 from turf and ortho-P loss was 0.42 kg ha-1 from tobacco versus 0.03 kg ha-1 from turf.

The ability to project amounts of pesticides in surface waters emanating from a turf site depends on several factors including: amounts and rates of degradation of specific pesticides to be applied, pest pressure, rainfall intensity at the site, topography and landscape design. Since pesticides vary in their chemical characteristics, they differ in their rate and mode of degradation (by microbial, photochemical and hydrolytic means), soil adsorptive tendencies, and volatilization. A thorough review of these characteristics is presented in several sources (Farm Chemicals Handbook, 1988; Herbicide Handbook, 1983; Saltzman and Yaron, 1986).

SUMMARY

The stabilizing effects of turf must not be overlooked in developing land use strategies. In developing such strategies, turf is often equated with impervious surfaces, which is far from the conclusions that have been documented by research. Before alternative ground covers are adopted for sensitive sites, we must first consider the environmentally beneficial aspects of turf and determine whether the alternative ground cover will provide improved results.

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TABLE 1

Comparison of leaf texture of turfgrasses mowed at 3.8 cm (Adapted from Beard, 1973)

Textural Category	Leaf Width --mm--	Turfgrass Species
Very Fine	Less Than 1	Creeping red fescue Velvet bentgrass
Fine	1-2	'Emerald' zoysiagrass Rough bluegrass
Medium	2-3	Kentucky bluegrass 'Meyer' zoysiagrass Annual bluegrass
Coarse	3-4	Annual ryegrass Redtop Centipedegrass Tall fescue
Very Coarse	Greater than 4	St. Augustinegrass Bahiagrass

TABLE 2

Effects of seeding rate on leaf texture of 9 month old tall fescue mowed at 6 cm in Silver Spring, Maryland (Welterlen, 1984, unpublished data).

Seeding Rate	Width of Second Leaf
lb./1,000 ft2	--mm--
2	5.7 a*
4	5.5 ab
6	5.3 bc
8	5.3 bc
10	5.3 bc
12	5.2 cd
14	5.1 d
16	5.0 d

* Means followed by the same letter are not significantly different at the 0.05 level according to Bayes Least Significant Difference.

TABLE 3

Comparison of tobacco versus tall fescue turf in surface movement of water, sediment and fertilizer (Gross, et al., 1987).

Crop	Runoff Volume	Sediment	Total-N	PO4-P
	$Lx10^3$ ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Conventional Tobacco	334.0	4730	11.7	0.42
Tall Fescue	74.5	5.8	0.11	0.03

TABLE 4

Sediment loss from corn versus tall fescue (Gross, et al. 1987).

Rain Intensity	Sediment Loss	
	Tall Fescue Turf	Corn
In. hr^{-1}	---- gm m^{-2} min^{-1} ----	
4.7	0.18	24.0
3.7	0.12	14.1
3.0	0.08	10.0

* Rainfall was imposed with a rainfall simulation device. Rainfall intensities of 4.7, 3.7, and 3.0 inches per hour correspond to 30 minute rainfall events which occur every 20, 5 and 2 years, respectively.

THE INFLUENCE OF TURFtech[tm] SEEDING ON SOIL COMPACTION IN SOUTHEAST IOWA AND A MID-SOUTH REGION

BY
Jim Schaefer
and
Larry Larson
Research and Development Department
Soil Technologies Corp.
51 West Adams
Fairfield, IA 52556

INTRODUCTION

TURFtech is a commercial microbial product composed of chlamydomonas, chlorella and cyanobacteria. The purpose of the product is to provide a seeding of viable dormant microorganisms at the rate of 18.2 x 10^9 cells acre-1, per application, to a turf's soil surface, thereby establishing an artificial advantage for these selected strains, and culturing the organisms for three to five weeks. The artificially induced large population of microbes then act as sources for the production of biopolymers or microbial polysaccharides, an organic soil-aggregating agent. These microorganisms grow on soils and secrete quantities of polysaccharides (Kroen, 1984). The addition of microbial polysaccharides to soil generally improves aggregate development and stability (Lynch and Bragg, 1985). Lewin (1977) and Metting (1986) collected empirical evidence suggesting these same microbes as efficacious agents for beneficial alteration of soil structure.

Considerable evidence is published which suggest that soil compaction of various forms seldom favors the economics of turf production and generally works against it (Gill, 1971). Soil structural degradation has been blamed by various researchers for plant growth reductions (Baver and Farnsworth, 1941; Lawton, 1945; Quastel, 1952; Gill and Miller, 1956; Hagin, 1952; Voorhees et al, 1975). This paper will report field results where bearing ring cone penetrometer readings were collected at sites which were seeded with the TURFtech product.

MATERIALS AND METHODS:

Two experimental regions were established for test sites for 1987 and one region for 1986. The regions were distinguished as having similar soil origins and climactic conditions. The regions were called Southeast Iowa (north of Highway 34, and south of I-80 and east of Knoxville) and the Mid-South (Eastern Arkansas and the northwest 1/4 of Mississippi). Each represented a single experimental area. Each test site belonged to a cooperating TURFtech customer. The operators purchased and applied the TURFtech product, which consists of single cells uniformly dispersed in a dry, suspendable, clay based powder. This material was mixed with water and applied with conventional spray equipment at the rate of 4 ounces with between 30 to 60 U.S. gallons of water per acre. Seeding, or application, was done in the spring. In each case, for 1986 in Southeast Iowa and for the Mid-South in 1987, the treated areas were receiving their first seeding with TURFtech . Southeast Iowa treated areas were treated again in 1987. A seeded and non-seeded area (or plots)

were located side by side at each site. The experimental measurement area was within this area. Each test or measurement area was 45m^2 with one half of the area the seeded area and the other half the non-seeded area. Each measurement area was selected for uniformity of soil type, slope, drainage pattern, and cultural history.

For compaction data collection a Soiltest bearing ring cone penetrometer was used. The cone had a cross sectional area of 2.54 cm^2 and had a 30 degree angle. Twenty subsample data sites were randomly selected, for each the seeded and non-seeded areas for probing. Each of the 80 Southeast Iowa and 38 Mid-South sites were probed one time, approximately 6 weeks after the TURFtech seeding. The twenty subsample measurements were integrated to produce a mean for each the seeded and non-seeded areas, and all measurements were adjusted to U.S. pounds/inch^2 for each replicate. Measurements were taken at the two and four inch depths in 1986 and 1987. A one inch soil core to the four inch depth was taken at every fourth to tenth subsample data site for each replicate. Gravimetric moistures were analyzed on each soil sample. The 2 to 5 gravimetric subsample moistures for each the seeded and non-seeded areas were integrated producing a percent moisture mean for each the treated and non-treated area of the replicate.

Each measurement area, containing a treated and non-treated plot, represented a replicate or block. Thus, the statistical design was that of a randomized complete block, with each measurement area or test site treated as a replication.

RESULTS

The bearing ring cone penetrometer measurements for all test sites are presented in Table 1. For all test sites the TURFtech seeded area had significantly less penetrometer resistance to both the two and four inch depths. The soil water content difference between the seeded and non-seeded areas was not significant.

DISCUSSION

Certain soil organisms produce polysaccharides that have a mucilaginous nature and may cement mineral particles together. Rennie et al. (1954) found that the addition of only 0.02g of an extracted and purified soil polysaccharide material to 100g of soil increased the water-stable aggregates > 0.1mm in diameter from 44g to 60g. Chesters et al. (1957) on analysis of a large number of soils, indicated that per unit mass, the polysaccharide fraction was more effective in stabilizing the mineral particles into structural units than was the non-polysaccharide portion of the soil organic matter.

In experimental work, it is frequently desirable to evaluate soil structure issues because the most suitable management practices may depend on the extent to which structure affects the growth of plants. With the advent of synthetic, organic soil-aggregating agents, with only small direct effects on the microbiological population and nutrient status of soils, structural effects on plant performance could be measured. It has been observed that in some cases the improvement of structure through field application of a synthetic organic soil-aggregating agent did not improve plant growth (Clement, 1961) and in other examples a definite improvement in plant growth could be attributed to structural improvements associated with the addition of the aggregating agent (Boekel, 1963). It is generally agreed that improved soil structure is beneficial to soil as a medium for plant growth.

Within one season, with four TURFtech seedings, the measurement of force required to displace or shear soil with a bearing ring cone penetrometer was significantly reduced at both the two and four inch depths, (Table 1). The measurement of greater comparative reductions at the two inch depths versus the four inch depths, is probably due to the majority of the microbial produced, organic, soil-aggregating agent being tied up with the soil mineralogy in the upper zone of the measurement depth. Each test site used a different type and design of spray equipment to seed soils with the product. The total number of sites should have minimized any bias in the data due to inconsistence in the equipment calibration. An inconsistent number of soil moisture readings per site was calculated. However, the total number of moisture evaluations was high and the moisture bias in the penetrometer calculations was statistically insignificant. These measurements appear to produce a correlation between the seeding of surface soils with a microbial product, a presumed biological source for an organic, soil aggregating agent, and decreases in surface soil compaction.

It is at least suggested by this work that a soil response may be associated with the TURFtech seeding of certain surface soils, possibly more so with those identified in need of structural improvement.

ACKNOWLEDGEMENTS

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TABLE 1

Bearing ring cone penetrometer measurements at two and four inch depths.

Depth Inches (a)	Replicates Region (b)	lbs./inch² Seeded Mean	% Moisture Seeded Mean	lbs./inch² Non-Seeded Mean	% Moisture Non-Seeded Mean
2/86	80/SEIA	40.63 (c)	---	58.24	---
2/87	80/SEIA	33.57 (c)	---	45.79	---
2/87	38/MS	47.96 (c)	---	71.67	---
4/86	80/SEIA	95.29 (c)	15.7 (d)	125.78	16.0
4/87	80/SEIA	94.23 (c)	---	117.79	---
4/87	38/MS	156.98 (c)	12.08 (d)	193.30	11.90

(a) Depth in inches per year.

(b) Each replicate treated as a randomized complete block. SEIA = Southeast Iowa and MS = Mid-South.

(c) Significant at 1% level.

(d) Insignificant at 5% level.

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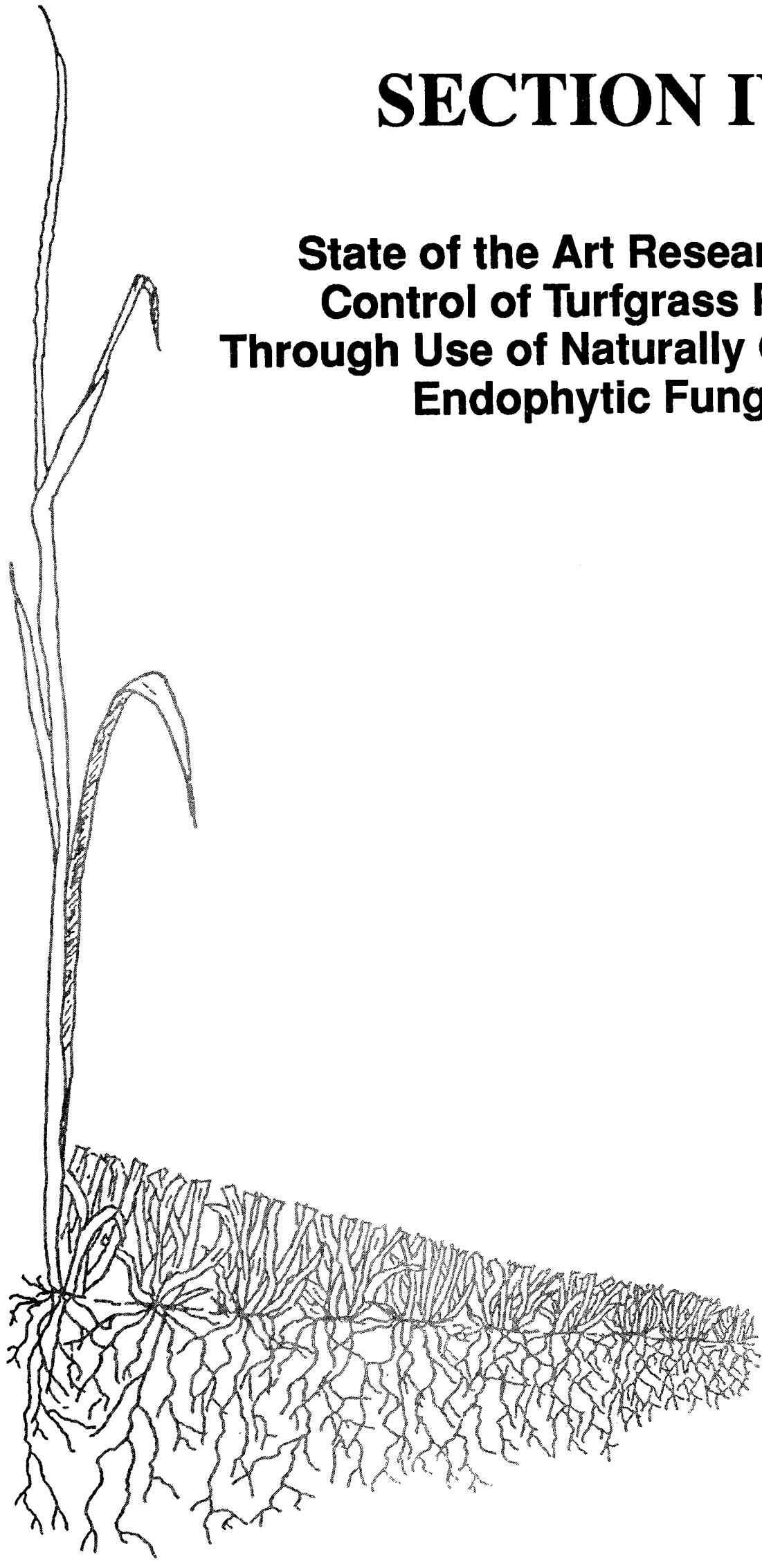

SECTION IV

State of the Art Research on Control of Turfgrass Pests Through Use of Naturally Occurring Endophytic Fungi

THE ROLE OF ENDOPHYTIC FUNGI IN GRASSES: NEW APPROACHES TO BIOLOGICAL CONTROL OF PESTS

Malcolm R. Siegel, Douglas L. Dahlman and Lowell P. Bush

**Departments of Plant Pathology,
Entomology and Agronomy,
University of Kentucky
Lexington, KY 40546-0091**

The infection of grasses by consistently symptomless nonsporulating endophytic fungi has been known for many years, but only recently attracted attention because of the economic importance associated with animal toxicoses and resistance to insect predation. Since the initial work of Bacon et al. (2) in 1977 and Fletcher and Harvey (11) in 1981, which established the respective associations of animal toxicosis with endophyte-infected tall fescue and perennial ryegrass, researchers have come to further understand the relationship between fungal endophytes and their host grasses. Recent studies have addressed the origin and incidence of endophyte-infected grasses, modes of dissemination of the fungi, identification of the chemicals responsible for mammalian and insect toxicoses, and the significance of ecological and physiological relationships between grass hosts and endophytes.

In this chapter, we will present a general review dealing with the biology, ecology and physiology of the host-fungus interaction as well as some specific information on the nature of the biological control of insects and diseases by endophyte-infected grasses. The aspect of biological control of pests deals with the potential use of infected turfgrasses in the urban environment. Introduction of these grasses could result in reduction of pesticide usage and the undesirable ecological side effects of chemicals used on turf. However, the successful use of endophyte-improved turfgrass cultivars depends on a number of factors which are related to the nature of the host-fungus interaction.

In addition to the information presented here, there are other chapters in this book by Bacon (Chapter 17) and Funk et al. (Chapter 18) that detail further the production of specific toxins in endophyte-infected grasses and endophyte-enhanced performance of turfgrass, respectively. Because there are a number of recent reviews on fungal endophytes (1,3,8,26,36,37), we will only reference those statements which represent new information or those which need further emphasis.

TAXONOMY, BIOLOGY AND ECOLOGY

The term endophyte, in regard to infection of grasses, was defined previously by Siegel et al. (37) as a fungus which is contained or growing (entirely) within the substrate plant, spending all or nearly all of its life cycle in the host. Almost all of the grass endophytes are grouped or related to fungi in the tribe Balansiae (genera; Atkinsonella, Balansia, Blansiopsis, Myriogenospora and

Epichloe) of the family Clavicipitaceae. They are common biotrophic inhabitants of grasses, which have a C-3 type photosynthetic pathway, and sedges. Other non-related endophytes (Phialophora-like and Gliocladium-like spp.) have been described as well (17).

A generalized life cycle of the grass endophytes is illustrated in Fig. 1. In relation to this life cycle, it is germane to emphasize those endophytes which remain symptomless versus those which produce sporulating fructifications and prevent flowering. The mycelia of both symptomless and symptom-producing endophytes grow intercellularly (10,13,35), infecting meristems, leaf sheaths, and sometimes blades. In addition, the symptomless endophytes infect seed, growing in association with the aleurone layer and seed embryo. Unless symptoms are produced, the plant appears to be undamaged and the fungus becomes incorporated into the plant's reproductive system. The only known means of dissemination of symptomless endophytes is through maternal transmission of infected seed (solid arrow, Fig. 1).

It is the group of systemic seedborne fungi for which no sexual state has been found (often called symptomless parasites), as well as related fungi in the genus Epichloe that currently offer new approaches to biological control of pests of turfgrass. Epichloe typhina is a common pathogen of grasses producing the striking symptom of mycelium surrounding the emerging flower inflorescence, with the subsequent prevention of flowering and seed production (called choke disease). This fungus is found on important grass genera, in primarily the Poaceae (e.g., Agrostis, Bromus, Dactylis, Festuca, Holcus, Hordeum, Lolium and Poa). There has been debate recently about the taxonomy of the anamorphic state (asexual) of E. typhina. Originally classified as Sphacelia typhina, it now has been reclassified by Morgan-Jones and Gams (23) and confirmed by White and Morgan-Jones (49) as Acremonium typhinum. Other important symptomless, seedborne endophytes found in grasses for which there are no known teleomorphic states (sexual) are now also classified in the same genus Acremonium sec. Albo-lanosa. While this classification implies morphological relatedness, Johnson et al. (15) have also demonstrated serological relatedness among some Acremonium spp. and E. typhina isolated from different grasses. The list of named Acremonium endophytes is shown in Table 1. It should be pointed out that by staining the mycelium in vegetative tissue and in seed, numerous endophytes have been found in grasses of the Poaceae but remain as yet unnamed (19,29,41,46).

The emergence of A. typhinum at flowering depends on the biology of the grass-fungus association, which will be discussed shortly. When choke symptoms occur, conidia of A. typhinum are produced on the stroma (broken arrow, Fig. 1). Whether the sexual ascomycetous state of E. typhina occurs depends on simple bipolar heterothalism (two mating types present) and insect transmission of conidia, which act as spermatia (43). While it has been suggested that species of the Balansiae producing external spores infect healthy plants via the stigma and style to the ovule (9), it is also possible that spores infect tillering buds of grasses as well. There is some uncertainty as to the role of ascospores in the life cycle of these organisms as well as to the mode of infection.

It has been known, since the work of Sampson (30), that E. typhina may remain symptomless for long periods and be seed disseminated in certain host grasses (12,29). Consequently, Siegel et al. (37) and Bacon and Siegel (3) consider E. typhina to exist as different biotypes in various host grasses. The existence of fungal biotypes suggests that there is a continuum within the symbiotic association as it relates to the compatibility of the partners (22,38). Some biotypes enter into agonistic (parasitic-pathogenic) interactions whereas others, like the symptomless Acremonium spp. infecting Festucoideae grasses, enter into mutualistic (beneficial) relationships.

White (42) has differentiated into three types the associations between E. typhina and related Acremonium endophytes, and their grass hosts (Table 2). The biology and ecology of the associations are important in understanding the distribution of infected plants in the population and

dissemination of the endophytes. In type 1 associations, infected plants produce stromata (an external mat of mycelium bearing fructifications) on nearly 100% of the flowering panicles. Populations of plants in this association tend to remain small, spreading primarily as the grass clone spreads vegetatively. All of the plants in this clonal population are infected. Type 2, like type 3 associations, have been found only in the Festuciodeae. The differences between these two associations are relatively minor and involve the identity of the fungus and the distinction between the low level (0 vs. 1-10%) of flowering panicles showing stromata. The spread of endophytes in type 2 and 3 associations is primarily by seed dissemination, however, ascospores may also be important in the former association.

The percent of the population infected in type 2 and 3 associations may depend on whether the grass is present in recent or older cultivations or is from native species. One would expect high levels of infection in the population of wild grass species as it has been hypothesized that the endophytes co-evolved with their hosts (37,42). High percentages of infected plants have been reported to occur in various Lolium and Festuca spp. growing in the wild in the U.S. and Europe (19,34,42). Populations of older cultivated grass species appear to be highly infected whereas others from recently introduced cultivars or new cultivation have low levels of infection. For example, 58% of the tall fescue plants, grown on 14 million hectares, in the U.S. have been reported to be infected with A. coenophialum (31); nearly 100% of the perennial ryegrass plants, grown on 6 million hectares, in New Zealand are infected with A. lolii (19,37). Seed of perennial ryegrass (19) and fine fescues (29) collected from old pastures and turf in Europe also had high levels of infection.

It is now clear that the seedborne and symptomless nature of the endophytes of type 2 and 3 associations has unintentionally resulted in their worldwide distribution along with their cultivated hosts. The reasons for the differences in levels of infection of cultivated grasses (old vs. new cultivars or plantings) may have more to do with the commercial methods of handling of seed than with a failure of the grass to remain infected.

Seed-borne endophytes survive for indefinite periods at low temperatures (0-5C), but generally lose their viability in much shorter storage periods (1-2 yr) at 20-30C and high seed moisture levels (40). Grass seed may be stored in the U.S. at ambient temperature for up to 18 months before it is sold; consequently, seed lots can contain infected seed with different levels of endophyte viability that result in reduced numbers of infected plants.

GRASS-ENDOPHYTE INTERACTIONS

Symptomless and seed disseminated Acremonium spp. and E. typhina (type 2 and 3 associations) can be considered as obligate biotrophs (20). That is, they cannot exist outside the host (except in laboratory culture) and additionally are not known to be capable of re-infecting, by natural means, susceptible grasses. As discussed earlier, these endophytes are also mutualistic symbionts, whereas E. typhina of type 1 associations and other specific endophyte species in the tribe Balansia are agonistic (parasitic) symbionts producing disease. The grass endophytes that are mutualistic symbionts receive benefit from the association with their hosts in the form of long term protection and enhanced survival and dissemination (via seed). These endophytes are of great interest because of the benefits they impart to the hosts. They cause or induce, in many instances, improved growth and persistence of the host plants, tolerance to herbivore feeding (animal and insect) and possible disease resistance. As will be discussed later, these endophytes can be manipulated for the production of improved turf-grass cultivars.

Improved plant growth and persistence

Acremonium endophytes confer improved growth performance to some infected cultivars and clones of perennial ryegrass and tall fescue. Plants of an infected perennial ryegrass clone had more dry matter, total leaf area, tiller number and growth of roots than plants of the non-infected clone (18) as well as improved seed set, germination and seedling growth (7). While it has been suggested that growth and survival are enhanced when field-grown infected tall fescue plants were grazed (27), experiments in Kentucky with Kenhy tall fescue showed no significant differences in plant growth and seed production between infested and non-infested mowed plots (34). However, in greenhouse tests, Bush et al. (6) have shown that infected tall fescue plants performed better (greater number of tillers, daily photosynthesis and net carbon fixed, and water use efficiency) than non-infected plants. Belesky et al. (5) have also reported greater tiller production and net growth in some tall fescue clones grown under controlled conditions. However, in these experiments, net photosynthesis rate was lower while stomatal resistance tended to be greater in infected than non-infected plants. These data support the hypothesis that infected cultivated grasses would have an adaptive growth advantage over non-infected plants in environments with abiotic stresses (deficient water and nutrients, high temperature and competition with weed species).

The reason for possible changes in growth patterns of endophyte-infected plants remains obscure, although it has been suggested that endophytes localized in stem base and sheaths of plants utilize reserve photosynthate (i.e., fructosans) (5). This utilization may impart source-sink dynamics, altering the production and partitioning of photosynthate and, hence, growth in infected plants. In addition, members of the Claviciptaceae may produce auxins or other plant growth regulators, or they may alter the hormone metabolism of their host. These are distinct possibilities when one considers that symptoms of infection by E. typhina and other members of the tribe Balansia include not only the inhibition of flowers and seed, but also enhanced plant growth, dwarfism or deformation of the flag leaf (1,8,9). Auxin-like indole compounds have been isolated in vitro from cultures of Claviceps purpurea and Balansia epichloe (25). The production of these indole compounds may reflect an alteration of nitrogen metabolism and assimilation in the infected plant (1).

Insect resistance

One of the most striking effects produced by endophyte-infected grasses is resistance to insect attack. This subject has been extensively reviewed and will be discussed in detail by Funk et al. (Chapter 18). An up-to-date list of species of insects reported to be affected by endophyte-infected Festuca and Lolium species of grasses has been presented elsewhere (37 -see Table 1). In addition, Pedersen et al. (24) reported that there were lower populations of the spiral (Helicotylenchus dihystera) and stubby root (Paratrichodorus christiei) nematodes in pots containing infected tall fescue than in those containing non-infected plants.

Acremonium and E. typhina-infected grasses produce an array of chemicals that have a wide range of biological activity. The chemistry and synthesis of these chemicals will be discussed by Bacon (Chapter 17). Table 3 summarizes the current information available concerning these active chemicals. Of notable interest is peramine, an insecticidal compound originally recovered from A. lolii-infected perennial ryegrass. This compound has also been found in many grasses infected with A. coenophialum or E. typhina (33). However, not all biotypes of E. typhina produce peramine, as the compound was not recovered from the naturally infected cultivar Ensylva (Festuca rubra rubra) or from Dawson (F. rubra litoralis) artificially infected (via seedling wounding) with an E. typhina

isolate from an unidentified cultivar of F. rubra grown in New Zealand (Siegel et al., unpublished data). Ergot alkaloids originally found in A. coenophialum-infected tall fescue have also been recovered from various E. typhina-infected grasses (Bacon and Siegel, unpublished data) as well as perennial ryegrass infected with A. lolii (28).

The number and quantity of compounds found in endophyte-infected grasses may play an important role in determining the spectrum of insecticidal activity as well as affect the potential for the development of insect resistance. Of the types of compounds listed in Table 3, only loline alkaloids are found in high concentrations in the plant. The reputation for a high level of insect resistance by infected tall fescue may be based, in part, on the concentration of loline as well as the presence of the other toxic chemicals. On the other hand, the compounds found in infected perennial ryegrass are present at ca. 250 fold less than the loline alkaloids but still exert a considerable spectrum of activity (37). The ability of certain fungal symbionts (e.g., A. coenophialum and A. lolii) to produce at least three biologically active compounds likely contributes to an improved spectrum of activity. If one hypothesizes that insects would become resistant to these compounds by different mechanisms, then potential for the development of resistance by the insect is negligible. From these aspects of the synthesis of insecticidal compounds in endophyte-infected grasses one might speculate that the level of the chemical may be less important than the number of chemicals produced by the host-fungus association.

While the topic of this chapter involves the nature of endophyte-infected grasses, endophytes from tall fescue and perennial ryegrass used in pasture have been removed to improve animal performance. These endophyte-free cultivars do not contain any of the biologically active compounds found in infected grasses. However, because the fitness of the partners in the grass-fungus association involves mutualism, some questions have been raised about whether these endophyte-free cultivars would be able to survive over long periods of cultivation (32,37). It is quite clear that removing the endophyte from perennial ryegrass in New Zealand resulted in loss of stands by predation of the Argentine stem weevil and animal overgrazing. Whether attack by insects, poorly managed grazing practices, reduced plant vigor and survival during periods of abiotic stresses will also cause loss of recently established endophyte-free tall fescue pastures in the U.S. is currently unknown. However, small plots of Ky 31 and other tall fescue cultivars containing low levels of infected plants have existed in the transition zone of the southeastern U.S. for many years (31,34).

We have devised laboratory assays to test for activity of some of the chemicals produced in infected plants. Figure 2 A,B illustrate one such assay system (14). The plastic cup contains a piece of dental cotton (holds 300 ml of water), one sunflower seed and five Oncopeltus fasciatus (large milkweed bug) nymphs (1-12 days old). Test chemicals in water or water alone are applied to the cotton and the nymphs are allowed to feed. At intervals the percent mortality is determined. The data in Table 4 indicate that N-formyl loline, ergotamine (peptide type of ergot alkaloid) and ergonovine (clavine type of ergot alkaloid) had ED50 values after 6 days of exposure of approximately 7.81 ug/ml. Higher concentrations produced more rapid onset of death. Ergocryptine (peptide type) was toxic only at 1 ug/ml. Ergovaline (peptide type), the predominant ergot alkaloid (40-70%) recovered from endophyte-infected tall fescue, was not available for testing.

The broad spectrum activity of N-formyl loline was evaluated via preliminary contact studies with a number of other insect species. Loline was toxic to the cat flea (Ctenocephalides felis), oat-birdcherry aphid (Rhopalosiphum padi), greenbug aphid (Schizaphis graminum), American cockroach (Periplaneta americana), adult face flies (Musca autumnalis), larvae of Japanese beetle (Papilia japonica), and eggs of the tobacco budworm (Heliothis virescens). Chronic exposure to 1 ug/ml in water during the entire life of the milkweed bug in the assay previously described resulted

in delayed development and reduced fecundity. In addition, 1 ug applied topically in acetone to adult milkweed bugs is sufficient to kill 50% of the test insects after 4 days of exposure, the dose being somewhat dependent upon the age and weight of the individual adult. An injected dose of 1 ug/adult results in approximately 50% mortality. The oatbird cherry and greenbug aphids can also be killed by ingesting lolines either from within infected tall fescue stems and leaves (the compounds are not present on the surfaces of the plant; Eichenseer, unpublished data) or from non-infected stems that had previously taken up the alkaloids from water (Siegel, unpublished data).

In summary, various insects were very sensitive to purified N-formyl loline in several different assay systems (contact, ingestion and injection). Eventually, all the toxic chemicals produced in infected plants will be similarly assayed and their modes of action determined. This information will aid in understanding further the host-endophyte interaction and how this interaction can better serve the needs of man as he uses grasses for aesthetics and conservation.

Disease resistance

Resistance to plant diseases by endophyte-infected grasses has not been reported. However, agar plate antibiosis assays have indicated that antifungal compounds were produced in vitro by isolates of Acremonium spp., Phialophora-like sp. and E. typhina from various grasses (44,45, Latch and Siegel, unpublished data). An example of the kind of antibiosis experiment conducted by Latch and Siegel is shown in Figure 2 C,D. Zones of inhibition of growth of the test grass pathogen by a soluble factor(s) from the endophyte colonies are clearly evident. This experiment and others indicate that a diverse range of antibiosis exists among isolates of E. typhina and various Acremonium species. Both the spectrum and amount of antifungal activity appears to be endophyte isolate dependent. In part, this dependency suggests the presence of fungal biotypes existing within the same grass cultivar or species.

Reasons for the lack of expression of antibiosis (disease resistance) in pasture and turf Festuca and Lolium spp. are unknown. It is possible that the antifungal compound(s) is produced, but not in sufficient quantity to control the pathogens.

MANIPULATION OF GRASS ENDOPHYTES FOR USE IN TURF

The use of the Acremonium endophytes in turfgrasses as agents of plant protection and improvement has certain unique advantages. As previously discussed, the natural association between the grass hosts and these endophytes is one of mutualism (benefits). In addition, the endophytes are propagated with the plant by vegetative means through tillers and by seed-dissemination. Thus, the endophytes can be regarded as compartments of maternally-inherited genetic information that can be removed, manipulated, and re-introduced into the grass plant. Genes contained within this compartment include those that direct or affect production of loline, ergot, and peramine alkaloids and lolitrem toxins, and other compounds (not yet identified) which directly or indirectly provide enhanced resistance to insects, plant pathogens and improved plant growth and survival.

Production of improved endophyte-infected grasses can be achieved by plant breeding (maternal line selection) (12) or by artificial (wounding) introduction of the endophyte into seedling meristem (synthetic complexes or combinations of endophyte and host grass) (16). The latter method is illustrated in Figure 2 E,F,G and can be used with naturally occurring or genetically modified endophytes.

Use of naturally occurring endophytes

A number of endophyte-infected grass cultivars have been developed for insect resistance by maternal line selection (12,29, see Funk, Chapter 18). In most cases, the endophyte is already present in the grass cultivar, usually at a low level of infection. It then becomes a matter of selection and increasing the number of infected tillers and plants. However, in some cases, the endophyte must be transferred from one cultivar to another within the same plant species. The resulting cultivar must not only contain the endophyte but also have desirable characteristics for turf use.

One of the current problems with the use of naturally occurring endophytes is the presence of biotypes which produce less of the desired beneficial chemicals. For example, it has been demonstrated that a biotype of E. typhina infecting Ensylva neither produces any of the known compounds (lolines, peramine and ergot alkaloids) responsible for insect resistance, nor can insect resistance be demonstrated using an aphid bioassay (Siegel, unpublished data). Biotypes of A. coenophialum exist which do not produce ergot alkaloids (4). Likewise, we have shown that biotypes of Acremonium spp. exist which apparently produce varying levels of antifungal chemical(s) in culture.

It is clear that considerable screening and characterization of the host-endophyte interaction will be necessary in order to ensure that all the required chemicals are produced. By using artificial inoculations one may be able to ensure that specific biotypes exhibiting superior performance in one plant can be introduced into others of the same species.

Use of genetically modified endophytes

Endophytes modified by recombinant-DNA techniques may be used to (i) enhance already existing beneficial characteristics; (ii) introduce foreign genes which are of benefit to the plant (these may include genes for the synthesis of antibiotics antagonistic to insects and causative agents of grass diseases, genes for the detoxification of herbicides, or factors that enhance growth and persistence of the host grass); and (iii) gain further understanding of how fungal-plant mutualistic relationships are established so that the genetic potential of endophyte genomes can be manipulated for crop improvement. Manipulation and improvement of grass endophytes by genetic means will require elucidation of the function(s) and role(s) of secondary compounds produced in the host-fungus interaction, particularly with regard to biosynthetic pathways and effects of chemicals on livestock, insects, microbes and plant growth. In addition, it will be necessary to develop DNA-mediated transformation systems and associated techniques of cloning, gene replacement and complementation. Development of a transformation system will, in turn, require a knowledge of the nature and requirements of gene expression in the endophyte as well as gene expression of the host in response to infection, expression of disease (choke) and synthesis of secondary metabolites.

CONCLUSIONS

The mutualistic relationship between grasses and the Acremonium fungal endophytes provides an excellent model system for studying the nature and expression of biologically active secondary metabolites, molecular genetic studies, and improvement of agriculturally important grasses. These fungi do not produce disease in their host grasses, are obligate biotrophic symbionts, grow in the meristems, leaf sheaths and leaf blades of their hosts, and are seed-disseminated. Because of

their ecological role and life cycle, the Acremonium endophytes are ideal agents for biological control of insects and possibly diseases of turfgrasses and for basic studies of mutualism.

New endophyte-infected turfgrass cultivars with enhanced resistance to insects are now available. Whether they are commercially successful depends on factors discussed elsewhere in this book. However, because the potential is so great for turfgrass improvement, it seems that future use of infected cultivars will be assured, particularly if endophytes with genetically modified genomes are developed.

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TABLE 1

Acremonium Fungal Endophytes of Grasses.

Fungus	Grass	Ref[a]
Epichloe typhina (Acremonium typhinum)	Lolium, Festuca, Agrostis, Dactylis, Holcus, Hordeum, Poa, etc.	(9,23, 49)
A. coenophialum	F. arundinacea, P. autumnalis	(23,50)
A. lolii	L. perenne	(17)
A. huerfanum	F. arizonica (Colorado)[b]	(47)
A. chisosum	Stipa eminens	(48)
A. starrii	F. arizonica (Texas)[b], Bromus anomalus, F. obtusa, F. subulata	(50)

[a] References for name of fungus and species of infected grass.

[b] Fungus isolated from the populations found in Colorado or Texas.

TABLE 2

Characterization of the association between Epichloe typhina and related Acremonium endophytes and their grass hosts[a].

Association No.	% flowering panicles showing symptoms	Fungus	Type of Association	% population infected	Fungal dissemination[c]	Grass host
1	≥ 98	E. typhina	Pathogenic[b]	≥ 98	Spread by clonal growth of host and ascospore infection	Several sub-families of Poaceae and sedges
2	1-10	E. typhina	Pathogenic[b] or mutualistic	50-70	Spread by clonal growth of host, seed and ascospore infection	Festucoideae only
3	0	Acremonium spp.	Mutualistic	≤ 90	Spread by seed and clonal growth of host grass	Festucoideae only

[a] Adapted from White (42).

[b] Same as parasitic in the sense of Lewis (21) and Siegel et al. (37). The term agonistic is now suggested by Lewis (22).

[c] Listed in order of importance.

TABLE 3

Biologically active compounds isolated from endophyte-infected Festuca and Lolium species of grasses[a].

Chemical	Origin (grass)[b]	Origin (fungus)[b,c]	Average amount (µg/g) dry wt in plant[d]	Distribution in plant[e]			Produced in culture	toxicity
				Roots	Stems	Leaves		
Ergot alkaloids	TF,PRG, HF,CF	A.c.,A.l., E.t.,E.t.	3-10 (TF)	ND	+	+	Yes	Insect & mammalian
Loline alkaloids	TF	A.c.	2,000 (TF)	+[f]	+	+	No	Insect
Peramine alkaloids	TF,PRG, HF,CF	A.c.,A.l., E.t.,E.t.	5-25 (PRG)	-	+	+	Yes	Insect
Lolitrems & Paxilline[g]	PRG	A.l.	3-25 (PRG)	ND	+	+	No,Yes	Insect & mammalian
Tetraenone steroid	TF	A.c.	ND	ND	ND	ND	Yes	Microbial & mammalian

[a] Summary of data from Ref. 1,3,4,37 and unpublished data of Siegel, Latch and Bacon.

[b] Abbreviations: TF, tall fescue (F. arundinacea); HF, hard fescue (F. longifola); PRG, perennial ryegrass (L. perenne); CF, Chewings and creeping fescue (F. rubra commutata and F. rubra litorales); A.c., Acremonium coenophialum; A.l., A. lolii, E.t., Epichloe typhina.

[c] Refers to the fungus which infects the grass listed in the previous column; i.e., A.c. infects TF, E.t. infects HF, etc.

[d] Average amount in the grass listed in parenthesis, includes vegetative parts and seed.

[e] ND, not determined; -, not present; +, present.

[f] 10-15% of total loline found in plant (Bush, unpublished data).

[g] Paxilline is a precursor of lolitrem B and is produced in both culture and the plant, whereas only lolitrem B has been detected in the plant (39).

TABLE 4

Percent mortality of Oncopeltus fasciatus (large milkweed bug) offered either N-formyl loline or various ergot alkaloids in water[a]

		Concentration (µg/ml)				
Day	Compound	1000	125	31.25	7.81	Control
	N-Formyl Loline					
2		80	55	10	10	10
4		100	100	70	20	10
6		100	100	90	55	10
	Ergotamine					
2		90	65	35	0	
4		100	90	75	35	
6		100	95	90	50	
	Ergonovine					
2		50	30	30	15	
4		85	55	35	25	
6		95	80	40	40	
	Ergocryptine					
2		5	0	0	0	
4		45	0	5	0	
6		65	5	5	0	

[a] Methods used the same as in Johnson et al. (14).

FIGURE 1

Generalized life cycles of grass endophytes. Question Mark (?); indicates that uncertainty exists as to the role of ascospores in the life cycle of these organism (e.g. E. typhina) as well as to the mode of infection (via stigma) (adapted, in part, from Ref. 1). Solid arrows; endophytes that are seedborne as in the Festucoideae grasses and in cleistogramous Balansiae-infected seeds. Broken arrows; transmission of endophytes via spores, in the case of Ephicloe typhina ascospores, from stromata of infected plants.

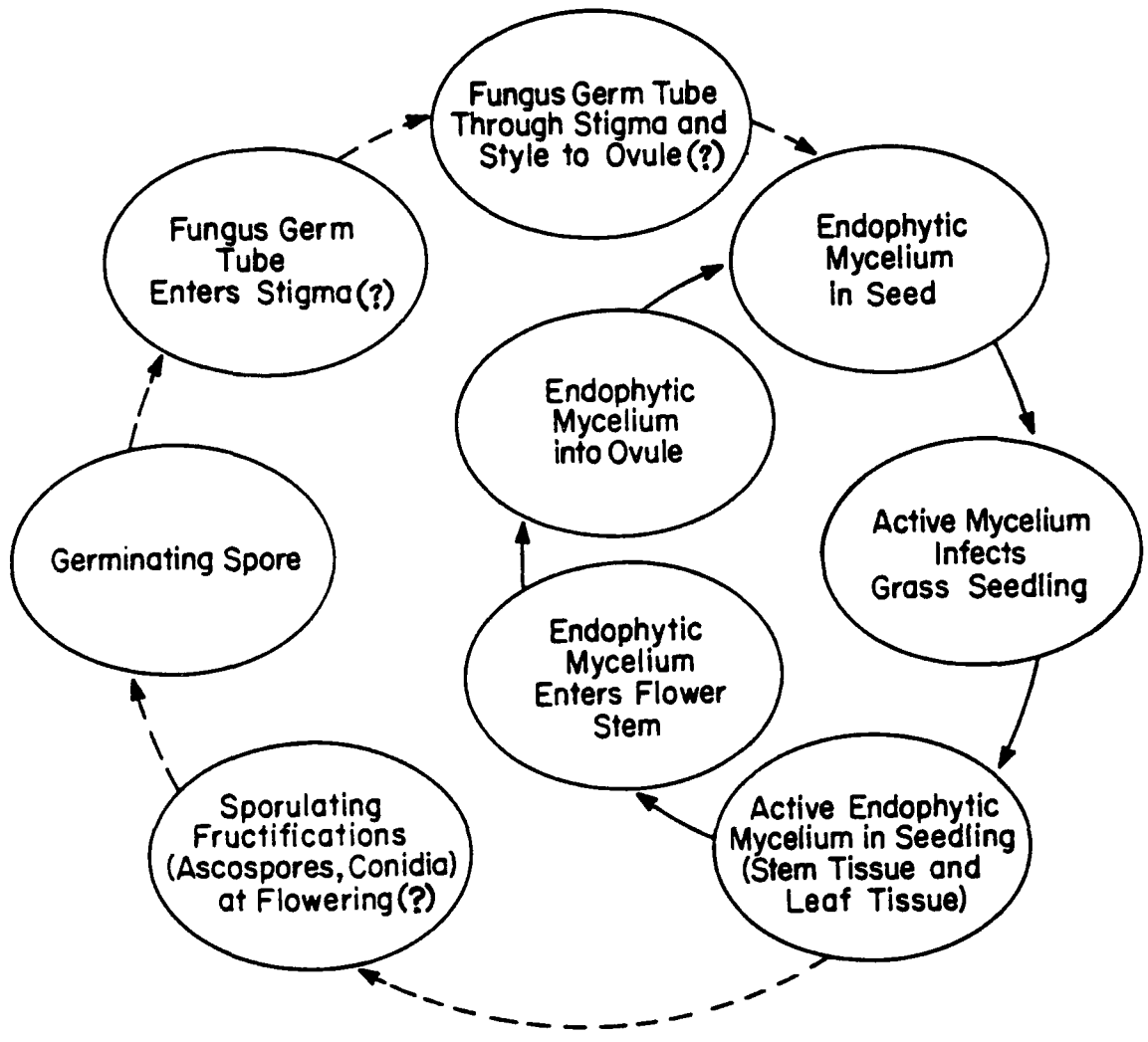
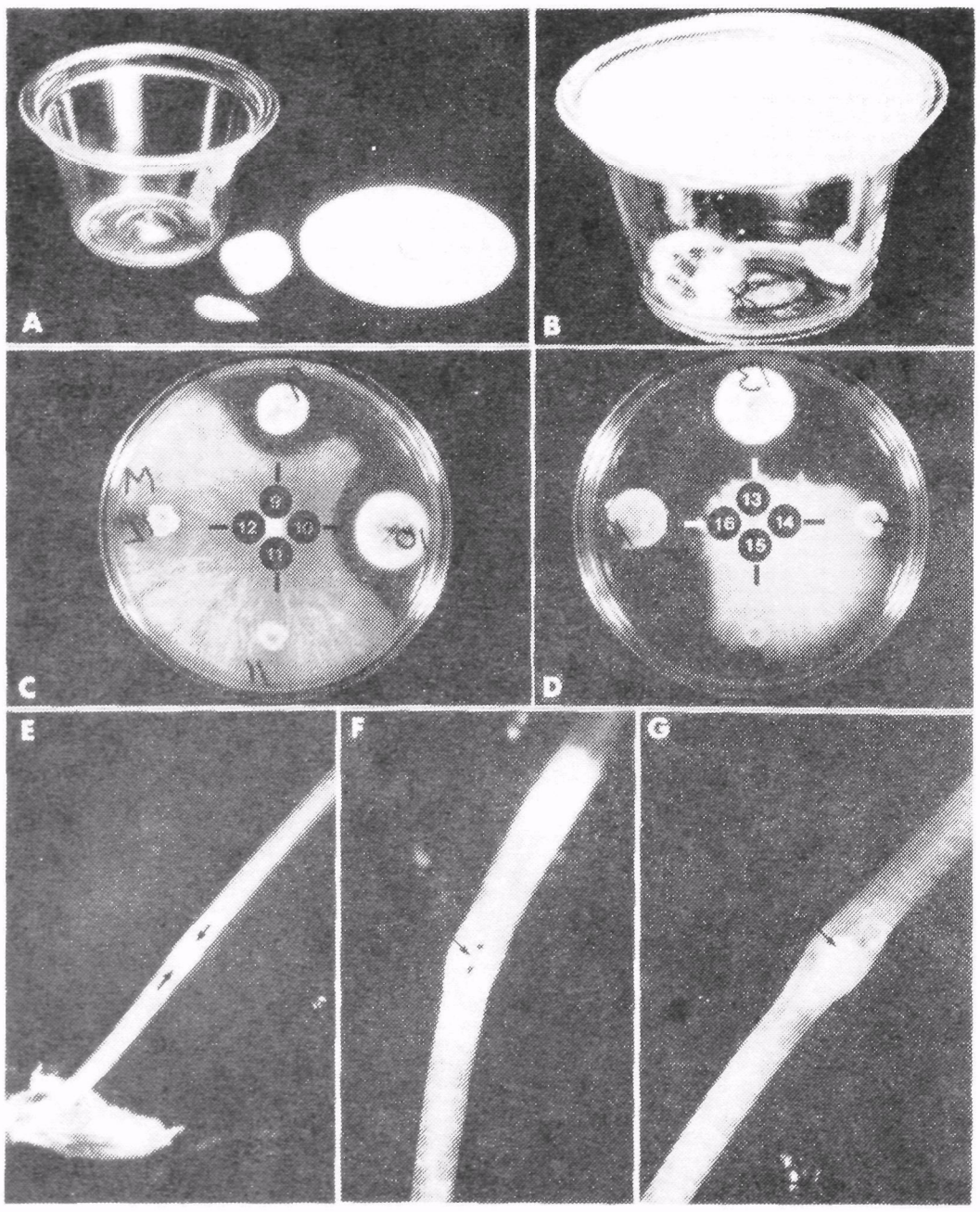


FIGURE 2

A, component parts of milkweed bug (Oncopeltus fasciatus) antibiosis assay (plastic cup, plug of dental cotton and cardboard top). B, assembled assay, includes 5 nymphs. C and D, antibiosis assay for chemical activity of various endophyte isolates. Photographs are of the underside of agar plates. Test grass pathogen growing from center of the plate, Rhizoctonia cerealis. Endophyte isolates of Acremonium coenophialum place on the periphery were isolated from tall fescue: 9, Ky 31; 10, Kenhy; 11, Fawn; 12, Alta; 13, unknown tall fescue cultivar from NZ; 14, Ky 31. Acremonium lolii isolated from: 15, Nui. Acremonium starrii isolated from: 16, Festuca arizonica. E, F, G: Artificial inoculation of one week old seedlings. Arrows indicates position of the meristem, wounded meristem and meristem inoculated with mycelium of the endophyte. Seedlings grown on water agar (2%) and wounding operation done under a stereo microscope using a scalpel, with disposable blade (see Ref. 16 for the detail).



UTILIZATION OF FUNGAL ENDOPHYTES OF GRASSES: LABORATORY MANIPULATIONS FOR SPECIFIC TOXINS

Charles W. Bacon
Toxicology and Mycotoxins Research Unit
USDA/ARS
Richard B. Russell Agricultural Research Center
P.O. Box 5677
Athens, Georgia 30613

The ecological necessity for an intimate association of a fungal endophyte with a grass is suggested by the widespread occurrence of these two vastly different organisms as a composite system (1,2,3). Fungal grass endophytes include species of Acremonium, Epichloe, and Balansia (Clavicipitaceae , Ascomycetes) that live within and are associated intimately with various species of grasses and sedges. The compatible nature of this relationship (4,5), as well as data from various laboratories led Siegel et al. (6) and Bacon and Siegel (7) to conclude that this association was a mutualistic symbiosis. The fungus receives nutrients from the grass, and is protected and disseminated. Infected grasses benefit by increased growth (8,9,10), reduced predation from vertebrate and invertebrate herbivores (11,12,13), and drought tolerance (14). Additional benefits, while observational, include disease resistance and stress sparing mechanisms (15,14). Before we can completely define the symbiotic nature and ecological success of endophyte-infected grasses, field data reflecting physiological responses of infected grasses to strenuous environmental stresses are needed. Nevertheless, it is the use of ecological benefits derived from the association that is the current focus of research.

Researchers are attempting to transfer endophytic fungi into grasses, primarily conservation and turf grasses, many species of which are not natural hosts. Benefits from these infections are expected to include increased pest resistances, improved appearance, and tolerance to environmental stresses. There are many potential uses for such symbiotic systems, but they may be grouped under two broad classes: biological controls for grass growth, stamina and appearance; and biological control for pests on grasses. Fungal endophyte-infected grasses are unique in that they are one of few biological controls that can be used, in addition to deterring pest, for controlling the morphology and stamina of a group of plants so essential to man's environment and health.

Use of infected grasses requires complete understanding of the in vitro and in vivo requirements for the fungus relative to predicting its performance when transferred to non-host grasses. After having accomplished infecting non-host grasses, experiments designed to determine agronomic performances of the infected grasses should pose no problem. However, when we try to attribute specific performance aspects of infected grasses to either the grass, fungus, or both we are faced with an experimental dilemma. The problem is compounded when we want specific information related to the fungus as a potential for forage improvement. Working with isolated fungus involves problems of defining and maintaining in vitro the desired in vivo characteristics. Thus, there is a need to 1) develop laboratory techniques for culturing the endophyte in vitro ; 2) develop media which will characterize and maintain useful specific physiological strains of the endophyte; and 3) develop techniques for transferring the endophyte to the desired grass species.

It is my intention to discuss the first of these two research needs, and to describe results of studies which established that while these fungi are varied and genetically unstable upon isolation, their in vitro culture may still be used to experiment with in situ resistance mechanisms after transfer to grasses. The infection of grasses, developed by Latch et al. for grass seedlings (16, and see companion chapter by Siegel et al. this proceeding), will not be covered. The discussion will center mainly around the endophytes of tall fescue and/or perennial ryegrass since these two are of considerable economic importance, and are the major focus of attention by various endophytologists. A more detailed discussion on morphology and taxonomy, and host parasite relationships of these two endophytes as well as other species of endophytes can be found in recent reviews (6,7,17,18) and in the chapter by Siegel in these proceedings.

ISOLATION OF FUNGI

The fungi (Table 1) may be isolated from either recently collected field or greenhouse grown material. Most endophytic fungi are located in the sheath portion of a grass leaf and it is an inner sheath that should be used since it is relatively free of debris and saprophytic fungi. For those fungi that are not located in leaves, it would behoove one to use the inner, least exposed plant tissue since it too will be free of debris. Material intended as a source for endophytes should be used immediately or stored under refrigeration (4 C) in tissue paper dampened with sterile water, but only for a few hours.

Small sections of sheaths are sterilized in full strength commercial bleach, rinsed in sterile water, cut into smaller sections (Table 2) and placed in either liquid medium or agar isolation media (Table 3). Additional isolation procedures have been reported for other endophytes and include such starting material as ascospores (19), and seed (16). The speed of isolating the fungus from grass tissue depends on tissue type and its preparation, genetic characteristics of each fungus and isolation media. The total time will vary from as early as 2 weeks on the liquid medium to as late as 6 weeks on the agar medium. Agar medium is solid and on solid media nutrients are more limited due to reduced diffusion of growth requiring compounds. Generally fungi producing choke symptoms (see chapter by Funk, this proceeding) will grow faster than nonchoke inducing species. This possibly reflects a difference in the nutritional fastidiousness of the two basic groups.

Once isolated, grass endophytes can be stored on either corn meal-malt agar or M102 medium (Table 3). Fungi may be stored under refrigeration only if they are freshly isolated and producing spores. Spores can survive the storage temperatures frequently used to preserve fungi (-20 to 0 C). Older nonsporulating isolates can be safely stored under warmer temperatures (4 to 10 C), or at room temperatures (20 to 26 C). Storage at room temperature is particularly recommended for those isolates that are nonchoke inducing as they rapidly loose the ability to produce spores. I have had no success with storage of endophytes on substrates traditionally used for fungi, i.e. silica gel, soil, etc.

The exact in vitro growth requirements of endophytic fungi have not been established. Most media are nondefined and complex and at best semisynthetic (19,20,21). One isolate of the endophyte of fescue was induced to grow on defined and relatively simple media after it was maintained in the laboratory for a considerable period of time (20,21). In another group of endophytes, Balansia which are associated primarily with weed grass species, a defined medium has been used to culture five species (22). I have not had any success using these defined media for initially isolating fungi from grasses. However, once endophytes have been isolated using a complex media of choice, defined media (20, 21, 22) may be tried.

Regardless of the media selected, shake culture of liquid media is favored over stationary culture when it is desired to obtain a rapid growth of fungus. Once maximum amount of growth is

produced, the culture may be continued as stationary cultures where several secondary products are produced (see below).

CULTURE

After an endophyte is isolated, it may be tested for the synthesis of specific substances on a specific culture medium. If one is trying to determine whether an isolate is toxic to cattle, or to insects, the procedure to follow should include a two-stage fermentation (Table 4) with the addition of specific substrates which are considered possible precursor for inducing the synthesis of specific metabolite, e.g. tryptophan for ergot alkaloids (Table 4). An alternative is to use either liquid or agar media to culture endophytes and use it directly to determine toxicity using one of many insect feeding bioassays (11,12,13). Of course negative bioassay results need not mean that an isolate is biologically inactive. Rather, it may mean that the in vitro requirement is not met. An in vitro test of isolates should be taken to mean that under test conditions they are either producing or not producing the desired compound. However, work on species of Balansia established that qualitative production of ergot alkaloids occurred both in vivo and in vitro (19). This same corollary was established for the endophyte of tall fescue (23,24,25), and is suggested from the work of Rowan et al. (13) for the production of peramine by the ryegrass endophyte. Concern for only mammalian need only be considered if the intended endophyte is for agronomic improvement of forage grasses and not conservation and turf grass species.

The competence of an endophyte to produce the desired biologically active compound should be done on the initial isolate as this ability may not be stable in culture, e.g. ergot alkaloids, Table 5. It is not known if in fact this loss in biosynthetic potential for a substance is restored to an isolate upon re-infecting it into grass material. Work on this aspect of the endophytes is being done (Siegel and Bacon, unpublished). An alternative procedure for working with endophytes is to obtain single spore isolates of the initial fungus. This procedure, while tedious, might lead to the selection of colonies that are superior or equal to the initial isolate, and contain one basic nuclear type. Such colonies should be stable for a considerable period of time, allowing for strain improvement using any of the processes, e.g. protoplast fusion, mutagenesis.

SECONDARY METABOLISM

This section will center on the production of several biologically active compounds which are secondary metabolites and whose intended use makes grass endophytes economically attractive. These compounds consist of a variety of chemically complex and structurally unrelated substances that have been associated with grasses, fungi and endophyte-infected grasses (Table 6). For the most part, compounds produced by endophytic fungi are alkaloids and they may or may not have the same biogenetic precursors since they have such diverse chemical structures. Of course there may be many more unknown secondary metabolites than currently reported, but the ones that are known are all produced from only a few biochemical intermediates of primary metabolism (Table 6). The compounds selected for inclusion in this table are those that were either studied in the past and related to some aspect of cattle toxicity, synthesis by the fungus in culture, or associated with some economic aspect of the infected grass.

Control of the biosynthesis of compounds availability of precursors. As is the case for the in situ origin of the final infected grass product, the origin of intermediates used in their biosynthesis might originate from the grass and/or the fungus. It must also be considered that the fungus might produce one portion of the molecule, and the grass chemically modifies it, as suggested for the synthesis of the neurotoxin, lolitrem B, found in infected perennial ryegrass (31). Table 6 lists, where possible, the class of compounds grouped according to the precursor biosynthetic origin for fungal

secondary metabolites following Turner's scheme (32) which may be useful for adding inducer substrates when formulating media to test for biosynthesis of specific classes of compounds.

Only recently have attempts been made to demonstrate whether substances are produced by the fungus independently of the grass and the reverse. Table 6 also lists those compounds that have been reported to occur in grasses whose infection status was unknown. Attempts to demonstrate that endophytes alone can make some of the major biologically active compounds in culture have failed, but these negative data may only mean that the culture conditions have not been met. It has been established that one of these, loline, is produced only in infected tall fescue, while another, perloline, is produced by both infected and noninfected grasses.

The media used for isolating and growing endophytes all have a high carbon to nitrogen ratio, and this ratio can vary within a range of 100 to 10, particularly for vegetative growth. I have found that this ratio is not optimum for the production of classes of secondary metabolites that are, at least partially, under nutritional control. One such class of compounds is the ergot alkaloids in which the qualitative and quantitative levels produced on media occur when the carbon to nitrogen ration is reversed in the direction of higher nitrogen. In addition to this ratio, media may be used where the form of nitrogen supplied is such that the rate of its utilization is slow. This suggest that the control mechanism for this class of compounds may involve nitrogen catabolite repression (27), as has been suggested for the mechanism for ergot alkaloid synthesis by a closely related fungus Claviceps sp. (28).

As indicated above, a characteristic of media useful for detecting secondary metabolites is the very slow growth rate. Slow growth rate is not only a factor of media, but also an inherent quality of each isolate. For the most part, ergot alkaloid-producing isolates that grow the slowest, but sporulate the most are the highest ergot alkaloid producers. This statement is based on data using endophytic species of Balansia (19,22). Information is not available one other endophytes to supports this generality.

Yates (29) has reviewed and he is indeed a leader in the research on the isolation and chemical identification of alkaloids and other substances isolated from tall fescue grasses. Garner et al. (30) have developed useful cattle toxicity bioassays for determining the activity of most compounds reported by Yates. In addition to these excellent reviews, a spectrum of biological activities for these and other compounds, as well as current bioassays can be found in the chapter by Siegel et al. (this book).

In the grass-fungus situation the environment is also expected to influence both the production of secondary metabolites and hence any associated animal pest, or fungus disease defense mechanism. Such environmental influences on the accumulation of secondary metabolites by plants (33,34), and in endophyte-infected tall fescue (13) are documented. These studies have only examined the effects of nitrogen and its interaction with soil moisture on the accumulation of ergot alkaloids, but similar effects should exist for other economically interesting metabolites. It has not been established which essential plant nutrient is more responsible for a particular metabolite associated with a desirable feature of infected grasses. A complex interaction is probably responsible for the reaction of infected grasses to any stressful situation.

The performance of infected grasses for any stress sparing mechanism should be measured under severe environmental conditions. Most studies have measured the performance of infected grasses under greenhouse conditions of constant temperature and moisture. Such ideal conditions will never differentiate between survival values and other effects of the endophyte on grass performance. Studies of infected grasses under severe environmental conditions can establish the value of an endophyte for use in other forages. A word of caution concerning this theoretical

approach is that The ecological success observed in naturally infected hosts may not be realized in synthetically infected hosts. It may be simpler to select naturally infected grasses and improve these for whatever desired character. Nevertheless, once identified, specific endophytes can be isolated and studied as described above; the continued use of specific endophytes will establish the utilitarian value of each endophyte for improved performance of nonhosts.

It is also important to use several cloned infected and noninfected grass material if at all possible since studies of such material might indicate differences due to infection, and not to the genetic makeup of different seed sowed seedlings. Studying cloned material should also identify grasses with superior tolerances to severe environmental factors, and which when infected by endophytes might produce an even better grass. Furthermore, it is important to study the performance of a variety of clones, since the work of Arechavaleta et al. (13) suggested and Belesky et al. (35) established that for each environmental factor, the behavior of each cloned will differ. The important point to remember is that the fungus apparently influences or exaggerate the basic genetic makeup of each grass.

CONCLUSIONS

The most important outgrowths of research devoted to etiologies of pasture grass toxicity (for review see 17) was establishing that the nature of the relationship of a fungus and its grass hosts was nonpathogenic, and that the fitness of infected grasses was improved. If indeed the fungus only modifies the basic physiology of the grass, it implies that there is in the basic genetic makeup of each grass species, a cultivar that is inherently superior without an endophyte.

Improved fitness observed in endophyte infected grasses indicates that ecologically we find yet another example of a mutualistic symbiosis. The nature of the benefits are still circumstantial, but then too so are many other mutualistic symbioses. The association of endophytes and grasses fits Smith and Douglas's definition as an intercellullar mutualistic endosymbiosis (36). This is a purely morphological definition and its use here reflects what is currently known with complete certainty.

Research should continue into the use of endophytes as biological controls for pests and for improved performance of grasses under stressful conditions. It is very seldom that such a biological system presents itself that will confer both pest resistant and stress resistant mechanisms. The fact that such a system is self-perpetuating, contained, and stable is all the more reason to use it. The present information on the variety of natural pest deterrents produced within the association predicts that there are obvious benefits derived from identifying the responsible agent, defining the nature of any stress sparing mechanisms, and using these for control processes in other plants.

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TABLE 1

Choke inducing and nonchoke inducing grass endophytes cultured on media and which may be useful for transferring to agronomically important grass species.

Endophytes*	Grass Hosts**
Epichloe typhina	Festuca rubra
E. typhina	F. longifolia
E. typhina	F. ligulata
E. typhina	Lolium perenne
E. typhina	Spenopholis obtusata
Acremonium coenophialum	Festuca arundinacea
A. lolii	L. perenne
Acremonium sp.	F. versuta

*Most species of Epichloe are considered choke inducing when infecting their hosts (and see chapter by Funk, this book).

**Natural hosts.

TABLE 2

Procedure for Isolating Grass Endophytes

A. GRASS TISSUE-ENDOPHYTE, 2.54 cm sections

B. STERILIZE, FULL-STRENGTH BLEACH, 5 min

C. RINSE, ASEPTICALLY CUT TISSUE INTO 0.5 cm SECTIONS

D. MACERATE TISSUE AND PLACE ON MEDIUM

E. INCUBATE UNTIL ENDOPHYTE DEVELOPS*

*The two basic endophytes, Acromonium typhinum and A. coenophialum, may be identified on media following published descriptions(2).

TABLE 3

Media Used to Isolate and Culture Endophytes

Isolation Agar Medium, CMM		Isolation Liquid Medium, M102	
Malt extract	10.0 g	Sucrose	30.0 g
Yeast extract	1.0 g	Malt extract	20.0 g
Corn meal agar	17.0 g	Peptone	2.0 g
Chloramphenicol	0.05 g	Yeast extract	1.0 g
Distilled water	1000 ml	MgSO	0.5 g
		KCl	0.5 g
		KH PO	1.0 g
		Chloramphenicol	0.05 g
		Distilled water	1000 ml

pH adjusted to 6.0 with NaOH

TABLE 4

Two stage fermentation procedure for choke inducing and nonchoke inducing fungal endophytes of grasses.

Fescue Tissue-Fungus
Complex Medium, e.g. M102, and 4 wks Shake Culture, 24 C
Alkaloid Producing Medium:

Sorbitol	50.0 g
Glucose	10.0 g
Glutamic acid	10.0 g
KH PO	0.5 g
MgSO	0.3 g
Yeast extract	1.0 g
Tryptophan	0.8 g
Distilled water	1000 ml

pH 5.6 adjusted with 10 N NaOH; incubate first as shake cultures at 24 C, then as stationary cultures (15-24 C) for 2 to 4 months.

TABLE 5

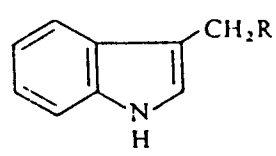
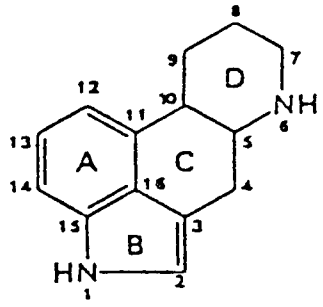
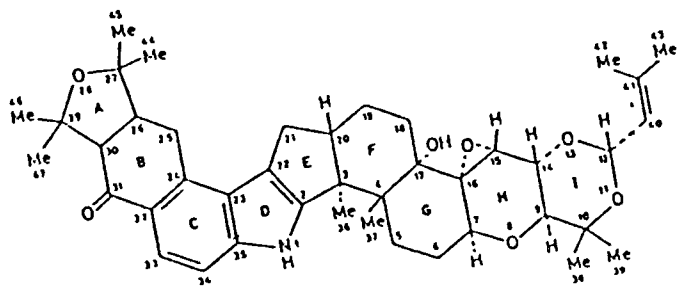
Stability of Ergot Alkaloid Producing Strains of Tall Fescue Endophyte during Culture

		Total Ergot Alkaloid (mg/l)*			
		Subculture			
Strain	**Initial**	**5**	**10**	**15**	**25**
347	524	487	382	400	390
338	214	517	114	93	1.5
351	18	20	0	0	0
357	0	0	0	0	0

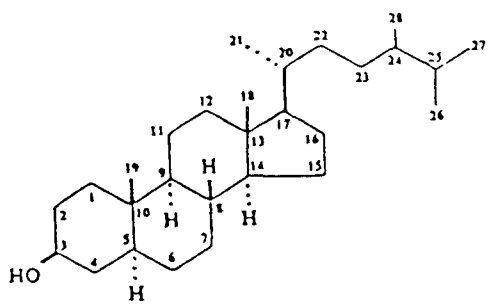
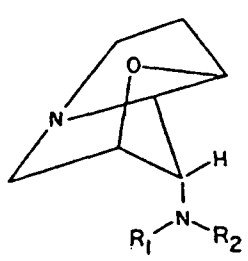
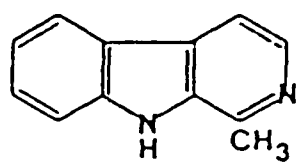
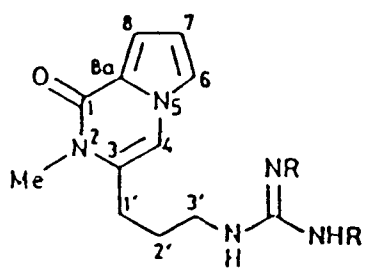
*Values are means of four replicates

TABLE 6

Major Classes of Secondary Metabolites Isolated from Toxic Grasses whose Endophyte Infection Status were or were not Known at Time of Chemical Isolation.

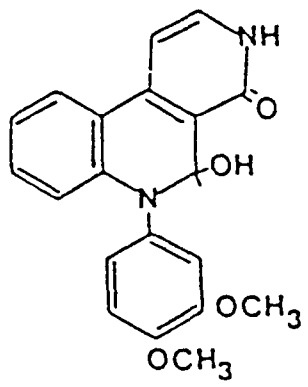
Chemical Class*	Examples	Source
A. Indole derivatives		
1. Simple indoles 	Erythro-1-(3-indolyl)propane-1,2,3-triol, 3-indole acetic acid, ethyl-3-indole carboxylate, indole ethanol, w-indole acetamide (also see single amino acid derivities)	Species of Balansia
2. Lysergic acid amides 	Ergovaline, ergotamine, ergosine, ergosinine, ergonovine, etc.	Balansia spp., endophytes of tall fescue, perenial ryegrass, and these infected grasses
3. Prenylated indoles  (lolitrem B)	Lolitrems A, B, C, and D, Paxilline	Perennial ryegrass

*Chemical classes following the scheme of Turner (32).

Chemical Class*	Examples	Source
B. Triterpens and Steriods		
1/. C_{28} Sterols 	Ergosta-4,6,8(14),22-trien-3-one, ergosta-4,6,8(14),22-tetraen-3-one, ergosterol peroxide	Infected fescue and cultures of A. coenophialum
C. Pyrrolizidine alkaloids 	N-formylloline, N-acetylloline, and demethyl-N-acetylloline	Infected tall fescue
D. Amino acid derivatives		
1. *Single amino acid*  (harmane)	Harmane, perlolyrine, norharmane, Halostachine	Tall fescue
2. Two amino acid derivatives  (1) R = H (2) R = Ac (peramine)	Peramine	A. lolii, A. coenophialum, infected tall fescue and perennial ryegrass

*Chemical classes following the scheme of Turner (32).

Chemical Class*	Examples	Source
D. Amino acid derivatives (Continued)		
3. Miscellaneous amino acid derivatives	perlolidine, perloline	Infected and noninfected tall fescue and perennial ryegrass.



*Chemical classes following the scheme of Turner (32).

ROLE OF ENDOPHYTES IN ENHANCING THE PERFORMANCE OF GRASSES USED FOR CONSERVATION AND TURF

C. R. Funk, B. B. Clarke, and J. M. Johnson-Cicalese

New Jersey Agricultural Experiment Station
Rutgers University
New Brunswick, New Jersey 08903

Grasses used for turf and conservation are exceedingly important in our efforts to enhance and beautify the environment, preserve and improve our precious soil resources, and provide recreation and enjoyment for all people. Improved cultivars are currently being developed to produce attractive, durable, and persistent turfs with reduced establishment and maintenance costs. Grasses exhibiting increased stress tolerance, improved insect and disease resistance, reduced pesticide, fertilizer, water, and mowing requirements, and better turf forming properties will also be of great benefit. We also need grasses adapted to poor soils, shade, heavy wear, close mowing, and other specialized uses and environments.

Turfgrass breeders have recently begun utilizing endophytic fungi (primarily Acremonium spp.) in their efforts to develop grasses with improved insect resistance and increased stress tolerance. In many instances, Acremonium endophytes living within the tissues of tall fescue (Festuca arundinacea Schreb.), perennial ryegrass (Lolium perenne L.), hard fescue (F. longifolia Thuill.) Chewings fescue (F. rubra L. subsp. commutata Guad.), and perhaps many other grasses have significantly modified host plant performance. Although plant scientists have been aware of the presence of endophytes in many grasses for over 100 years, endophytes received very little attention until recently when a number of significant discoveries were made. These included: (1) instances of poor performance when animals grazed on endophyte-infected perennial ryegrass and tall fescue, (2) reports of insect resistance in many endophyte-containing grasses, and (3) suggestions of improved growth, summer survival, and stress tolerance of grasses containing endophytes.

Animal health problems associated with endophyte-produced toxins have prompted programs to eliminate the fungus from new cultivars and seed lots of tall fescue, an important pasture grass. On the other hand, dramatic instances of improved insect resistance, persistence and performance have been observed in endophyte-containing plants. Thus, the Acremonium endophyte is generally considered to be a desirable attribute in grasses grown for turf and conservation.

INSECT RESISTANCE

New Zealand scientists (Prestidge et al., 1982) were the first to report that an endophytic fungus, Acremonium lolii Latch, Christensen, and Samuels, was associated with resistance to the Argentine stem weevil, Listronotus (= Hyperodes) bonariensis Kuschel in perennial ryegrass. Several toxins have since been associated with the presence of endophytes and are believed to be responsible for the enhanced insect resistance (Bacon et al. (Chapter 17). Larvae of the Argentine stem weevil, a small billbug-like insect, can cause extensive damage to perennial ryegrass and many other grasses used for pasture, turf and conservation in New Zealand and several other countries of the southern hemisphere (Stewart, 1986 and 1987). Larval damage is especially severe during hot, dry summer months resulting in extensive tiller loss, apparent drought stress, and slow fall recovery. In fact, endophyte-free plants seldom persist in old pastures and turfs in many parts of New Zealand because they are crowded-out and replaced by perennial ryegrass plants containing the Acremonium endophyte.

Although adult Argentine stem weevils cause only minor damage to established grasses, they can inflict severe damage during the seedling establishment stage. Again, the Acremonium endophyte confers a high level of resistance. Interestingly, even old ryegrass seeds containing nonviable endophyte, produce seedlings resistant to stem weevil feeding for a few days following germination and emergence (Stewart, 1985).

Resistance of perennial ryegrass to lepidopterous sod webworms has also been associated with the presence of the Acremonium endophyte. This important insect pest damages many turf and conservation grasses, especially in regions with warmer summers. The larvae spend the daylight hours protected in silken underground tunnels. During the night they feed extensively on grass leaves, primarily during late summer and early autumn. In a New Jersey trial (Funk et al, 1983), perennial ryegrasses rated as highly resistant to sod webworms were shown, through microscopic examination and enzyme-linked immunosorbant assay (ELISA), to contain a very high percentage of endophyte-infected plants. Ryegrasses exhibiting substantial injury from larval feeding, however, were free or mostly free of the endophyte. Field resistance to sod webworms was expressed both as a 10-fold reduction in larval feeding and a nearly complete absence of larvae from the soil beneath endophyte-containing plants. The maternal transmission of sod webworm resistance was very striking in that single-plant progenies descending from the same mother line were either all resistant or all susceptible. Maternal transmission of endophyte-mediated pest resistance occurs because almost all seed produced from an endophyte-infected plant contains the endophyte. We have not observed any evidence of pollen transfer. The role of endophytes in conferring resistance to various species of sod webworm in other grasses needs further study.

Billbugs (Sphenophorus spp.) can seriously damage many grasses used for turf and conservation, especially under conditions of drought stress during mid-summer. Adult billbugs, like the Argentine stem weevil, lay their eggs in the base of grass tillers during early summer. Upon hatching, the young larvae feed within the tiller and later upon adjacent plants immediately below the soil surface. Subsequently, wilted or dead grass tillers can be easily pulled from the soil exposing insect frass and feeding injury at the base of each tiller. Billbug injury, while easy to diagnose, is frequently mistaken for summer drought or disease injury. Moreover the more open turf and subsequent warmer, drier microclimate created by billbug damage makes conditions very favorable for additional damage by chinch bugs (Blissus leucopterus hirtus Montandon). Endophyte-enhanced resistance to billbugs has been observed in a number of perennial ryegrass field trials in New Jersey (Ahmad et al., 1986). Resistance to billbugs in these trials was primarily associated with the presence of the Acremonium endophyte. However, evidence of a limited level of genetic resistance

was apparent in selected ryegrasses. As a result, optimum billbug resistance would seem to require at least a moderate level of genetic-mediated resistance enhanced by an effective endophyte.

Endophyte-enhanced resistance to chinch bugs has been observed in New Jersey turf trials of perennial ryegrass, hard fescue, and Chewings fescue (Funk et al., 1985; Saha et al., 1987). At least two factors appear to be involved; (1) an intrinsic resistance to the chinch bug enhanced by various Acremonium endophytes, and (2) a less favorable environment for chinch bug development resulting from a healthier denser turf. This second factor may either be the result of endophyte-enhanced stress tolerance or from less damage caused by billbugs and other insects in high endophyte turfs.

STRESS TOLERANCE

Funk et al. (1985) reported striking differences in persistence, recovery from summer stress, and ability to resist weed invasion during the early fall of 1983 in perennial ryegrass and tall fescue turf trials conducted in North Brunswick, New Jersey. These tests, seeded in 1976, were irrigated and maintained at moderately high fertility with frequent close mowing (2-cm) until June 198l. At that time, the mowing height was raised to 5-cm, irrigation and weed control treatments were discontinued, and fertility applications drastically reduced. A substantial amount of crabgrass (Digitaria spp.) invaded the test by midsummer 1982 and produced an almost complete ground cover on the ryegrass trial. The tall fescue test also sustained moderate crabgrass invasion during this period.

By 1983, most perennial ryegrass entries exhibited 95 to 100 percent turf loss and were almost completely replaced by crabgrass and other weeds. However, several entries persisted with over 90 percent ryegrass turf cover. Indications of maternal inheritance of this dramatically improved persistence and resistance to weed invasion suggested that turfgrass endophytes were involved. It was later confirmed, through laboratory analysis, that 98 percent of all ryegrass tillers sampled from surviving plots contained the Acremonium endophyte. Unfortunately, remnant seed from this test had been discarded making it impossible to assess endophyte levels in the ryegrasses that failed to survive. However, since all 15 surviving ryegrasses were highly infected with endophyte, it seems unlikely that progenies free of endophyte could have survived. On the other hand, it is possible that some progenies with endophyte did not survive.

Optimum performance may well require a combination of non-endophytic sources of pest resistance and/or stress tolerance enhanced by an effective endophyte. It would seem likely that endophytes vary as much as other biological organisms in their ability to enhance pest resistance, stress tolerance, and plant persistence. Good performance may also require a high frequency of endophyte-infected plants within a cultivar.

Endophyte-enhanced performance was also strikingly apparent in the adjacent trial of tall fescue cultivars and single plant progenies(Funk et al., 1985). The 32 single-plant progenies that had the best performance contained an average of 98 percent infected tillers. Progenies exhibiting poor fall recovery and extensive weed invasion contained an average of only eight percent endophyte-infected tillers. This strongly suggests that the dramatic differences in persistence, resistance to crabgrass invasion, and recovery from summer stress of the tall fescues were associated with the presence of an Acremonium endophyte.

Enhanced resistance to sod webworms, billbugs and perhaps other insect pests was undoubtedly a contributing factor in the survival of the endophyte-containing perennial ryegrasses in this test. In another turf trial at Adelphia, NJ, many of the endophyte-free turf-type ryegrasses

were able to completely recover from prolonged defoliation by sod webworms. However, in this trial crabgrass was not present. The severe crabgrass competition at North Brunswick undoubtedly reduced the recovery of plants weakened by insects and environmental stress. It is likely that endophytes did more than just enhance insect resistance to produce the observed response. Insect populations and apparent insect damage did not appear sufficient to account for the great differences observed. Either the insects escaped our attention, or the improved performance and persistence of endophyte-infected ryegrasses and tall fescues were associated with physiological factors related to improved stress tolerance and competitive ability.

It has been our experience that endophytes appear to have little if any effect on turf performance when conditions are favorable. The endophyte-free ryegrasses 'Tara' and 'Gator' have performed well in a four year national testing program and have an excellent reputation in the turfgrass industry. Observations of endophyte-enhanced performance have normally occurred under conditions of severe stress or attacks by some, but not all, insect pests. Thus turfgrass endophytes may be similar to insurance, of little value when everything is favorable but of great value under certain conditions of biological and/or environmental stress. It also appears that the favorable effects of endophytes occur more frequently and are more significant in perennial ryegrass than in tall fescue, at least under field conditions in New Jersey.

Field studies near Dallas, Texas (Read and Camp, 1986) demonstrated that endophyte-enhanced performance is common in tall fescue pastures growing in an area with significantly higher summer temperatures than in most other areas of tall fescue usage. Endophyte-free tall fescue pastures and lawns have generally performed well in limited short term studies in New Jersey, Kentucky and Alabama. Although tall fescue is noted for its good overall insect resistance, deep root system and good heat and drought tolerance, there is some concern that the increased use of endophyte-free cultivars may result in greater pest problems. Moreover, previously unimportant insect and nematode species may be able to increase and thrive on endophyte-free grass. Loss of stress tolerance and persistence could also occur in especially stressful environments and in long-term plantings.

Fortunately, a number of stress physiologists, ecologists, botanists, and agronomists are now studying the role of endophytes in grasses of economic importance. Controlled studies have demonstrated that Acremonium endophytes in perennial ryegrass and tall fescue can increase plant yield and vigor (Clay, 1987; Latch et al., 1985), enhance root growth (Ellis, 1987), and modify water relations (Ellis, 1987; White and Comeau, 1987). However, this situation is very complex and is not fully understood at present. Interactions between host plant genotype, biotype of the endophytic fungus, plant nutrition, drought stress, and temperature are commonly detected in these studies.

The possible role of endophytic fungi in enhancing disease resistance also needs to be studied. Research has shown that many biotypes of Acremonium endophytes isolated from tall fescue and perennial ryegrass will inhibit the growth of a number of plant disease-inducing fungi in vitro(White and Cole, 1985; Bayaa et al., 1987). However, this has yet to be demonstrated in the field.

DEVELOPING TURFGRASS CULTIVARS WITH ENDOPHYTE- ENHANCED PERFORMANCE

Turfgrass breeders are currently using traditional plant breeding procedures including backcrossing, recurrent selection, and other population improvement methods to incorporate desirable endophytes into existing cultivars and elite breeding populations. This germ plasm is being used to develop new cultivars with both endophyte-enhanced performance and genetic

improvements in turf quality, pest resistance and stress tolerance. Increased knowledge of turfgrass endophytes is making breeding and evaluation programs much more efficient.

Large amounts of time and money were wasted in past breeding and evaluation programs as efforts made to improve and evaluate animal performance, pest resistance, and stress tolerance were confounded by the unrecognized effects of endophytic fungi. As a result, our most efficient approach to long-term cultivar development may well be to (1) remove endophytes from existing breeding populations, (2) select for genetic improvements in insect resistance, stress tolerance, etc., and (3) then incorporate the best available endophyte to enhance performance wherever appropriate. Concurrent with the plant breeding efforts, biologists should identify and/or develop endophytes tailored to specific host populations and uses. Recent and anticipated advances in molecular genetics may prove to be useful in endophyte selection and improvement programs.

Perennial Ryegrass

Tremendous progress has been made in the genetic improvement of perennial ryegrass for turf usage during the past quarter century. Each cycle of breeding has resulted in a stream of new cultivars with better stress tolerance, increased resistance to many of the most important diseases, a lower growth profile, and a more attractive appearance. Useful Acremonium endophytes are currently being incorporated into an increasing percentage of new perennial ryegrass releases. An estimated 10 million pounds of turf-type perennial ryegrass seed containing a high percentage of endophyte was harvested in 1987. Perennial ryegrass cultivars containing at least 70 percent Acremonium endophytes in some seed lots include: 'Regal', 'Pennant', 'All*Star', 'Repell', 'Omega II', 'Citation II', 'Dasher II', 'Sunrye 246', 'SR-4000', and 'SR-4100'. Additional perennial ryegrasses with high endophyte levels will be available after the 1988 seed harvest. They will include 'Pinnacle', 'Commander', 'Sherwood', and 'Dandy'.

Turfgrass managers desiring the benefits of endophyte-enhanced performance must be careful in their selection of seed. Endophyte viability declines during seed storage, especially under hot, humid conditions. Therefore, seed harvested in June or July should maintain a high level of viable endophyte as long as it is stored under cool dry conditions and used before or during the following spring. At present, seedlings produced from a grow-out test must be examined to determine the viability of the endophyte. This can be done through either microscopic examination of properly stained plant tissues or by an ELISA test conducted by a well-trained laboratory technician. A number of states are currently offering this service. A dated seed label showing percent viable endophyte would also be useful.

It is also important to recognize that different seed lots of the same cultivar may vary in initial endophyte concentrations. For example, in a few of the older cultivars some seed production fields were established with old seed containing non-viable endophyte. When this occurred the benefits of endophyte-enhanced performance were lost.

Normal fungicide applications made to established turfs usually have little or no effect in reducing the level of endophyte.

Hard Fescues

Hard fescues are receiving increased attention in the turfgrass industry. Improved cultivars of this valuable species can produce a dense, disease resistant, attractive and fine-textured turf on poor soils with little or no supplemental fertilization or irrigation. The greatest weakness of hard fescues, however, may be their slow recovery from excessive wear or insect damage. Acremonium endophytes have been identified which enhance both summer performance and resistance to chinch bugs (Saha et al., 1987). Turfgrass breeders are currently utilizing these useful endophytes in their

cultivar improvement programs. To date commercial seed production has been initiated on 'SR-3000', a hard fescue with a high level of endophyte.

Chewings Fescues

Turfgrass breeders in Europe and the United States have developed a number of attractive turf-type cultivars of Chewings fescue. They are especially useful for medium-to-low maintenance turfs, in moderate shade and in regions with cool summer climates. Useful Acremonium endophytes have been identified in Chewings fescue which can enhance summer stress tolerance and increase resistance to chinch bugs (Saha et al., 1987). Turfgrass breeding programs at Seed Research of Oregon, Pure-Seed Testing, Pickseed West, E. F. Burlingham, Rutgers University and the University of Rhode Island are attempting to develop improved cultivars of Chewings fescue with high levels of useful endophytes.

Other Fine Fescues

Acremonium-type endophytes have been discovered in strong creeping red fescue (F. rubra L. subsp. rubra), blue fescues (F. glauca Lam.), and sheeps fescue (F. ovina L.) (Saha et al., 1987). Studies are currently underway to assess their usefulness in enhancing insect resistance and turfgrass performance. Current sources of endophyte in strong creeping red fescue have failed to produce peramine, a toxin shown to be responsible for insect resistance, and have reacted negatively (less than or equal to 10% dead) to an aphid bioassay test (Siegel et al. Chapter 16). Acremonium endophytes in perennial ryegrass, Chewings fescue and hard fescue, however, have been shown to produce this compound and have given positive results on the aphid bioassay. Breeders are currently looking for endophytes in strong creeping red fescue that will produce peramine and thus enhance insect resistance. It would also be of interest to determine whether non-peramine producing endophytes have other mechanisms that might enhance resistance to insects and stimulate turfgrass performance.

Tall Fescue

Tall fescue has been widely used for pasture, conservation and turf purposes during the past four decades, with Kentucky 31 the primary cultivar grown. Significant genetic improvements in color, texture, and disease resistance during this time led to the development of many improved turf-type tall fescues. These cultivars are rapidly increasing in popularity in many parts of the United States and southern Europe. Many, including 'Adventure', 'Apache', 'Mustang', and 'Rebel II', have characteristics that could also make them very useful pasture grasses in various regions. However, only seed lots completely free of viable endophyte should be used for forage establishment in order to avoid livestock toxicoses.

Selected Acremonium endophytes would undoubtedly be useful in enhancing turf performance, insect resistance and stress tolerance of turf-type tall fescues, especially in highly stressful environments and low maintenance turfs. However, to date, seed companies and plant breeders have been somewhat reluctant to develop tall fescue cultivars with high levels of endophyte since there is always the possibility that they might be used for pasture establishment. This is especially likely to occur with poorer quality seed that fails to meet certification standards. Therefore, until appropriate seed labeling and educational programs are in place, breeding for high endophyte-containing turf-type tall fescues is likely to be delayed. Current progress in developing lower-growing, "dwarf-type"tall fescues may encourage breeders to incorporate useful endophytes since such premium turfgrasses would be less likely to be used for non-turf purposes.

Kentucky Bluegrass

Kentucky bluegrass (Poa pratensis L.) is often considered the Cadillac of lawn grasses in temperate climates of North America. It is hardy, attractive and widely adapted. The development of lower-growing, turf-type cultivars with good resistance to the Helminthosporium leaf spot and melting-out disease has made Kentucky bluegrass even more useful as a turfgrass in humid regions. Moderate levels of genetic resistance to billbugs, sod webworms, greenbug aphids (Schizaphis graminum Rondani) and chinch bugs have been identified in Kentucky bluegrass.

Endophyte enhancement of this genetic insect resistance would be very useful; however, attempts to find a non-choke-inducing endophyte in Kentucky bluegrass have been unsuccessful to date. Likewise, there are no reports of a successful inoculation of an Acremonium endophyte from other genera of grasses into this valuable turfgrass species. Even if inoculation were accomplished, it is questionable whether the intergeneric transfer of an endophyte would be successful in enhancing insect resistance and stress tolerance. Endophyte-host interactions are likely to be very specific as a result of a long period of coevolution into a mutually beneficial relationship (Clay, 1988). If this is the situation, then additional efforts should be made to find useful endophytes in Kentucky bluegrass and other closely related species of Poa. Successful inoculation of such endophytes into leading cultivars of Kentucky bluegrass may well prove to be very beneficial. Because of apomictic reproduction and high levels of heterozygosity present in all elite cultivars of Kentucky bluegrass, inoculation techniques will be of greater immediate value than the transfer of endophytes through hybridization techniques.

Most elite Kentucky bluegrass cultivars originated as the progeny of a single, highly apomictic plant. This results in essentially all plants of a given cultivar being genetically identical to each other as well as to the original parental plant. Successful inoculation of only one plant would, therefore, be sufficient to incorporate a useful endophyte into such a Kentucky bluegrass cultivar. Because of the highly heterozygous genotype in Kentucky bluegrasses, the backcross technique cannot be used to transfer endophytes or genetic characters into a given cultivar. Hybridization and a modified backcross technique could be used, however, to generate highly heterogeneous and highly heterozygous populations of Kentucky bluegrasses containing useful endophytes. Elite, new and unique, and highly apomictic cultivars containing useful endophytes could eventually be selected from such populations.

Endophytes in Other Grasses

Endophytes are also being discovered in many other grasses used for turf and conservation. White (1987) examined over 800 herbarium specimens in 93 genera of grasses and found endophytic fungi present in 43 grass species in the following 11 genera: Agrostis, Bromus, Cinna, Elymus, Festuca, Lolium, Melica, Poa, Sitanion and Stipa. These grasses were collected from Africa, Argentina, Canada, Europe, India, Mexico, New Zealand and the United States. Many of the endophyte-containing grasses examined were species "native" to the continental United States. Additional work is needed on the possible significance of endophytes in these other grass species.

In conclusion, utilizing endophytes to enhance the performance, insect resistance and stress tolerance of turf and conservation grasses has considerable potential, and is highly compatible with goals for reduced pesticide usage. Moreover, an increasing awareness of the role of endophytes is making cultivar evaluation and genetic improvement programs much more efficient. As our knowledge of endophytic fungi expands, including a better understanding of their genetic diversity and how they interact with both plants and the environment, they will become even more useful to the turfgrass breeder and ultimately to all who enjoy and benefit from improved grasses.

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SECTION V

State of the Art Research on Use of Entomophilic Nematodes for Control of Turfgrass Insects

FIELD EFFECTIVENESS OF ENTOMOPHILIC NEMATODES NEOAPLECTANA AND HETERORHABDITIS

Ramon Georgis
Biosys
1057 East Meadow Circle
Palo Alto, CA 94303

and

George O. Poinar, Jr.
Department of Entomological Sciences
University of California
Berkeley, CA 94720

INTRODUCTION

High levels of pest resistance to conventional pesticides together with growing public concern about potential health and environmental hazards associated with chemical pesticides, are forcing the industry and public to seek less toxic pest management methods. Entomophilic nematodes of the genera Neoaplectana (=Steinernema) (Family: Steinernematidae) and Heterorhabditis (Family: Heterorhabditidae) are regarded as having excellent potential as biological control agents (Kaya 1985, Poinar 1986). The broad host range and high virulence of these nematodes make them attractive candidates for industrial development. Extensive testing has demonstrated a lack of mammalian pathogenicity, and the U.S. Environmental Protection Agency has subsequently exempted these nematodes and their associated bacteria Xenorhabdus from registration and regulation requirements. There are a number of described species of Neoaplectana and Heterorhabditis (Poinar 1979, 1986, 1987), however, to date, most studies have been conducted with N. carpocapsae (S. feltiae) and H. heliothidis.

BIOLOGY

The ensheathed third-stage juvenile of N. carpocapsae and H. heliothidis (approximately 500u long and 20u wide) is the invasive form which locates new hosts, initiates infection and is the only stage in the nematode's life cycle that occurs outside the host in the soil. Besides persisting in the soil environment without taking in nourishment, the infective stage searches for insect hosts using sensory organs that are capable of detecting insect excretory products, temperature gradients and carbon dioxide (See Kaya 1985). These nematodes are characterized by their mutualistic association with bacteria in the genus Xenorhabdus (Poinar 1979, 1986). The infective juveniles enter the hosts via natural body openings (mouth, anus or spiracles), exsheath and penetrate

mechanically into the hemocoel (Poinar 1979). Heterorhabditids can also enter directly through the host's cuticle (Bedding & Molyneux 1982). The infectives liberate the bacteria causing septicemic death of the host 24-48 hours later. The nematodes feed on the multiplying bacteria and the dead host tissues, passing through several generations in which their numbers increase tremendously. Eventually, ensheathed infectives, carrying the mutualistic bacteria in their gut, emerge from the depleted insect cadaver. Depending on the temperature the complete life cycle in most insects takes 10-20 days.

FIELD EFFICACY

Above-ground applications: In general, attempts to control foliar insects with N. carpocapsae have been discouraging, with low host mortality, insignificant population reduction, or inadequate crop protection (Kaya 1985). Poor control has been attributed to the failure of the nematodes to survive drying of the spray deposit. Recent developments in inducing infective nematodes to enter anhydrobiosis (Table 4) may increase the survival of nematodes and subsequently achieve successful control (Georgis 1987, Ishibashi et al 1987b, Wojcik & Georgis 1987). Other factors limiting the use of nematodes on foliage are solar radiation (Gaugler & Boush 1978) and temperature extremes (Schmiege 1963). The most successful use of nematodes has been against insects which spend part of their life cycle in protected habitats avoiding harsh environmental exposure. Insects such as wood borers in the family Sesiidae (Deseo 1986), the artichoke plume moth, Platyptilia carduidactyla (Bari & Kaya 1984), and beet armyworm, Spodoptera exigua in chrysanthemum production beds (Begley 1987), were successfully controlled with these nematodes.

Soil applications: Soil inhabiting insects are a logical target for control by these nematodes. The nematode naturally occurs in moist cryptic environments, especially soil. In the soil they have advantages over pesticides and microbial pathogens by virtue of their attraction and mobility towards an insect host. Field applications of N. carpocapsae and H. heliothidis with conventional sprayers frequently have shown that infective nematodes possess high efficacy for controlling a wide range of insects that affect man, such as imported fire ants (Poole 1976; Quattlebaum 1980), turfgrass (Table 1), vegetables (Table 2), ornamentals, shrubs, flowers and caneberries (Table 3). In many situations, the efficacy of the nematodes will depend on their persistence in the soil. Nematodes introduced into the soil are capable of remaining infective for weeks or even months (Harlan et al 1971, Miller 1987, Georgis & Hague 1988), more than sufficient time to find a host and cause mortality; but in some situations persistence may be adversely affected by lack of moisture, extreme temperatures, soil texture and natural enemies (Molyneux & Bedding 1984, Ishibashi & Kondo 1987, Ishibashi et al 1987a). Infectivity of nematodes is mostly influenced by soil texture (Georgis & Poinar 1983a, Molyneux & Bedding 1984), temperature (Molyneux 1984, Simons & Van der Schaaf 1986), and moisture (Molyneux & Bedding 1984, Kondo & Ishibashi 1985). Differences in field efficacy exist between neoaplectanid and heterorhabditid nematodes and their various species and strains (Tables 1, 3). For example, heterorhabditids are highly effective against Japanese beetles and billbugs (Table 1), but provide extremely poor results when mole crickets are challenged. In contrast, N. carpocapsae are effective against mole crickets but provide only modest control of Japanese beetles. Differences in field efficacy in part may be related to the vertical distribution of the nematodes in the soil after application. N. carpocapsae seem to show a preference for soil near the surface (Moyle & Kaya 1981, Georgis & Poinar 1983a), and therefore may be best adapted to attack insects like mole crickets and cutworms which feed at the soil litter interface or on the soil surface. Heterorhabditids have a greater tendency to move downwards (Georgis & Poinar 1983b) and has

superior host seeking abilities (Gaugler & Campbell, in press), making them efficacious against Japanese beetles, billbugs and root weevils which are present at the root zones of their host plants.

APPLICATION CONSIDERATIONS

For successful application of nematodes, the following steps should be taken into consideration:

1. Nematodes should be applied to moist soil. Pre and post-application irrigation and moderate soil moisture are essential for the movement and persistence of these nematodes. According to Poinar (1986), most nematodes applied to dry soil will perish; however, if they are applied to damp soil which later becomes dry, many will survive for some period because of their ability to withstand gradual desiccation. Field applications of nematodes to dry turf with 0.64 cm pre-treatment irrigation followed by 0.64 cm post-treatment irrigation with normal rainfall resulted in Japanese beetle grub control comparable to a standard insecticide (Shetlar 1987). Non-irrigated turf showed less control. Nematodes are less effective in soils close to the saturation point (very wet) (Molyneux & Bedding 1984).

2. Soil temperature between 18-30ºC is adequate for nematode survival, movement and host infection. Temperatures above 30ºC and below 18ºC (Tables 1, 3) may reduce nematode effectiveness (Schmiege 1963, Molyneux 1984). For effective field control at temperatures below 18ºC, cold-active strains of N. carpocapsae such as the Umea strain (Pye 1987) or the HL81 isolate of Heterorhabditis sp (Simons & Van der Schaaf 1986) are required.

3. To avoid the effects of solar radiation (Gaugler & Boush 1979) and temperature extremes (Schmiege 1963), application in the early morning or early evening is recommended.

4. Concentrations exceeding 2.5 billion nematodes/hectare (1 billion/acre) are needed to ensure that a sufficient population will come into contact with the insect to provide consistent pest control. A high concentration is needed to overcome the impact of soil environment, pathogens, predators and other factors that can form an ecological barrier to nematode effectiveness. High concentrations are required against certain insects such as root maggots which only remain for a few days in the soil before tunneling in roots (Table 2) or those which are not highly susceptible to nematode infection (Tables 2, 3) because of their small size (i.e., early immature stages of mole crickets, root maggots and root weevils).

5. The spray volume needed depends upon characteristics of the turfgrass or soil being treated. In order to penetrate the deeper thatch (thatch is a tightly bound layer of dead and living roots and stems that accumulates between the soil surface and green vegetation in turfgrass), or denser turfgrass a high spray volume may be needed to incorporate nematodes to the depth frequented by the target insect. Under these conditions, 4 to 5 gallons/1,000 ft^2 (0.2 liters/m^2) is usually acceptable. It is well known that both moisture and pore size influence the movement of soil nematodes (Wallace, 1963). A nematode cannot move between soil particles when the pore diameter is less than the width of the nematode. Although N. carpocapsae can migrate through clay soil, movement will be much less than in sand and sandy loam (Georgis & Poinar 1983a). In most field tests, 150 gallons/acre (230 liters/hectare) appears to be adequate, but research is needed to determine the proper spray volume in relation to the soil type and insect activity at the application site.

6. When nematodes are applied against root-feeding insects such as white grubs, mole crickets, billbugs, and root weevils, it may take 10-30 days before the insect population is significantly reduced (Shetlar 1987, Cobb & Georgis, in press); but against lepidopterous larvae such as cutworms and sod webworms, which can be found on or close to the soil or turf surface, control can be achieve 2-5 days after treatment (Lossbroek & Theuissen 1985, Shetlar 1987).

7. More than one application of nematodes may be required for acceptable control when soil environments are not adequate for nematode persistence. Repeat applications may be needed against insects that feed over a two-month period (i.e., root weevils and mole crickets), and against insects with more than one generation/year (i.e., root maggots).

8. Nematodes can often be applied with the same equipment used for the application of conventional pesticides. Neoaplectanids can withstand application pressures up to 300 psi. Accordingly, nematodes have been applied with small pressurized sprayers, mist blowers, electrostatic sprayers and helicopters (Kaya, 1985). The infective stages are resistant to shear but cannot easily pass through a screen with openings less than 50u in diameter. Also, some pumping equipment produces a considerable amount of heat, and should the temperature rise above 32ºC, the nematodes could be damaged (Poinar 1986).

APPLICATION METHODOLOGY

As with chemical insecticides, soil surface spraying of nematodes is the method most often used in response to insect attack. The broadcast approach is quick, easy, and gives good coverage, but in most cases high concentrations are needed to ensure that sufficient numbers of nematodes will come close to the active site of the insect. In some situations nematodes were found to have potential when applied at planting time (Georgis et al 1983, Pye & Pye 1986, Bari unpublished); but in certain soil environments that require nematode persistence 4-6 weeks before the appearance of the target insect stage, (i.e., corn rootworm, Diabrotica spp and crucifer flea beetle, Phyllotreta cruciferae), insect damage was not prevented (Munson & Helms 1970, Morris 1987), probably due to inadequate soil moisture and the non-susceptible nature of some early larval stages. Other methods of delivering nematodes to the soil are by means of injection (Glaser, & Farrell 1935), baits (Georgis et al. 1989) and alginate capsules (Kaya & Nelson, 1985). Practical implementation of these techniques will require further investigation. It is expected that these application strategies will require fewer nematodes for effective control and will provide better protection for nematodes from extreme environments. Nematodes may also be applied by drip irrigation (Reed et al 1986), and overhead sprinkler systems (Kaya 1985). Further research may establish these techniques as practical for nematode applications. Against wood-boring insects, neoaplectanids and heterorhabditids have been delivered into galleries with a syringe, cotton swab plug, oil can, and back pack sprayer (Deseo 1986). Application of nematodes to nylon pack cloth bands lined with pellon fleece or terry cloth and placed around tree trunks are control tactics used for the control of late stage gypsy moth larvae Lymantria dispar (Reardon et al 1986), or for overwintering codling moth prepupae Cydia pomonella (Kaya et al 1984). Such tactics may be useful if nematodes are to be used in concert with other control measures. Preliminary investigations have suggested that certain formulations provide an efficient delivery system, and these results should provide an impetus to attempt control programs against insects that were previously thought to be difficult or impractical to control with these nematodes (Table 4).

CONCLUSION

Neoaplectana and Heterorhabditis nematodes have emerged as the only alternative candidates to chemical insecticides for the control of a wide host range of soil-inhabiting insects. While the efficacy of the nematode can be affected by undesirable biotic or abiotic factors, the potential benefits (safe to vertebrates, reduced insecticide use, no environmental contamination) are great. Recent development in the mass production of nematodes through a liquid fermentation process, and the ability to induce anhydrobiosis in nematodes may enable them to be used economically in the management of insect pests in different habitats (Tables 1 -4). Given our rapidly developing understanding of nematodes and our increasing ability to manipulate them (e.g., genetic improvement, application techniques, formulations), it would be surprising if they did not eventually fill an important role in crop protection.

TABLE 1

Summary of the field trials with Neoaplectana and Heterorhabditis nematodes against selected turfgrass insects (1984-1987).

Nematode[a]: billion/hectare	Number of[b] tests	% Control Reduction range	average
Japanese beetles, popillia japonica			
Hh: 2.5-12.5	12	27 - 90	61
HP88: 2.5-12.5	7	55 -100	76
Nc: 2.5-12.5	8	18 - 72	47
Standard insecticide	16	29 - 98	77
Northern masked chafer, Cyclocephala borealis			
Hh: 2.5-12.5	7	12 - 95	53
HP88: 2.5-12.5	2	14 - 74	44
Nc: 2.5-12.5	5	9 - 61	43
Standard insecticide	6	39 - 99	65
June and May beetles, Phyllophaga spp			
Hh: 1.0-12.5	4	48 - 81	61
Nc: 2.5-12.5	4	39 - 62	53
Standard insecticide	3	35 - 72	54
European chafer, Rhizotrogus majalis			
Hh: 2.5-12.5	2	54 - 61	57
HP88: 1.2-12.5	3	56 - 70	63
Nc: 1.2-12.5	2	36 - 52	44
Standard insecticide	4	36 - 68	59
Mole crickets, Scapteriscus spp			
Hh: 2.5-12.5	3	3 - 12	8
Nc: 2.5-12.5	6	42 - 73	62
Standard insecticide	6	52 - 79	69
Black cutworms, Agrotis ipsilon			
Hh: 1.2-5.0	3	56 - 92	76
Nc: 2.5-12.5	3	44 -100	84
Standard insecticide	3	68 -100	89
Armyworms, Pseudaletia unipuncta			
Hh: 2.5-12.5	2	68 - 95	81
Nc: 2.5-12.5	2	74 -100	87
Standard insecticide	2	75 -100	96
Bluegrass billbug, Sphenophorus parvulus			
HP88: 2.5-7.5	4	61 - 79	77
Nc: 2.5-7.5	4	55 - 65	56
Standard insecticide	3	71 - 88	84

a: Hh = Heterorhabditis heliothidis, HP88 = Heterorhabditis sp HP88 isolate, Nc = Neoaplectana carpocapsae All strain.

b: Biosys, unpublished reports. Plots were 9-36 sq. meters, 4-5 replicates, moderate to high insect pressure. Soil temperature & moisture varied from 13-27° & from 16-27% (w/w) respectively throughout the test periods.

TABLE 2

Summary of Neoaplectana carpocapsae All strain field trials (2.5 billion/hectare) applied at planting or 2-3 weeks after planting against selected important soil-inhabiting vegetable insects (1985-1987)[a]

Insect[b]	Host	Field Efficacy[c]	Remarks[d]
Banded cucumber beetle, Diabrotica balteato	Curcurbits	Fair - moderate	Neonate larvae relatively unsusceptible
Black cutworm Agrotis ipsilon	Lettuce, tomato, corn	Moderate - high	Time of application is very critical.
Flea beetles Epitrix spp	tobacco, sweet potato	Fair - moderate	Neonate larvae relatively unsusceptible
Root maggots Delia spp	Cabbage, bean onion, turnip	Fair - moderate	Neonate larvae relatively unsusceptible - short exposure time between larvae and nematodes.
Wireworms Limonius spp	sugar beet, sweet potato	Fair - moderate	Larvae relatively unsusceptible.

a: Based on 4-7 tests. Biosys, unpublished reports. Rows 10-20 M long, 4-5 replicates. Soil temperature ranged between 16-28°C and kept moist throughout the test periods.

b: Low to moderate insect pressure.

c: Fair: Reduction in plant damage over control but crop protection inadequate. Nematodes are probably useful in an Integrated Pest Management (IPM) program.
Moderate: 50-80% crop protection. Useful in an IPM program if complete protection is mandatory.
High: Over 80% crop protection.

d: Unsusceptible insects: LD50 above 50 nematodes/larva under laboratory conditions.

TABLE 3

Summary of the trials with Neoaplectana and Heterorhabditis against important soil-inhabiting insects of ornamentals, shrubs, flowers and caneberries (1985-1987)[a]

Condition	Nematode:dosage[b]	Results[c]	Remarks
	Black vine weevil, Otiorhynchus sulcatus Strawberry root weevil, O. ovatus		
Greenhouse, potted plants	Hh, Nc: 50-100/cm^2	Moderate - high	Moderate control obtained when early stage larvae (less susceptible than later stages) are highly present in pots.
Outdoor, potted plants (average)	Hh, Nc: 50-100/cm^2	Moderate - high	Soil temperatures above 16°C
Field[d] 16°C	Hh, HP88: 300-600/cm^2	Moderate - high	Soil temperatures above (average)
	Nc: 300-600/cm^2	Moderate	
	Japanese beetles, Popillia japonica		
Greenhouse, potted plants	Hh, HP88: 90/cm^2 Nc: 100-500/cm^2	High Low - moderate	Hh & HP88 were equivalent to standard insecticides
	European chafer, Rhizotrogus majalis		
Greenhouse, potted plants	Hh, HP88: 90/cm^2 Nc: 100-500/cm^2	Moderate Low	Hh & HP88 were equivalent to standard insecticides

a: Based on 4-8 tests. Biosys, unpublished reports, Stimmann et al 1985, Klingler 1986, Rutherford et al 1987, Wright et al 1988, Shanks & Agudelo-Silva 1987.

b: Hh: H. heliothidis; HP88 = Heterorhabditis sp. HP88 isolate; Nc: = N. carpocapsae All strain.

c: Low = under 50% control; Moderate: 50-80% control; High: Above 80% control.

d: Low control was obtained at soil temperatures below 14°C (Rutherford et al 1978, Biosys unpublished reports).

TABLE 4

Recent investigations in applications technology of Neoaplectana carpocapsae

System	Application Site	Target Insects	Results	Ref.
Anhydrobiotic nematodes mixed with sucrose	Laboratory, plastic containers	Carpenter ant, harvest ant, Western yellow-jacket (adults)	90-100% infection (n=20)	Georgis, 1987
Anydrobiotic nematodes mixed with bran bait	Laboratory, plastic containers	Black cutworms, mole crickets, house crickets, vagrant grass-hopper (late stages).	70-100% infection (n=20)	Georgis 1987; Georgis, et al, 1988
Anhydrobiotic nematodes mixed with antidesiccants	Laboratory, plant seedlings	Tomato hornworm, beet armyworm, imported cabbage worm, corn ear-worms (various larval stages).	50- 90% infection	Georgis, unpubl.
Anhydrobiotic nematodes in alginate capsules	Laboratory, petri dish lined with moist foam	German cock-roach (male)	60% infection (n=12)	Georgis, unpubl.
Nematodes in alginate capsules (slow release system)	Laboratory, capsules contain-ing tomato seeds in soil	Root-feeding insects (e.g., corn rootworms, cabbage maggot	high infection of wax moth larvae	Kaya et al 1987
Nematodes in alginate capsules (delivery system)	Laboratory, petri dish (moist environment)	Imported fire ants	Adult ants carried capsules to mounds	Biosis, unpubl.
Nematodes on specific moist pads in traps	Laboratory, plastic containers	German cock-roach (various stages), house fly adults	70 - 100% infection	Renn et al 1985, Georgis unpubl.

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ENTOMOGENOUS NEMATODES FOR CONTROL OF TURFGRASS INSECTS WITH NOTES ON OTHER BIOLOGICAL CONTROL AGENTS

David J. Shetlar
Research Scientist, Entomology
ChemLawn Services Corporation
Research and Development
P.O. Box 85-816
Columbus, OH 43085

The lawn care industry grew exponentially in the 20 years prior to 1985-86, with major changes in usage of equipment, chemicals and personnel. In general, small single owner businesses which operated out of garages or sheds have yielded to large multi-state corporations. The industry passed the $2 billion receipt marker in 1985 and has continued to grow. Increasing buy outs, consolidation of companies, and a slowing of total growth have marked the 1985 to 1987 years.

Many early programs utilized more fertilizer and pesticides, especially insecticides, than what was probably needed for quality turf. Applications were usually applied in a dilute liquid form sprayed over the entire lawn. As research information was accumulated, environmental concerns were expressed, and business competition required cost savings, considerable reductions in chemical usage and changes in application have occurred. To maximize profits while satisfying customer expectations, most lawn care companies now provide complete fertilization, annual grass and broadleaf weed control and insect control. Many southern and western markets also require fungicide usage in order to maintain quality turf.

Though there had been increasing numbers of activist groups raising concern over lawn care chemicals, no major effects were noted until 1985 to 1987. During these years, national media began to exploit the sensationalism provided by these environmental activists. Many states have begun to more actively regulate the industry and the way lawn care is delivered. Many states have enacted regulations on applicator training and certification, customer right to now, pre and post application notification and posting of treated lawns. Unfortunately, the scientific data base is inadequate to fully answer the questions raised about long-term chemical exposure, synergistic effects of chemicals and possible water contamination. Though there is little scientific information to support claims of damage there is also little information available which has proved that damage can not occur. This raises the problems of risk and risk assessment. Some people want no risk in life while others can accept reasonable risks. This dilemma is difficult to resolve with reason.

Because of perceived changes in customer wants and a desire to provide safe and effective alternatives to standard lawn care treatments, ChemLawn Services Corporation and its research and development staff have been investigating alternative controls and systems for the last five

years. In order for alternatives to be used, they must be easy to use, effective and comparable in cost. Unfortunately, the few alternatives available for insect pest control have been, historically, costly and/or marginally effective.

Insect parasitic (entomogenous) nematodes have been studied since the 1920's, but they were difficult and expensive to produce and did not produce lasting effects. From 1929 to 1940, R. W. Glaser et al. (1940) detected, reared and field tested an entomogenous nematode, Neoaplectana glaseri Steiner. Possibly because of the war effort and discovery of synthetic organic insecticides, little work on entomogenous nematodes for control of Japanese beetle grubs was subsequently undertaken. Glaser attempted to produce N. glaseri in large numbers using a veal pulp medium but this was labor intensive, difficult and did not provide sufficient nematodes for applications to large areas. Recent interests in entomogenous nematodes have yielded better culture techniques for N. carpocapsae Weiser and Heterorhabditis heliothidis (Khan, Brooks and Hirschman) (Dutky et al. 1964, Bedding 1981, Wouts 1981). Recently, a new venture capital company, Biosys (Palo Alto, CA), had developed additional improved rearing procedures so that commercial production of these nematodes (Neoaplectana spp. [=Steinernema] and Heterorhabditis spp.) was possible and field evaluations could be undertaken. This paper contains information derived from research on these nematodes as well as some comparative studies with other alternative products such as Bacillus thuringiensis (Bt) strains.

LAWN INSECT PESTS AND THEIR CONTROL

The major turfgrass pests include: a) surface feeding insects such as chinch bugs, sod webworms, cutworms, armyworms and greenbugs; as well as, b) soil or root feeding insects such as white grubs, billbugs and mole crickets. These pests are appropriately discussed by, Niemczyk (1981), Baker (1982), Shetlar et al. (1983), and Tashiro (1987).

The white grubs (Japanese beetle, Popillia japonica Newman; masked chafers, Cyclocephala spp; May-June beetles, Phyllophaga spp; European chafer, Rhizotrogus majalis [Razoumowsky]; Oriental beetle, Anomala orientalis Waterhouse; Asiatic garden beetle, Maladera castanea [Arrow]; and, green June beetle, Cotinis nitida [L.]) are, by far, the most troublesome widespread turfgrass pests. The highly mobile adults seek out quality turf and lay eggs in the soil. The larvae, white grubs, come to the soil surface to feed on plant roots and other organic material included in the thatch. Since most turf insecticides are easily bound to the living and dead turf tissue (Niemczyk and Krueger 1982; Sears and Chapman 1979; Niemczyk 1987), white grubs are difficult to challenge without considerable irrigation following an insecticide spray and reduction of the thatch layer. Even when white grub populations are below damaging levels, mammal predators such as raccoons, skunks, opossums and moles can severely damage turf in their search for an arthropod meal.

Since the Japanese beetle is one of the most important turf damaging grubs in the eastern United States, extensive research has been undertaken to control this pest using many tactics (Fleming 1976). Considerable work on biological controls, especially bacterial milky diseases (Klein et al. 1976), has been undertaken for control of Japanese beetle grubs as reviewed by Fleming (1968). Bacillus popilliae has been proven effective but the lawn care industry has made little use of this product. This is probably because of difficulty of application, reliability in cool soils, expense, lack of availability of large quantities of spore powder and long time of establishment. Similar

experience has been met with the other biological controls such as parasitic wasps (Tiphia spp.), parasitic flies (several Tachinidae), and fungal diseases (Metarrhizium spp. and Beauveria spp.). Because of these problems with white grub biological controls, we were most interested in concentrating our nematode research in this area.

Mole crickets (tawny mole cricket, Scapteriscus vicinus Scudder; southern mole cricket, S. acletus Rehn and Hebard; and short wing mole cricket, S. abbreviatus Scudder) are the most troublesome and damaging turf insects in Florida as well as surrounding southern states (Walker et al. 1984). These pests damage turf by uprooting plants during tunneling and direct feeding. Mature nymphs and adults can easily dig deep into the soil and thus avoid short residual, surface applied insecticides. Insecticide laced baits have been used effectively in some cases, but these baits rapidly decompose or lose their feeding attractiveness in periods of rainfall. As with the Japanese beetle, imported mole crickets have not responded well to control by biologicals. Because of these problems, we were interested in the possibility of using parasitic nematodes as an alternative biological control measure.

We placed less emphasis on development of entomogenous nematodes for control of surface insects because surface applied insecticides such as diazinon and chlorpyrifos are so effective at low rates.

Our early research using entomogenous nematodes was a multifaceted approach. We performed laboratory evaluations of nematode species and strains for infectivity against Japanese beetle and northern masked chafer (C. borealis Arrow) grubs. At the same time we investigated irrigation requirements essential to the establishment of nematodes into soil covered by turfgrass and evaluated the compatibility of the nematodes with the liquid lawn care system.

WHITE GRUB CONTROL STUDIES

Nematode Strain Evaluations

There are four species of Neoplectana (=Steinernema) (N. glaseri Steiner, N. bibionis Bovien, N. carpocapsae Weiser and N. intermedia Poinar) and numerous recognized strains (Poinar 1986a). Several species of Heterorhabditis, including undescribed ones, have been evaluated for insect control. The common species are H. heliothidis (Khan, Brooks & Hirschmann), H. bacteriophora Poinar, and H. spp. "HP88".Biosys was able to collect and maintain cultures of all of these species as well as numerous strains.

In 1983, Keith Kennedy (former ChemLawn Services Research Scientist; now Senior Entomologist, S.C. Johnson & Son, Inc.) and his research associate, Jeff Rodencal, performed initial evaluations of nematode strains for control of Japanese beetle and northern masked chafer grubs. These tests were performed in PVC cylinder micro plots, a technique initially developed by Kennedy. The micro plots are 20.5 cm (8-inch) long pieces of 15.3 cm (6-inch) diameter polyvinyl chloride (PVC) drain pipe driven into the soil to a depth of 15.3 cm. Each cylinder has a bottom screen which allows drainage but prohibits insect escape. A 15.3 cm golf course cup cutter can be used to take turf plugs from established turf. The plugs, consisting of the turf with 8-10 cm of soil, are placed in the cylinders. Field collected white grubs, usually third instars, are used to infest each turf plug. In most cases, ten white grubs are placed head down into small holes produced by forcing a 8.0 mm

sharpened wooden dowel through the thatch. Any grubs not digging in within 1-3 hours are replaced with fresh grubs. The grubs are allowed 2-3 days to acclimate before control substances are added to the cylinders.

Initial strain evaluations against Japanese beetle grubs are presented in Table 1. From this test it appeared that N. carpocapsae 'Breton' and N. glaseri could produce moderate and excellent control respectively. A similar study using lower rates of nematodes indicated a definite rate response (Table 2). This was also seen when northern masked chafers were challenged with low rates of nematodes (Table 3). These three tests indicated that nematodes could control white grubs if high rates were used.

In 1984, we continued strain evaluations but decided that a smaller laboratory screen might give more consistent results. Third instar white grubs were placed in 2.5 cm diameter by 10 cm long plastic vials filled with sterilized potting soil to a depth of 7 cm. Two Japanese beetle grubs or one northern masked chafer grub was placed in each vial and treatments (approximately 250 infective nematodes per vial) were replicated six times. The vials were examined at 2, 4 and 7 days after treatment (DAT).

Mortalities at 2, 4 and 7 DAT are presented in Table 4 for Japanese beetle grubs and Table 5 for northern masked chafers. From these studies, it appeared that the northern masked chafer might be less susceptible to nematode attack. The H. spp. 'HP88' provided adequate mortality for both grub species. However, N. carpocapsae '42' (='Breton' x 'DD136') and N. c. 'Breton' produced the best control of Japanese beetle grubs while N. c. 'Italian' worked best on northern masked chafers.

This experiment was performed again with larger vials (5.0 cm diameter x 10.0 cm deep) using four Japanese beetle grubs per vial. The grubs were allowed to acclimate for 48 hours and inactive grubs were replaced before the 450 infective nematodes per vial were added. The vials were rated at 7, 14 and 21 DAT. The mortality data are presented in Table 6. It appeared that H. heliothidis 'NC' and H. spp. 'HP88' produced the higher mortality, 76% and 82% respectively, at 21 DAT. Most of the N. carpocapsae strains, except for N. c. 'Breton x DD136', did not provide reasonable mortality.

Application Evaluations

By 1985, we had decided that entomogenous nematodes should be field tested on small plots for control of white grubs. We also wanted to know if the nematodes were compatible with the liquid lawn care application system and chemicals. Of most concern, was knowing if fertilizers, herbicides or insecticides would adversely affect the infective juvenile nematodes.

Nematodes were added to sample tank mixes containing water, water + fertilizer (nitrogen, phosphorus, potassium), water + fertilizer + broadleaf herbicide, water + fertilizer + broadleaf herbicide + insecticide, and water + fertilizer + broadleaf herbicide + preemergence (crabgrass, etc.) herbicide. These mixtures were agitated continuously on a shaker tray and samples were withdrawn at 1, 2, 3, 5, 8, 12 and 24 hours. By five hours only the preemergence mix had caused significant nematode mortality. By 12 hours the fertilizer, fertilizer + broadleaf herbicide and fertilizer + broadleaf herbicide + insecticide had mortality no greater than nematodes in water. In fact, the fertilizer alone had significantly less mortality. By 24 hours the insecticide mix had caused considerable mortality. When nematode infectivity was bioassayed (with wax moth larvae), only the water, fertilizer and fertilizer + broadleaf herbicide had not caused a significant reduction by five hours. The water or fertilizer mixes remained equally benign at 12 hours. In summary, the

nematodes are compatible with liquid fertilizers and commonly used broadleaf herbicides. This was encouraging because the nematodes would most likely be used when preemergence herbicides would not be used and supposedly insecticides would not be necessary.

Effect of Irrigation

Another concern with applying nematodes was their requirement for establishment into the turf and soil. Entomogenous nematodes are highly intolerant of environmental extremes, especially moisture and temperature (Gaugler 1981). Jackson et al. (1983) greatly increased establishment of H. bacteriophora in pasture soil for white grub control if applications were made during rain or followed with irrigation. We wanted to know if irrigation was needed and if so, how much, when the ChemLawn nozzle was used. The ChemLawn nozzle, a low pressure showerhead type which delivers 0.16 liter/m^2 (=4 gal/1000 ft^2) is the liquid lawn care standard.

The previously described PVC microplots were used in a greenhouse. Turf plugs were taken from a two year old stand of Kentucky bluegrass grown on Blount silt loam (32% sand, 36% silt, 32% clay) with pH's of 6.5-8.0. Each plug had an average of 0.75 cm of thatch. The greenhouse was maintained at 20ºC (±5ºC) and the turf was allowed to acclimate for seven days. The turf was then given a water drench and allowed to dry to the wilting point (soil moisture = 18.5%). Small holes were drilled radially around the soil plug at two levels (5 holes at each level of 2.5 cm and 5.0 cm). Each turf plug was inoculated with approximately 24,000 infective nematodes (=12.35 x 10^9/ha; = 5.0 x 10^9/a) in 3.2 ml of water. N. carpocapsae 'Mexican', N. glaseri and H. heliothidis 'NC' were used. Treatments were followed with 0.0, 63.0, 126.0 or 252 ml water/cylinder irrigation (=0.0, 0.25, 0.50, 1.0 inch). The cylinders were then capped with aluminum foil to reduce evaporation. A greater wax moth larva (Galleria mellonella L.) was placed in each of the holes and restrained for 48 hours at 3, 5 and 11 DAT. The larvae were then removed, incubated for five days, and dissected to check for nematode infection.

The data indicated that there were few differences between the nematode species so the data were pooled for each irrigation amount in each bioassay (Shetlar et al. 1988). These data are graphically presented in Figure 1. From this graph one can readily see that at least 0.64 cm (=0.25 inch) of irrigation is needed to establish nematodes for up to five days after treatment. At least 2.5 cm (=1.0 inch) irrigation is needed to sustain the nematodes to 11 DAT in dry soil.

Small Plot Grub Tests - 1985

On 28 August 85, two areas with Japanese beetle grubs were selected beside two fairways at a country club in central Ohio. The soil (a Blount silt loam) was at the turf wilting point and was thinly covered by Kentucky bluegrass mixed with small amounts of fine fescue and crabgrass. N. carpocapsae 'Mexican' was used because of availability. Each treatment was replicated five times in each area (A and B) in a randomized complete block design using 6.1 x 6.1 m treatment blocks. Treatments were: 1) 12.35 x 10^9 nematodes (nemas)/ha with a ChemLawn nozzle at 0.16 liter/m^2 (=4 gal/1000 ft^2); 2) 6.18 x 10^9 nemas/ha with a ChemLawn nozzle; 3) 12.35 x 10^9 nemas/ha with an eight pinhole nozzle boom at 0.16 liter/m^2; 4) Isozophos 4E (=Triumph,, Ciba-Geigy Corp.) Insecticide at 2.24 kg (AI)/ha with a ChemLawn nozzle; and 5) water treated check (0.16 liter/m^2). Area A was treated 9 September and no irrigation was applied after treatment. Area B was treated 10 September and treatments were irrigated with about 0.64 cm water immediately following application. A trace of rainfall occurred the night of 9 September but this was not enough to wet the

soil. Area A was evaluated on 2 October, 23 DAT, and Area B was evaluated on 9 October, 29 DAT. Grub populations were assessed by taking four 0.09 m^2 (1.0 ft^2) samples at random from each treatment block. Only traces of rainfall had occurred during the experiment and the soil was very dry (16-18% moisture) at the end of the experiment.

The data for Area A and Area B are presented in Table 7 (Shetlar et al. 1988). From these data it is evident that irrigation increased grub control and possibly increased infection. However, good control was not achieved in either area when compared to an insecticide. We felt this was most likely due to the extremely dry conditions.

Small Plot Grub Test - 1986

In 1986, we repeated the field test of nematodes using irrigation before and after nematode applications. We were also able to obtain sufficient quantities of H. heliothidis 'NC' to be included.

On 10 September 86, an area with Japanese beetle grubs was treated beside a fairway at a central Ohio country club. Treatment blocks were 1.2 x 1.5 m and each block was irrigated before application with 22.7 liter water (=0.64 cm). Treatments were: 1) 12.35 x 10^9 nemas/ha of N. carpocapsae 'Mexican'; 2) 12.35 x 10^9 nemas/ha of H. heliothidis 'NC'; 3) Isofenphos 2I (=Oftanol, Mobay Chemical Co.) at 2.24 kg (AI)/ha; and, 4) water treated checks. Treatments were applied in 7.6 liter water from watering cans using shower head nozzles and each block was irrigated after treatment with 15.1 liter water (=0.64 cm total). Pretreatment grub counts were taken from four blocks in the area and posttreatment counts were taken 39 DAT using three 0.09 m^2 samples in each treatment block.

The data from this experiment are presented in Table 8 (Shetlar et al. 1988). This field test demonstrates that adequate grub control (> 70%) can be achieved using entomogenous nematodes though this control may be significantly less than using an insecticide. Also indicated is that Heterorhabditis spp. may be better suited than N. carpocapsae.

Discussion of Use of Nematodes for White Grub Control

Entomogenous nematodes appear to show promise as a biological control agent to manage white grubs in turfgrass. The nematodes are compatible with the materials (at least fertilizer) and equipment used by liquid lawn care applicators. For soil insect control, irrigation and soil moisture seem to be the most critical factors for success of the nematodes. The nematode species and strains also exhibit a considerable range of activity. In our tests H. heliothides 'NC' and H. spp. 'HP88' appear to be more useful than the N. carpocapsae strains. Unfortunately, N. glaseri, the first species identified for grub control (Glaser et al. 1940), remains difficult to culture and thus difficult to evaluate.

CONTROL OF TURF LEPIDOPTERA

Screening of Nematodes and Other Biologicals

Surface feeding turf Lepidoptera such as sod webworms (Pyralidae: Crambinae) and the armyworm-cutworm (Noctuidae) complexes are periodic pests. Though these are easily controlled with low rates of insecticides, we are very interested in biological alternatives. The literature indicates that these pests should be susceptible to entomogenous nematodes (Poinar 1986b) as well as other biologicals such as Bacillus thuringiensis (Bt) (Ignoffo and Gregory 1972; Krieg and Langenbruch 1981) and Beauveria or Metarhizium (Ferron 1981). Since the nematodes were available and Bt was commercially marketed, we undertook numerous tests to evaluate the efficacy of these agents for caterpillar control.

In the fall of 1984, an outbreak of sod webworms (mainly the tropical sod webworm, Herpetogramma phaeopteralis Guenee) occurred in the Boynton Beach, Florida area. Larvae were field collected and shipped to Columbus, Ohio for testing. The larvae were maintained on bermudagrass clippings until they were about 1.0 cm long. In the first test, glass petri dishes (20 x 80 mm) were lined with two pieces of 80 mm diameter filter paper wetted with 2.0 ml distilled water. Several leaf blades of bermudagrass were added and dishes were inoculated with about 800 nematodes in 1.0 ml water. Four larvae were placed in each dish and treatments (N. carpocapsae 'Breton', N. c. 'Agriotos' and water check) were replicated three times. By 4 DAT most of the larvae had spun webbed tunnels along the upper surface of the petri dishes. Apparently, this behavior effectively isolated the larvae from the nematodes. Out of 12 larvae per each treatment the following mortalities were recorded: two in the checks, seven in the N. c. 'Breton' and eight in the N. c. 'Agriotos'.

A second test was established using 5.0 x 10.0 cm snap cap vials filled with 2.5 cm of potting soil upon which were placed six blades of bermudagrass. Four sod webworms and about 800 nematodes were added and the treatments (N. c. 'Breton', N. c. 'Agriotos', N. c. 'Italian' and water check) were replicated five times. The vials were evaluated 3 DAT and the larvae were dissected to confirm nematode infection. Fewer larvae sheltered themselves above the soil and the infection rate is presented in Table 9.

A petri dish test in 1985 using the armyworm, Pseudaletia unipuncta (Haworth), provided excellent control within seven days. Though all larvae subjected to nematodes had been killed, the percent of larvae with active infections was dramatically different. N. c. 'Breton' had 100% infection and N. glaseri had 87% infection but no nematodes were recovered from the H. heliothidis treated larvae.

PVC cylinder micro plots were used in 1986 and the parasitic nematodes were compared to commercial preparations of Bt (Thuricide and Javelin, Sandoz, Inc.) and surface insecticides. In the first two evaluations, armyworms were laboratory reared on artificial diet until they were approximately 2.0 cm long. Each turf plug was infested with eight larvae and irrigated with 60 ml water 24 hours before treatment. Each cylinder was covered with a screen top to prohibit armyworm escape or predator/parasitoid contamination. Each treatment was replicated five times and evaluations were made 3 DAT for nematode treatments and 7 DAT for Bt and water control treatments. Chlorpyrifos (Dursban 4E,, Dow Chemical Co.) was used as a standard surface insecticide. The results of these two tests are presented in Tables 10 and Table 11.

In the first test, the nematodes gave excellent control and the N. carpocapsae strains were not significantly different ($P < 0.05$, $df = 6$)than the chlorpyrifos treatment. H. heliothidis 'NC' was evaluated as providing good control (> 70%) though it was significantly lower than the chlorpyrifos treatment. The Bt treatments did not provide adequate control and all the turf was eaten by the end of the study.

The second test was somewhat the same though H. heliothidis 'NC' provided inadequate control (< 70%). N. bibionis was also considered inadequate. This may have been caused by the lower soil moisture. Soil moisture in the first study was 26% by weight while the second study had only 18% moisture. The Bt treatments, even at 4X rates, still did not provide control of armyworm larvae. This is partially due to the large size of the larvae and some soil Lepidoptera seem to be refractive to Bt toxins.

DISCUSSION ON BIOLOGICALS FOR CONTROL OF TURF CATERPILLARS

Our initial screenings indicate that entomogenous nematodes appear to have excellent potential for control of turf lepidopterous pests. N. carpocapsae strains seem to be the most active nematodes. Tests with commercial Bt preparations indicate that problems exist concerning soil Lepidoptera species controlled and timing, or size of larvae to be controlled. In other words, Bt does not seem to have a broad spectrum of control when compared to entomogenous nematodes.

MOLE CRICKET CONTROL

Field Evaluations

Preliminary screening of entomogenous nematodes for infectivity to mole crickets was performed by Ken Lawrence (Associate Research Scientist, ChemLawn Services R&D, Boynton Beach, FL) in soil filled cups or petri dishes in 1984. He noted that mole crickets (Scapteriscus acletus and S. vicinus) could be infected and killed though nematode reproduction was often sporadic.

In late 1985, Ken Lawrence and Richard Miller (Entomologist, Biosys, Palo Alto, CA) performed another bioassay of parasitic nematodes for mole cricket infectivity. N. carpocapsae 'Mexican' and 'All' and N. bibionis 'SN' were applied to moistened filter paper in 15 x 100 mm plastic petri dishes. A single adult S. acletus was placed in each petri dish and mortality was recorded at 4 and 6 DAT. Dead mole crickets were removed and placed on sterile moistened filter paper in fresh dishes for 72-120 hours for incubation. After incubation the insects were dissected to evaluate nematode reproduction. These data are presented in Table 12. The higher rates of N. carpocapsae strains were able to achieve 100% mortality and nematode reproduction was more successful than with N. bibionis.

In 1985, we undertook a series of field applications of parasitic nematodes to attempt to control mole crickets. A Boynton Beach, FL golf course driving range was selected. This area was well populated by mole crickets as evidenced by numerous trails and mounds which were easily

assessed in the short cut bermudagrass. Area A consisted of treatment blocks 9.1 x 9.1 m replicated five times in a randomized complete block design. Area B consisted of large unreplicated treatment blocks, 15.2 x 24.4 m. Area A was evaluated by counting all the mole cricket tunnels within each treatment block while Area B was evaluated by counting all the tunnels in a 9.1 m wide transect running the length of the blocks. A pretreatment flushing determined that most of the mole crickets were adults and most (> 70%) were S. vicinus. The nematodes were applied using a ChemLawn nozzle calibrated at 0.16 liter/m^2. Both areas were irrigated through the golf course system the evening following applications.

Mole cricket activity was evaluated a week after treatment and the data are presented in Table 13 and Table 14. These data indicate that N. carpocapsae was effective in reducing adult mole cricket activity and there was a definite rate response. Unfortunately, nematode infected mole crickets were not recovered using a soap flush a week after treatment and mole cricket activity resumed in all plots within four weeks after treatment.

A summer application of nematodes was made to bermudagrass containing numerous nymphal mole crickets (1.5-2.5 cm long) using the design of Area A (above). These data are presented in Table 15. At this time no significant control was achieved using nematodes or insecticides.

Discussion on Using Parasitic Nematodes for Mole Cricket Control

Our experiences indicate that entomogenous nematodes have the ability to attack mole crickets. However, there seems to be some problem with the nematode's ability to enter mole crickets in field conditions. This may be due to the almost constant mole cricket activity or the dense covering of hydrophobic hairs. We feel that better control may be achieved if a bait containing nematodes can be developed.

MISCELLANEOUS TURF INSECT CONTROL

Bluegrass Billbug

The bluegrass billbug, Sphenophorus parvalus Gyllenhal, is an important pest of cool season turf across the northern states (Niemczyk 1983, Tashiro & Personius 1970). This pest is especially difficult to control because the adults are highly migratory and are susceptible to surface insecticides for a short time during the spring (Niemczyk 1982). Soil insecticides are often effective against the larvae when they emerge from turf plants. However, the larvae may emerge over an extended period.

In 1983, a ChemLawn Services branch in Boise, Idaho applied N. carpocapsae 'Breton' to six lawns with active billbug larvae. The nematodes were applied at a 7.75 x 10^8 nemas/ha (= 3.1 x 108 nemas/a) using the ChemLawn nozzle at 0.16 liter/m^2. Mark Mahady (Associate Research Scientist, ChemLawn Services Corp., Monterey, CA) supervised the application and subsequent sampling. Sampling at 14 and 21 DAT revealed a majority of dead larvae (creamy yellow in color), some moribund larvae (slow moving) and few normal larvae. Dead larvae were collected and

shipped to George Poinar, Jr. (Univ. California, Berkeley, CA) for evaluation. Positive nematode infection was confirmed. By 28 DAT, no live billbug larvae were found on the treated lawns, but by 35 DAT two lawns contained fresh young larvae and displayed new injury. This test indicates that N. carpocapsae is able to infect and control the bluegrass billbug larva.

Crane Flies

The European crane fly, Tipula paludosa Meigen, or 'leatherjacket' is a northwestern Europe native which has become established in the Pacific Northwest (British Columbia, Washington and Oregon) (Jackson and Campbell 1975). This pest can cause considerable damage to turfgrass. An European test of nematodes for control of the European crane fly indicated that the larvae are susceptible to infection (Lam and Webster 1972).

In 1986, Patrice Suleman (Research Associate, ChemLawn Services Corp., Columbus, OH) located an area of golf course turf with significant damage apparently due to a native (range) crane fly (Tipula spp.). Larvae were field collected and transported to the laboratory for a petri dish test. Glass petri dishes (15 x 80 mm) were lined with filter paper and five larvae per dish were distributed. Each dish received 2.0 ml distilled water and 1.0 ml aliquot containing 200 or 400 nematodes. Four nematode strains plus a water check were evaluated with three replicates. Mortality was recorded at 2, 4 and 8 DAT and dead larvae were examined for nematode infection. The data for this test are presented in Table 16. The data indicate that this crane fly larva is susceptible to all the strains evaluated.

SUMMARY

Our present day knowledge of the susceptibility of turfgrass insect pests to entomogenous nematodes indicates that this may be the first biological control agent with a broad spectrum of activity. We have laboratory and field data confirming activity against surface insects such as sod webworms, cutworms, armyworms and crane fly larvae. We also have laboratory and field data confirming activity against soil insects such as white grubs (Japanese beetles and northern masked chafers), mole crickets, and billbug larvae. The only major pest not evaluated has been chinch bugs. This pest is probably too small for successful infection but a trial test should be performed. Other sporadic and minor pests not likely to be controlled by parasitic nematodes are greenbug, winter grain mite, Bank's grass mite, bermudagrass mite and several scales and mealy bugs.

Future challenges include: 1) identification of soil conditions most conducive to nematode survival and activity; 2) refinement of application techniques (sprays, irrigation, baits, etc.); and 3) improved mass production which maintains the nematodes' hardiness and infectivity while lowering cost.

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TABLE 1

Japanese beetle larval control in turfgrass plugs with entomogenous nematodes, Milford Center, OH.

Treatment (13/v/83)	Rate (nemas/ha)	$\bar{X}$ larvae/cylinder 10 DAT	% control
Check		8.2 a	-
N. c. 'Breton'	$14.1x10^9$	2.5 cd	69
N. c. 'HOP'	$14.1x10^9$	3.8 bc	53
N. c. 'Mexican'	$14.1x10^9$	7.8 a	4
N. g.	$14.1x10^9$	0.8 d	90
H. spp 'HP88'	$14.1x10^9$	6.0 ab	27

N. c. = *Neoaplectana carpocapsae*; *N. g.* = *N. glaseri*; *H.* = *Heterorhabditis*.

Equivalent to $5.7x10^9$ nemas/a.

Ten 3rd instar larvae per cylinder; N = 6; means followed by the same letter are not significantly different (*P* = 0.1; Duncan's [1955] multiple range test).

Calculated by Abbott's (1925) formula.

TABLE 2

Control of 2nd and 3rd instar Japanese beetle larvae with varying rates of Neoaplectana carpocapsae and N. glaseri, Milford Center, OH, 1983.

Treatment (21/ix/83)	Rate (nemas/ha)	$\bar{X}$ larvae/cylinder 14 DAT	% control
N. carpocapsae 'Breton'	1.25×10^8	6.8 ab	2
	2.50×10^8	6.2 ab	12
	5.00×10^8	5.8 ab	17
	10.00×10^8	5.7 ab	19
N. glaseri	1.25×10^8	6.8 ab	2
	2.50×10^8	5.7 ab	19
	5.00×10^8	6.0 ab	14
	10.00×10^8	4.8 bc	31
Triumph 4E	2.24 kg(AI)/ha	3.2 c	55
Check	-	7.0 a	-

Equivalent to 0.5, 1.0, 2.0 and 4.0 x 10^8 nemas/a, respectively.

Ten 3rd instar larvae/cylinder; N = 6; means followed by the same letter are not significantly different (P = 0.1; Duncan's [1955] multiple range test).

Calculated by Abbott's (1925) formula.

TABLE 3

Control of Northern masked chafer larvae with two rates of Neoaplectana carpocapsae "Breton" and N. glaseri, Milford Center, OH 1983.

Treatment (5/x/83)	Rate (nemas/ha)	$\bar{X}$ larvae/cylinder 14 DAT Top 2" of soil	Entire soil plug	% control Top 2" of soil	Entire soil plug
N. glaseri	5.5x10[8]	6.2 a	6.2 b	11	24
N. carpocapsae	5.5x10[8]	7.2 a	8.0 ab	0	3
N. glaseri	10.9x10[8]	8.0 a	9.5 a	0	0
N. carpocapsae	10.9x10[8]	7.0 a	9.0 a	0	0
Triumph 4E	2.24 kg(AI)/ha	1.5 b	1.8 c	86	79
Oftanol 2F	2.24 kg(AI)/ha	0 b	0.2 c	100	97
Check		7.0 a	8.2 ab	-	-

Equivalent to 4.4 and 2.2x10[8] nemas/a respectively.

Ten 3rd instar larvae cylinder; N = 4; means followed by the same letter are not significantly different (P = 0.1; Duncans [1955] multiple range test).

Calculated by Abbott's (1925) formula.

TABLE 4

Mortality of Japanese beetle grubs caused by parasitic nematode strains.

Nematode Strain	$\bar{X}$ of surviving larvae (% control) 2 DAT	4 DAT	7 DAT
N. c. 'Agriotos'	0.83 (38)	0.83 (38)	0.50 (61)
N. c. 'All'	0.83 (38)	0.67 (48)	0.67 (48)
N. c. 'Breton'	0.67 (49)	0.16 (88)	0.16 (88)
N. c. 'Breton x DD136'	0.50 (62)	0.16 (88)	0.16 (88)
N. c. 'DD136'	1.16 (12)	0.83 (38)	0.50 (61)
N. c. 'HOP'	1.50 (00)	0.83 (38)	0.67 (48)
N. c. 'Italian'	1.16 (12)	0.50 (61)	0.50 (61)
N. c. 'Mexican'	1.33 (00)	0.33 (75)	0.33 (75)
H. spp. 'HP88'	1.00 (24)	0.67 (48)	0.33 (75)
Check	1.33 (--)	1.33 (--)	1.33 (--)

N. c. = Neoaplectana carpocapsae; H. = Heterorhabditis; 250 nemas/vial.

Calculated by Abbott's (1925) formula.

TABLE 5

Mortality of northern masked chafer grubs caused by parasitic nematode strains.

Nematode Strain	$\bar{X}$ of surviving larvae (% control) 2 DAT	4 DAT	7 DAT
N. c. 'Agriotos'	0.83 (17)	0.83 (17)	0.67 (33)
N. c. 'All'	0.83 (17)	0.67 (33)	0.50 (50)
N. c. 'Breton'	0.83 (17)	0.50 (50)	0.50 (50)
N. c. 'Breton x DD136'	0.67 (33)	0.67 (33)	0.67 (33)
N. c. 'DD136'	1.83 (17)	0.83 (17)	0.67 (33)
N. c. 'HOP'	0.83 (17)	0.67 (33)	0.67 (33)
N. c. 'Italian'	0.83 (17)	0.16 (84)	0.16 (84)
N. c. 'Mexican'	0.67 (33)	0.50 (50)	0.50 (50)
H. spp. 'HP88'	1.00 (00)	0.67 (33)	0.33 (67)
Check	1.00 (--)	1.00 (--)	1.00 (--)

N. c. = Neoaplectana carpocapsae; H. = Heterorhabditis; 250 nemas/vial.

Calculated by Abbott's (1925) formula.

TABLE 6

Mortality of Japanese beetle grubs caused by parasitic nematode strains.

Nematode Strain	$\bar{X}$ of surviving larvae (% control) 7 DAT	14 DAT	21 DAT
N. c. 'Agriotos'	2.0 (44)	2.0 (39)	1.2 (64)
N. c. 'All'	2.3 (36)	1.5 (55)	1.5 (55)
N. c. 'Breton'	2.8 (22)	1.8 (46)	1.6 (52)
N. c. 'Breton x DD136'	2.8 (22)	1.6 (52)	1.0 (70)
N. c. 'DD136'	2.3 (36)	2.1 (36)	1.6 (52)
N. c. 'HOP'	3.0 (17)	2.6 (21)	2.5 (24)
N. c. 'Italian'	2.6 (27)	1.8 (46)	1.5 (55)
N. c. 'Mexican'	3.0 (17)	2.8 (15)	2.5 (24)
N. c. 'PYE'	3.0 (17)	2.5 (24)	2.5 (24)
H. h. 'NC'	2.3 (36)	1.0 (70)	0.8 (76)
H. spp. 'HP88'	1.8 (50)	1.0 (70)	0.6 (82)
H. b.	3.3 (8)	2.0 (39)	1.5 (55)
Check	3.6 (--)	3.3 (--)	3.3 (--)

N. c. = *Neoaplectana carpocapsae*; *H. h.* = *Heterorhabditis heliothidis*; *H.* = *Heterorhabditis*; *H. b.* = *H. bacteriophora*; 450 nemas/vial.

Calculated by Abbott's formula.

TABLE 7

Average number of normal ±sd (% control) and nematode infected grubs per 0.09m² per treatment in Areas A and B.

Treatment	$\bar{X}$ Grubs (%)	$\bar{X}$ Infected
Area A (not irrigated)		
12.35x10⁹/ha		
w/CL nozzle	15.8± 8.9 (6%)a	2.1±2.6a
6.18x10⁹/ha		
w/CL nozzle	15.1± 5.7 (7%)a	0.5±0.4 b
12/35x10⁹/ha		
w/ph nozzle	15.7±10.1 (10%)a	0.2±0.3 b
Isozophos		
2.24 kg(AI)/ha	4.0± 2.0 (76%) b	0.0±0.0 b
Check	16.8± 4.8 (---)a	0.0±0.0 b
Area B (irrigated)		
12.35 bill/ha		
w/CL nozzle	10.0± 3.5 (34%)a	1.9±1.6a
6.18 bill/ha		
w/CL nozzle	11.4± 2.2 (25%)a	1.9±1.4a
12.35 bill/ha		
w/ph nozzle	13.5± 1.6 (11%)a	1.4±0.8a
Isozophos		
2.24 kgAI/ha	3.8± 2.6 (76%) b	0.0±0.0 b
Check	15.2± 6.4 (---)a	0.0±0.0 b

Means in the same column for each area followed with the same letter are not significantly different ($P = 0.05$; Duncan's [1955] multiple range test)

CL = ChemLawn shower head nozzle

ph = Pinhole nozzle boom

TABLE 8

Average number ±sd of Japanese beetle white grubs per 0.09m² per plot 39 DAT with entomogenous nematodes and insecticide followed with irrigation.

Treatment	$\bar{X}$ Grubs/0.09m²	(% control)
N. carpocapsae		
12.35x10⁹/ha	7.8±3.9 b	55%
H. heliothidis		
12.35x10⁹/ha	4.5±3.3 c	74%
Isofenfos 2F		
2.24 kg(AI)/ha	1.3±1.5 d	93%
Check		
1.27cm water	17.3±5.9a	---

Means followed by the same letter are not significantly different (P = 0.05; Duncan's [1955] multiple range test).

percent control determined using Abbott's (1925) formula (pretreatment counts = 16.9 grubs/0.09m²).

TABLE 9

Sod Webworm mortality when subjected to various parasitic nematode strains 3 DAT.

Treatment	# Alive	# Dead	# Infected	% Infected
Water Check	11	9	0	0
N. c. 'Breton'	3	17	17	85
N. c. 'Agriotis'	3	17	15	75
N. c. 'Italian'	1	19	12	60

N. c. = Neoaplectana carpocapsae

TABLE 10

Control of armyworm (Pseudaleta unipuncta) larvae using entomogenous nematodes and Bacillus thuringiensis products.

Treatment 17/vii/86	Rate (nemas/ha)	$\bar{X}$ Larvae/cylinder	(% control)
N. c. 'All'	$12.5x10^9$	0.0 A	(100)
N. c. 'Mexican'	$12.5x10^9$	0.4 A	(95)
H. h. 'NC'	$12.5X10^9$	1.8 B	(78)
Thuricide®	2.4 l/ha	6.6 C	(18)
Javelin®	2.4 l/ha	7.2 CD	(10)
Chlorpyrifos 4E	1.1 kg(AI)/ha	0.4 A	(95)
Control	-	8.0 D	-

$12.5x10^9$ nemas/ha = $5.0x10^9$ nemas/a; 2.4 l/ha = 1 qt/a; 1.1 kg(AI)/ha = 1.0 lb(AI)/a.

Numbers followed by the same letter are not significantly different ($P = 0.05$; Duncan's [1955] multiple range test).

Calculated by Abbott's (1925) formula.

TABLE 11

Control of armyworms (Pseudaleta unipuncta) larvae using entomogenous nematodes and Bacillus thuringiensis products.

Treatment 5/viii/86	Rate	$\bar{X}$ Larvae/cylinder	(% control)
H. h. 'NC'	$12.5x10^9$	3.0 B	(61)
N. b.	$12.5x10^9$	4.8 C	(31)
Javelin®	9.5 l/ha	6.2 D	(21)
Thuricide®	9.5 l/ha	7.0 DE	(10)
Chlorpyrifos 4E	1.1 kg(AI)/ha	0.0 A	(100)
Control	-	7.8 E	-

$12.5x10^9$ nemas/ha = $5.0x10^9$ nemas/a; 9.5 l/ha = 1.0 gal/a; 1.1 kg(AI)/ha = 1.0 lb(AI)/a.

Numbers followed by the same letter are not significantly different (P = 0.05; Duncan's [1955] multiple range test).

Calculated by Abbott's (1925) formula.

TABLE 12

Percent mortality and percent confirmed infection of adult S. acletus confined on filter paper innoculated with various rates of N. carpocapsae "Mexican"or "All"or N. bibionis "sn".ChemLawn R&D Center, Boynton Beach, FL, 26 Dec 85.

Treatment	Rate (nemas/dish)	Replicates	% Mortality 4 DAT	% Mortality 6 DAT	% Infected
N. c. 'Mexican'	10,000	8	100	100	88
	5,000	9	89	89	67
	1,000	10	60	60	50
	100	10	70	70	40
N. c. 'All'	10,000	5	80	100	80
	5,000	5	100	100	80
	1,000	5	60	60	60
N. b. 'SN'	10,000	9	56	56	56
	5,000	8	63	75	38
	1,000	9	67	78	89
	100	10	50	60	20
N. b. 'SN'+X77	1,000	7	100	100	14
Check	---	10	10	10	--

N. c. = Neoaplectana carpocapsae, N. b. = N. bibionis

Based on dead insects with various stages of nematodes in body cavity compared to number of replicates.

X77 = Ortho X-77® spreader, Chevron Chemical Co., 0.3 ml/l.

TABLE 13

Application of entomophageous nematodes to area A for mole cricket control, 11/iv/85, and evaluated one week later.

Treatment	Rate nemas/ha	$\bar{X}$ Mole Cricket Mounds/Plot Pre-treat	7 DAT	% Control
H. h. 'NC'	$12.4x10^9$	96	87	9%
H. h. 'NC'	$2.5x10^9$	64	63	2%
N. c. 'Mexican'	$12.4x10^9$	89	42	53%
N. c. 'Mexican'	$2.5x10^9$	60	42	30%
Check		83	85	--

H. h. = Heterorhabditis heliothidis; N. c. = Neoaplectana carpocapsae

$2.5x10^9$ nemas/ha = $1.0x10^9$ nemas/a; $12.4x10^9$ nemas/ha = $5.0x10^9$ nemas/a

Calculated using Abbott's (1925) formula.

TABLE 14

Application of entomophagous nematodes to area B for mole cricket control, 12/iv/85, and evaluated 6 days later.

Treatment	Rate nemas/ha	$\bar{X}$ Mole Cricket Mounds/Transect Pre-treat	6 DAT	% Control
H. h. 'NC'	$7.4x10^9$	53	53	0
N. c. 'Mexican'	$7.4x10^9$	28	15	42
Check		28	26	--

H. h. = Heterorhabditis heliothidis; N. c. = Neoaplectana carpocapsae

$7.4x10^9$ nemas/ha = $3.0x10^9$ nemas/a

Calculated using Abbott's (1925) formula.

TABLE 15

Application of entomophagous nematodes for mole cricket control, 27/iv/85, and evaluated 11 and 19 days later.

Treatment	Rate nemas/ha	$\bar{X}$ Mole Cricket Mounds/Plot Pre-treat	11 DAT	19 DAT	% Control
N. c. 'Mexican'	$12.4x10^9$	51.4	62.4	72.4	---
N. c. 'Mexican'	$4.9x10^9$	61.6	67.2	78.0	---
Isofenphos 2I	2.24 kg(AI)ha	35.6	55.2	34.2	4
Check		70.0	60.6	74.0	

N. c. = Neoaplectana carpocapsae; Isofenfos = Oftanol® (Mobay Chemical Company)

$12.4x10^9$ nema/ha = $5.0x10^9$ nemas/a; $4.9x10^9$ nemas/ha = $2.0x10^9$ nemas/a; 2.24 kg(AI)ha = 2.0 lb(AI)/a

Calculated using Abbott's (1925) formula.

TABLE 16

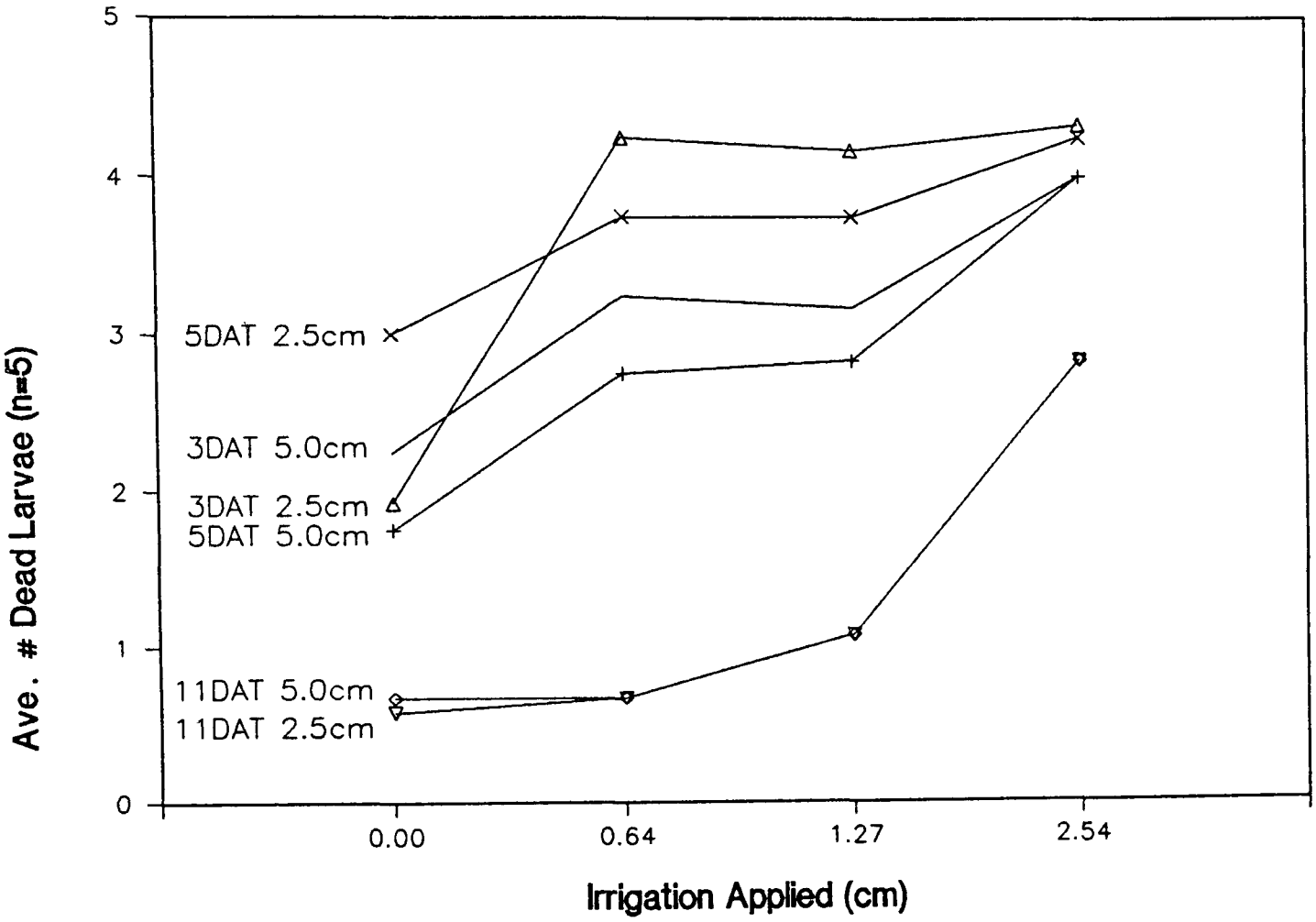
Petri dish evaluation of entomogenous nematodes for infection of a range crane fly (Tipula spp.) larvae.

Treatment 23/iv/86	Nemas/dish	% Mortality (N = 15) 2 DAT	4 DAT	8 DAT
N. b.	200	20	20	80
	400	0	20	100
N. c. 'Mexican'	200	0	40	100
	400	20	40	100
N. c. 'All'	200	0	20	80
	400	0	40	100
H. h. 'NC'	200	0	40	100
	400	20	40	100
Check		0	0	0

N. b. = Neoaplectana bibionis; N. c. = N. carpocapsae; H. h. = Heterorhabditis heliothidis.

FIGURE 1

Pooled average wax moth larval mortality (N=5) for 3, 5, and 11 days after treatment (DAT) at two soil depths (2.5 and 5.0 cm) followed by different amounts of irrigation (cm).



BIOLOGICAL CONTROL OF SOCIAL INSECTS WITH NEMATODES

George O. Poinar, Jr.
Department of Entomological Sciences
University of California,
Berkeley, CA 94720

and

Ramon Georgis
Biosys
1057 E. Meadow Circle
Palo Alto, CA 94303

INTRODUCTION

For the present review, social insects are meant to comprise bees, wasps and ants of the order Hymenoptera and termites of the order Isoptera. Various diverse groups of nematodes are associated with these insects in nature (Poinar, 1975, Bedding, 1986), either as phoretics, facultative or obligate parasites. However, our discussion will be restricted to those nematodes which show potential in regulating these insects in specialized habitats and which can be manipulated by man to serve as biological control agents. The nematodes which fit these categories today belong to the genera Neoaplectana and Steinernema of the Steinernematidae and Heterorhabditis of the Heterorhabditidae.

TERMITES

In the world today, there are some 2000 species of termites that are distributed into six families. On the basis of their habits, termites have been placed into ecological groups which include the drywood termites (Kalotermitidae) which live in dry wood and have little or no contact with soil, the dampwood termites (Hodotermitidae) which live in buried timber or rotting logs and the subterranean termites (Rhinotermitidae) which construct their nests in the soil and build protective shelter tubes when searching for food above ground (Edwards & Mill, 1986). Since the subterranean termites rely principally on the soil for moisture, they are potential hosts for steinernematid and heterorhabditid nematodes. Laboratory studies showed that Neoaplectana carpocapsae could kill workers of Coptotermes, Nasutitermes and Termes (in Poinar, 1979) and Georgis et al (1982) reported 96-98% mortality (N=10) of Zootermopsis and Reticulitermes three days after being placed in standard petri dishes with 2000 infective stage N. carpocapsae (Breton strain) (Fig. 1, 2) as well as Heterorhabditis heliothidis, respectively.

The next step was to test the effectiveness of these nematodes in the field. Some initial studies using the DD-136 strain of N. carpocapsae against the Formosan termite Coptotermes formosanus

were reported by Reese (1971). In these studies, large numbers of termites were trapped, infected with nematodes, and returned to the colonies. The lack of success was attributed to the large number of termites in a single colony, and because the termites in some colonies would recognize infected workers, then collect and isolate them behind earthen barriers. This behavior was only observed in some colonies however and it is not known if such actions constitute serious threats to the use of nematodes against subterranean termites.

In 1981, Bedding and Stanfield reported that by baiting with a species of Heterorhabditis obtained from Australia, large laboratory colonies of Mastotermes were totally eradicated within a week. Nematode suspensions were applied to termite-infested Pinus carabea plantations near Darwin. Nematode-infected termites were recovered from neighboring untreated trees within one week after treatment. Each termite cadaver yielded about 10,000 nematodes and dead termites were not walled off sufficiently to prevent exit of nematode progeny nor eaten by other termites or associated mites. However, the investigators noted that there was a tendency for the termites to vacate trees that had received nematode applications.

In 1985, Mix reported studies conducted by R. Beal in Mississippi. Beal placed nematodes at rates of 5,000 to 40,000/foot^2 in a pine forest and placed pine boards over the treated area. The area was heavily infested with subterranean termites and as the termites were attracted to the boards, they would encounter the nematodes. The boards were examined after one and two months and the damage rated as percent of termite attack to the pine boards (see table 1). Although no chemical treatment was applied for this experiment, the results reveal two interesting points. The results are variable, however there is evidence that some nematode species and strains are more effective against termites than others. This variability in susceptibility was also demonstrated using Neoaplectana carpocapsae (All strain) and Heterorhabditis heliothidis (NC strain) in petri dish experiments against Reticulitermes hesperus. Using a similar dose, N. carpocapsae killed the same number of termites twice as quickly as H. heliothidis (Mangan & Miller, 1986). Secondly, although Mix said that "There was no kill," the 40,000 applications of the Breton strain of N. carpocapsae definitely did exhibit some "kill"and although it was not complete, it was better than the untreated control. Also, it should be noted that even a dose of 40,000 nematodes per square foot is extremely low to be used against an infinite supply of termites coming out of the soil.

When used against subterranean termites attacking dwellings, some success with the nematodes was reported. Olkowski et al (1985) reported on data supplied by Post and Drucker, two pest control operators who distributed SAF-T-SHIELD, a product composed of Neoaplectana carpocapsae. On the basis of treating 4000 structures, they reported that the success rate for the nematodes was about 80%, compared to a 92% maximum success rate with chlordane. Post emphasized that it was very important to use a high dose, have adequate moisture and to position the nematodes as close to the structure as possible. Hall (1986) reported the experiences of Paul Leck, a pest control operator in Pennsylvania. Leck treated some 38-40 houses with nematodes and had a call back rate of only 13 percent (87% success).

Using a Heterorhabditis isolate from Darwin, Australia, Danthanarayana and Vitarana (1987) successfully controlled the live-wood tea termite, Glyptotermes dilatatus infesting tea plants in Sri Lanka. The nematodes were applied to 50 tea bushes with a pipette inserted into the galleries inside exposed stems at a rate of 240,000 nemas per bush. At periodic intervals, the plants were uprooted and examined to count living and nematode-infected individuals (see Table 2). Equally good results were obtained using a pressurized knapsack sprayer with a hypodermic needle in place of the nozzle. About 1000 infective stage juveniles were produced in each of 32 parasitized termites after

8 days. The authors concluded that the nematodes from such cadavers parasitized healthy termites, thus establishing a chain infection. Termite colonies were annihilated within 2-3 months with a single nematode application, thus convincing the authors that these nematodes could be used to control the tea termite in Sri Lanka.

A recent study tested the efficacy of Neoaplectana carpocapsae against foraging workers of Reticulitermes tibialis in a pasture in Colorado (Epsky & Capinera, 1988). The nematodes were applied to the soil at a rate of 1×10^7 per m^2 directly beneath the baited traps. There was a significant decrease in number of termites per trap between treated and untreated traps and protection was provided for a period of 2-3 weeks.

A general assessment of the above reports concerning the effect of nematodes on subterranean termites suggests several points. First, that it is difficult to compare results obtained experimentally in field conditions (often with infinite numbers of termites) with situations associated with controlling termites in structures (where the number of termites may be large, but finite). Second, that although results reported by pest control operators who understand how to work with biological organisms and apply adequate numbers of nematodes in choice areas, appear promising, quantitative data on the number of termites killed and colony reduction is still lacking. Such data is necessary before any official statement can be made regarding the effectiveness of neoaplectanid nematodes in controlling subterranean termites in structures.

FORMICIDAE

Ants, as Aculeate Hymenoptera, have the ability to sting and this fact, coupled with damage they do in constructing their nests in human dwellings, is why control measures are sometimes necessary.

Early studies showed that under laboratory conditions, Neoaplectana carpocapsae was able to infect adults of the fire ant, Solenopsis geminata, larvae and adults of Camponotus spp., larvae, pupae and adults of the parasol ant, Acromyrmex octospinosus (Reich) (Kermarrec, 1975; Laumond et al, 1979) and workers of Myrmica and Camponotus (Bedding, 1984). (Figure 3).

Some interesting aspects of the association between N. carpocapsae and A. octospinosus were discussed in a later work (Kermarrec et al, 1986). There appeared to be some host resistance to nematode penetration in mature pupae and adult ants. Besides a decline in penetration, there was also a decrease in nematode development. Whereas penetration and development to the adult stage occurred in 95-100% of the third and fourth stage larvae, penetration in older pupae dropped to 5% and only 10% of these parasitized pupae contained nematode adults. Although adult ants were killed none contained developing stages of the nematodes. When three million infectives of N. carpocapsae were introduced into the fungus gardens of the ants, intense social grooming, together with cleaning and building activities resulted in the elimination of the nematodes after ten days.

Kermarrec et al (1986) point out some aspects to consider when infecting ants with nematodes. If the ant contains an infra-buccal filter, then this device may retain nematodes in the infra-buccal pocket and not allow them to enter the pre-pharynx. Such a filtering device is usually absent in ant larvae. If this device is effective in adult ants, then the nematodes would have to enter the buccal area and force themselves through the pharyngeal glands to enter the hemocoel. Aside from opening size, other barriers hindering nematode infection in adult ants could be spinules in the spiracular chamber, closure of the mouth and pilosity around the anus.

In 1976, Poole completed a study on the use of Neoaplectana carpocapsae (=N. dutkyi) to control the fire ants, Solenopsis richteri and S. invicta in Mississippi. Reproductives and brood of both species were susceptible to infection. Under laboratory conditions after 48 hrs, a mean dose of 20 nematodes/inch^3 resulted in 50% larval mortality, a mean dose of 31 infective juveniles/inch^3 resulted in 50% pupal mortality and a mean dose of 109 nematodes/inch^3 produced 50% mortality of winged males and females. Poole found that the workers were less susceptible than the other stages and could only achieve 50% mortality of media workers when a mean dose of 880,000 nematodes/inch^3 was used. A dose of 9,100,000 nematodes/inch^3 was required to produce 50% mortality of the minor workers after 48 hrs. It was concluded that the nematodes entered the adult ants per os.

Using a concentration of 1 million nematodes per mound in the fall, the nematodes were capable of causing 35% mortality (12% worker infection) up to 90 days post-treatment, reducing the mound size by 18%. With the same concentration in the spring, 80% mortality was recorded (22% worker infection) and the mound size was reduced by 28%. Greater colony mortality was achieved against smaller colonies. In field tests against S. richteri, the nematodes destroyed 80% of the mounds in the spring and 36% of the mounds in the fall.

Reasons why the workers were infected less than other stages were their greater overall activity and grooming behavior. Also, workers regurgitated introduced nematodes to the alates and larvae. A single winged male or female ant could produce up to 3,000 infective stage juveniles.

Poole concluded by stating that Neoaplectana would be an effective biological agent in the control of the imported fire ants if timing of the application, mound size and climatic conditions were taken into consideration.

In 1980, Quattlebaum reported on tests with the DD-136 strain of N. carpocapsae and the NC strain of H. heliothidis on mounds of the red imported fire ant, S. invicta and the black imported fire ant, S. richteri, in Boykin and Bounan Counties in South Carolina. Quattlebaum used a 2-gallon compressed air sprayer calibrated to deliver 300 ml/20 sec. in applying the nematodes to the mounds. A vertical hole 2 inches in diameter and 12-24 inches deep was made into the center of the mound. The sprayer wand was inserted into the mound and discharged for 20 sec. Check mounds were sprayed with water. Assays were based on ant and mound mortality or the percentage of inactive mounds in a plot. Mounds were considered active if any living ants were found associated with them. Mortality was determined by holding fire ants from treated mounds in large vials 24h post-treatment and recording the number that died after 4 days. Control ants were taken from the water-treated mounds. The results of two years' tests are shown in Tables 3 and 4.

Quattlebaum (1980) concluded that both N. carpocapsae (DD-136) and H. heliothidis (NC-19) were able to reduce field populations of the red imported fire ant (S. invicta). Of the two nematodes, N. carpocapsae gave the best control. Quattlebaum (1980) felt that this might be the quicker reproductive cycle of Neoaplectana in the nest, thus releasing more infective nematodes. He also noted that results varied under conditions of different soil texture (sand versus silt) and it would be desirable to note this condition in further field testing. In combining N. carpocapsae (DD-136) with various insecticides (Sevin, Pennwalt, Knox-out and Orthene) in field tests against S. invicta, Quattlebaum (1980) found that a synergistic interaction often occurred between insecticides and nematodes. In these experiments a mound mortality of only 37.5% was recorded when the nematodes (N. carpocapsae DD-136) were used alone at a rate of a 1 X 10^6 per mound. Recent studies by Georgis (1987) show that desiccated nematodes (N. carpocapsae All) in a sugar solution

were infective to carpenter and harvester ants. Such formulations might be successful against fire ants also.

BEES AND WASPS

Bees and wasps of the Aculeate Hymenoptera have the ability to sting and it is primarily this character which necessitates their occasional control. It is mainly the social species of bees and wasps that cause concern, the latter especially are attracted to food and produce.

Bees

Bees are beneficial to man and are tested with biological insecticides for compatibility studies so that the agents could be used against insect pests in the bee's environment.

Whereas original reports indicated that honeybee adults were resistant to Neoaplectana carpocapsae (Dutky & Hough, 1955; Cantwell et al, 1972), Hackett & Poinar (1973) showed that adult worker honeybees could be parasitized and killed when infectives of N. carpocapsae were added to sugar solutions, honey or a fruit concentrate which were fed to bees. The authors suggested that nematode baits placed outdoors for yellowjackets should be unattractive to honeybees. Kaya et al (1982) tested N. carpocapsae against worker and brood stages by spraying infective juveniles on frames in bee hives. They observed adult worker mortality but larvae and pupae were not infected. Absence of parasitism in the brood was attributed to temperature ranges between 33.3 and 35.2 C, which was detrimental to the infective stages. Desiccation of the infectives under hive conditions of high temperature and low relative humidity (40-78%) was also considered to act as a nematode mortality factor. The conclusions of the study were that general spraying of nematodes in the vicinity of the hive and even direct spraying of the hive might kill some bees but would not be detrimental to the colony. If some worker bees did become infected, they would be removed and the nematodes would not be able to recycle in the hive. To reduce exposure of bees to nematodes applied to the environment, applications could be done at times when the bees were still in their hives (early morning or in the evening).

Yellowjackets

Representatives of the subfamily Vespinae of the family Vespidae include yellowjackets and hornets of the genera Vespula and Paravespula. Yellowjackets in particular can constitute a serious problem because of their attraction to foodstuffs (sweet sources or high protein substances depending on the season). Although human deaths from yellowjacket stings in the United States are rare (Parrish, 1963), the discomfort felt, especially by hypersensitive individuals, may be considerable. In 1968, an estimated loss of $200,000 due to the action of Vespula spp. in agricultural operations was reported just in California (Hawthorne, 1969). Although natural infections of Vespinae by rhabditid nematodes would be unexpected, Bedding (1984) reports discovering a queen Vespula germanica infected with N. carpocapsae, hibernating beneath Eucalyptus bark in Tasmania.

Initial studies showed that workers of Vespula pennsylvanica, V. rufa atropilosa and V. vulgaris are killed by the infectives of several strains of N. carpocapsae as well as H. heliothidis (Poinar & Ennik, 1972; Gambino, 1984).

There are two basic methods of applying neoaplectanid nematodes to control yellowjackets.

One is to apply the nematodes directly to the nest, the other is to attract yellowjacket workers to nematode-treated baits.

Preliminary studies relating to the latter method were reported by Poinar and Ennik (1972) when they showed that the workers of V. pennsylvanica and V. rufa atropilosa from California and Vespula sp. from the Netherlands could be killed when they ingested infective stages of N. carpocapsae (Agriotos strain) placed in a fruit concentrate or on sugar cubes. In order to avoid attracting honeybees, the bait could be composed of a protein base such as tuna or other pet foods. Such baits containing insecticides have been successful in controlling yellowjackets in the field (Ennik, 1973; Reid & MacDonald, 1986). If contamination was a problem, then utilizing synthetic lures to attract the yellowjackets might be feasible (Davis et al, 1973).

The problem of nematodes drying out and dying in the baits could be alleviated by using desiccated nematodes that revive when ingested by the hosts. Such desiccated nematodes have been shown to be infective to V. pennsylvanica workers (Wojcik & Georgis, 1987).

Introduction of aqueous suspensions of N. carpocapsae into colonies of mixed populations of V. pennsylvanica and P. vulgaris in California were performed by removing some of the overlying soil and making a hole in the exposed nest envelope (Gambino & Pierluisi, 1987). The water suspension of infective nematodes was poured in through the hole. Thirty-six hours after treatment, the authors caught insects that were being carried out of the treated colonies by yellowjacket workers. Seventy percent of these insects (both adults and larvae) had been parasitized by N. carpocapsae. Prompt removal of infected individuals by healthy nestmates would eliminate recycling of the nematodes and reduce their effectiveness.

CONCLUSION

The use of nematodes for the control of social insects is beset with two difficulties. The first is how to introduce the nematodes into the colony which may be concealed (termites, wasps) or have a relatively small opening (ants). The other is how to establish cycling of the nematodes in diseased members of the colony when the instinct of the workers is to avoid the diseased forms (termites) or to remove them from the nest (wasps, ants).

Thus, either a heavy dose must be used in or near the colony in order to kill enough of the workers or brood to reduce and hopefully eventually eliminate colony activity or a nematode-treated bait be used that the workers will take and feed to the developing brood. Attempts at killing the queen may be difficult and successful only in single queen colonies where new queens are not readily produced. New types of formulation, such as embedding the nematodes in calcium alginate together with an attractant (Poinar et al., 1985) or utilizing desiccated nematodes in baits (Georgis, 1987) may result in innovative delivery systems that could be used against social insects.

The success of these efforts will depend on the ingenuity of the researcher in understanding the biology and behavior of the insects involved in order to utilize the nematodes effectively in any control program.

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TABLE 1

Percentage of damage caused by subterranean termites to pine boards placed over areas treated with Neoaplectana and Heterorhabditis, respectively (modified from Mix, 1985).

Nematode	Dosage (sq. ft.)	Percent of Damage 1 month	2 months
Heterorhabditis sp. (HP88)	5,000	60	80
"	20,000	60	60
"	40,000	80	100
N. carpocapsae (Breton)	5,000	40	100
"	20,000	20	100
"	40,000	20	60
N. carpocapsae (Mexican)	5,000	40	80
"	20,000	80	100
"	40,000	80	60
Untreated Control	---	40	100

TABLE 2

Mortality of the live-wood tea termite, Glyptotermes dilatatus after applying Heterorhabditis sp. to tea bushes at a rate of 240,000 nemas per plant (modified from Danthanarayana and Vitarana (1987)).

	Treatment		Control	
Days after application	Total number of termites per plant	Percentage dead	Total number of termites	Percentage dead
10	354	92	-	-
15	291	76	-	-
31	379	81	-	-
50	9	100	380	16
95	6	100	773	17

TABLE 3

Mortality of fire ant (S. invicta) mounds treated with the DD-136 strain of N. carpocapsae (approximate figures obtained from Figures 6 and 7 of Quattelbaum (1980)).

Dose (nematodes/mound)	% Mortality after 30 days	% Mortality after 180 days
Control	7[A] (5)[B]	15 (9)
0.5×10^6	57 (55)	72 (81)
1×10^6	85 (68)	93 (86)
2×10^6	100 (97)	99 (98)

A = numbers represent 1978 tests.

B = numbers in parentheses represent 1979 tests.

TABLE 4

Mortality of fire ant (S. invicta) mounds treated with the NC-19 strain of Heterorhabditis heliothidis (approximate figures obtained from Figures 8 and 9 of Quattelbaum (1980)).

Dose (nematodes/mound)	% Mortality after 30 days	% Mortality after 180 days
Control	6[A] (5)[B]	12 (9)
0.5 x 10^6	- (40)	- (52)
1 x 10^6	64 (69)	64 (70)
2 x 10^6	89 (80)	89 (82)

A = numbers represent 1978 tests.

B = numbers in parentheses represent 1979 tests.

FIGURE 1

A worker of Reticulitermes surrounded by infective stages of Neoaplectana carpocapsae.

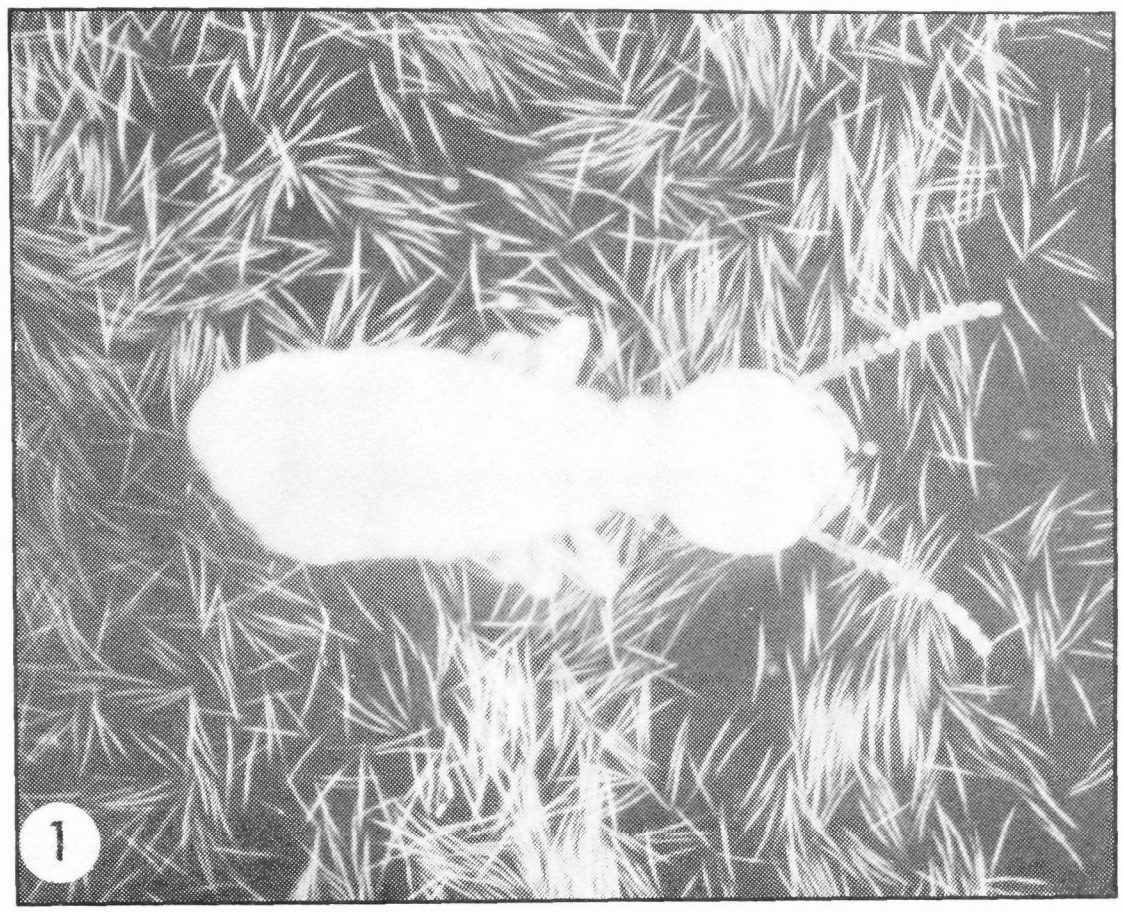


FIGURE 2

Developing stages and adults of Neoaplectana carpocapsae removed from the body cavity of an infected Reticulitermes.

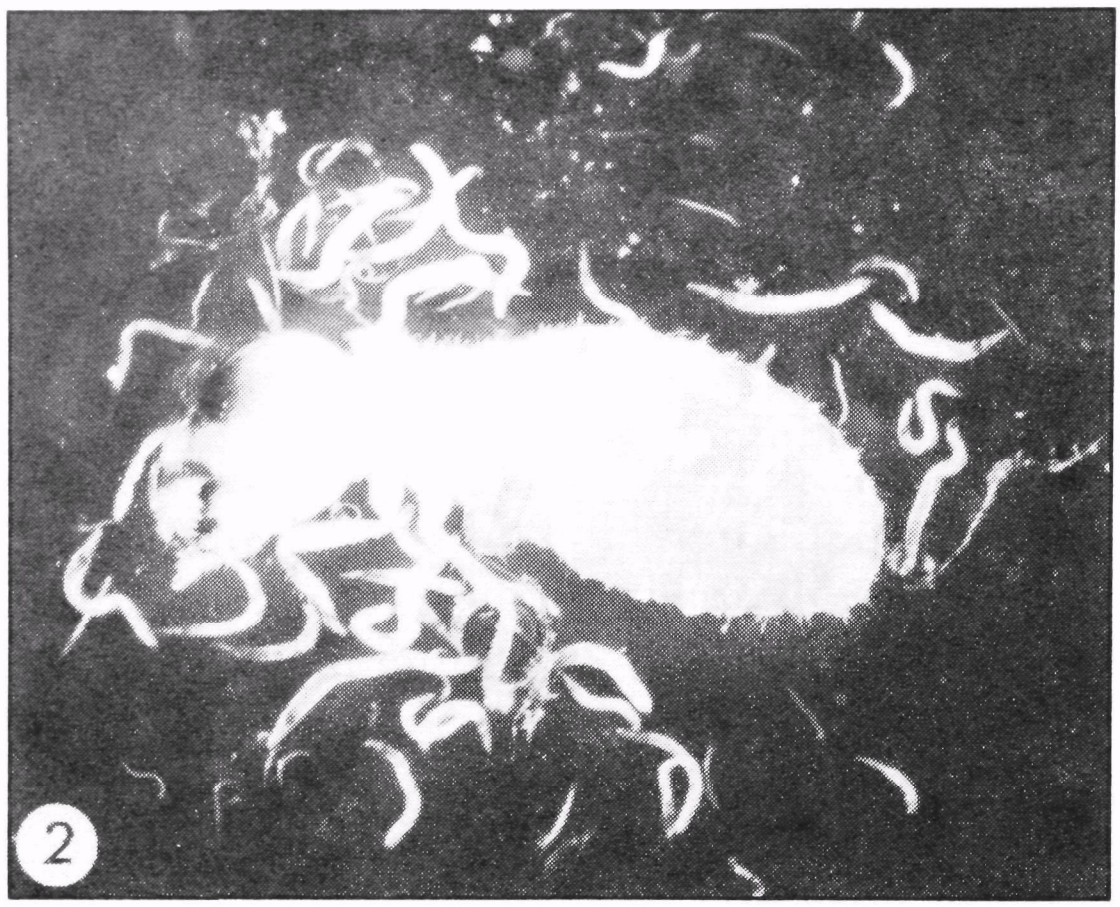
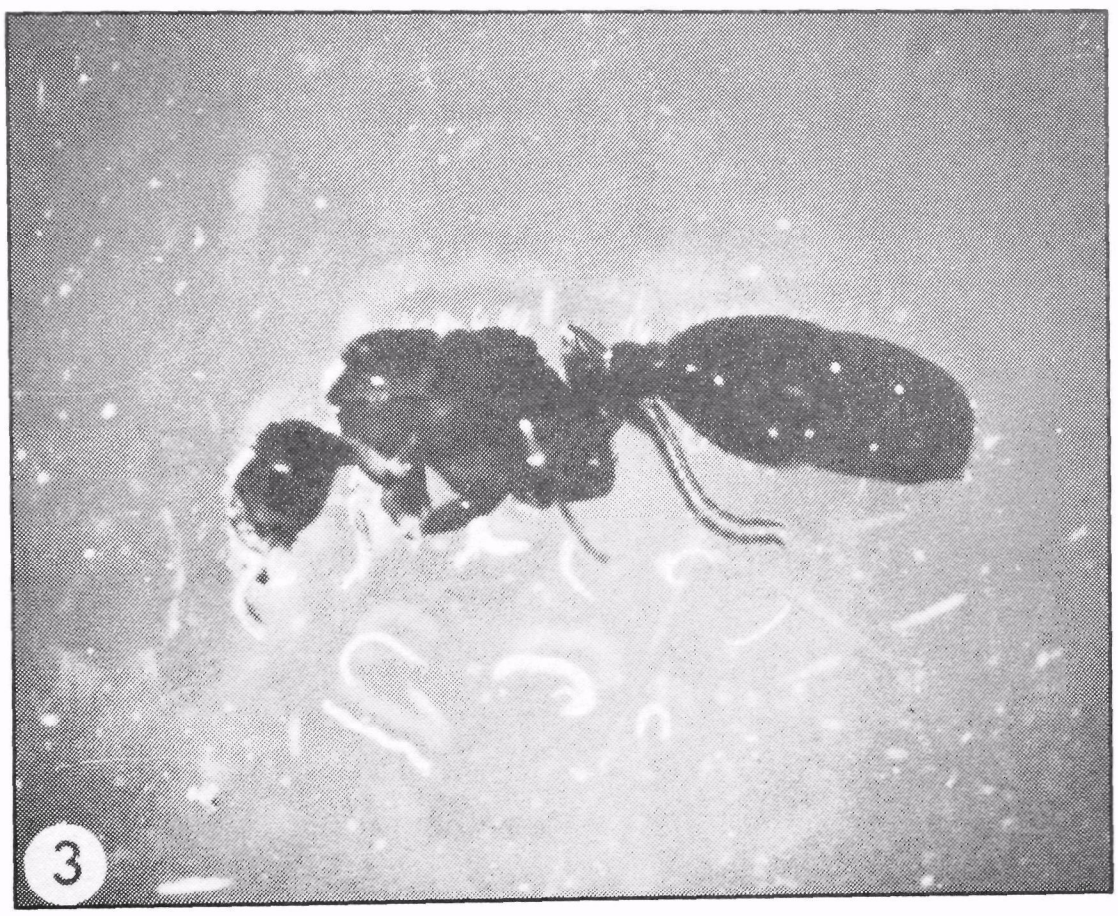


FIGURE 3

Fire ant queen surrounded by developing stages of Neoaplectana carpocapsae removed from the host's hemocoel. Specimen courtesy of Brad Vinson, under whose direction the fire ant control program with entomogenous nematodes is being conducted.



SECTION VI

Manual of Current Practices for Control of Turfgrass Diseases, Insects and Poa Annua

SYMPTOMATOLOGY AND MANAGEMENT OF COMMON TURFGRASS DISEASES IN TRANSITION ZONE AND NORTHERN REGIONS

Peter H. Dernoeden, Ph.D
Department of Agronomy
The University of Maryland
College Park, MD 20742

INTRODUCTION

Most turfgrass diseases are caused by pathogenic fungi that invade leaves, stems and roots of plants. As a result of the injurious effects of a disease, the plant will exhibit various symptoms such as leaf spots, root rots or death of leaves, tillers or entire plants. Sometimes these fungi produce visible signs such as mushrooms; white powdery mildew; white, fluffy mycelial growth; pink gelatinous mycelial growth; red or black pustules on leaves, etc. Mycelium is the vegetative body of a fungus that is composed of a network of fine tubes that often appear cottony. It is through the use of these symptoms and signs that disease problems are diagnosed. Time of year and turfgrass species also provide important clues in diagnosing diseases. For example, brown patch and Pythium blight are seldom a problem when night temperatures fall below 65F, and Pythium blight does not cause severe injury to mature stands of Kentucky bluegrass. Conversely, dollar spot tends to be more damaging under conditions of cooler nighttime temperatures in late spring and early fall than during the hottest weeks of summer. Summer patch is strictly a high temperature, summer disease of Kentucky bluegrass, fine leaf fescues and annual bluegrass. Species such as perennial ryegrass, creeping bentgrass and tall fescue are resistant to summer patch.

Most turfgrass diseases are caused by fungi rather than bacteria or viruses. In the pages to follow, the most common fungal diseases of turfgrasses, as well as plant parasitic nematodes, are described and cultural and chemical approaches to their management are outlined. A more complete list of turfgrass diseases, hosts and pathogens is provided in Table 1.

SPRING AND FALL DISEASES

DOLLAR SPOT

The dollar spot pathogen (Sclerotinia homoeocarpa) is widespread and extremely destructive to turfgrasses. The disease is known to attack most turfgrass species including annual bluegrass, bentgrasses, red fescue, Kentucky bluegrass, perennial ryegrass, bermudagrass, zoysiagrass, centipedegrass and St. Augustinegrass. The symptomatic pattern of dollar spot varies with turfgrass species and management practices. Under close mowing conditions, as with intensively maintained bentgrass or zoysiagrass, the disease first appears as small, circular, straw-colored spots of blighted turfgrass about the size of a silver dollar. With coarser textured grasses such as Kentucky bluegrass

or perennial ryegrass suited to higher mowing practices, the blighted areas are considerably larger, irregularly-shaped, straw-colored patches three to six inches in diameter. Affected patches frequently coalesce and involve large areas of turf. Grass blades often have straw-colored or bleached-white lesions shaped like an hour glass. The hour glass banding on the leaves is often made more obvious by a definite narrow brown, purple, or black band which borders the bleached sections of the lesion from the remaining green portions. When the fungus is active and moisture is present, a fine, cobwebby mycelium may cover the diseased patches during early morning hours. Disease severity has peak periods in late spring-early summer and again late summer-early fall. In the upper Midwest, however, the disease tends to be most damaging during autumn. Dollar spot can remain active during mild periods throughout fall and into early winter in some regions.

There are at least two strains of the dollar spot fungus, (referred to tentatively as species of Moellerodiscus and Lanzia) which may account for the ability of the disease to be damaging during cool and warm periods. Presently, the taxonomy of the two strains is imperfectly understood. Dollar spot tends to be most damaging in poorly nourished turfs, particularly if soils are dry but when humidity is high or when a heavy dew is present. Avoiding drought stress, watering deeply during daytime hours, maintaining a balanced N-P-K fertility program, and controlling thatch and compaction are cultural approaches that minimize dollar spot injury. Except for maneb, mancozeb and thiram, most fungicides effectively control dollar spot.

HELMINTHOSPORIUM LEAF SPOT and MELTING OUT

Many of the fungi that cause leaf spotting and melting-out diseases of turfgrasses were once assigned to the genus Helminthosporium. Today, these fungi are more appropriately referred to as species of Drechslera or Bipolaris, but the common name of the diseases they cause remains Helminthosporium leaf spot, melting-out or netblotch.

Among the most important spring and autumn diseases of Kentucky bluegrass is leaf spot, which is caused by Drechslera poae. This disease is not as devastating as it once was because of the development and widespread use of resistant bluegrass cultivars. South Dakota, Kenblue, Park and other "common"types of Kentucky bluegrass are very susceptible to leaf spot. The common types, which generally survive extreme environmental stresses, are still used today as components of bluegrass blends in some regions of the U.S. because they lend genetic diversity to the stand.

Drechslera poae is a cool weather pathogen that is most active during the spring (especially April and May), autumn (especially September and October), and throughout mild winter periods. D. poae causes disease that may occur in two phases: the leaf spot phase, and the melting-out phase. Typically, distinct purplish-brown leaf spot lesions with a central tan spot are produced on the leaves of affected plants. In a heavily infected stand, the turf appears yellow or red-brown in color when observed from a standing position. During favorable disease conditions, lesions may increase in size to encompass the entire width of the blade causing a die-back from the tip. Leaf spot lesions are initially associated with older leaves, which die prematurely as a result of the invasion. If favorable environmental conditions for disease continue, particularly overcast, cool and drizzling weather, successive layers of leaf sheaths are penetrated, and the crown is invaded. Once the crown is invaded the disease enters the melting-out phase. During this phase, entire tillers are lost, and the turf loses density. Hence, it is the melting-out phase that is most damaging to the sward.

Net-blotch disease of tall fescue and perennial ryegrass is caused by another of the helminthosporia, Drechslera dictyoides. D. dictyoides is also a cool, wet weather pathogen that

attacks turf primarily during cool and moist periods of spring and fall. Initially, symptoms appear as minute, purple-brown specks on leaves. As the disease progresses, a dark brown, net-like pattern of necrotic lesions develop on tall fescue. These net blotches may coalesce, leaves turn brown or yellow, and die-back from the tip. On leaves of perennial ryegrass, numerous oblong, brown lesions are produced. Under ideal environmental conditions the fungus may invade crowns and roots, causing a melting out of the stand. Both diseases can be active during relatively warm, rainy periods of winter.

Cultural practices that minimize injury from leaf spot or melting-out diseases are as follows: raise the mowing height; avoid spring and summer applications of water soluble nitrogen fertilizers; avoid light, frequent irrigations; control thatch; overseed with resistant cultivars; and avoid the use of broadleaf, phenoxy herbicides during periods when these diseases are active. Fungicides that effectively control leaf spot disease include anilazine, chlorothalonil, iprodione and maneb.

SPRING DEAD SPOT

Spring dead spot (SDS) is perhaps the most damaging disease of bermudagrass turf and is caused by Leptosphaeria korrae and possibly other fungi. As the name implies, SDS injury becomes apparent in the spring. The actual infection, however, may begin as early as autumn, but root injury by the pathogen becomes rapid prior to spring green-up, during late winter or early spring. As bermudagrass breaks dormancy, circular patches of brown, sunken turf two inches to three feet in diameter become conspicuous. Rhizomes and stolons from nearby, healthy plants eventually spread into and cover the dead patches. This filling-in process is slow, a period which may last four to eight weeks following spring green-up. The slow filling process is believed to be due to toxic substances generated in the soil below the dead patches. Weeds commonly invade the dead patches. These weeds should be controlled to reduce competition with the bermudagrass and thereby speed up the recovery process.

Spring dead spot is most commonly associated with mature bermudagrass turfs older than three years. The disease, however, may appear the spring following sprigging with stolons from sites that previously had SDS. SDS injury is most likely to occur where thick thatch layers exist and where nitrogen fertilizers have been heavily applied during late summer. Benomyl and fenarimol applied in late September help alleviate SDS. Ammonium sulfate (applied at 1.0 lb N/1000 ft) and other water soluble nitrogen fertilizers plus potassium (applied at 1.0 lb K/1000 ft) applied on monthly intervals from mid-May to mid-August speed the recovery of turf injured by SDS.

NECROTIC RING SPOT

Necrotic ring spot (NRS) is a newly described disease of Kentucky bluegrass and is caused by Leptosphaeria korrae. Although newly described, NRS probably has been around for some time, but has been confused with Fusarium blight.

Necrotic ring spot was first suspected as being a new disease in Wisconsin, where the fungicide triadimefon had been applied unsuccessfully to control what was believed to be Fusarium blight. Unlike Fusarium blight, NRS primarily is a cool, wet weather disease of spring and fall. Fusarium blight and another recently described patch disease that mimics Fusarium blight, summer patch, are both high-temperature diseases of summer. The confusion over NRS, summer patch and Fusarium blight has occurred because all three diseases can appear as rings of dead grass with

living turf in the center. To date, NRS has been observed mainly in Kentucky bluegrass turf grown in the Northeast, upper Midwest and Pacific Northwest regions.

Currently, there is no information regarding cultural control of NRS or cultivar susceptibility to the disease. Early spring applications of fenarimol and propiconazole have been reported to control NRS.

STRIPE SMUT and FLAG SMUT

Stripe (Ustilago striiformis) and flag smut (Urocystis agropyri) are diseases that occur primarily in mature Kentucky bluegrass stands and occasionally in bentgrass and perennial ryegrass turf. Symptoms are most conspicuous during the cool, moist seasons of spring and fall. Infected plants are often stunted and pale green or yellow in color. Narrow, silvery or gray-black streaks will appear on the leaves. These streaks are fruiting structures (sori) in which large masses of spores (teliospores) are produced. When sori mature, the cuticle and epidermis rupture, and the leaves shred and curl releasing the teliospores. During summer months, infected plants may appear amazingly healthy if properly maintained. In spring or autumn, however, badly infected stands may appear chlorotic and in need of nitrogen fertilizer. During winter, leaves that had been shredded by matured fruiting bodies develop a gray-brown, desiccated appearance.

Stripe and flag smut are most damaging to infected plants during periods of heat and drought stress. If properly irrigated and fertilized, however, badly smutted stands often survive, exhibiting only a decrease in turf quality and some thinning during stressful summer months. These smut diseases most commonly occur in mature (two to four years and older) stands that have been managed with high levels of nitrogen fertilizer. Merion, Windsor and Fylking Kentucky bluegrasses are among the most susceptible cultivars. Recently introduced cultivars are less susceptible to these diseases, which has led to a reduction in the occurrence of stripe and flag smut. Using a balanced N-P-K fall fertilizer program, increasing the mowing height in summer and deep irrigation at the first sign of drought stress are effective management practices that greatly minimize smut injury in Kentucky bluegrass. Hence, cultural control of smut diseases is aimed at blending disease resistant cultivars, avoiding excessive use of nitrogen fertilizer, controlling thatch and preventing severe drought stress of infected turfs. Smut diseases are effectively controlled with a spring or fall application of a systemic fungicide such as benomyl, fenarimol, propiconazole, or triadimefon.

RED THREAD

Red thread (Laetisaria fuciformis) is a common disease of turfgrasses, and its development is favored by cool (65-75F), wet and extended overcast weather of spring and fall. Red thread may also occur during warm to very cold weather in the presence of plenty of surface moisture or at snow melt in winter. This disease may become widespread among turfgrass species during mild winters.

Red thread is most damaging to perennial ryegrass, common-type Kentucky bluegrasses, and the fine leaf fescues. Red thread may also attack improved cultivars of Kentucky bluegrass, tall fescue, bentgrass, and bermudagrass, but generally does not cause a significant level of injury to these species when they are sufficiently fertilized with nitrogen.

The symptoms and signs of red thread are distinctive and unmistakable. In the presence of morning dew or rain, a coral pink or reddish layer of gelatinous fungal growth (mycelium) can easily be seen on leaves and sheaths. The infested green leaves of these plants soon become

water-soaked in appearance. When leaves dry, the fungal mycelium becomes pink in color and is easily seen on the straw-brown or tan tissues of dead leaves and sheaths. During the final phase of disease activity, bright red, hard and brittle strands of fungal mycelium called "red threads" or sclerotia may be seen extending from leaf surfaces, particularly cut leaf tips. These red threads fall into the thatch and serve as resting structures for the fungus by surviving long periods that are unfavorable for growth of the pathogen. From a distance, affected turf has a straw-brown, tan or pinkish color. Symptoms are concentrated in circular or irregularly shaped patches two inches to three feet in diameter that frequently coalesce to involve the whole sward.

Red thread is generally most injurious to poorly nourished turfs. Frequently, the disease is best controlled by an application of 0.5-1.0 lb nitrogen/1000 ft. Application of nitrogen during periods too cool for turf growth will not aid in reducing disease severity. This is because nitrogen alleviates red thread disease symptoms by stimulating plant growth and vigor. The nitrogen-stimulated plants are able to replace damaged tissues more rapidly than the fungus can inflict injury. Fungicides that control red thread are anilazine, chlorothalonil, iprodione and triadimefon.

POWDERY MILDEW

Powdery mildew (Erysiphe graminis) is a disease confined to shaded environments. The presence of grayish-white mycelium and spores on the upper surfaces of leaves is a conspicuous, diagnostic sign of the disease. The lower, older leaves of the plant are generally more heavily infected than upper, younger leaves. In heavy infestations, leaves appear to have been dusted with ground limestone or flour. The abundant surface mycelium absorbs nutrients from the epidermal cells and the leaves turn yellow. Eventually leaves and tillers may die and the turf will exhibit poor density. The fungus seldom kills plants; however, its presence severely weakens plants and therefore can predispose them to injury from environmental stresses or other diseases.

Powdery mildew can be found at almost any time of year, but peak activity normally occurs in the fall. Spores are produced in abundance on leaf surfaces and they move rapidly to adjacent, healthy leaves. The spores germinate rapidly, even in the absence of dew or water. Disease activity is most prevalent during cool, humid and cloudy periods of spring and fall. Because shade is the primary predisposing factor for powdery mildew, reducing shade and improving air circulation is a cultural, but often impractical approach to reduce damage. Planting or overseeding with shade-tolerant cultivars, increasing mowing height, avoiding drought stress and using a balanced fertilizer program will promote turfgrass growth and help to minimize injury from powdery mildew. Fungicides should be applied in situations where the disease is yellowing plants and thinning the stand. Some effective fungicides are benomyl, propiconazole and triadimefon. Tank mix a leaf spot fungicide with the mildewcide.

RUST

Rust diseases in turf are caused by several Puccinia spp. and they are most damaging to poorly nourished turfs and turfs grown under a low mowing height. Stem rust (P. graminis) of Kentucky bluegrass, crown rust (P. coronata) of perennial ryegrass, and zoysiagrass rust (P. zoysiae) are most commonly observed during cool, moist periods of fall. Rust-affected turfs exhibit a yellowish or reddish-brown appearance from a distance. Close inspection of diseased leaves reveals the presence of conspicuous red, black, orange or yellow pustules. Sterol inhibiting fungicides (such as propiconazole and triadimefon) effectively control rust. Contact fungicides (such as chlorothalonil, maneb and mancozeb) will help somewhat to alleviate injury. A balanced fertility

program may be preferred to fungicides in situations where rust is damaging poorly nourished turfs. Also, irrigate early in the day to insure leaf dryness prior to nightfall, water deeply but infrequently, increase mowing height and increase mowing frequency. By increasing mowing frequency, leaves bearing immature spores are removed and this reduces the potential for more leaf infections.

SUMMER DISEASES

BROWN PATCH

Brown patch is caused by Rhizoctonia solani and it is a common, summertime disease of turfgrasses. In southeastern states, R. zeae may also cause symptoms typical of brown patch. The pathogen attacks nearly all grasses used as turf, but is most damaging to tall fescue, perennial ryegrass, creeping bentgrass and annual bluegrass. Kentucky bluegrass, zoysiagrass and other species are only occasionally injured by Rhizoctonia solani. The symptoms of the disease vary according to host species. On closely mown turf, affected patches are roughly circular and range from three inches to three feet or greater in diameter. The outer edge of the patch may develop a one to two inch wide smoke ring. The smoke ring is blue-gray in color and is caused by mycelium in the active process of infecting leaves. Smoke rings are not always present and patches may have an irregular rather than circular shape. Close inspection of leaf blades reveals that the fungus primarily causes a dieback from the tip down, to give affected turf its brown color. In tall fescue and perennial ryegrass turfs, affected areas are frequently irregularly shaped and smoke rings are only occasionally present. R. solani produces distinctive and often greatly elongated lesions on tall fescue leaves. The lesions are a light, chocolate brown color, and are bordered by narrow, dark brown bands of tissues. In perennial ryegrass, smaller leaf lesions are produced and tip dieback commonly occurs. During early morning hours, when the disease is active, the cobweb-like mycelium may be observed on leaves in the presence of water or heavy dew.

Environmental conditions that favor disease development are day temperatures above 85F and high relative humidity. A night temperature above 68F is perhaps the most critical environmental requirement for disease development. Although textbooks underscore the importance of high surface moisture or high soil moisture in disease severity, the disease can be very damaging to wilted tall fescue and perennial ryegrass if the relative humidity is high. Summer application of fertilizers, in particular water soluble N fertilizers, may enhance disease injury from brown patch. Avoiding nitrogen when the disease is active and irrigating early in the day are the only cultural practices that may help alleviate brown patch. Benomyl, chlorothalonil, iprodione, maneb, mancozeb, propiconazole and the thiophanates effectively control brown patch.

PYTHIUM BLIGHT

Pythium blight is among the most destructive turfgrass diseases. During periods of high relative humidity, nighttime temperatures above 70F and abundant surface moisture, the disease may progress rapidly, destroying large turf areas within 24 hours. The disease often is first observed in areas that are shaded, low lying and adjacent to water where air circulation is poor. While there are several species capable of causing the disease, P. aphanidermatum and P. ultimum are the most commonplace.

It is a general misconception that Pythium blight is a common, widespread disease. Although Pythium spp. can cause damping-off of any seedling species, it rarely, if ever, attacks mature lawns

comprised of Kentucky bluegrass, tall fescue, fine fescue or zoysiagrass. Pythium blight is most likely to attack creeping bentgrass or perennial ryegrass grown under the high management conditions commonly found on golf courses.

On closely mown bentgrass putting greens, the disease kills turf in circular patches, rings or streaks that follow the water drainage pattern. During morning hours when the disease is active, bentgrass turf displays an orange-bronze color and there may be a gray smoke ring on the periphery of affected patches. In low lying areas where water collects the patches are brown and all plants are often killed. In perennial ryegrass, affected foliage develops a dark-gray color and leaf blades have a water soaked appearance. Blades then collapse, mat together and turn brown.

A cottony web of mycelium covers the grass leaves and is visible during early morning hours when leaves are wet. Pythium spp. are capable of producing an abundance of mycelium in a few hours, which bridges leaf blades, giving turf the cottony appearance. The fungus primarily spreads over a turf by rapid mycelial growth or by movement of mycelial fragments in rain or irrigation water. Pythium species also produce motile spores called zoospores, which also serve to spread the disease.

Water management may greatly influence disease severity. It is therefore helpful to water early in the day to avoid a moist foliage prior to nightfall. Improving water and air drainage will help reduce disease development, but these cultural measures are often expensive and difficult to achieve. A fall fertilization program using a balanced N-P-K fertilizer, avoiding the use of lime in alkaline soils and avoiding nitrogen fertilizers during summer stress periods may help to reduce disease incidence and severity.

While fungicides are not generally used in lawn care for Pythium blight control, they are considered a necessity in golf course management in most regions of the U.S. Before the advent of systemic fungicides targeted for Pythium blight in the early 1980's, the disease was combatted with short residual chemicals such as chloroneb and etridiazol. Metalaxyl was registered for use on turf in 1981 and provides over 20 days of control and can be used either preventatively or curatively. The widespread reliance and continuous usage of metalaxyl on golf courses has led to reduced effectiveness and in some cases the selection of Pythium spp. biotypes resistant to metalaxyl. Reduced residual effectiveness is attributed to a build-up of microorganisms that degrade the active ingredient of the fungicide. Propamocarb and fosetyl-Al are other fungicides that provide long, residual Pythium blight control, but they should be applied preventatively and they are expensive to use.

To avoid the build-up of fungicide resistant biotypes and to avoid reduced residual effectiveness of compounds due to microbial build-up, fungicides should always be rotated and they should be applied in tank-mix combinations whenever economically feasible. Recent research indicates that the aforementioned problems can be avoided by tank mixing reduced rates of metalaxyl and propamocarb or reduced rates of metalaxyl + propamocarb + fosetyl-Al. Tank mixing metalaxyl with mancozeb is also believed to help reduce the probability of resistant Pythium biotypes from dominating. Alternating systemics with contact sprays, although the latter may only provide three to seven day control, will also help to reduce these potential problems from occurring.

SUMMER PATCH

Summer patch is incited by Magnaporthe poae and is a most destructive disease of Kentucky bluegrass and annual bluegrass turf. Symptoms of summer patch initially appear as wilted, dark-green areas of turf. Initially the straw-brown dead patches resemble the symptoms of dollar spot disease, but these patches soon increase in size and may take on crescent shapes, elongated streaks, or circular patches. Healthy turf may persist in the center of blighted patches producing rings or "frog eye" symptoms. The frog eye symptom, however, is only occasionally observed and the dead patch symptom is more commonplace. Affected regions may coalesce, and large areas of turf are destroyed within a seven to ten day period. There are no distinctive leaf lesions associated with the disease, but leaves generally dieback from the tip.

Summer patch most commonly occurs in Kentucky bluegrass turfs that are three years of age or older. To date, the disease has principally been a problem in Kentucky bluegrass, annual bluegrass and fine leaf fescues. Environmental conditions play a significant role in the predisposition of turf to the disease. The disease generally appears in late June or early July when daytime temperatures above 90F prevail. The disease is most severe on sunny, exposed slopes or other heat-stressed areas of lawns such as those adjacent to paved walks and driveways. The disease most frequently occurs following a period of drought stress. Turf allowed to enter drought-induced dormancy is often severely damaged. Mysteriously, the disease may flair up following rainy periods in late summer and September. Other predisposing factors include: spring applications of high levels of nitrogen fertilizer, accumulation of thatch, frequent light irrigations or rain storms, and compaction. The most important environmental factor required for disease development is for root zone temperatures to exceed 86F. For home lawns, increasing mowing height to 3.0 inches in late spring, applying water deeply and only at the onset of wilt and use of a slow release nitrogen fertilizer, such as sulfur coated urea, are the best approaches to minimizing summer patch. Preventative applications of triadimefon, or curative applications of benomyl or iprodione drenches may provide a satisfactory level of control on close-cut Kentucky bluegrass fairways, but no fungicide program is known to control the disease in annual bluegrass on putting greens. Fungicides are ineffective if turf is allowed to enter drought induced dormancy.

FUSARIUM BLIGHT

Fusarium blight was first observed in the late 1950's, but is a controversial disease that primarily attacks Kentucky bluegrass. A complex of Fusarium culmorum and F. poae were implicated as the incitants of the disease. Fusarium blight occurred in California primarily as a severe crown rot; whereas in the eastern U.S., the foliage blight symptom is most commonplace. Early symptoms first appear as scattered, light-green or wilted patches two to six inches in diameter. Over a period of 36-48 hours, under high-temperature stress conditions, patches fade to a tan or light-straw color. Affected areas may take on crescent shapes, elongated streaks or circular patches. Healthy turf may persist in the center of blighted patches, producing rings of frog-eye symptoms. Leaf blades may develop bleached white lesions that appear similar to dollar spot lesions. Fusarium species can be isolated from the lesions.

In California, the disease typically occurs in the absence of foliar blighting. Patches appear when foliage dies as a result of the destruction of crowns and attached roots by F. culmorum. The pinkish mycelium of the pathogen can be seen on crown surfaces when soil moisture is high. Stem bases and crown tissues eventually develop a dark brown or black, firm rot.

Currently, the name Fusarium blight is retained to describe foliar blight, crown rot and root rot symptoms in situations where signs of Fusarium spp., such as spores and pink mycelial growth, are abundant. Two additional diseases, described previously, are now recognized as summer patch and necrotic ring spot, where Fusarium spp. are not involved and roots bear dark-brown, runner hyphae. The control measures for Fusarium blight are the same as those described for summer patch.

MELTING-OUT

In summer, Kentucky bluegrass, fine leaf fescues and other grasses may decline due to invasion by B. sorokiniana. This fungus also may cause a leaf spot and melting-out phase. B. sorokiniana is normally most severe when temperatures exceed 85F and humidity is high. This disease is generally aggravated when turf is subjected to drought stress. Today, the fine leaf fescues are frequently more severely damaged in summer by this fungus than Kentucky bluegrass. Again, this is principally related to the development of resistant cultivars of Kentucky bluegrass; whereas, highly resistant cultivars of fine leaf fescues are not yet available. Also during warm, dry periods B. cynodontis may become a severe crown, stolon and root rot pathogen of bermudagrass. See the "Helminthosporium and Melting-Out" section for management of melting-out.

FAIRY RINGS

Fairy rings may be caused by any one of 60 or more species of fungi. The activity of these fungi in the thatch and soil results in rings or arcs of dead or unthrifty turf, or rings of dark green, luxuriantly growing grass. The most destructive rings are classified as Type 1 rings. Type 1 rings are very common, especially in old pasture turfs or any mature turf with a lot of thatch. Type 1 rings normally appear as circles or arcs of dark green, fast growing grass. The most common fungus known to cause Type 1 fairy ring is Marasmius oreades. These rings are distinguished by three distinct zones: an inner lush zone where the grass is stimulated and grows luxuriantly; a middle zone where the grass may be dead; and an outer zone in which the grass is stimulated. The distance from the inside of the inner zone to the outside of the outer zone may range from a few inches to one or more feet wide. The dead zone is due to a massive build-up in the thatch and soil of fungal mycelium. It accumulates in such large amounts to form a hydrophobic barrier that prevents entry of rain or irrigation water, thus killing the plants by drought. The formation of the three zones is noticeable from early spring to winter.

Control of fairy rings is made extremely difficult due to the impermeable nature of the infested soil. Chemical control has been ineffective because the fungus grows deeply into the soil and lethal concentrations of fungicide do not come into contact with the entire fungal body. Suppression is the most practical approach to combating fairy rings in most situations. The suppression approach is based upon the premise that fairy rings are less conspicuous and less numerous where turf is well watered and fertilized. This method of control involves a combination of aeration, deep waterings and proper fertilization. Aeration is beneficial, as it aids in the penetration of air and water. The entire area occupied by the ring, to include a two foot periphery beyond the ring, should be core aerified on two to four inch centers. The area should then be irrigated to a depth of four to six inches. Use of a wetting agent should help improve water infiltration. The ring area should be retreated in a similar fashion at the earliest indication of drought stress; that is repeat the process whenever the dark green grass turns blue-gray and begins to wilt. When an aerator is not available, a deep root feeder with garden hose attachment may be useful to force water into the dry soil. About 3.0 to 4.0

lb N/1000 ft should be applied to cool season turfgrass species in three to four applications during fall or late winter.

There are two methods of eradication: fumigation and excavation. Both methods are laborious, costly and not always successful. To fumigate, the sod must be removed from an area two feet to the inside and at least two feet to the outside of the rings. It is essential not to spill any soil or sod onto the healthy grass. The most commonly used fumigants are methyl bromide and metam. Fumigation with methyl bromide must be carried out by a licensed pesticide applicator. Special precautions must be taken to insure that children or pets do not come into contact with these fumigants. The second alternative to fairy ring eradication is to carefully dig out and discard all infested soil in the ring. This would involve removal of soil to a 12-inch depth, and the excavation should be wide enough to extend at least two feet beyond the outer most evidence of the ring. The excavation must then be filled with fresh, uncontaminated soil and the area reseeded or sodded. Hence, the eradication approach for fairy ring control is impractical and seldom performed.

WINTER DISEASES

SNOW MOLD DISEASES

Snow protects dormant turfgrass plants from dessication and frost, but also provides a microenvironment conducive to development of some low temperature, pathogenic fungi. Like most other disease problems, there is no shortage of fungal species that are capable of damaging turf during cold periods between late fall and early spring. The most common low temperature fungal diseases are pink snow mold (Microdochium nivalis), and gray snow mold (Typhula incarnata and T. ishikarensis). Other diseases known to be active under snow cover or during winter months include red thread (Laetisaria fuciformis) and leaf spot (Drechslera spp.). During cool moist periods of late fall or early spring, cool temperature brown patch (Rhizoctonia cerealis) is a common disease of putting green turf.

Snow mold fungi are remarkable in being active at temperatures slightly above freezing. Snow molds are damaging when turf is dormant or when growth of turf has been retarded by low temperatures. Under these conditions, turfgrasses cannot actively resist fungal invasion. Although known as snow molds, these fungi can attack turf with or without snow cover. In general, these diseases develop whenever temperatures are cool (32-60F) and there is an abundance of surface moisture.

Conditions favoring pink snow mold include low to moderate temperatures; plenty of moisture; prolonged deep snow; snow fallen on unfrozen ground; lush turf stimulated by late season application of excessive amounts of nitrogen fertilizer, and alkaline soil conditions. Symptoms of this disease appear as small water soaked patches two to three inches in diameter that may increase in size to one to two feet in diameter and coalesce. The pink coloration of affected turf at the edge of the patches is produced by the pinkish color of the mycelium. The mycelium mats the leaves, and plants eventually collapse and die. Mycelium on the leaf blades produce fruiting bodies (sporodochia) upon which spores are borne in prodigious numbers. These spores are easily spread by machinery and foot traffic. When damage occurs under snow the extent of injury is usually more severe than without snow cover. The pathogen, once known as Fusarium nivale, is able to survive

unfavorable environmental conditions as spores and as resting mycelium that remain viable in plant debris.

Pink snow mold attacks a wide range of turfgrass species under snow including perennial ryegrass, Kentucky bluegrass, bentgrass and the fescues. This disease is generally most destructive to annual bluegrass and bentgrass. For many years the standard fungicidal control has been phenyl mercury acetate or mercurous plus mercuric chloride. The soluble mercuric chloride provides quick disease suppression and the insoluble mercurous chloride provides persistent protection. Mercury-based fungicide may only be applied to putting greens and tees, and only for the purpose of snow mold control. Pentachloronitrobenzene (PCNB), benomyl, iprodione and triadimefon also provide good control. Fungicidal control is best achieved with a preventative application prior to the first big snow storm of the year. Subsequent applications should be made during mid-winter thaws and early spring snow melt in areas where the disease is a chronic problem.

Gray snow mold, or Typhula blight, is also a serious disease of turfgrasses as well as cereals in North America and Europe. Initially, symptoms appear as light brown or gray patches two to four inches in diameter enlarging to two feet in diameter and coalescing. Gray snow mold also occurs with and without snow cover; however, damage is usually minimal in the absence of snow. Like pink snow mold, Typhula blight is more damaging under prolonged deep snow, particularly when heavy snow accumulates on unfrozen ground.

Gray snow mold initially begins its disease cycle as a saprophyte colonizing dead organic matter. Under snow, however, the fungus moves onto living leaves, sheaths and may ultimately invade the crown. Normally, Typhula spp. do not completely kill crowns so plants generally recover during the spring. Conversely, pink snow mold more frequently invades crown tissues and kills turf. Typhula spp. survive unfavorable environmental conditions as sclerotia. Sclerotia are compact masses of fungal mycelium covered with a dark colored, protective rind. Sclerotia are chestnut brown or black in color and are less than 1/8 inch in diameter. When cool, moist weathers conditions return in late fall, these sclerotia germinate to produce fungal mycelium or a specialized fruiting body upon which spores are borne. All species of Typhula that attack turf produce similar symptoms. Sclerotial color is one of the primary characteristics pathologists use to differentiate between the two species of Typhula known to cause gray snow mold.

Gray snow mold, like pink snow mold, is best controlled using a mercurial applied on a preventative schedule. Iprodione and triadimefon as well as cadmium based fungicides also provide effective control of the disease. Cadmium (like mercury)-based fungicides, however, may only be applied to golf course greens and tees. Snow mold prevention with fungicides is generally only warranted for golf course turf in most regions of the U.S.

Researchers in Canada have shown that the fungus Typhula phacorrhiza applied on grain inoculum suppressed gray snow mold on creeping bentgrass greens by 44% to 70%. Although not yet commercially available, these Canadian researchers believe that this biological control agent can be formulated into pellets and be applied by standard fertilizer spreaders.

Snow mold injury can be reduced by applying a balanced N-P-K fertilizer in fall. Ammonium sulfate use was associated with reduced pink snow mold injury in Washington. Continue to mow late in the fall to insure that snow does not mat a tall canopy. On golf courses, snow fences and windbreaks should be used to prevent snow from drifting on chronically damaged greens. Avoid

compaction of snow by skiers and snow mobiles on greens. Also avoid the use of limestone where soil pH is above 7.0, as alkalinity may encourage pink snow mold.

Cool temperature brown patch, also known as yellow patch, is a disease of bentgrass, annual bluegrass and perennial ryegrass turf. It is most frequently observed on putting greens producing rusty-brown and yellow rings, or yellow patches a few inches to one or more feet in diameter. Damage is generally superficial but significant thinning of turf may occur during prolonged, wet and overcast weather of late winter and early spring. A broadspectrum fungicide such as anilazine, chlorothalonil or iprodione will prevent severe thinning, but no fungicides or cultural practices are known which help to prevent the formation of rings and patches.

FACTORS ASSOCIATED WITH FUNGICIDE USE

Arriving at the decision of whether to apply a fungicide to any turf area is often difficult and generally based upon economic considerations. Aside from cost, the primary determinants in using a fungicide are the prevailing environmental conditions, host species and cultivars present, and the pathogen. The environmental factor has unique implications in turfgrass pathology because the intensity and nature of turfgrass management greatly influences plant vigor and therefore the incidence and intensity of diseases.

Promoting vigorous growth through sound cultural practices is the first step in minimizing disease injury. Frequently, however, environmental stresses, traffic and poor management weaken plants, predisposing them to invasion by fungal pathogens. When disease symptoms appear, it is imperative that a rapid and accurate diagnosis of the disorder be made. The prudent manager also attempts to determine those factors that have led to the development of the disease. The most common cause for extensive disease injury in lawn turf can frequently be related to poor management practices by the homeowner. Abusive practices include frequent and close mowing; light and frequent irrigations; and inadequate or excessive nitrogen fertility. The development of excessive thatch layers, shade, poor drainage and traffic also contribute significantly to disease problems. A good case in point is Helminthosporium diseases, which are particularly damaging when turf is mown too closely, given light and frequent irrigations, and when turf is excessively fertilized. Despite hard work and adherence to sound management practices, diseases often become a serious problem. This normally occurs when environmental conditions favor disease development, but not plant growth and vigor. For example, summer patch and brown patch are most damaging when high summer temperatures stress plants and impair their growth and recuperative capacity. In this situation, fungicides may be recommended in conjunction with cultural practices that promote turf vigor.

Fungicides may be applied preventatively (i.e. before anticipated disease symptoms appear) or curatively (i.e. when disease symptoms first become evident). Applying a fungicide after the turf has been damaged significantly is generally a waste of time, money and effort. Curative applications are more economical and environmentally wise, but only if the disease can be treated rapidly. In general, a single or possibly two, properly timed applications will provide effective control of most disease problems encountered on home lawns. Contact fungicides are less expensive and provide good control. Contact fungicides, however, may only provide 7-14 days of control under high disease pressure conditions. Where sudden and severe, or chronic disease problems occur, a systemic alone, or a systemic plus contact may be needed. Systemic or local systemic fungicides will provide

14-21 days protection during high pressure disease periods. Tank mixing a systemic plus a contact fungicide provides a longer residual effect and a wider spectrum of control. Frequently, a fungicide may only be needed to help the turf better survive a high pressure disease period. Favorable changes in weather such as alternating hot-humid and cooler periods, however, provide the most effective means of reducing or eliminating disease problems in the summer.

THE FUNGICIDE DILEMMA IN LAWN CARE

Proper utilization and selection of fungicides is too difficult and complicated for most homeowners. Because of this, only lawn care companies can provide the most reliable lawn disease service. Fungicides, however, should not become a part of a normal application schedule. As a general rule, use of fungicides is not encouraged in most home lawn situations because (a) proper diagnosis and proper fungicide selection is difficult, (b) it is generally too late to achieve the economic and aesthetic benefits of a fungicide once extensive injury has occurred, (c) lawn care companies capable of only dry or granular applications do not have the proper spray equipment or they cannot obtain the desired fungicide(s) in granular form, and (d) it may be less expensive, and better in the long run, to overseed a damaged turf area in the autumn with disease-resistant cultivars.

There are several disease situations of lawn turf that are best controlled through a preventative fungicide application. These disease situations are: (1) Kentucky bluegrass lawns injured in previous years by summer patch, necrotic ring spot, stripe smut and perhaps dollar spot, (2) perennial ryegrass lawns injured in previous years by Pythium blight, brown patch or dollar spot, and (3) tall fescue lawns chronically damaged by brown patch. Many diseases, however, are effectively controlled with curative fungicide applications when disease symptoms first appear. For example, leaf spot in lawns of common-type Kentucky bluegrasses (e.g., Kenblue, Newport, Park, South Dakota, etc.) and fine leaf fescue (e.g., Pennlawn and Jamestown), and brown patch in perennial ryegrass can be effectively controlled with a curative fungicide application. Dollar spot disease is extremely common and if allowed to go unchecked, may cause extensive injury to Kentucky bluegrass, perennial ryegrass, red fescue and zoysiagrass lawns. When diagnosed in its early stages, however, dollar spot is also effectively controlled by fungicides. Given these situations, it becomes obvious that effective fungicide programs hinge upon (a) knowledge of past disease problems in a particular lawn or neighborhood, (b) ability to distinguish between turfgrass species and sometimes cultivars within a species, and (c) ability to diagnose turfgrass diseases. Hence, in addition to the expense of fungicides and logistical problems associated with sending trucks to specialized fungicide accounts, the lawn care company must also educate its employees to diagnose diseases. This educational process is best achieved by in-house training programs. This knowledge must be reinforced by encouraging employees to attend turf workshops and conferences held by state universities and other organizations, as well as maintaining subscriptions and reading articles in trade magazines. Expecting the employee to be proficient by reading alone is not realistic, even for highly motivated individuals.

In Table 2, the most common lawn diseases are listed, as well as their primary season(s) of occurrence, and those species that are most commonly damaged. Remember, once a disease has severely reduced stand density, fall overseeding with resistant cultivars is normally suggested. Fact sheets describing the disease and a list of cultural practices that will help minimize disease injury should be provided by the lawn care company to homeowners.

THE FUNGICIDE DILEMMA ON GOLF COURSES

Where extremely high quality turf is desired, fungicides will be needed in most years, and in nearly all areas of the U.S. The indiscriminate use of fungicides or employment of numerous, preventative applications of fungicides for many diseases should be discouraged. Other than economic restraints, reasons why repeated fungicide applications may not be desirable include:

1. Fungicides may reduce the population of beneficial microorganisms in the soil, which could lead to excessive thatch build-ups.
2. Fungicides may disturb a delicate balance among microorganisms that compete with and antagonize disease-causing fungi. This may explain why some diseases recur more rapidly and cause more injury in turfs previously treated with fungicides.
3. A fungicide may control one disease, but encourage other diseases.

When used repeatedly, certain fungicides have been shown to enhance thatch accumulation. Benzimidazole fungicides, such as benomyl and the thiophanates, and sulfur-containing fungicides such as mancozeb, maneb and thiram can cause thatch to accumulate by acidifying soil. The effect of these fungicides is indirect, that is they inhibit the thatch decomposition capacity of beneficial microorganisms by lowering soil pH. Cadmium fungicides and iprodione also may enhance thatch accumulation. In the case of these latter two compounds, thatch build-up is attributed to direct toxicity of microorganisms that degrade thatch. Fungicides may also contribute to thatch build-up by being toxic to earthworms. Earthworms help reduce thatch by mixing soil with organic matter. Benomyl, mancozeb, anilazine, chlorothalonil and various nematicides have been shown to be toxic to earthworms.

Turf managers have observed that some diseases may recur more rapidly and severely in turfs previously treated with fungicides, as compared to adjacent untreated areas. Dollar spot is probably the most common disease to exhibit this phenomenon. Data, recorded in a Maryland study, showed that red thread was more severe in the spring of 1983 in Manhattan perennial ryegrass plots last treated with benomyl in July, 1982. These phenomena are attributed to non-target effects of fungicides, i.e., the fungicide(s) were toxic to microorganisms which antagonize and help keep disease-causing fungi in abeyance.

The development of fungal strains resistant to fungicides has been well documented. Resistant strains of the dollar spot fungus first developed as a result of repeated usage of cadmium based fungicides and benomyl on golf courses. Thiophanates, anilazine, and iprodione resistant strains of the dollar spot fungus have also been reported. The development of resistant strains of fungi likely occurs in response to a selection process that eventually enables a small, but naturally occurring population of resistant biotypes to predominate in the fungicide-treated turfgrass microenvironment. It is very unlikely, however, that occasional fungicide use on home lawns would lead to the development of fungicide-resistant biotypes.

Fungicides applied to control one disease may encourage other diseases. As previously noted, benomyl can encourage red thread. Benomyl has also been shown to enhance Helminthosporium leaf spot and Pythium blight. Thiophanate-methyl may increase crown rust in perennial ryegrass, iprodione can increase yellow tuft, and maneb may enhance dollar spot. Encouragement of disease

in these situations may again be attributed to offsetting the delicate balance between antagonistic and pathogenic microorganisms in the ecosystem.

The phytotoxicity that accompanies the usage of some fungicides is generally not severe. Most phytotoxicity problems occur when fungicides are applied to bentgrasses, particularly during periods of high temperature stress. Repeated applications of sterol-inhibiting fungicides such as fenarimol, propiconazole or triadimefon may elicit a blue-green color in foliage of creeping bentgrass and other turfgrass species.

It should be noted that many of the harmful side effects just described were either isolated events or occurred only after repeated use of one fungicide over the course of several years. Experienced turfgrass managers have long recognized that tank mixing fungicides and rotating fungicides greatly minimizes these potential problems. The importance of rapid and accurate disease diagnosis, and the judicious use of fungicides are integral in management programs where fungicides are commonly employed.

NEMATODES

Nematodes are known to cause extensive injury to turfgrasses in warm temperate and sub-tropical areas in the U.S. In northern climates, the loss of turfgrass that can be attributed to nematodes is unknown. However, nematodes may be more troublesome in the transition zone and Mid-Atlantic area than is commonly believed. This would be particularly true following a mild winter. In general, nematodes most actively feed on turfgrass during environmental periods favorable for growth of the grass. Hence, feeding would be more active on cool season species in spring and fall, while on warm season grasses heaviest feeding would occur during summer. The injurious effects of this feeding, however, may not become noticeable until turf is subjected to environmental stresses in mid-to late summer.

Nematodes are very small eel-like worms, ranging from 1/50 to 1/8 inch in length. Nematodes reproduce by eggs, which hatch to liberate larvae. Larvae molt four times before reaching adult size. Each female is capable of producing hundreds of eggs and the entire life cycle is completed in five to six weeks under suitable conditions for most species. Because plant pathogenic nematodes are obligate parasites, they must feed on living tissues in order to grow and reproduce. Most nematodes are capable of attacking a wide range of plant species, and can survive on weeds in the absence of turfgrasses. Most nematodes store large quantities of food, which enables them to survive long periods in soil in the absence of suitable plants. Many also survive in frozen soils and may overwinter in living roots or in dead plant tissues.

Literally millions of nematodes can inhabit a few square feet of soil, but most nematodes are non-pathogenic. Some non-pathogens, may actually perform a beneficial service in soil by helping to degrade organic matter. Although there are thousands of species, only about 50 species are known to parasitize turfgrasses. All plant parasitic nematodes bear a hollow, spear-like structure called a stylet. The stylet is similar to a hypodermic syringe, and is used to inject enzymes into plant cells. Simultaneously, partially digested food is withdrawn. Plant pathogenic nematodes are grouped according to feeding habit. Endoparasitic nematodes partially or totally burrow into plant tissues and feed primarily within; whereas, ectoparasitic nematodes feed from the plant surface, although a small portion of the body may be embedded. The ectoparasitic are more commonly injurious to turfgrasses than endoparasitic nematodes. Nematode activity is favored by warm and moist soil conditions. Nematode populations generally peak in June or July and again in late August or early

September. Their activity is also enhanced in light textured soils and reduced in compacted or heavy soils where aeration becomes restricted. Nematodes are unable to move more than a few millimeters in soil, but they may be transported over larger distances by moving water and soil.

The symptoms of nematode injury include yellowing, stunting, wilting or early signs of drought stress, and thinning of the stand. These symptoms are related to the injury nematodes inflict upon the root system. Therefore, symptoms of injury may not become noticeable until water becomes limiting. Due to the similarities between environmental stress symptoms and nematode injury, the source of the problem is difficult to diagnose. Like many so-called weak or secondary fungal pathogens, nematodes may not cause much of a problem until environmental extremes reduce the vigor of a turf. There is often no pattern to nematode injury, but generally affected areas may appear in streaks or oval-shaped areas. Severe infestations may result in a nearly total loss of grass plants, which are soon replaced by weed species. Inspection of roots may or may not reveal some indication of nematode feeding. Roots may exhibit one or more of the following symptoms: swellings, red or brown lesions, excessive root branching, necrotic root tips and root rot. Some of the more common plant parasitic nematodes, which are known to injure turfgrasses, are listed in Table 3.

Turfgrass areas damaged by nematodes do not respond readily to an application of fertilizer or fungicides. This lack of response may be a good indicator of a nematode problem. In this situation a soil sample should be sent to a nematologist for analysis. Soil should be collected from a dozen or more areas at the edge or interface between healthy and injured turf. Sampling from severely thinned areas may yield unreliable results, because these obligate parasites will not survive in large populations in the absence of living plants. Soil samples should also be collected in the root zone region, normally the upper three to six inches in heavy soils, but six to twelve inches or deeper in sandy soils. The samples should be combined, as in a routine soil-fertility sample, and at least a pint of soil is needed. Samples should also be taken from nearby, healthy turf so that the nematologist can compare numbers and species of nematodes between the two areas. The soil must be kept moist and given to the nematologist as soon as possible. Refrigerate the sample, but do not freeze it, if there will be a delay in transport to the lab. In the laboratory, various methods for extraction are used. Unfortunately, there are no reliable data correlating nematode number per sample and expected degree of turf injury in the field. The nematologist, however, will generally be able to make a relatively good management recommendation based on species and number of nematodes present in a sample.

An absolute determination of a nematode problem from visual symptoms and even soil analysis is difficult. Frequently, the best indication of a nematode problem is a positive response from a nematicide. It should be pointed out, however, that turf green-up invariably occurs following a nematicide application, presumably because of the death of nematodes as well as other invertebrates which liberate nitrogen upon decay. Nematicides are highly toxic, organophosphate derivatives. They must be handled with extreme caution and used only according to the procedure and at the rates given on the label. Because the target of a nematicide is in soil, it is essential the chemical be thoroughly watered-in, and aerification prior to application will facilitate the downward movement of the chemical. Ethoprop is the only nematicide registered for use on home lawns, but it must be applied by a certified pesticide applicator. Other nematicides include fenamiphos and fensulfothion. All three are available in granular form. Fumigants are of little practical value because they kill turf as well as all other living organisms they come into contact with. Obviously, fumigants would only be used prior to establishing a turf or if total renovation is desired.

Because nematodes may only be injurious in northern regions during summer stress periods, cultural practices that alleviate stress may help minimize injury. Such practices would include judicious irrigation, increasing the mowing height, and use of a balanced fertilizer. Application of soluble nitrogen fertilizer during environmental stress periods of summer will place an additional (and perhaps lethal) stress on an already dysfunctioning root system under attack from nematodes. There are some research data indicating that use of organic forms of nitrogen fertilizer (e.g. sewage sludges) can discourage development of high populations of some parasitic nematodes, when compared to the use of inorganic forms. Currently, researchers are evaluating a dried, granular chitin-protein material called Clandosan, which is obtained from crab and shrimp shells, for control of nematodes. The mode of action of Clandosan presumably is to stimulate growth of soil microorganisms that produce enzymes such as chitinase. These enzymes also degrade the cuticles and eggs of plant parasitic nematodes, thereby providing an indirect, biological means of nematode control. To date, however, there is insufficient data and information regarding the effectiveness of Clandosan in turf.

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TABLE 1

The most frequently encountered diseases of lawns, golf courses, athletic fields, and other turf areas in transition zone and northern regions of the U.S.

Disease	Primary Hosts	Pathogen
I. PATCH DISEASES CAUSED BY ROOT INVADING PATHOGENS		
Summer Patch	ABG, FLF, KBG	Magnaporthe poae
Necrotic Ring Spot	KBG, ABG, FLF	Leptosphaeria korrae
Take-All Patch	CBG	Gaeumannomyces graminis var. avenae
Spring Dead Spot	Bermudagrass	Leptosphaeria korrae
II. FOLIAR DISEASES		
Dollar Spot	All species except TF	Sclerotinia homoeocarpa
Red Thread	Most species	Laetisaria fuciformis
Pink Patch	CBG, PRG	Limonomyces roseipellis
Brown Patch	PRG, TF, CBG	Rhizoctonia solani
Leaf Spot (Helminthosporium)	All species	Drechslera or Bipolaris spp.
Gray Snow Mold	All species	Typhula incarnata and T. ishikarensis
Cool Temperature Brown Patch (Yellow Patch)	ABG, CBG, PRG	Rhizoctonia cerealis
Gray Leaf Spot	St. Augustine	Pyricularia grisea
White Blight	TF	Melanotus phillipsii
III. FOLIAR/STEM OR ROOT DISEASES		
Pythium Blight	ABG, CBG, PRG	Pythium aphanidermatum, P. ultimum
Pink Snow Mold	All species	Microdochium nivalis
Anthracnose	ABG, CBG	Colletotrichum graminicola

Disease	Primary Hosts	Pathogen
III. FOLIAR/STEM OR ROOT DISEASES-(Continued)		
Pythium Induced Root Dysfunction	ABG, CBG	Pythium spp.
Nematodes	Most species	Many species
Melting-out	KBG, FLF, PRG	Drechslera or Bipolaris spp.
Fusarium Blight	KBG, FLF	Fusarium culmorum and F. poae
IV. DISEASES CAUSED BY OBLIGATE PARASITES		
Stripe Smut	KBG	Ustilago striiformis
Flag Smut	KBG	Urocystis agropyri
Powdery Mildew	KBG in shade	Erysiphe graminis
Rust	PBG, KBG, Zoysia	Puccinia spp.
Yellow Tuft	All species	Sclerophthora macrospora
V. DISEASES CAUSING HYDROPHOBIC THATCH OR SOIL, OR THATCH SHRINKAGE		
Fairy Ring	All species	Many Basidiomycetes
Yellow Ring	KBG	Trechispora alnicola
Superficial Fairy Ring	Putting greens	Basidiomycetes
Localized Dry Spot	Putting greens	Unknown Basidiomycetes
VI. SEEDLING DISEASES		
Damping-Off	All species	Pythium spp. Fusarium spp. Rhizoctonia solani Bipolaris spp. Drechslera spp. Curvularia spp. Others

Hosts: ABG = annual bluegrass
KBG = Kentucky bluegrass
CBG = creeping bentgrass
PGR = perennial ryegrass
FLF = fine leaf fescue
TF = tall fescue

TABLE 2

Common diseases of transition zone and northern lawn grasses, the primary season of occurrence, and the primary grasses most likely to be damaged.

Disease	Primary Season of Occurrence	Primary Lawn Grasses Damaged
Helminthosporium Leaf Spot, Melting-out and Net-blotch	Spring and Fall Summer	Common-type Kentucky bluegrass, Fine leaf fescues, Perennial ryegrass
Red Thread	Spring and Fall	Perennial ryegrass, Fine leaf fescues, Kentucky bluegrass
Necrotic Ring Spot	Early Spring to Early Winter	Kentucky bluegrass
Dollar Spot	Early Spring to Early Winter	Perennial ryegrass, Kentucky bluegrass, Fine leaf fescues
Brown Patch	June, July, August	Perennial ryegrass, Tall fescue
Summer Patch and Fusarium Blight	June, July, August	Kentucky bluegrass, Fine leaf fescues
Pythium Blight	June, July, August	Perennial ryegrass
Stripe Smut	Spring and Fall	Kentucky bluegrass
Rust	Spring and Fall	Perennial ryegrass, Kentucky bluegrass, Zoysiagrass
Powdery Mildew	Spring and Fall	Kentucky bluegrass, Fine leaf fescues
Fairy Rings	Spring to Early Winter	All species

TABLE 3

Common plant pathogenic nematodes known to be injurious to turfgrasses.

Nematode Common name/ genus	Feeding group	Turfgrasses injured/root symptoms
Lesion (Pratylenchus spp.)	Endoparasitic	Cool and warm season grasses are injured. Root lesions initially minute and brown, but enlarge and may prune the root system.
Lance (Hoplolaimus spp.)	Endoparasitic	Warm season grasses and annual bluegrass are injured. Causes swelling of roots followed by necrosis and sloughing of cortical tissues.
Ring (Macroposthonia spp.)	Ectoparasitic	Especially important in centepedegrass, also injured are Kentucky bluegrass, bentgrass, bermudagrass, and zoysiagrass. Roots are stunted; produces brown lesions on roots.
Spiral (Helicotylenchus spp.)	Ectoparasitic	Cool and warm season grasses injured. Roots are poorly developed with premature sloughing of cortical tissues.
Stunt or stylet (Tylenchorhynchus spp.)	Ectoparasitic	Warm and cool season grasses injured. Roots shortened, shriveled, brown; no lesions evident on roots.
Root-knot (Meloidogne spp.)	Endoparasitic	Warm season (especially zoysiagrass) and cool season grasses (especially bentgrass) injured. Galls (i.e. swellings or knots) on roots. Galls may be small and difficult to see.
Stubby root (Trichodorus spp.)	Ectoparasitic	Warm season grasses, Kentucky bluegrass and tall fescue injured. Large brown lesions on roots; swelling of root tips.
Sting (Belonalaimus spp.)	Ectoparasitic	Bermudagrass, zoysiagrass and St. Augustinegrass are injured. Lesions evident, especially root tips.
Dagger (Xiphinema spp.)	Ectoparasitic	Warm season grasses (especially zoysiagrass) and perennial ryegrass are injured. Root lesions are reddish brown to black and sunken.
Pin (Paratylenchus spp.)	Ectoparasitic	Kentucky bluegrass, fine and tall fescues are injured. Tillering and rooting increased, but fewer lateral roots. Distinct lesions on roots.

TABLE 4

Trade Name*	Common Chemical Name	Nematicidal Rate (Formulated)	Comments
Mocap	ethoprop	2.3 lb. of 10B/ 1000 ft^2 or 100 16/A.	Only the 10G formulation is registered for use on bahia, bermuda, centipede, fescue, Kentucky bluegrass, St. Augustine and zoysia grass turfs, labelled for control of dagger, lance, lesion, ring, root-knot, spiral sting, stubby root, stunt, and other nematodes. May be used at lower rates to control some insects. Use on established turfs only. Can be used on home lawns by a certified applicator.
Nemacur	fenamiphos	2.3 - 4.6 lb of 10B/1000 ft^2 or	Only the 10G formulation is registered for use on bermuda, 100-200 lb 16/A. centipede, bluegrass and bentgrass turf. Do not use on residential lawns or public recreation areas other than golf courses. Do not use on newly seeded areas and do not apply more than twice per year. Turf should not be cut for sod for 21 days after treatment.
Dasanit	fensulfothion	1.5 - 3.0 lb of 15G/1000 ft^2 or 68-134 lb/A	Only the 15G formulation is registered for use on commercial (i.e., sod farms, golf courses, cemeteries) turf grasses. Turf should not be cut for sod for 30 days after treatment. May be used for control of white grubs.

* Nematicides may only be applied by commercial or professional certified pesticide applicators.

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BIOLOGICAL SUPPRESSION OF WHITE GRUBS IN TURF

Michael G. Klein
Horticultural Insects Research Laboratory
Application Technology Research Unit
USDA - Agricultural Research Service
Ohio Agricultural Research and Development Center
Wooster, Ohio 44691

The term white grubs, as used here, refers to larvae of beetles in the family Scarabaeidae. Tashiro (1987) notes that there are 10 species of grubs in five subfamilies that are pests of turfgrass in the United States. Scarab grubs are the most serious pests of turfgrass in the Northeast, major pests throughout the Midwest (Tashiro 1987), and of increasing importance in warm season turf (Cobb 1988). Both introduced and native Scarabs are turfgrass pests. Grubs in two native genera, Cyclocephala and Phyllophaga, cause problems in almost all areas of the country. Introduced species are most prevalent in the Northeast, where the Japanese beetle, Popillia japonica Newman, the European chafer, Rhizotrogus majalis (Razoumowsky), the oriental beetle, Anomala orientalis Waterhouse, and the Asiatic garden beetle, Maladera castanea (Arrow), in that order, all are pests in the urban environment (Tashiro 1987).

The Japanese beetle is the most serious turf pest in the United States (Tashiro 1987). Fleming (1972) reported that 22 states east of the Mississippi River, and Iowa and Missouri to the west, had Japanese beetle infestations in 1972. Since that time, beetles have moved into Alabama, and within one county of the Florida border (Hall 1987). In addition, isolated infestations of beetles have been found in Wisconsin, Oregon, and twice in California (both eradicated). Ahmad et al. (1983) estimated the losses caused by Japanese larvae to be 240 million dollars per year. This included $78 million for control costs and an additional $156 million for replacement of damaged turf. Unlike most of the white grub complex, the adults of the Japanese beetle are also serious pests. Fleming (1972) lists almost 300 plants fed on by the beetles. New additions to this list will be made as beetles move into new areas and as their feeding behavior is further studied. It is estimated that damage and control costs are at least as great for the adults as that reported for larvae.

Fleming (1976) summarized the components available for control of the Japanese beetle in 1976. This included a variety of both chemical and biological agents. However there has been little effort at a truly integrated program of suppression against the Japanese beetle or other white grub species. Recently, states such as Massachusetts (Vittum 1987) and Maryland (Hellman 1988) have developed turf and ornamental IPM efforts. Vittum (1988) states that "several standard insecticides give acceptable levels of control for most grub species". However, concerns about grub control and environmental safety persist. Villani et al. (1988) note that the organophosphate and carbamate insecticides now in use are less effective than materials previously available. Factors as diverse as insect resistance, microbial degradation of insecticides, the importance of pH and moisture, and the role of the thatch or organic matter in preventing movement of the insecticides to the target organisms have been reported by several authors as explanations for the reduction in insecticide effectiveness (Villani et al. 1988, Niemczyk and Chapman 1987, Niemczyk 1980). In addition, there

is an increasing concern about the fate of insecticides in the environment and the potential of pesticide runoff causing water contamination (November 1988, Watschke et al. 1988). All of the above factors make the use of biological agents in the suppression of turf insects more attractive. I will examine the biologicals that are available and access their place in suppression programs.

MICROORGANISMS

Several recent reviews and books examine the role of microorganisms in pest management (Burges 1981, Samson et al. 1986, Fuxa 1987, Fuxa and Tanada 1987). Fleming (1968) reviewed the history and status of biological control of the Japanese beetle up to 1968. In addition, Klein (1982, 1988) reported on the state of biological suppression of turf insects in 1982, and pest management of all soil-inhabiting insects with microorganisms in 1988. These sources will give the reader additional details on those subjects. Bacteria are the most important microorganisms available for biological suppression of white grubs. Protozoa and fungi are important natural microorganisms in regulating grub populations, but neither is commercially available at the present time (Klein 1988a).

Milky Disease Bacteria

The value of Bacillus popilliae Dutky and its role in the regulation of white grubs has been examined in several recent book chapters (Klein 1988[a], 1981[a]). This bacterium, B. popilliae, has been used in the suppression of the Japanese beetle for over 50 years (Fleming 1968), and was the first microbial insecticide registered in the United States. When the bacteria develop in the hemolymph of Japanese beetle larvae, they produce billions of refractile spores and parasporal bodies thus turning the infected grub a milky white and giving rise to the common name of the disease (Fleming 1968). Between 1939 and 1951, Federal and State agencies produced and distributed about 90 tons of spore powder at 132,299 sites in 15 different eastern states (Fleming 1968). At the present time, there are three commercial brands of milky disease products available. Doom(R) and Japidemic(R) are manufactured as a powder containing 100 million spores/g by Fairfax Biological Laboratories, Clinton Corners, NY. Reuter Laboratories, Manassas Park, VA produces a powder and granular formulation under the brand name Grub AttackTM. For many years, milky disease products were made by collecting Japanese beetle larvae from the field, injecting them with B. popilliae, and harvesting spores from infected larvae (Fleming 1968). However, more recently, Fairfax has been collecting naturally infected Japanese beetle larvae in the field (Chittick 1987), and Reuter Laboratories intends to produce the bacteria in artificial media (Obenchain 1988).

An application rate of 10 lb/acre is recommended by both manufacturers. This is normally accomplished by placing about 2 g of spore powder in spots in a grid on four foot intervals. When large areas of turf are to be treated, a reduced rate of 2 lb/acre (10 foot intervals) has been registered. Community wide treatment programs have been the most successful in reducing larval damage and adult populations (Fleming 1968, Fleming and Ladd 1979, Ladd and Klein 1982). However, since the milky disease bacteria spread naturally in the field (Fleming 1968), it can be beneficial to treat only a portion of the beetle infested area. Application of spore powder to portions of two fairways of a Northeastern Ohio golf course resulted in the finding of milky larvae throughout the course after two years (Klein 1978). Several years can elapse between application of milky disease bacteria, and suppression of Japanese beetle populations (Fleming and Ladd 1979, Ladd

and Klein 1982). The disease builds up and spreads as larvae ingest spores, become infected, die, and release 1-2 billion spores back into the soil (Fleming 1968). Although one might expect that the use of the granular material distributed over the whole area would speed up the larval suppression, that may not be the case. Even though the broadcast treatment uses twice as many spores per acre (Klein 1982) as the spot treatment, the spores may be spread so thinly that the larvae do not become infected more quickly.

Soil temperatures may have a greater impact on larval suppression by milky disease bacteria than does the application method (Klein 1988[a], 1981[a]). Although temperatures of at least 16° C. are necessary for development of the disease, temperatures of 21° C. are required for optimal development (Fleming 1968, Fleming and Ladd 1979). Concerns about low soil temperatures have caused State personnel in several New England states question the value of milky disease bacteria in their areas. It should be noted however, that Fairfax Biological Laboratory obtains its naturally infected milky grubs in these same areas (Chittick 1987) so the disease is working to some degree. Daar (1988) has recommended quadrupling the dosage in areas above latitude 40° to speed up development of the disease. More information is needed about the role of milky disease in the northern ranges of the Japanese beetle. It is also possible that if B. popilliae can be grown on artificial media that strains could be isolated that will be effective at lower temperatures. There is also a concern about the persistence of B. popilliae spores in the environment (Klein 1988a). Although spores are clearly present in soil that was last treated 25-30 years previously, it is not clear if that is due to persistence or periodic replenishment as subsequent larvae become infected and die.

Production of B. popilliae on artificial media may also help to expand the host range of commercial products to other white grubs. Although Grub Attack is listed as being effective on certain May and June beetles, oriental beetle, and rose chafer in addition to Japanese beetle, numerous studies indicate that each species is most susceptible to its own strain of B. popilliae (Fleming 1968, Klein 1981[a], 1982, 1986, 1988). Masked chafers (Cyclocephala spp.) are serious turf pests nation wide, but are not infected by the commercial milky disease formulations (Klein 1981[a], Warren and Potter 1983). B. popilliae infections are credited with holding Cyclocephala parallela Casey to sub-economic levels in Florida sugarcane fields (Boucias et al. 1986). Since Cyclocephala strains of B. popilliae have grown on artificial media (Obenchain 1989), it may be possible to produce a product for masked chafers. However, the costs in registering such a product may not be supported by the potential market. In addition, although it is common to find high incidences of natural milky disease in Cyclocephala larvae in turf areas, the true value of the disease in population suppression has not been assessed. I have seen repeated turf damage in an area following 50+% milky larvae the previous fall. The black turfgrass ataenius, Ataenius spretulus (Haldeman) is another potential target for a milky disease product produced on artificial media. These larvae have several strains of milky disease bacteria that build-up too late in the season to have the full impact on the population (Tashiro 1987, Klein 1981[a]). Introduction of the spores into the population earlier in the season may improve the situation.

Concerns about the attenuation of B. popilliae spores in Connecticut are still being expressed (Hanula and Andreadis 1988). Although Tashiro (in 23) found in the laboratory that about 75% of larvae became infected when placed in soil from Connecticut, Hanula and Andreadis (1988) noted an incidence of only 3.5% milky larvae during extensive field surveys.

Other Bacteria

Bacillus thuringiensis Berliner is the most widely used microorganism in commercial production (Klein 1988a). Although it makes up at least 90% of the bioinsecticides on the market, it still makes up less than 1% of the $13 billion pesticide market. B. thuringiensis products have been used primarily against lepidopteran pests of forests and ornamentals. Strains of B. thuringiensiswith activity against Coleoptera have been isolated (Klein 1988a) giving rise to suggestions of using them against the Japanese beetle (Bio Integral Resource Center 1987). However, recent tests have shown that the coleopteran strains have no activity against either Japanese beetle larvae or adults (Klein 1988b). It may be possible to isolate or create strains with activity against the Japanese beetle or other Scarab adults. However, because of the short persistence of B. thuringiensis activity in a soil environment ((West et al. 1984) it is unlikely that it will be an important microorganism against the white grubs in the near future.

Bacteria in the genus Serratia have been associated with a disease of the grass grub, Costelytra zealandica (White) in New Zealand (Jackson et al. 1986). The bacteria cause the grubs to turn an amber or honey color by colonizing the gut, resulting in the starvation of the larvae and depletion of the fat bodies. Commercial production of the bacteria is moving forward in New Zealand (Jackson 1988). Similar honey colored Japanese beetle larvae have been observed in the United States, and Serratia species have been isolated from them (Jackson 1988). The potential exists to develop certain Serratia species for control of white grubs in the future.

Other Microorganisms

In addition to the bacteria, fungi and protozoa influence white grub populations. There are no commercial fungal preparations available for use against Scarab beetles or larvae. Species of Beauveria and Metarhizium are associated with insect mortality world wide (Klein 1988a), and have been isolated from dead white grubs in this country (Tashiro 1987, Fleming 1968, Hanula and Andreadis 1988). Work in Europe with the cockchafer, Melolantha melolantha (L.), has shown that a Beauveria species is effective when applied to the soil or to swarming females (Keller 1986). We have a great deal to learn about the potential of fungi to aid in the suppression of white grub populations.

Several genera of protozoa, in particular Nosema and Adelina, have been isolated from Scarab larvae (Fleming 1968, Hanula and Andreadis 1988). Very little is known about the true effects of these protozoa on white grub populations, and they are often overlooked. Recently a new protozoan has been described from the Japanese beetle in Connecticut (Hanula and Andreadis 1988, Andreadis and Hanula 1987). Ovavesicula popilliae Andreadis and Hanula was found infecting up to 90% of Japanese beetle larvae locations (Hanula and Andreadis 1988). This microorganism has the potential to be more fully utilized in the suppression of the Japanese beetle in the Eastern United States.

ATTRACTANTS

The vast majority of work on attractants for Scarab species has been done with the Japanese beetle. Fleming (1969) has summarized the work on Japanese beetle attractants from shortly after the discovery of the beetle in New Jersey in 1916 up to 1969. Although chemical attractants have

been noted for several other Scarab beetles, none have been developed commercially. Black lights are available to attract several night flying beetles.

Japanese Beetle Attractants

At the present time, seven companies are producing Japanese beetle traps and lures. The best lure is a combination of the synthetic female sex attractant, Japonilure, (Tumlinson et al. 1977) and three sweet smelling floral or food type lures: phenethyl propionate, eugenol, and geraniol in a 3:7:3 combination (Ladd et al. 1981). Even though the sex attractant captures only male beetles when used alone, when exposed in the presence of the floral lures it causes increased captures of both male and female beetles (Ladd et al. 1981, Klein et al. 1981).

Although large numbers of beetles can be captured by Japanese beetle traps, the best uses for the traps is still being studied. Klein (1981[b]) reported on several studies where traps were used to reduce infestations of beetles. However, most workers agree that traps cannot be depended upon to protect specific plants from beetle feeding (Fleming 1976, Ladd and Klein 1982, Fleming 1969). Recent studies involving heavy populations of beetles in Kentucky showed that there was an increased damage to plants in the vicinity of Japanese beetle traps (Gordon and Potter 1985, 1986). The use of traps did not increase the population of larvae in near by turf. It has been suggested that an antifeedant material such as neem may be applied to foliage to protect it when traps are used in an area. A commercial product, Margosan-O (W. R. Grace, Co., Fogelsville, PA), has recently been made available for testing. It is still to early to establish the value of such a product. Since the material is an antifeedant for the Japanese beetle, and not a repellent, it would appear that there is little future in spraying it on turf to discourage adult egg laying as had been suggested (Bio Integral Resource Center 1987).

Other Attractants

Sex attractants have been demonstrated for the northern and southern masked chafers, Cyclocephala borealis Arrow, and C. immaculata (Oliver) (Potter 1989). More recently, both a sex attractant and an aggregation pheromone have been found in the green June beetle, Cotinus nitida (L.) in Arkansas (Domek and Johnson 1987, 1988). In addition, a chemical attractant, butyl sorbate was shown to be an attractant for males and females of the European chafer(Tashiro 1987). Commercial development of these will await the identification of the pheromones involved and a demonstration of the value of the attractants.

CONCLUSIONS

Bacillus popilliae is the most important commercially available microorganism available for suppression of white grub species. Its value should increase in the next few years if the promise of production on artificial media is realized. We need more information about the value of other microorganisms such as the fungi and protozoa so that they can be integrated into suppression programs. Attractants for the Japanese beetle will continue to be available to consumers who wish to use them. More information is needed on the value of all attractants for scarab beetles so their full potential can be reached.

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FOOTNOTES

Mention of a proprietary product does not constitute endorsement by the USDA. In cooperation with the Ohio Agricultural Research and Development Center, Ohio State University, Wooster and approved for publication as Journal Article No. 268-88.

ANNUAL BLUEGRASS TO BENTGRASS CONVERSION WITH TURF GROWTH RETARDANTS (TGRs)

Dr. Milton E. Kageyama
and
Dr. Larry R. Widell

O. M. Scott and Sons Co.
Research Division
Marysville, OH 43041

INTRODUCTION

Another chapter has begun in the never-ending struggle between man and that baneful, pernicious weed we collectively call annual bluegrass (Poa annua). Within the past several years, an increasing number of golf course superintendents have chosen turf growth retardants (TGRs) as an option to their existing, rather unsuccessful, control methods for reducing the spread of this undesirable grass. This new dimension to Poa annua control is especially appealing to those who desire a gradual transition to the more desirable grasses, such as bentgrass, without temporarily taking greens and fairways out of play. However, we have observed that some turfgrass managers are more adept than others at making turf growth retardants work for them. It cannot be overemphasized that product knowledge and careful execution of the TGR program for Poa control are the keys to greater success in the use of these products.

WHAT ARE TURF GROWTH RETARDANTS?

Turf growth retardants are a diverse group of plant growth regulators that act by blocking gibberellic acid (GA) biosynthesis, a plant hormone influencing cell elongation, among other functions. Retardant activity on turfgrasses results in shortened stem internodes and reduced leaf and rhizome elongation. Diversion of photosynthate and altered hormone levels may be responsible for increased tillering and subsequent greater turf density observed with TGR applications. These effects are overcome by application of GA.

Examples of turf growth retardants currently being used on golf courses either commercially or on an experimental basis include paclobutrazol (Fertilizer + TGR Poa annua control from O. M. Scott & Sons Company) or flurprimidol (Cutless from Elanco Products). Both are gibberellin antagonists but are not similar in chemical structure. Paclobutrazol is a triazole, a compound containing a five-membered ring structure with three nitrogen atoms. Flurprimidol belongs to a class of compounds possessing a six-membered ring containing two nitrogen atoms, the pyrimidines. Despite their chemical dissimilarities, both compounds work in the same manner, selectively controlling the growth of Poa annua and thereby resulting in a shift in competitive ability to favor the more desirable, perennial grasses.

HOW DO TGR's WORK?

The most important concept for the golf course superintendent to keep in mind when using growth retardants for Poa annua control is that these compounds are mobile only in the xylem (movement upward only) and therefore require root uptake to reach basal growing points. In addition, differential species sensitivity is primarily attributed to greater uptake of the retardants by the shallower-rooted annual bluegrass plants. Turfgrass managers can enhance TGR response on Poa and maximize tolerance on desirable grasses by remembering this mode of action and employing management techniques prior to application that are effective in spatially separating actively-absorbing root zones of Poa annua from other grass roots.

Within one to two weeks following application of TGRs, growth control and discoloration of annual bluegrass will become evident. During the period of growth regulation, the Poa annua plants will remain alive but be very stunted in growth. Bentgrass will continue to grow but in a more prostrate condition and may possibly appear "stringy" during this period of Poa growth regulation. Poa seedhead suppression is attained by a reduction in the stalk, greatly reducing seedhead visibility. The tremendous proliferation of spring seedheads causing poor playing surface conditions can be avoided by making TGR applications in the spring just prior to the time seedheads begin emerging on south-facing slopes or in warm soil areas. Applications at this time will greatly improve playing conditions on fairways and greens for up to six weeks. Some seedheads will become visible in late May/early June, but these will also be somewhat stunted and should not seriously impair playability. Fall applications can also effectively reduce Poa seedhead visibility the following spring but for a shorter duration (three to five weeks). Poa regreening should occur just prior to regrowth about five to ten weeks after application . Inspection of the fairways and greens at this time should reveal greatly improved coverage of bentgrass at the expense of annual bluegrass.

TURF RESPONSES TO TGR APPLICATION

- Severe reduction in growth of Poa annua 7 to 14 days after application, lasting from 4 to 10 weeks
- Shoot tissue discoloration (yellow-green to brown) of Poa annua for 3 to 8 weeks
- Aggressive growth of bentgrass for 4 to 8 weeks after an initial 14 to 20 day period of reduced (50%) growth
- Spring seedhead stalk stunting for 5 to 6 weeks with spring or previous fall applications
- Regreening/regrowth of Poa annua 5 to 10 weeks after application
- Enhanced greening of bentgrass for 6 to 8 weeks
- Reduction in Poa annua coverage after application by 10 to 50%
- No reduction in bentgrass root growth
- No thinning of Poa annua under non-stress conditions

PERFORMANCE VARIABILITY

It is not unusual for pesticides to perform variably. This is especially true for growth regulators where the desired rate may be a fine line between too much and too little activity. Delivery of effective doses of TGRs into the Poa annua plant can be achieved by considering the physico-chemical characteristics of TGRs. For instance, paclobutrazol displays rather low water solubility (30 ppm) and readily adsorbs to organic matter and thatch. Therefore, its movement through the soil profile is very limited except in sandy soils containing little organic matter. The insightful turf manager can usually predict the nature of the growth regulation response of TGRs on Poa annua vs. bentgrass by reflecting on the seasonal root growth dynamics of the two turf types and the soil type (texture). The greatest differential response can be achieved with early summer applications on heavy soils when uptake of nutrients and water occurs lower in the soil profile than paclobutrazol can move. However, this response may not be desirable since it may result in aesthetically unpleasing color on Poa annua for too long a time, especially on greens. The target regulation differential that is most accepted by turfgrass managers occurs with mid-spring and late summer applications when a moderate amount of activity is achieved on Poa annua. Less differential growth regulation will be seen with fall applications when Poa annua roots begin to move deeper into the soil profile and cooler, more moist weather conditions favor the growth of Poa.

Watering-in is essential for these systemic TGRs to work, whether they are formulated as a granule or liquid. It is even more important to remove liquid TGRs from foliar surfaces to minimize foliar uptake, volatilization, and photodecomposition. Recommendations state the need for 1/4" of water within 48 hours to optimize activity, except in heavily-thatched areas where greater amounts are needed. Aerating prior to application has proven to be very beneficial in these areas. Lack of adequate rainfall or irrigation after application can greatly delay and/or reduce activity, especially on heavy soils.

The degree of growth regulation can also be influenced by turf biotype. Conversion to predominantly bentgrass greens where the initial amount of Poa annua is high has been unsuccessful with the more upright colonial bentgrasses. Apparently these bentgrasses are not aggressive enough to dominate while Poa annua is under regulation. Conversion on fairways also appears to be less successful where the more perennial Poa annua biotypes proliferate.

PROGRAM SCHEDULING

It must be understood that Poa annua control with TGRs is a gradual process, requiring sequential applications until the desired level of control is achieved. Applications must be made in a constant, routine manner twice a year. Omitting applications before this time can lead to slower long-term control. Once control has been achieved, routine annual treatments in late summer or early fall should keep the Poa in check. Repeat applications over a two to three year period may be required in some areas of high initial contamination. Programs using lower application rates with greater application frequency do not provide any greater long-term benefits on fairways. However, recent research on greens has shown promise when using lower rates every three to four weeks in eradicating Poa annua without as much discoloration.

Proper time of application has already been considered with respect to root growth dynamics. Timing must also be considered with respect to seeding, aerating and topdressing, and herbicide application. The superintendent's primary consideration in the fall should be the sequence of events

with respect to overseeding, a highly-recommended practice for high contamination areas. TGRs offer greater flexibility than most preemergence controls since applications are not phytotoxic to bentgrass seedlings. However, to avoid seedling growth regulation and slowed fill-in, wait at least six weeks after overseeding before application; or in treated areas, wait at least two weeks after application before overseeding.

AREAS OF USE

Retardants are effective in eradicating Poa annua on fairways, greens, and collars. Long-term control of Poa on tees is more difficult because of the excessive wear on perennial turfgrasses and the advantage annual bluegrass has reestablishing in divoted areas routinely irrigated. Overseeding and filling divots with a sand/seed mix has proven to be a sound management practice in conjunction with TGR use on especially those tees containing large amounts of Poa annua. The unevenness of turf height on collars and greens caused by TGR use can result in undesirable lies and bumpy putting conditions for a period of time. A light sand topdressing during the cooler periods of the season can certainly improve ball roll on greens. Applications of retardants to nearby perennial bluegrass collars should be avoided since the extent to discoloration in these highly visible areas may not be acceptable.

THE NEED FOR NITROGEN

Best encroachment and stoloniferous action of bentgrass on fairways and greens are accomplished when these areas are well-fertilized at the time of TGR application. Abiding by the long-standing rule of encouraging the bentgrass by starving the predominantly annual bluegrass turf through a very judicious fertilizer program does not necessarily apply when using TGRs.

Conversely, moderate-to-heavy fertilizations just before bentgrass starts growth in the spring will actually provide greater Poa annua suppression. Spring applications of TGR and nitrogen should be applied early enough to minimize the risk of lush growth when hot severe weather develops and Pythium invasion is likely. In areas of recurrent disease problems, fungicide applications should be used on a preventative basis and intervals tightened somewhat, since TGRs can increase the turf's susceptibility to Pythium and snow mold. In addition to shifting the uptake and assimilation of nitrogen to bentgrass, the use of TGRs with fertilizers also results in a very dramatic greening of bentgrass, lasting longer than conventional fertilizers alone. Poa annua will also benefit from this combination treatment after the growth retardation subsides, resulting in a greener, healthier Poa annua/bentgrass turf throughout the ensuing stress periods.

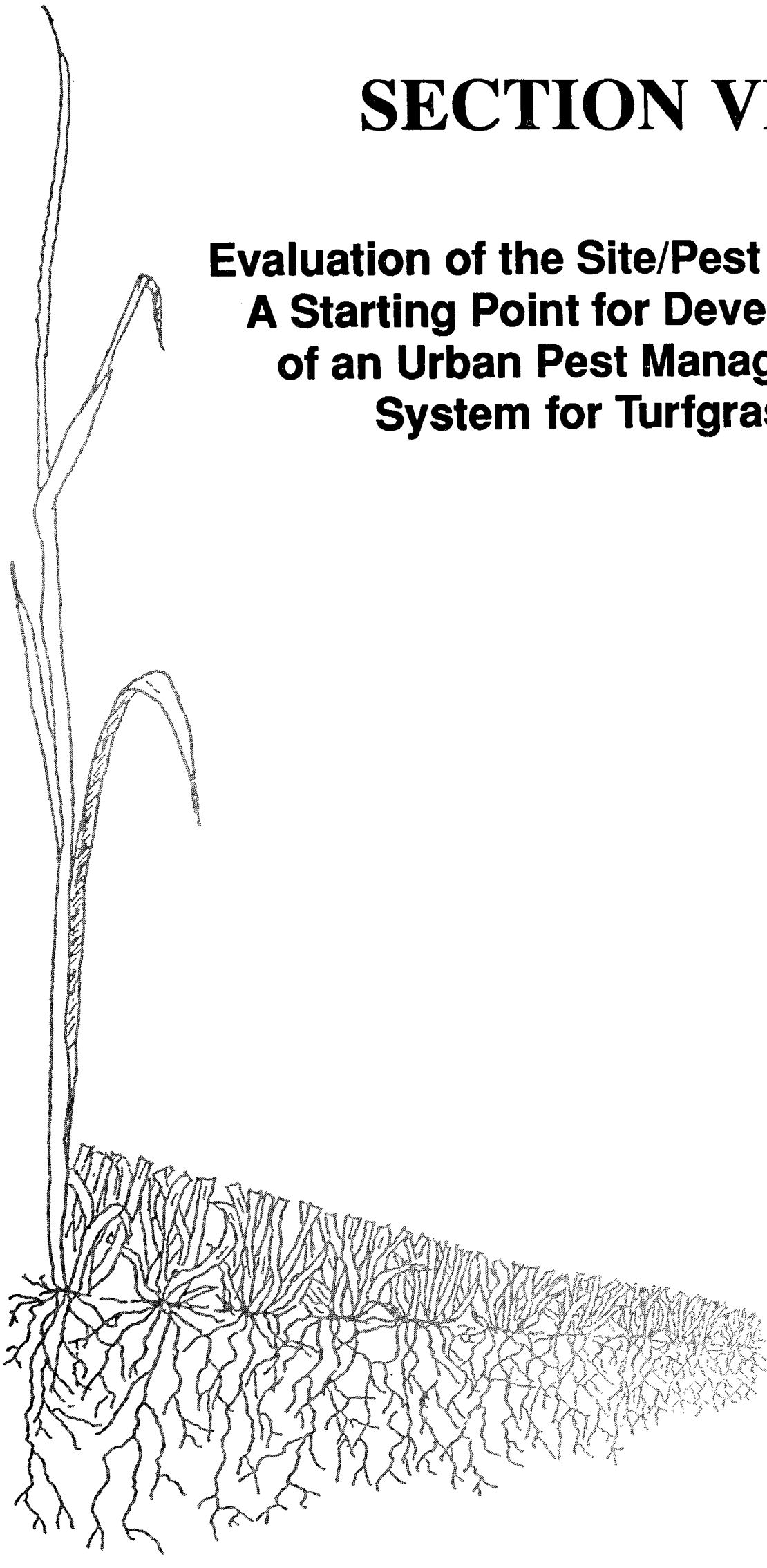
OTHER BENEFITS

Not only will TGRs provide more consistent, higher quality bentgrass fairways and greens but other benefits that the superintendent can enjoy include (1) significant labor savings in the spring and fall due to fewer required mowings on fairways and less clippings to dispose of on greens, (2) reduced water use due to the lower water requirements of bentgrass (a significant benefit in areas faced with impending watering restrictions), (3) reduced fertilizer use, and (4) faster, more true ball roll on greens containing primarily bentgrass.

CONCLUSION

The science of growing turfgrass has taken a significant leap forward with the introduction of growth retardant chemistry. Users of these sophisticated tools must be informed about their proper application and the way they fit into existing turf management programs. It is essential to inform the greens committee and membership of this course of action to explain the visual results. It is also a good idea in some situations to begin a program on a limited basis to understand how these chemicals are used and what to expect. The progress of this program can most easily be measured by leaving a small portion of one fairway untreated by covering the area with a cloth or piece of plywood.

The committed, informed superintendents are now making major strides in controlling the fate of their golf courses. Growing and maintaining high quality bentgrass fairways and greens is not an accident but the result of responsible blending of turfgrass art and science.



SECTION VII

Evaluation of the Site/Pest Complex: A Starting Point for Development of an Urban Pest Management System for Turfgrass

DEVELOPMENT OF AN IPM PROGRAM FOR TURFGRASS

Anne R. Leslie
U.S. Environmental Protection Agency
401 M Street SW
Washington, DC 20460

A number of promising biological controls and cultural practices for turfgrass have been presented in detail above. Although some of these are not yet available for general use, they are expected to form an important part of the management tools needed to deal with pest problems. However, the basic steps to design an IPM program for turfgrass can be presented so that turfgrass managers can make best use of all control methods and realize economy in management with no loss of turfgrass quality.

We start with our working definition: Integrated Pest Management is the coordinated use of pest and environmental information with available pest control methods to prevent unacceptable levels of pest damage by the most economical means, and with the least possible hazard to people, property and the environment. The goal of the IPM approach is to manage pests and the environment so as to balance costs, benefits, public health and environmental quality. IPM systems use all available technical information on the pest and its interaction with the environment. Because IPM programs apply a holistic approach to pest management decision-making, they take advantage of all appropriate pest management options, including but not limited to pesticides. Thus, IPM is:

- A system utilizing multiple methods
- A decision-making process
- A risk reduction system
- Information intensive
- Cost effective
- Site specific.

COMPONENTS IN A GENERIC PEST MANAGEMENT SYSTEM

A generic pest management system includes the eight distinct steps that are outlined here:

1. Define the roles of all the people involved in the pest management system (i.e., occupant, pest manager, decision-maker), assure understanding and establish communications between them.
2. Determine the management objectives for each of the specific areas of the site as a basis for deciding on possible control methods for the pest.
3. Set action thresholds--a point when pest populations or environmental conditions indicate that some action must be taken; no action is taken until that point is reached.

4. Monitor the site environment and pest population on a periodic, consistent basis to determine when the action threshold is reached and to determine whether the action taken is effective.
5. Take action that modifies the pest habitat to reduce carrying capacity of the site, exclude the pest, or otherwise make the site environment incompatible with the needs of the pest.
6. Take appropriate pesticidal action. A preferred pesticide would provide the longest dwell time in contact with the pest while presenting the least possible hazard to the people, property and the environment. It should be applied when the pest is in its most vulnerable stage.
7. Evaluate the results of the habitat modification and pesticidal treatment actions by periodically monitoring the site environment and pest populations.
8. Keep written records of site pest management objectives, monitoring methods and data collected, actions taken, and the results obtained by the pest management system methods.

All components of this system must be addressed and implemented in some form for the system to be most effective. Omission of portions of the system, in our experience, has led to greater unnecessary dependence on repeated pesticidal treatments.

Since IPM is site specific and information intensive, each site manager will need to develop a plan that meets the management goals established in Step One. Some thought should be given to identify all the people who fall into the categories of occupant, pest manager and decision-maker.

For instance, people who do not golf but who use the land neighboring a golf course must be considered occupants if management practices on the course can potentially impact their environment. Similarly, the golf course management, in setting management goals that include very short, smooth greens for fast play, should consider the needs of the people using a water supply that may be impacted by the pesticides required to attain the desired greens quality. That consideration might involve choosing between a costly groundwater monitoring program and a slightly altered mowing height that can result in a lower pest pressure. Other innovative solutions to problems may be achieved if all the "actors"are willing to communicate their real concerns and work productively toward their resolution.

An outstanding example of the progress that can be achieved is the cooperative effort in Massachusetts between the Massachusetts Golf Course Superintendents Association and the state regulatory agencies and universities. This effort has led to implementation of IPM programs at golf courses across the state.

With the above components in mind, we can define the strategies that would be important for turf areas with different management goals. A number of strategies will be listed for three kinds of sites. A good monitoring plan, with action thresholds and proper record keeping, will be used to evaluate the effectiveness of these strategies.

Site A: High Management Turf.

Example: Golf Course Greens and Tees

1. Establish pest-resistant varieties of grass suitable to the site, climate, and expected use.
2. Use bacterial or biochemical control, such as plant growth regulators, for poa annua on tees and greens.

3. Use biological controls, such as nematodes for control of white grubs, and endophytic grasses for surface feeding insects.
4. Raise mowing height and reduce watering frequency to reduce weed populations and expression of fungus disease; evaluate problem areas and the need for drainage control and/or irrigation system improvements; use slow release fertilizers along with soil amendments.
5. Use caning and syringing as methods of stress reduction to reduce threat of fungus damage in summer months.
6. Put fungicide use on a strict degree/moisture threshold schedule by use of computerized monitoring and diagnostic tests to determine disease potential; select least invasive effective fungicidal treatment; consider rotation or tank mixes of fungicides to reduce resistance buildup.
7. Monitor for changes in populations of flora and fauna, beneficial as well as destructive.
8. Educate the public and the course management on the strategies being used at the site.

Site B: Medium Management Turf.

Example: Home lawn or public lawn other than golf course

1. Evaluate the soil for pH, texture and type; use soil amendments and consider renovation rather than heavy use of pesticides to solve problems.
2. Overseed or plant a variety that suits the use pattern and site.
3. Set up action thresholds and monitoring methods for weeds and insects. Note that disease problems in home lawns are almost always due to over fertilization and over watering. Note also that there should be greater tolerance for pest populations and the use stress on the grass will probably be less than on site A.
4. Establish proper cultural practices; for example, water deeply when the wilt point is reached rather than on a calendar schedule, use slow release fertilizer, increase mowing height and frequency, leave clippings on the lawn and include periodic aeration by vertical mowing or dethatching.

Site C: Low Maintenance (or "No Pesticide") Turf.

Example: Some Park Sites, Homeowners Interested in Alternatives to Turf

1. Use mowing to control woody plants, and encourage growth of native species, rather than adhere to a monoculture of grass.
2. Use grass varieties suitable to the use pattern; have paving where heavy traffic is expected.
3. Convert some areas to meadow by planting wildflower cover, minimizing long term maintenance, especially in areas where it is difficult to maintain grass.
4. Use monitoring to help with decisions on aggressive plant control. Not much is known of the life cycle of many such plants, and if this is studied carefully, the manager will be better able to choose the least invasive method of control.
5. Use biological controls on pests wherever feasible.
6. Use good cultural practices as in Site B.

To continue to improve IPM programs, there should be continuing research on a number of questions, such as:

1. What are the effects of pesticides on beneficials in greens and tees?
2. Is there a pest population difference between greens, tees, fairways and roughs that is the result of pesticide use, and are pesticides perpetuating problems?
3. What natural predator biocontrols can be found to decrease high populations of pests on monoculture areas?
4. Does healthy turfgrass act as a barrier to surface water and groundwater pesticide contamination in golf course watersheds? What kinds of irrigation systems and soil amendments will minimize problems?
5. What are the real economic benefits of an IPM program for turfgrass?

EPA is planning projects at several of the sites discussed. A Memorandum of Agreement is being processed between EPA and the Military District of Washington to establish cooperation on a survey of IPM practices at military establishments in the D.C. area. This agreement addresses the presidential order of September 2, 1979, which requests all agencies to "support and adopt IPM strategies whenever practicable" and to "assess the potential for increased emphasis on integrated pest management." The military establishments offer managed turfgrass at all levels listed, including parade grounds, home lawns, parks and golf courses.

In addition, because golf courses involve high level management and are highly visible targets for environmental concern, EPA has proposed to develop an IPM demonstration project at several golf courses in the northeast. We believe that such projects will greatly contribute to the establishment of safe, sound pest management of the growing recreational land use demanded by the American public. Such land use should be compatible with the surrounding environment and the plans should address the reasonable concerns of the neighboring residents. By cooperative efforts landowners should be able to develop their holdings as they wish and still contribute something of value to the entire community.

Only continued, careful investigation and a commitment to meaningful use of IPM techniques in urban turfgrass management will enable managers to achieve reduction of dependence on chemical controls. It is hoped that expert systems will be developed that will assist the professional turfgrass manager. The final chapter addresses this technology and what such a system can and cannot do.

KNOWLEDGE BASED SYSTEMS FOR USE IN INTEGRATED PEST MANAGEMENT: REQUIREMENTS, PITFALLS, AND OPPORTUNITIES

Jan P. Nyrop
Department of Entomology
New York State Agricultural Experiment Station
Cornell University
Geneva, NY 14456

Bernie Huber
IPM Program
New York State Agricultural Experiment Station
Cornell University
Geneva, NY 14456

Walter Wolf
Department of Computer Science
Rochester Institute of Technology
Rochester, NY

Naive, prophylactic application of pesticides continues to be a frequently used pest control tactic. This approach to pest control results in needless expense by crop managers, unjustified exposure of the environment to chemical toxicants, and hastened resistance by pests to chemical pesticides. To counter the myriad costs of excessive chemical pesticide use, a more economic and ecologically rational pest control paradigm has been advocated; integrated pest management (IPM). Ideally, IPM entails a multi-faceted pest control effort through the use of cultural practices, the conservation and possible augmentation of biological control agents, and the judicious use of chemical pesticides. Even in its most simplified form of using monitoring and action thresholds to schedule pesticide applications, IPM can greatly reduce the use of chemical pesticides. In many cropping systems a library of IPM technologies has been developed through research. However the adoption and use of IPM has been frustratingly slow.

Wearing (1988) groups causes for this slow acceptance into five classes. First, requisite tools for IPM such as simple monitoring methods and selective control strategies may be lacking. Second, the actual and/or perceived costs of practicing IPM may not be conducive to its adoption. Third, deficiency in knowledge required by growers to use IPM methods may hinder adoption. Fourth, crop managers are generally satisfied with chemical control and often lack confidence in IPM methods. Finally, the lack of trained experts needed to educate and provide consultation to growers about IPM may limit its adoption. This paper will focus on a relatively new computer technology that offers a means of overcoming this last impediment to the adoption of IPM.

Use of IPM necessitates a considerable degree of expertise in applying and integrating many sources and types of information and often requires the simultaneous consideration of multiple crop protection goals. In addition crop managers often do not have the skill or background to effectively use many IPM tools. A recently proposed solution to the problem of insufficient availability of

expertise in IPM is the development of expert or knowledge based systems (Coulson and Saunders 1987, Naegle et al 1986, Stone et al 1986). Unfortunately, the term "expert system" has been badly misused and misunderstood. Thus we will employ the more generic name"knowledge-based systems" (KBS). In this paper we present our views on the requirements, pitfalls and opportunities associated with developing KBS's for use in pest management. These views have developed as a result of our work on a KBS for use in apple pest management (EASY-MACS; Expert Advisory SYstem for Managing Apple Cropping Systems) and through study of the literature dealing with KBS's. While EASY-MACS deals specifically with apple cropping systems, the discussion presented here is germane to all pest management systems including those in the urban environment. The paper is composed of three sections. First, we provide a brief overview of what knowledge based systems are and present some details about the EASY-MACS system in order to illustrate an actual system. Our intent here is to provide a setting for the remainder of the paper and not to provide a full explanation of how knowledge based systems work. There are a number of accessible reviews detailing the nature of KBS's (e.g. Waterman 1986, Davis 1986). In the second section, we discuss requirements for building a KBS for use in pest management and present pitfalls that we and others have encountered in developing knowledge based systems. An understanding of these requirements and pitfalls is important because they are frequently masked by the hyperbole that ensconces a new technology. Finally we discuss the opportunities for use of KBS's in IPM.

WHAT ARE KNOWLEDGE BASED SYSTEMS?

A knowledge based system is a computer program specially designed to represent human expertise in a particular domain of knowledge. It attempts to mimic a human being's ability to make complicated decisions and is designed to assist a user to make similar decisions. For this reason, knowledge based systems may also be called decision support systems. These systems act as intelligent assistants to human experts, and also assist people who might not otherwise have access to expertise. They have been developed and used extensively in medicine and industry, and are now finding application in agriculture.

The techniques used to develop KBS's are products of investigations that have delved into the possibility that computers could behave in a way that would be perceived as intelligent. This line of research, known as artificial intelligence (AI) had its roots in a conference that took place in 1956 at Dartmouth College. Early work in AI emphasized development of computer systems that could solve very general problems. Repeated failures at this endeavor led to the realization that much of the power in problem solving lies in possessing a great deal of specific knowledge about the problem and its likely solution. This led to research that examined how to represent such knowledge on a computer and how to manipulate it. The end products of this work are the tools for developing knowledge based systems.

The principal parts of an expert system are a knowledge base coupled with an inference engine, and a user interface. The knowledge base is a collection of facts, expert opinions, 'rules-of-thumb' or heuristic knowledge, and procedural knowledge including relationships amongst these facts, etc. The knowledge is that which an expert would employ to solve a particular problem. The inference engine drives the system during a consultation by a user. It controls what portion of the knowledge base should be used to solve a particular problem.

One of the most frequently used methods of representing knowledge is through a construct known as if - then rules. If the antecedent of such a rule (the if part) is true, then the consequent portion (the then part) is also true. An example of an if - then rule in pest management might be; if

the density of pest A is greater than Y and if the median development of pest A is at least Z then it is appropriate to treat for pest A. The inference engine controls the linking of the if - then rules in order to reach a conclusion. Other rules would likely have to be used to determine the density of pest A and if the median development exceeded Z. The inference engine would control the execution of these rules. One can also envision a group of rules being used to determine the best pesticide to use once it is established that a treatment should be made.

The user interface elicits needed information from the user, presents the results of a consultation (i.e. a diagnosis or recommendation) to the user, and offers explanations supporting those results. In addition to these major components, a KBS may also access databases and simulation models to obtain needed information.

One way to picture a KBS is by way of analogy to a system of logic (Denning 1986). A system of logic consists of axioms that are self-evident or universally recognized truths and rules of inference. New knowledge, usually in the form of proofs, are derived from this system by sequencing strings of axioms or prior proofs using the rules of inference. A KBS is analogous with some notable differences. A KBS may contain axioms but it also contains other statements of fact (e.g., expert opinion) that are used as axioms but clearly do not meet the definition of an axiom. In addition, the rules of inference used by a KBS will often not be universally agreed upon.

We will now provide a description of the EASY-MACS system in order to more specifically illustrate some of the points made above. EASY-MACS is designed to be a coach for implementing integrated management of arthropod pests of apples. It runs on an Apple Macintosh computer and is being developed using NEXPERT (Neuron Data, Palo Alto, CA). Like a human consultant, the system asks the client for detailed information about the current condition of his orchard block. It then makes a recommendation for action based upon that information, the history of that orchard block, and the system's own knowledge of pest dynamics. EASY-MACS may also warn the user of upcoming events and make tentative predictions about the future.

In the process of arriving at a recommendation, EASY-MACS takes into accountstate-of-the-world considerations, such as the physical makeup and the phenological stage of the apple trees, and the current pest infestation level. These external conditions are then combined with internal considerations, such as the interactions that occur when more than one pest is present, or that the presence of a biological control agent is important, or user preference requests an alternate recommendation.

The system is made up of three components: 1) A Rule Base and Inference Engine. The rule base encodes knowledge needed to make decisions about apple pest control. The inference engine links relevant portions of the knowledge base in order to obtain needed data from a user and to arrive at a recommended course of action. The following is a fairly complex example of the kind of considerations that compose a rule and allow the system to arrive at a recommendation. The first block of statements (the "IF"part) are conditions which may or may not be true. If all the conditions listed in a rule are true, then the hypothesis (the "THEN"part) is true and the actions (the last block of statements) associated with that rule are carried out. These actions may in turn affect the evaluation of further conditions composing other hypotheses.

IF the phenological stage of the block is Pink,
AND Spotted Tentiform Leafminer infestation is a problem,
AND Rosy Apple Aphid infestation is not a problem,
AND the block has a history of Oblique Banded Leafroller damage,
AND Recommend applying Lannate at Petal Fall to control Spotted Tentiform Leafminer and Oblique Banded Leafroller (TRUE),
AND you choose not to follow this recommendation,
AND the pesticide Dimilin is not currently available,
AND Recommend applying Vydate at Pink to control Spotted Tentiform Leafminer (TRUE),

THEN a recommendation for pest control has been made,

AND record that Vydate has been recommended at Pink to control Spotted Tentiform Leafminer,
AND record that Rosy Apple Aphid was not a problem at Pink,
AND inform the user that he should sample for Oblique Banded Leafroller at Bloom.

In this example the conditions end with a recommendation of Vydate because the best expert opinion does not have a good alternate recommendation to make. The dynamic features of the system, however, allow that the user may actually use a different treatment, and so, any rule which considers a spray material that has already been applied will explicitly ask the user what, if any, material he used.

An interesting feature of the system is that recommendations are treated as conditions which are always true. This allows that other conditions may follow before a given hypothesis is determined to be true. In the above example, an additional condition is that the user accept the recommendation. Here he rejects the recommendation, and an alternate recommendation is made after checking a further condition (the availability for use of Dimilin).

The example rule belongs to a set of similar rules; each rule in that set leads to the same hypothesis. In the course of a consultation, this particular hypothesis will always be proven true, and one and only one rule in its rule set will have all of its conditions be true. An individual knowledge-base may contain many such hypotheses, each with its own rule set. This kind of rule organization allows for maximum flexibility in dealing with pest interactions, user preferences, and conditions which may vary over time (such as the availability of a particular pesticide). This flexibility is most evident in that the rules that belong to a particular set do not have to be composed of a uniform set of conditions. For instance, if both Spotted Tentiform Leafminer and Rosy Apple Aphid were a problem in a particular orchard block, then a single pesticide recommendation would be made to control both of these pests, and a history of Oblique Banded Leafroller damage would not be a condition in that particular rule since it would not affect the recommendation.

A condition may itself represent a set of rules. In the example given, those conditions that deal with pest infestation levels are in turn dependent upon other condition sets, ones that are made up of block characteristics, past pesticide use, and results of samples taken to determine the density of the pest in question. Just how that information is gathered will be described in the next section.

It should be noted that this example is a logical rendering of the state of the system after its hypothesis has been proven. Actual implementation details are different in some small respects, and will not be discussed here since they would unnecessarily complicate the description and might

obscure our view of the logical situation. Procedural details (that is, the operation of the inference engine) are best summed up by saying that the system considers the conditions in the order in which they appear, and that alternate rules contain the alternate evaluations of those conditions which are necessary to arrive at a recommendation. The overall operation of the inference engine as it works its way through the whole system (a collection of hypotheses and associated rule sets) will not be described here.

2) A User Interface. The user of this system sees a series of pre-designed screens. These screens are displayed on the computer and consist of text and graphic images. The only data actually typed into the system is a block name that is used to index data written to a database and can be used by the system at a later time. All other information is supplied by selecting labeled boxes on the screens. The screens are of three types: data entry; instruction and illustration; and recommendation and explanation.

Whenever the system needs information that it can not deduce or that has not been previously entered, it displays a screen that will be used to obtain the data from a user. The screen will ask the user to supply the necessary information, and it will display all the alternatives that the system recognizes. The user's only choice is to choose one of those alternatives via the "point and click" operation of a mouse system. Care has been taken to include all reasonable alternatives, and to include such options as "unknown"and "other"to take care of those cases where the user does not know the information, or knows a different alternative than those that were considered by the system's designers. The system can accept such catchall alternatives by converting them into default values, ones that usually represent the most conservative interpretation of the condition. The advantage of such a closed system for eliciting information from the user is that the chance for minor errors such as spelling inconsistencies or typing errors are eliminated. While such minor errors might pass unnoticed between human beings, they would of course be catastrophic to the system, which believes that "lannate"is always "lannate"and never "lanate".

While eliminating mechanical errors is important to the smooth operation of the system, it is even more important to insure that the alternative chosen by the user does indeed reflect the state of the orchard block. In order to assist the user in choosing the correct alternative, instruction and illustration screens are provided. In some cases this is as simple as providing a picture to show what an insect looks like at a particular stage in its life cycle. In some cases, however, the kind of information required of the user goes beyond mere identification, and involves quantitative analysis (how many Rosy Apple Aphids have to be present to justify applying a pesticide, for instance). In these cases, much more detailed instructions are given to the user. These instructions may involve many screens giving the user detailed instructions on how to determine the density of a pest population. These more complicated instructions involve extensive use of hypercard and hypertext facilities provided by the Macintosh computer and the capabilities of the development tool. The user is free to move back and forth through these screens; he may browse the instructions provided, and he may choose to read more detailed presentations of what he does not understand. All of these instruction and illustration screens have been implemented in the same "point and click" fashion as previously mentioned.

The third kind of screen belongs to the area of recommendation and explanation. When the system has enough information, it makes a recommendation for treatment (two such recommendations occur in the example rule above). Attached to these recommendation screens are screens which give detailed explanations of why a particular action is being recommended to control a particular pest. These screens may also partially justify the recommendation by reminding the user of some

of the information he has previously entered in response to the system's queries. However, the major focus of the explanation screens is not to justify, but rather is to explain the expert's reasons for recommending a particular treatment, or perhaps, a lack of treatment. The explanation screens attempt to address the user's concerns, and to deal with subtleties that could not be addressed in the rules. They may, for instance, give information about the effects of the recommended pesticide on other pests, or on certain cultivars or strains of apples. These explanation screens attempt to mimic a human expert by giving all those details that are not expected from a computerized system. While the rule system itself will only remember what value went into what slot, the user will have access to a great deal of additional information.

3) Data Bases. EASY-MACS has been designed to be consulted at certain key times throughout the course of a growing season. These key times correspond to various phenological stages in the growth of apples. In addition, only a predetermined set of conditions are considered at each growth stage. This situation has been reflected in the design of the knowledge base which is broken up into a number of smaller knowledge bases. Each of these modules is designed to be consulted at a particular phenological stage. Several data bases retain information generated by consultations at successive growth stages. These databases serve as a history of the block for the current season. They also serve as communication among the various knowledge bases, so that information gained at one session is available for use at a later session. For instance, the system would like to know at the summer sessions what pesticides have been previously applied to the block. Such information can be useful in determining whether there is a possibility of the block containing predators that feed on phytophagous mites. The presence of mite predators may in turn obviate the need for an early summer application of a miticide. Besides serving as a communication between the knowledge bases, the data bases also serve as record keepers, allowing us to see what kind of pest pressure has been encountered throughout the growing season, and how often the system users have chosen treatments other than those recommended by EASY-MACS. Such information can then be considered when making changes to future versions of the system.

In the previous example information would be written to the database that would record the recommendation of Vydate as a treatment for Spotted Tentiform Leafminer at Pink, and that would record that Rosy Apple Aphid was not a problem at Pink. In addition, the data base would record the fact that the user should sample for Oblique Banded Leafroller infestation at Bloom. The user will be reminded of this when he consults the system at Bloom; in the course of the same consultation, he will be asked what spray he actually applied at Pink.

REQUIREMENTS FOR BUILDING A KBS FOR USE IN IPM

There are many requirements that must be met prior to and during development of a KBS. Before embarking on a KBS project, the effort should be deemed justified and feasible. During development of the system it is important that an appropriate methodology be used to codify the knowledge and that management and evaluation of the system be considered from the start. We will now discuss these requirements in more detail and relate them to our work on the EASY-MACS system.

Developing an expert system is an expensive and time-consuming endeavor. A prototype system based on a few hundred rules can often be built in a couple of months. However, it is not unusual that a KBS requires several thousand rules and several years to build. In addition, once a complete KBS is developed, a final deliverable product must be produced. This will usually involve

significant product enhancement where factors such as performance, usability, documentation, and reliability come into play. This stage of the KBS effort may require two to three times the effort required to develop the basic system (Cupello and Mishelevich 1988). As a result of development costs, prudence dictates that a careful evaluation be made of both the justification and feasibility of a proposed project. Waterman (1986) provides a list of criteria which should be satisfied in order to justify the development of a KBS and another set of criteria that can be used to assess the feasibility of a KBS project. Prerau (1985) also discusses criteria appropriate for determining the feasibility of a KBS project. We used these criteria to evaluate whether a KBS for apple pest management was justified and feasible. Justification for development of a KBS rests on two principal criteria; 1) solution of the problem to be dealt with by the KBS should have a high payoff and 2) expertise required to solve the problem dealt with by the KBS should be a scarce resource. The goal of the EASY-MACS system is to provide expertise necessary to realize integrated control of apple pests at the farm level. The desirability of IPM and potential benefits accruing from its adoption justify the cost of developing a KBS in this domain. It is also clear to us that in this problem domain human expertise is scarce. That is, there are few experts who can provide expertise required to realize apple IPM. In addition, the cost of providing human expertise for this purpose is high. Concluding that human expertise is scarce does not however guarantee that the expertise necessary to develop a KBS exists. This is a particularly dangerous trap to fall in, especially from the standpoint of developing KBSs for use in agriculture. Many of the experts to be relied on for contributing knowledge to a KBS are principally involved in research rather than applications or are experts in only a portion of the complete problem domain. Therefore, the potential exists to overestimate the availability of the knowledge necessary to develop the system.

There are two principal criteria which must be met in order to conclude that expert system development is possible. First, it must be determined that the problem to be solved is sufficiently well understood that a solution can be found. As a corollary, genuine experts must exist and they must be able to articulate the methods they use to arrive at a solution. Also, if multiple experts are used, the experts must agree on solutions. We feel that the best way to determine that the expertise necessary to render a solution to a problem exists is to observe this expertise in action under a real world setting. Thus, one year prior to beginning development of EASY-MACS, part of the knowledge to be encoded in the system was put into practice under the guidance of some of the experts to be used in system development. Essentially we were asking whether an expert's performance on this problem was measurably better than that of an inexperienced individual. While this did not ensure that all the expertise required would be available, it did provide us with some assurance that a reasonable knowledge base existed.

The second criteria that must be met in order to conclude that KBS development is possible is that the task to be addressed should not be too difficult nor should it be too simple. Whether a task is so simple that a KBS is unnecessary can usually be ascertained. If a task is simple it should be possible to write down instructions that are to be carried out in order to complete it. If this can be done, then a KBS is not necessary. Whether a task is too difficult for a KBS solution is more difficult to determine. Some insight in this regard can by obtained by determining whether the problem domain is reasonably bounded. In other words, can the extent of the knowledge required to solve the problem be delimited or is a vast array of knowledge required that resides outside of the boundaries of the problem. Another strategy is to develop a prototype system to test the concept of building a more complete system.

KBS's are unlike many other computer programs in that the gathering of knowledge for inclusion in them tends to be harder and more important than the actual coding of the system. Typically, KBS's are constructed by a team consisting of an expert, a knowledge engineer and a programmer (the same person may serve the latter two functions). The role of the knowledge engineer is to elicit the knowledge of the expert through a series of interviews and state it in a form amenable to computer codification. Furthermore, a rapid prototyping methodology is frequently advocated (Waterman 1986). This approach places an emphasis on rapidly achieving a working system, even if only a simplified one, rather than on design and specification. A system may have to be discarded and rewritten many times before the final program is arrived at. The main advantage of this method is that it is often difficult to specify a KBS in advance; the process itself assists in arriving at the specification. However, this reasoning has probably been taken too far. For example, McKinion and Lemmon (1985) state that through the use of a rapid prototyping methodology, system developers can explore ill-specified, ill-understood, and changeable requirements and that a problem does not necessarily have to be well understood in order to be amenable to a KBS solution. We strongly feel that this is not true. Taken to this extreme, the rapid prototyping approach is likely to produce an inconsistent and incomplete knowledge base. In short a system produced using this methodology is not likely to be reliable (Denning 1986).

There are at least two good reasons not to follow this paradigm for KBS development explicitly. In the EASY-MACS project we departed from this paradigm by using a team of experts that included an individual who was knowledgeable about KBS technology and apple IPM and by employing some more conventional software engineering methods.

The first reason for not using the frequently cited development model centers on codifying the knowledge to be placed in the system. IPM knowledge is rather diffuse, that is experts are usually knowledgeable in rather limited sub-fields and in the areas where experts overlap they often don't agree. Thus, to develop EASY-MACS a team of experts was used that met as a group and were required to come to consensus concerning the knowledge to be incorporated into the KBS. The process of consensus was difficult and only worked because a project coordinator was available who could serve as an intermediary. This individual was a expert in the field, but also was familiar with computers and their requirements for knowledge representation and manipulation. The second reason for using the team of experts centers around articulating the knowledge to be placed in the KBS. Parnas (1985) has argued that a trial and error approach to eliciting knowledge for use in a KBS is likely to produce an incomplete and inconsistent knowledge base and that instead of examining how people (experts) solve problems, attention should be devoted to studying the problem itself. An expert may not know why a particular method works and a knowledge engineer may not ask the right questions which will allow an expert to articulate his methods. We found that by using a team of experts considerable attention was devoted towards studying the problem itself and as a result, a more consistent and complete knowledge base was developed.

EASY-MACS is not a typical system in that it deals with a series of consultations over time rather than a single session. This immediately suggested using a modular design and incorporating a system 'memory' (data base). Each of the smaller knowledge bases could have sub-goals of their own, which would contribute to the problem solution. Also, their organization could differ (inasmuch as the development tool would allow) to reflect their particular purpose. The memory would allow the system to refer to what treatments and infestations had occurred previously, as a real expert would.

Thus because of the nature of the problem being tackled and because of misgivings about the rapid prototyping methodology, a rapid prototyping philosophy was used, but imposed on it was a modular organization, so only small parts of the system were under development at any one time. This modular approach allowed us to keep the individual knowledge-bases small, which makes them more comprehensible and easier to maintain. It also allowed us to use a more conventional software development strategy wherein specifications about the modules were determined prior to actual coding.

The final point to be considered in this section is that of evaluation of the system. Excellent reviews of this topic are presented by Cupello and Mishelevich (1988) and O'Keefe et al (1987). Therefore, we will focus only on one important point and relate them to our work on EASY-MACS. We feel it is very important to evaluate a KBS both for correctness and usability early in the developmental cycle. Although EASY-MACS is still in an early phase of development, we feel it is important to allow potential users access to it. Thus we have provided copies (and computers) to several apple growers. The information gained from them will be incorporated into the next test system to be distributed.

We have already obtained some useful advice from our trial users. One point that has become obvious is that dynamically constructed screens need to be added to the interface. This is necessary in order to provide a more useful explanation of the reasoning process employed by the system when arriving at a recommendation. Since this is beyond the capabilities of our development tool, we are required to code these ourselves. Another, unexpected, problem involves the knowledge itself. Users desired access to the expertise in the system at other times and in other ways than during consultations designed to provide a management recommendation. For example, a user might be interested in querying the system to determine the toxicities of various insecticides to mite predators. The current system does not allow this, nor could it without a major redesign, such as going to an object-oriented programming environment, rather than a rule-based one. This last point is not trivial because a major difficulty in developing KBS's is to express knowledge about a problem without committing to a particular way of using it.

We also watched fruit growers use the system, which was, in effect, an evaluation of our presentation method. Their choice of which screens to read and which to skip showed us that the examples chosen were not always the most relevant ones, and that certain facts must be included in every possible path through the system, including highly unlikely ones. This will insure that certain information is presented, but can not guarantee that it will be read, understood or acted upon.

PITFALLS TO AVOID

When a nascent technology is embraced by a new discipline it is often surrounded by misunderstanding and overly ambitious claims about its potential. This is certainly true with respect to KBS's and IPM. The danger here is that when the technology fails to meet its advertised potential, it is prematurely judged ineffective and inappropriate. To guard against this it is important that those who may use the technology or who evaluate tools produced by it be aware of pitfalls that may befall them. Towards this end we have constructed the following list.

1) KBS's, especially those with sophisticated graphical interfaces, are inherently high-tech and impressive. However, like any computer program, they only function as well as their design and content allow. The temptation to present in this format ideas we are not certain of is great, for they

are likely to be accepted solely due to the manner of presentation. We must be sure to produce only systems that incorporate what we know, not ones that present what we would like to know.

2) The amount of work involved in EASY-MACS, a relatively small system, is immense and inherently long-term. It is essential that other projects of this type not be undertaken unless adequate, long-term resource commitment (personnel and equipment) is insured. Coordinate with this is recognition of the value of this type of activity for the participants, something which may be difficult at a traditional, research-oriented institution.

3) Are our expectations about KBS realistic? These systems do not think and only seem to display any type of intelligence. In reality, KBS use programmed rules of inference to reach a conclusion. They manipulate symbols, but in a context free situation and without any understanding of what the symbols mean. A KBS is constrained by the knowledge it contains and can not reach conclusions that are not implicit in that knowledge. Most KBS can not detect faulty data or if they are being employed for a problem not in their domain. In either case, answers will be provided, but almost certainly they will be incorrect, and the user is more apt to blame the system then themselves.

4) Is thought being given to ensure that a KBS is consistent and complete? A trial and error or case study approach to eliciting knowledge may produce an incomplete and inconsistent knowledge base. This type of software is likely not to be as reliable as that developed from precise specifications. The system may well reproduce any errors the expert would make. The designer and user may well disagree at to whether this is a feature or a fault of the system.

5) Are we using the elicited knowledge effectively? Knowledge encoded in rules, by far the most common representation in KBS's, can only be accessed in a manor consistent with the way the inference engine manipulates the rules. That is, certain questions may be answered, but others can not be, even though the knowledge to answer them is in the system. This is because the form of the system itself limits the ways the knowledge can be accessed. If knowledge was encoded as facts, multiple access paths would be possible, but coding would become much more difficult. Until tools are developed to assist the KBS developer in this form of knowledge representation, we will continue to waste the very resource we are trying to conserve, expert knowledge.

OPPORTUNITIES FOR USE OF KBS's IN IPM

In this final section of the paper we list five conventional opportunities and benefits of KBS's and then discuss what we feel is the most fundamental opportunity for use of KBS in IPM. There are a number of important advantages of KBS's compared to conventional text-based or computer-based decision aids that are often cited. First, the information base not only consists of objective information (published technical data) but also includes expert opinions on issues and problems not necessarily addressed by such information. Second, KBS's provide a format for dealing with imprecise or incomplete data, precisely that with which a real expert must often contend. Third, because a KBS can record its logical chain of reasoning, it has explanatory power, although it should be noted that providing such explanations in a form a user can comprehend is not a trivial task. Fourth, little technical expertise is required to use the system. Finally, interactive graphics can provide a visual display of information for diagnostic and educational purposes, thereby improving the usefulness of the system and increasing the user's confidence in the system's recommendations.

The fundamental opportunity in the use of KBS's is to deliver IPM related knowledge in a form that will facilitate its use. It is important though to address this opportunity in the proper framework.

We do not think it is appropriate to ask "how can we build a system that will behave like an expert solving a pest management problem". The reason for this is that KBS's use rationalistic problem solving; given a precise statement of a situation they enumerate alternatives for solution and find the best solution based on some objective criteria. However, this type of problem is only a partial description of how people solve problems. A person processes data within a framework of interpretation whereas a KBS does not. As a result, it is more appropriate to ask "how can KBS's be designed to help people do things more effectively". If this is kept in mind KBS's will likely make a significant contribution to the adoption of IPM practices.

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LIST OF CONTRIBUTORS

LIST OF CONTRIBUTORS

ANGLE, J. S.
Department of Agronomy
University of Maryland
College Park, MD 20742

BACON, C. W.
Toxicology and Mycotoxins Research Unit
USDA/ARS
Richard B. Russell Agricultural Research Center
P.O. Box 5677
Athens, GA 30613

BROWN, W. M., JR.
Department of Plant Pathology and Weed Science
Colorado State University
Fort Collins, CO 80523

BUSH, L. P.
Department of Plant Pathology, Entomology and Agronomy
University of Kentucky
Lexington, KY 40546-0091

CLARKE, B. B.
New Jersey Agricultural Experiment Station
Rutgers University
New Brunswick, NJ 08903

CRANSHAW, W.
Department of Entomology
Colorado State University
Fort Collins, CO 80523

COCKFIELD, S. D.
Department of Entomology
University of Kentucky
Lexington, KY 40546

DAHLMAN, D. L.
Departments of Plant Pathology, Entomology and Agronomy
University of Kentucky
Lexington, KY 40546-0091

DANNEBERGER, T. K.
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

DAVIDSON, J. A.
Department of Entomology
University of Maryland
College Park, MD 20742

DERNOEDEN, P. H.
Department of Agronomy
University of Maryland
College Park, MD 20742

DETWEILER, R.
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

FUNK, C. R.
New Jersey Agricultural Experiment Station
Rutgers University
New Brunswick, NJ 08903

FUNK, R. C.
The Davey Tree Expert Company
1500 North Mantua Street
Kent, OH 44240

GEORGIS, R.
Biosys
1057 East Meadow Circle
Palo Alto, CA 94303

GOLD, A. J.
Departments of Natural Resources Sciences and Plant Sciences
Rhode Island Agricultural Experiment Station
University of Rhode Island
Kingston, RI 02881

GRANT, Z.
Board of Supervisors
70 W. Hedding St.
San Jose, CA 9510

GROSS, C. M.
Department of Agronomy
University of Maryland
College Park, MD 20742

GROTHAUS, G. D.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

HILL, R. L.
Department of Agronomy
University of Maryland
College Park, MD 20742

HUBER, B.
IPM Program
New York State Agricultural Experiment Station
Cornell University
Geneva, NY 14456

HULL, R. J.
Departments of Natural Resources Sciences and Plant Sciences
Rhode Island Agricultural Experiment Station
University of Rhode Island
Kingston, RI 02881

JOHNSON-CICALESE, J. M.
New Jersey Agricultural Experiment Station
Rutgers University
New Brunswick, NJ 08903

KAGEYAMA, M. E.
O. M. Scott and Sons Co.
Research Division
Marysville, OH 43041

KLEIN, M. G.
Horticultural Insects Research Laboratory
Application Technology Research Unit
ARS/USDA
Ohio Agricultural Research and Development Center
Wooster, OH 44691

KNOOP, W.
Texas A&M University
Research and Extension Center
17360 Coit Road
Dallas, TX 75252

LARSON, L.
R & D Dept.
Soil Technologies Corp.
600 North 12th Street
Fairfield, IA 52556

LANKOW, R. K.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

LESLIE, A. R.
U. S. Environmental Protection Agency
Office of Pesticide Programs
Field Operations Division (H7506C)
401 M Street, S.W.
Washington, DC 20460

METCALF, R. L.
Department of Entomology
University of Illinois
Urbana, IL 61801

MILLER, S. A.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

MORRIS, T. A.
Department of Entomology
University of Kentucky
Lexington, KY 40546

NYROP, J. P.
Department of Entomology
New York State Agricultural Experiment Station
Cornell University
Geneva, NY 14456

OTTO, M.
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

PETERSEN, F. P.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

PLUMLEY, K. A.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

POINAR, G. O., JR.
Department of Entomological Sciences
University of California
Berkeley, CA 94720

POTTER, D. A.
Department of Entomology
University of Kentucky
Lexington, KY 40546

RASMUSSEN-DYKES, C.
Jefferson County Cooperative Extension
Golden, CO 80401

RAUPP, M. J.
Department of Entomology
University of Maryland
College Park, MD 20742

RITTENBURG, J. H.
Agri-Diagnostics Associates
2611 Branch Pike
Cinnaminson, NJ 08077

ROBERTS, D.
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

SCHAEFER, J.
R & D Dept.
Soil Technologies Corp.
600 North 12th Street
Fairfield, IA 52556

SHETLAR, D. J.
ChemLawn Services Corporation
Research and Development
P.O. Box 85-816
Columbus, OH 43085

SIEGEL, M. R.
Departments of Plant Pathology, Entomology and Agronomy
University of Kentucky
Lexington, KY 40546-0091

SMITH, M. F.
Department of Entomology
University of Maryland
College Park, MD 20742

SULLIVAN, W. M.
Departments of Natural Resources Sciences and Plant Sciences
Rhode Island Agricultural Experiment Station
University of Rhode Island
Kingston, RI 02881

VARGAS, J. M., JR.
Departments of Botany and Plant Pathology, and the Pesticide Research Center
Michigan State University
East Lansing, MI 48824

VILLANI, M. G.
Department of Entomology
New York State Agricultural Experiment Station
Cornell University
Geneva, NY 14456

WELTERLEN, M. S.
Grounds Maintenance Magazine
P.O. Box 12901
Overland Park, KS 66212;
formerly, Department of Agronomy,
University of Maryland
College Park, MD 20742

WIDELL, L. R.
O. M. Scott and Sons Co.
Research Division
Marysville, OH 43041

WILKINSON, J. F.
Professional Lawn Care Association of America
101 Buena Vista Drive
North Kingston, RI 02852

WOLF, W.
Department of Computer Science
Rochester Institute of Technology
Rochester, NY 14623

WRIGHT, R. J.
Department of Entomology
University of Nebraska
Lincoln, NE 68583

☆ U.S. GPO: 1989—625-030