Annu. Rev. Entomol. 1991. 36:383–406

ECOLOGY AND MANAGEMENT OF TURFGRASS INSECTS

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KEY WORDS: turf insects, urban integrated pest management, lawn insects, insecticide, low input sustainable agriculture

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PERSPECTIVES AND OVERVIEW

"The grasses are the least noticed of the flowering plants. They seem to be taken for granted like air and sunlight, and the general run of people never give them a thought" (73). Sixty years later, this view of grasses has changed. Turfgrasses have become the most widely used and intensively managed urban plantings, and the management of turfgrass insect pests is an increasingly important concern. In this first review of turfgrass entomology printed by the *Annual Review of Entomology,* we critically appraise the status of biological and integrated pest management (IPM) research on turfgrass insects, discuss some of the problems of implementing IPM in this unique system, and identify areas of promise for future research.

Turfgrass may be defined as a uniform stand of grass or a mixture of grasses maintained at a relatively low height and used for recreational or functional purposes or to enhance and beautify human surroundings (177). The culture of mowed lawns dates back at least to medieval times when turf was used for outdoor sports and recreation and was considered a symbol of the

0066-4170/91/0101-0383$02.00

rich and powerful (78). Use of turf in the United States skyrocketed during the 1950s and 1960s as large tracts of land were developed to accomodate the growing urban population. Turfgrasses now cover an estimated 10.1 to 12.1 million hectares in the US. About 81% of this area is subdivided among more than 50 million lawns; the remainder is in parks, golf courses, athletic fields, cemeteries, sod farms, roadsides, and other sites (156). Turfgrass culture, in its many forms, is at least a $25 billion per year industry in the US. About 500,000 people make their living directly from establishment and maintenance of turf (156, 177). Commercial lawn-care receipts increased at an average annual rate of 22% from 1977–1984 (110). In 1987, more than 20 million US golfers played about 445 million rounds (156).

Turfgrass has functional, aesthetic, and monetary value. Attractive landscaping conveys a favorable impression in a business setting and increases the value of residential property by as much as 15% (82). Living turf supplies oxygen, reduces erosion and surface runoff, glare, and noise pollution, moderates surface temperatures, and filters dust from the air (14, 82). Turfgrasses enhance the safety and enjoyment of sports and leisure activities, and they help to make urban areas a more pleasant place to live and work. These benefits are increasingly important to the physical health and mental well-being of the urban population (167).

Demand for high quality turfgrass has been accompanied by growing public concern about the negative aspects of pesticides, especially ground water contamination (129) and potential risks to human health (104). Urban pesticide usage has become a volatile political issue (58, 215). Beset with increased litigation and rising insurance costs, loss of registrations, and local ordinances restricting pesticide use, the turfgrass industry will be forced to make greater use of alternative pest control methods (58).

Commitment of personnel, extramural funding, and other resources to turfgrass entomology is woefully inadequate. In 1980, the total allocation of professional assignments to university research and extension in the US was the equivalent of only 7.2 and 6.7 full-time positions, respectively (121). Much of that effort was divided among persons who had 10% or less of their time assigned to turfgrass. Twenty-five states had no research assignment at all in this area. Only 41 of the 8,418 research papers (0.49%) presented at national conferences of the Entomological Society of America during 1984–1989 dealt specifically with turfgrass insects (D. A. Potter & S. K. Braman, unpublished survey).

THE TURFGRASS SYSTEM

Turfgrass consists of the roots, stems, and leaves of individual grass plants, together with a tightly intermingled layer of living and dead roots, stolons, and organic debris commonly called thatch (14). Turfgrass species grown in the US are classified on the basis of their climatic adaptations (14). Cool-season grasses, including bluegrasses, fescues, ryegrasses, and bentgrasses, are the main species grown in the northern two-thirds of the US. Warm-season grasses, including bermudagrasses, zoysiagrass, St. Augustinegrass, bahiagrass, and centipedegrass, predominate in the southeast and in the warm, semiarid zones of the south and southwest. A transitional climatic zone extends south from Delaware to central Georgia and west from southern Kentucky to Oklahoma (14).

According to Beard (14), the six basic components of turfgrass quality are uniformity, density, texture, growth habit, smoothness, and color. The relative importance of these factors varies with individual perceptions and with the purpose for which the turf is used. Color and uniformity are desirable for golf fairways and home lawns, whereas smoothness is essential for golf putting greens. Aesthetic standards are often so high that even limited insect damage is considered intolerable. Consequently, insecticide treatments are often viewed as insurance, especially by the lawn-care and golf-course industries.

ARTHROPOD PESTS OF TURFGRASS

Arthropod pests of turfgrass include soil-inhabiting species that feed upon roots or damage turf through their burrowing activity, those that consume leaves and stems, and those that suck plant juices. Here, we briefly discuss the biology and damage caused by the main species. Tashiro (177) provides more complete accounts and citations.

Soil-Inhabiting Turfgrass Pests

MOLE CRICKETS The tawny mole cricket, *Scapteriscus vicinus,* and the southern mole cricket, *Scapteriscus acletus,* are major pests of warm season turfgrasses, especially in the southeastern US. Neither species is native; both were apparently first introduced between 1899 and 1904 (119, 207, 209).

Male mole crickets stridulate from within specially constructed burrows in the soil that amplify their species-specific songs (51, 118, 193, 194). Individual variation in intensity of calls may lead to greater mating success by larger males (51). Louder male calls may also be indicative of superior oviposition sites where higher moisture favors both efficient burrow construction for calling and for incubation of eggs (51, 53, 69).

Calling songs of mole crickets have been used in species separation (52), together with such characters as foreleg morphology, pronotal markings, maxillae, and cuticular lipids (177). Acoustical traps have been used for population studies of the pests (206) and their parasitoids (54). While crickets may be attracted by the thousands to recorded or electronically synthesized male calls (206), population control via sound trapping has not proven effective. In fact, such callers may increase populations in the vicinity of the trap by attracting individuals that escape capture (113).

The southern mole cricket is primarily carnivorous, damaging turf mainly through its burrowing activity that mechanically dislodges roots and leaves piles of soil on the surface. The tawny mole cricket causes similar damage, but, because it also feeds on leaves, stems, and roots, it is considered the more significant pest (193). Both species are particularly damaging to bahiagrass and bermudagrass, especially on light sandy or loamy soils (177). Use of radioisotopes to trace underground movements of mole crickets has been explored (75).

Dispersal flights of females, which occur during spring and fall, have contributed to the rapid range extension of these two species (208, 210). Both species are univoltine throughout most of their range; in south Florida the southern mole cricket may be bivoltine (53, 210).

WHITE GRUBS Scarabaeid grubs feed on the roots of all species of commonly used turfgrasses, and they are the most important insect pests of cool-season grasses in the US (154, 155, 177). Heavily infested turf develops irregular dead patches that can be lifted or rolled back like a carpet. Avian or mammalian predators (e.g. moles, skunks) often cause further damage by tearing up the turf in their search for grubs. The subterranean habits of white grubs make them especially difficult to control because insecticides applied to the surface must move through the thatch and into the soil (120, 177). At least 10 species are pests of turfgrasses; many also do damage as larvae or adults in other agricultural settings (49, 154).

Several of the turf-infesting white grubs are introduced species. The most significant is the Japanese beetle, *Popillia japonica* (49, 50), followed (in order of importance) by: the European chafer, *Rhizotrogus majalis* (63, 179); oriental beetle, *Anomala orientalis* (1); and asiatic garden beetle, *Maladera castanea* (56, 64). The latter three species are of regional importance mainly in the Northeast. Since the discovery of the Japanese beetle in New Jersey in 1916, it has spread throughout the eastern US as far south as Georgia and Alabama and west to Iowa and Wisconsin. Efforts to eradicate localized infestations in California and Oregon are ongoing (177). Adult Japanese beetles feed upon foliage of more than 300 plant species (49).

Several widely distributed native species, including the northern and southern masked chafers, *Cyclocephala borealis* and *Cyclocephala lurida* [formerly *C. immaculata* (42)] (134, 154); the black turfgrass ataenius, *Ataenius* *spretulus* (213); and many of the 152 species of *Phyllophaga* (68, 106, 155), can also be very destructive turf pests. Green June beetle larvae, *Cotinus nitida,* feed mainly on detritus (26) but damage turf by their burrowing activities.

Temperature, soil type, and especially soil moisture influence scarabaeid oviposition, egg and larval survival, adult emergence and flight activity, and expression of damage (35, 59, 63, 96, 134, 135, 143, 161). Eggs absorb water from the soil and cannot survive below critical moisture thresholds (139, 145); vertical movement of grubs is also governed by soil moisture and temperature (198). Noninvasive radiography techniques have recently been used to study white grub behavior below the soil surface (198).

Most turfgrass-infesting scarabaeids have one-year life cycles, hatching from eggs laid in June and July and inflicting their greatest damage in the late summer and early fall before moving deeper into the soil for overwintering (177). *A. spretulus* completes two generations per year in some areas (213), and portions of the population of other species (e.g. European chafers, oriental beetle) or species at the northern limits of their range (e.g. Japanese beetle) may require two years to complete development. Life cycles of *Phyllophaga* spp. vary from one to four years depending upon species and location; three-year life cycles are most common in cool-season turf (68, 155). *Phyllophaga crenata* and *Phyllophaga latifrons* are annual grubs that cause extensive damage to turf in Texas and Florida, respectively.

BILLBUGS The two most widespread and important curculionid beetles that damage turfgrasses in the US are the bluegrass billbug, *Sphenophorus parvulus,* a pest of cool-season grasses (65, 89, 184), and the hunting billbug, *Sphenophorus venatus,* considered a pest mainly of warm-season grasses in the southern US and Hawaii (86). However, recent work on this poorly known group revealed a complex of four abundant species, including both the bluegrasss billbug and the hunting billbug, that damage cool-season grasses in New Jersey (81). This work also yielded a key to the eight known billbug turf pests in the US.

Both the bluegrass and the hunting billbug overwinter as adults in protected areas, emerging in early spring. Adults feed on and deposit eggs in stems, leaf sheaths, and crowns; young larvae tunnel in the stem and crown, causing the damaged plants to break off easily. Older larvae enter the soil and feed on the roots before pupating and becoming adults by fall. Numbers of adults migrating over adjacent paved surfaces in spring may be an indicator of subsequent larval damage (184). Another curculionid, *Listronotus maculicollis* (formerly *Hyperodes* sp. near *anthracina*), damages annual bluegrass, *Poa annua,* and can be a pest on golf courses in the northeastern US (203).

Insects that Consume Leaves and Stems

SOD WEBWORMS About 100 species of sod webworms (Lepidoptera: Pyralidae) are recognized in North America (16), dozens of which infest turfgrasses in the US (3, 112, 189). Ainslee (3–7) described the biology of important native species including: the striped sod webworm, *Fissicrambus mutabilis;* the silver striped webworm, *Crambus praefectellus;* the larger sod webworm, *Pediasia trisecta;* and the bluegrass webworm, *Parapediasia teterrella*. The western lawn moth, *Tehama bonifetella,* and *Crambus sperryellus* are the main webworm pests of California lawns (16), while *Herpetogramma phaeopteralis,* the tropical sod webworm, is important in Florida (87). The grass webworm, *Herpetogramma licarsisalis,* is the principal turf pest in Hawaii (174). The cranberry girdler, *Chrysoteuchia topiaria,* damages grasses grown for commercial seed production in the Pacific Northwest (83) and lawns in northern Illinois and Michigan.

Most temperate-region sod webworms have one to four generations per year depending upon species and location (e.g. 16, 189). Larvae overwinter in the thatch or soil. First instars feed only on the surface tissues of leaves and stems; older larvae construct silk-lined burrows from which they emerge at night to feed upon grass blades or shoots. Adult emergence, mating, and oviposition are nocturnal events for some species (e.g. 174), while in others these behaviors are crepuscular (13) or diurnal (32). Temperature and relative humidity affect development and survival of eggs (70, 115). Sculpturing of the chorion is species-specific and was used to construct a key to the eggs of 15 species in Tennessee (111).

CUTWORMS, ARMYWORMS, AND SKIPPERS Tashiro (177) recognized five noctuid species as pests of turfgrasses in the continental US: the black cutworm *Agrotis ipsilon,* the variegated cutworm *Peridroma saucia,* the bronzed cutworm *Nephelodes minians,* the armyworm *Pseudaletia unipuncta,* and the fall armyworm *Spodoptera frugiperda*. Cutworms and armyworms feed mainly on graminaceous hosts; many are pests of field crops (105, 205).

Cutworms are named for the larval habit of severing food plants at their base and pulling them into a subterranean burrow before feeding (205). The black cutworm, a widespread and destructive species (153), is especially damaging to golf greens. Larvae stay in aeration holes and emerge at night to feed. It overwinters in the pupal stage at Ohio and Illinois latitudes, with an additional influx of migrating adults from the south resulting in several annual population peaks arising from asynchronous ancestries (190).

The fall armyworm annually invades much of the continental US and southern Canada, yet is unable to survive the winter in the temperate zone (105, 165). Sporadic outbreaks of fall armyworms cause significant damage to field crops and turf, especially in the Southeast and Gulf states. The insects deposit egg masses indiscriminately on buildings, golf carts, and other objects as well as on host plants. Mating behavior, developmental biology, and feeding preferences of the fall armyworm have been extensively studied (25, 105, 165). The fiery skipper, *Hylephila phyleus,* is another species that sometimes damages bermudagrass and other grasses. Although widely distributed, it is considered a turf pest mainly in Hawaii and California (16, 182).

FRIT FLY Larvae of *Oscinella frit* (Diptera: Chloropidae) cause occasional damage to golf-course greens. The maggots damage cool-season grasses by killing their growing points (8), and the adults are a nuisance because they are attracted to and land on white golf balls (177). Its biology as a turf pest has recently been studied (187, 188).

Arthropods that Suck Plant Juices

CHINCH BUG COMPLEX Chinch bugs are well known pests of Graminocea (100, 101). Two species, the hairy chinch bug, *Blissus leucopterus hirtus,* and the southern chinch bug, *Blissus insularis,* are important turfgrass pests (177). The chinch bug, *B. leucopterus leucopterus,* is a migratory species that feeds mainly on small grains and corn (74) but occasionally damages turf.

The hairy chinch bug attacks cool-season turfgrasses and zoysiagrass in the northeastern US and Canadian border provinces west to Minnesota and south to Virginia. Aggregations of nymphs and adults suck sap from stems and crowns, causing localized injury that may coalesce into large patches of dead and dying turf. Damage, which may be compounded by moisture stress, is reportedly greatest on sandy soils and in full sunlight (114, 177). The hairy chinch bug overwinters as an adult, completing one generation per year in southern Ontario (103) and two in the southern parts of its range (108, 114, 120). Developmental biology of the hairy chinch bug has been studied in the laboratory (11).

The southern chinch bug is the most injurious pest of St. Augustinegrass in Florida and the Gulf Coast region (88, 150), where repeated spraying to control as many as 7–10 generations per year has led to widespread insecticidal resistance (151). Densities of southern chinch bug frequently exceed 500–1000/0.1 m^2; open, sunny areas, heavily fertilized lawns, and those with thick, spongy thatch are reportedly preferred (150). Brachypterous adults predominate; dispersal is mainly short-range by walking (88, 100).

ACARINE PESTS Bermudagrass mite, *Eriophyes cynodoniensis,* was first reported from the US in 1959 (192), but its occurrence throughout much of the southern US in the 1960s (37) suggests an earlier introduction. The mites overwinter beneath leaf sheaths of dormant plants. Oviposition begins in the spring. Multiple generations are completed in a growing season. Heavy infestations cause shortening of the internodes, rosetting, browning, and dieback that encourages subsequent encroachment by weeds. The mites reportedly prefer well-fertilized lawns, and moisture stress aggravates their damage (192).

Winter grain mite, *Penthaleus major,* is a widely distributed pest of small grains, vegetables, and several species of cool-season turfgrasses (23). It feeds by rasping grass blades, causing damage that resembles winter desiccation. Eggs hatch in October and develop into adult females by November; all life stages may be present during the winter months. Mites are most active at night or on dark, cloudy days. Two generations have been reported; second-generation females deposit eggs that aestivate and hatch the following fall (172, 173). The clover mite, *Bryobia praetiosa,* and the Banks grass mite, *Oligonychus pratensis,* also occasionally damage turf (177).

SPITTLEBUGS The twolined spittlebug, *Prosapia bicincta,* can be a serious pest of pastures, especially in the southeastern US (43, 130). Spittlebugs also damage southern lawns, especially bermuda and centipedegrass, where dense uniform turf, combined with regular irrigation, may favor egg hatch and nymphal survival. Eggs overwinter on soil, in vegetation, or on plant debris; two generations occur annually in the Southeast. Adults and nymphs feed upon plant sap, causing withering and phytotoxemia (169).

APHIDS, SCALES, AND MEALYBUGS The greenbug, *Schizaphis graminum,* is mainly a pest of small grains (204), but damage to bluegrass lawns was reported as long ago as 1907 (212). Since 1970, the aphid has caused sporadic, severe damage to cool-season grasses in the midwestern states, and host resistance studies suggest the probability of new biotypes (127). In northern states, where most of its damage to turf occurs, greenbugs overwinter mainly as eggs adhering to grass blades, fallen tree leaves, and debris (127). The first spring generation consists of wingless females that give rise to as many as 15 additional generations per year. Damage results from withdrawal of phloem sap and from phytotoxemia in response to salivary secretions.

Several other sucking insects can be pests of warm season turfgrasses, especially bermudagrass, or tall fescue in the southern US. Feeding by rhodesgrass mealybug, *Antonina graminis* (24), and bermudagrass scale, *Odonaspis ruthae* (186), causes loss of vitality and browning that may be compounded by drought. Ground pearls, *Margarodes* spp., are subterranean scale insects that infest the roots of warm season grasses (94). Eggs are deposited in a clump enclosed in a waxy sac; the newly hatched nymphs secrete a pearl-like shell or cyst. Ground pearls may occur as deep as 25 cm in the soil, precluding practical means of control (120).

Other Pests

Numerous other arthropods, e.g. ants (especially imported red fire ant, *Solenopsis invicta*), crane fly larvae, wasps, and fleas, may sometimes become pests in turfgrass by feeding upon the plants themselves, by producing burrows or mounds, or by being a nuisance to people. Tashiro (177) discusses their biology in this context.

CURRENT STATUS OF INTEGRATED PEST MANAGEMENT

Insecticides

Conventional insecticides are the mainstay of turfgrass insect control, and their efficacy is being constantly evaluated (e.g. 10, 122, 199, 201). At present, use of an insecticide is often the only practical way to prevent significant damage from unexpected or heavy pest infestations.

Highly persistent cyclodiene insecticides, including chlordane, dieldrin, aldrin, and heptachlor, were used very effectively in the 1950s and 1960s. A single application often provided residual control for many years (175). By the early 1970s, the effectiveness of cyclodienes had become limited by increased insect resistance (147, 176), and environmental concerns resulted in cancellation of cyclodiene registrations for turf. Subsequently, organophosphates (OPs) such as chlorpyrifos, diazinon, trichlorfon, ethoprop, and isazophos and carbamates, including bendiocarb and carbaryl, came into general use on turf. Their versatility is limited by relatively short residual toxicity (95, 158, 175) and by their sometimes inconsistent performance under differing edaphic conditions (67, 181). Isofenphos, an OP with relatively long residual toxicity in soil (175, 201), became widely used in the 1980s, and the synthetic pyrethroids fluvalinate and cyfluthrin were more recently labelled for use on turf. Resistance to OPs or carbamates has been documented for chinch bugs and greenbugs (147) and, in at least one instance, for white grubs (2). Few new insecticides are targeted for turfgrass because the market is relatively small and offers limited opportunity for recovery of the massive development and registration costs. Effective insect growth regulators, chitin inhibitors, and other so-called third generation insecticides have not yet been labelled for use on turf.

INFLUENCE OF THATCH Immediate post-treatment irrigation is usually recommended when OPs or carbamates are applied for control of rootfeeding insects, ostensibly to leach the insecticide through the thatch and into the soil. Even with irrigation, most of the residues may become bound in the highly adsorptive thatch (122, 125, 126, 158) where they are rapidly degraded by chemical hydrolysis or microbial decomposition (17). Contact with and ingestion of residues at the thatch-soil interface or in the thatch itself may be the primary source of the lethal dose (122, 126). Further study of the mobility of insecticide residues in thatch and soil, and of movement of white grubs and other insects in response to soil moisture (e.g. 198) is needed to better understand the factors that limit control of these pests. Binding of insecticides in thatch probably reduces their potential for leaching from turfgrass into ground water or for run-off into benthic systems.

ENHANCED BIODEGRADATION Enhanced biodegradation, in which pesticides are degraded at an accelerated rate by microorganisms in soils that have been conditioned by repeated exposure to a pesticide, has been reported for isofenphos, diazinon, ethoprop, and other insecticides used on turf (45). Enhanced biodegradation has been implicated in reduced residual effectiveness of isofenphos on golf courses previously treated with that chemical (123).

ENVIRONMENTAL SIDE-EFFECTS Excessive thatch is a common problem on highly maintained turfgrass, contributing to reduced water infiltration, shallow rooting, and increased vulnerability to stress and pest problems (14). Use of certain pesticides or fertilizers may encourage thatch accumulation by adversely affecting earthworms and other soil organisms that are important to decomposition processes (137, 138, 140, 142). A single spring application of bendiocarb, carbaryl, ethoprop, or the fungicide benomyl to Kentucky bluegrass resulted in 60–90% reductions in earthworm abundance; effects lasted for at least 20 weeks (21, 137a). Insecticides may also suppress populations of predators and parasitoids (9, 29, 30, 196) and apparent resurgences or secondary outbreaks of certain pests (e.g. chinch bugs, winter grain mite) have been reported (146, 170, 172).

Certain turfgrass pesticides (e.g. diazinon) are very toxic to birds and fish (131). Application of chlorpyrifos to freshwater ponds resulted in poisoning of waterfowl, apparently from ingestion of moribund, chlorpyrifos-contaminated insects (79). Birds may gorge upon dead or moribund mole crickets (18) or *Cotinus* grubs (D. A. Potter, unpublished observation) that have come to the turf surface following an insecticide treatment. Mortality of waterfowl following foraging on insecticide-contaminated turfgrass or invertebrates contributed to recent cancellation of diazinon usage on golf courses and sod farms.

Sampling, Monitoring, and Risk Assessment

Turfgrass insects often go unnoticed until feeding damage becomes obvious or the more active and visible adult stages emerge. Simple, reliable, and cost-effective survey techniques other than visual inspections are lacking for most species. This absence of practical methods of risk assessment, together with low damage thresholds, are factors that contribute to insecticide use.

Direct population survey techniques for turfgrass insects include soil sampling, often with a golf-cup cutter or motorized sod-cutter (117), flotation (107), irritant drenches (183), pit-fall traps (81), sweep net or suction sampling, sound traps (206), and heat extraction from thatch and soil (120). These techniques are useful for research purposes, but in practical usage they are often prohibitively destructive and time consuming, especially for the lawn-care industry. Moreover, their value in decision-making is limited by the general lack of established damage thresholds (136). Spatial distributions have been studied and sequential sampling plans developed for several turfgrass pests (77, 103, 109, 116, 117, 188), but relationships between population density of the damaging life stage and injury to turf have been studied for only a few species (28, 135).

Pheromones or sex attractants have been identified for a number of important turfgrass insects including the Japanese beetle (191), fall armyworm, armyworm, cranberry girdler, western lawn moth (for review, see 84), black cutworm (72), and bluegrass webworm (27) and demonstrated for several others including the larger sod webworm (12), masked chafers (133), and the green June beetle (38). Other adult-trapping and survey methods include blacklight traps for night-flying species (180, 189), food-type baits (98), and sticky plastic sheets (46).

Potential uses for semiochemicals and other trapping methods include monitoring for the purpose of treatment timing, detection and evaluation of pest populations, and direct suppression by mass trapping (91) or disruption of sexual communication (84). Semiochemicals could be used to target high-risk lawns or golf fairways for selective treatments, but little work relates trap captures of adults to subsequent larval populations or damage. This approach would work better for species in which adults tend to remain in the area where they fed as larvae (e.g. sod webworms, masked chafers) than for species capable of long-distance flight to traps (e.g. Japanese beetles, armyworms).

Models based on accumulated degree-days that allow prediction of phenology or adult emergence have been developed for several turfgrass pests, including chinch bugs (103), Japanese beetles (144), masked chafers (134), sod webworms (189), and frit flies (187). Timing of emergence, flight, or egg-laying of some species, e.g. European chafer and *A. spretulus*, has been related to dates of flowering of common plants (178, 212).

Biological Control

The fact that insect outbreaks are relatively uncommon in low-maintenance turfgrass suggests that many pests are normally held in check by indigenous natural enemies. Several surveys document the diverse community of entomophagous invertebrates inhabiting turfgrass in the US (31, 76, 146, 171) and Europe (33, 85). Practically every turfgrass pest has one or more natural enemies associated with it (177), but manipulation of these beneficial arthropods as components of IPM has progressed little (92, 136).

The ecological, economic, and sociological difficulties of implementing biological control in urban settings have been discussed elsewhere (47, 55, 128, 136). The urban landscape, with its diversity of pests and plantings, its frequent modifications and disruptions, and its kaleidescope of public attitudes and expectations, poses formidable challenges to biocontrol. Conservation of natural enemies and other beneficials should be a factor in pesticide selection, but comparative data (e.g. 29) upon which to base such decisions are sparse.

Between 1920–1933, about 49 species of parasitoids and predators were imported to the US from the Orient and Australia and released into Japanese beetle–infested areas (48). Only a few of these became established. The most important are two species of tiphiid wasps that parasitize the grubs. Their present impact is limited (48). An introduced parasitoid, the tachinid *Hyperecteina aldrichi*, was recovered from about 20% of the adult Japanese beetles sampled in central Connecticut in 1979 (177).

A sphecid wasp, *Larra bicolor*, was imported into Puerto Rico from Brazil in the late 1930s for suppression of mole crickets (216), and efforts to establish this and other imported parasitoids in Florida were recently reviewed (76). Importation of an encyrtid parasitoid from India to Texas provided almost complete biological control of the rhodesgrass mealybug, with reported savings of $17 million/year (36).

Propagation and dissemination of milky disease bacteria, mainly *Bacillus popilliae*, by the USDA and cooperating state agencies during the 1930s and 1940s was credited with reducing Japanese beetle populations over much of the eastern US (48, 92, 97, but see 40, 66). Other species or strains of milky disease bacteria attack other white grubs, including *Cyclocephala* spp. (211, 214), *A. spretulus* (166), and *R. majalis* (185), but commercial formulations are presently marketed only for control of Japanese beetle larvae.

Aspects of the pathology, host specificity, and application of milky disease bacteria for area-wide suppression of Japanese beetles have been extensively studied (for reviews, see 41, 90, 157), and a 1976 bibliography listed 239 references on the subject (93). Nevertheless, presently no published data document the performance of milky disease bacteria in replicated field trials or in the urban landscape. The turfgrass industry has not made greater use of milky disease bacteria for reasons that include its relatively high cost, difficulty of application, limited availability, inconsistent performance, lack of field-efficacy data, and the long establishment period required for control. Commercial milky disease bacteria formulations have been relatively expensive because their production required hand collection and inoculation of individual grubs. Early in vitro propagation efforts were disappointing (19, 157), but recent advances in large-scale fermentation production of *B. popilliae* (152) may increase the availability and reduce the cost of milky disease bacteria formulations. In vitro production methods may also make producing milky disease bacteria formulations that are infectious to other grub species commercially feasible.

Bacillus thuringiensis formulations are labelled for lepidopteran turf pests, but they are not widely used and are frequently omitted from control recommendations. Current *B. thuringiensis kurstaki* strains have limited activity on soil-dwelling caterpillars (159). Naturally occurring epizootics of the fungus *Beauveria bassiana* may suppress populations of southern and hairy chinch bugs (108, 146), but the value of the fungus in IPM is limited by its requirement for specific environmental conditions. Other microbial pathogens infect particular turf pests (66, 92, 177), but none has yet been successfully manipulated for IPM.

Commercially available steinernematid and heterorhabditid nematodes have provided satisfactory control of white grubs in turf (159, 160, 197), but efficacy was variable and required irrigation following application and moderate to high soil moisture for nematode establishment. Bait and spray formulations containing nematodes controlled black cutworms and tawny mole crickets in laboratory tests (60, 159). Nematodes offer a promising alternative to conventional insecticides, but problems of availability, storage, cost, handling, and reliability must be resolved if they are to become more widely used by the turfgrass industry.

Cultural Control

Routine cultural practices such as fertilization, irrigation, and mowing affect pest populations and their damage (14, 61, 96, 135), but published accounts are mostly anecdotal and data are sparse. Leafhoppers and flea beetles may favor fertilized pasture and turfgrass (9, 141). Frequent mowing did not affect leafhopper populations, but adult frit flies displayed short-term attraction to recently mowed plots (44). Use of a heavy roller on pastures in New Zealand gave more than 60% control of scarabaeid grubs, with negligible mortality of earthworms (168). Rainfall and irrigation patterns affect the distribution and abundance of grubs on golf courses and home lawns (59, 139, 143).

Work conducted in Ohio in the 1950s suggested that Japanese beetle oviposition preference and grub survival were adversely affected by high soil pH (132), but, in more-recent studies, manipulation of soil pH had little effect on Japanese beetles or European chafer grubs (200, 202). Because most turfgrasses grow best at pH 6–7 (14), manipulation of pH outside of this range would probably be impractical even if it did affect insect populations.

Host Plant Resistance

Laboratory and field screening has identified turfgrass genotypes that are relatively resistant, tolerant, or less preferred by particular insects or mites (for review, see 148). Notably, little work has focused on host resistance to mole crickets and almost none on scarabaeid grubs. Variation in cultivar damage ratings between trials and locations (e.g. 80) suggests that expression of resistance may be modified by different management regimes or by environmental conditions.

Turfgrass breeders have rarely attempted to combine genetic insect resistance with other desirable traits. Genotypes that have been released as new cultivars include Floratam and Floralawn St. Augustinegrass, which are resistant to the southern chinch bug (39, 149), and Bell rhodesgrass, resistant to rhodesgrass mealybug (148). Recently, some southern chinch bug populations in Florida have caused extensive damage to previously resistant Floratam and Floralawn (20), underscoring the potential for genetically variable pest populations to overcome host resistance.

The endophytic fungi, *Acremonium lolii* and *Acremonium coenophialum*, form mutualistic symbioses with perennial ryegrass and tall fescue, respectively (for reviews, see 34, 163, 164). Both endophytes are carried as intracellular hyphae in infected plants and are transmitted by seed via the maternal parent. Endophytes are not presently known from Kentucky bluegrass. The endophytes are associated with production of neurotoxins that cause toxicoses in livestock that graze on infected pastures (164), and efforts to remove the fungi to improve forage quality first revealed their importance in host defense.

Endophyte-enhanced resistance has been demonstrated for perennial ryegrass, tall fescue, and hard and Chewings fescues; cultivars are being marketed with high endophyte levels that enhance resistance to webworms, billbugs, chinch bugs, and other pests (57, 163). Endophyte-associated alkaloids are concentrated in stems, leaves, and seeds (163), but low levels in the roots may also deter some feeding by white grubs (D. A. Potter, unpublished data). Viability of *A. lolii* and *A. coenophialum* mycelium in seed declines during storage at ambient temperature, so seed of infected grasses will require refrigerated storage and certification to guarantee endophyte viability (164). Techniques now exist for transferring endophytic fungi between host grasses and to grasses not known to be hosts via inoculation (99) or by plant breeding (57). Augmentation of endophyte levels in grass species or cultivars with other desirable characteristics may provide a broad-based mechanism for developing new turfgrasses with multiple resistance to insects.

Prospects for Integrated Pest Management

Implementation of IPM for turfgrass faces many of the same hurdles that have been identified for other urban settings (15). Only a small number of specific, alternative control methods are available for turfgrass insects, and these often are slower acting, less reliable, or more difficult to use than conventional insecticides. From the industry perspective, aesthetic standards for lawns and golf courses leave little margin for error. Homeowners with little agronomic experience may be unable or unwilling to translate IPM information into appropriate action. Progress in IPM implementation will depend as much upon modification of public attitudes and expectations as on research advances and new technology. Indeed, it would be naive to assume that the public is ready to accept lower standards for lawns and sports turf in exchange for reduced pesticide usage and IPM programs developed by entomologists (22).

A small number of pilot IPM programs for turfgrass has been developed and implemented under special circumstances and on a limited scale (62, 71, 162). Acceptance of comprehensive IPM will probably be fastest among golf superintendents and other skilled landscape managers, many of whom already monitor their landscapes and use cultural tactics to minimize pest problems. The highly competitive lawn-care business poses special challenges because the time required to monitor and sample individual lawns may be prohibitive and because clients are perceived as more likely to cancel service if told that treatments are unnecessary. Traditionally, it has been simpler, more reliable, and more profitable for companies to apply routine, scheduled treatments than to hire or train qualified IPM consultants to engage in sampling, monitoring, and decision-making.

Nevertheless, growing public concern about potential environmental and human health risks of pesticides, and associated political and legal issues surrounding urban pesticide usage will almost certainly mandate much more limited and selective pesticide use on turf. Such concerns are creating a new market of pesticide-conscious consumers, and unprecedented incentives for the turfgrass industry to explore pest-control alternatives (58, 215).

Existing information on the ecology of turfgrass insects is meager. To target insecticides more efficiently, we must better understand how environmental factors affect pest populations. We presently know little about why particular sites are attractive to insects, or even how such routine practices as watering or fertilization affect insect abundance and damage. More work is needed on genetic and endophyte-enhanced host resistance, especially for key pests such as white grubs, chinch bugs, billbugs, and mole crickets. Simpler monitoring and sampling methods and better decision-making guidelines are needed to support the transition toward IPM. Relationships between the more easily sampled adult stages of holometabolous insects and subsequent larval densities would be especially useful.

Extramural funding for turfgrass entomology research has been and continues to be largely in the form of grants-in-aid from the agrichemical industry. Not surprisingly, insecticide-related topics have dominated the literature. Still more work is needed on the factors that limit insecticide performance, on new application methods (e.g. high pressure soil injection), on pesticide movement into soil and ground water, and on compatibility of pesticides with the beneficial fauna. Nematodes, microbial agents, and insect growth regulators will play a bigger role in IPM, but the factors that presently limit their performance must be better understood. Conventional insecticides will no doubt remain essential components of turfgrass IPM for the foreseeable future. However, there must be much greater research emphasis on the biology and ecology of turfgrass insects to reduce reliance on insecticides, and to increase the efficacy of those applications that are necessary.

CONCLUSIONS

By the year 2025, more than 85% of the North American population will reside in urban areas (195). Public perceptions of entomology will be governed more and more by our capability to provide safe, effective solutions to everyday pest problems. Demand for quality turfgrass with less usage of pesticides is providing strong motivation for the turfgrass industry to explore IPM and putting greater demands on the entomological profession to support this transition. Present meager levels of personnel and funding for turfgrass entomology must be expanded if these challenges are to be met.

ACKNOWLEDGMENTS

We are grateful to P. P. Cobb, K. F. Haynes, W. G. Hudson, D. J. Shetlar, and K. V. Yeargan for their comments on drafts of this review, and to our colleagues who provided reprints, unpublished manuscripts, and suggestions. We especially thank Gwyn Ison for her help in preparing the manuscript. This contribution (no. 90-7-10) is in connection with a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director.

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