IPM, What Has It Delivered?

A Texas Case History Emphasizing Cotton, Sorghum, and Pecan

Cotton, sorghum, and pecan are important commodities in the southwestern United States, where integrated pest management (IPM) has been researched and implemented for more than 25 years. Each of these crops is unique in the application and impact of IPM. Each commodity will be addressed with a brief history of the crop and a description of its pest complex to provide the context in which IPM was developed and applied. Then the impact of IPM in each crop will be assessed. Measurement of the impact of IPM requires a suitable time frame to allow a realistic assessment. IPM emerged as an answer to shortcomings of a reliance on chemical pest control (6,32). Producer management costs and amounts of pesticide used are relatively simple measures that begin to address the impact of IPM and will be used in these analyses. They are, however, inadequate measures to capture the full impact of IPM in many respects, including overall attitudes on pest control, interdisciplinary and interagency cooperation, education, food and fiber quality, short- and long-term effects on human health, legislation, commodity pricing, etc., which will be discussed in the summary.

Cotton

Cotton, *Gossypium hirsutum*, is a perennial shrub whose production is terminated artificially and temporarily to allow harvesting of fibers from mature bolls (Fig. 1). The economic success or failure of large areas throughout the southern United States has often hinged on this crop and its associated pests (Fig. 2). Early evidence of this comes from the now legendary invasion of the boll weevil, *Anthonomus grandis* (Boheman) (Coleoptera: Curculionidae), around the turn of the twentieth century, which devastated cotton-depend-

ent communities from the Lower Rio Grande Valley (LRGV) of Texas to Georgia (37). Cotton was eliminated as a crop in many areas and persisted with reduced production in the remainder through varied combinations of cultural, mechanical, and pesticidal controls, as well as a resigned determination to harvest a crop, however damaged, from what was often the only cash crop in the region (Fig. 3).

Use of early-maturing cottons, timely plant destruction following harvest, and migration of production to weevil-free areas were the principal practices that supported continued cotton production in Texas from 1900 to 1945. These practices worked best in the more arid 60- to 90-cm-per-year rainfall zone (36). Pesticides, particularly calcium arsenate, were used sparingly on irrigated cotton in more fertile, wetter regions, but this was a minor component of overall production and too cumbersome and unremunerative for lower yielding producers to adopt. The advent of DDT and other organochlorines with improved application machinery in the 1940s

appeared to make boll weevil (Fig. 4) management cheap and easy and was soon widely adopted. The temptation was to grow the crop longer to increase yield. Hand picking, not entirely phased out until the early 1960s, facilitated growing plants until frost.

Boll weevil resistance to organochlorines first became apparent in 1956, causing a switch to more frequent application of shorter residual organophosphates (OP) and carbamates to protect the crop from late-season pests. Within a decade, routine outbreaks of carbamate- and OP-resistant tobacco budworm, *Heliothis virescens* (Lepidoptera: Noctuidae) (Fig. 5), and other secondary pests were eliciting late-season pesticide applications at 5-day or shorter intervals in the worst-affected areas (e.g., LRGV, Brazos River Bottom) and causing damage throughout the state (2). Growers with traditionally the highest yields were often the most affected. The entire, recently revitalized cotton community viewed their plight, shared in varying degrees, with a trepidation seasoned by the

Fig. 1. Nearly mature cotton, A, and cotton defoliated and ready for harvest, B. (Courtesy W. Sterling)

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memory of the boll weevil invasion and the meager living to be made from cotton when insects could not be well managed. Yield per acre had been more than doubled since 1940 (Fig. 3), spreading prosperity far beyond the farm gate. Threats of cotton crop failure reverberated throughout society; the failure of 700,000 acres of cotton in northeastern Mexico due to *Heliothis* (1) provided vivid confirmation of the potential for devastation if alternative management practices were not developed.

Integrated pest management of cotton, funded in a pilot program from USDA-

APHIS, producers, and the Texas Agricultural Extension Service, began on 34,000 acres in 1972 with scouting action level concepts that delayed pesticide treatment until pest densities increased to damaging thresholds. This typically reduced pesticide treatments and allowed natural enemies to exert much greater levels of biological control, especially against secondary pests like the pesticide-resistant tobacco budworm. The scouting program provided an information conduit to producers, advisors, and researchers essential to both real-time decision making and further evaluation and

refinement of the program as it expanded from a four-person effort on cotton in 1972 to six in 1973, 23 in 1975, and 27 in 1995. The program also addressed sorghum, peanuts, pecan, corn, alfalfa, citrus, wheat, and vegetables in various degrees. The scouting effort provided a proving ground for reintroducing old and integrating new technologies into production programs on a real-time basis, correcting deficiencies and exploiting successes through timely evaluations among participants.

Entomological research during the late 1960s and 1970s carefully examined the boll weevil-cotton interaction and supported the earlier intuition of Mally (36) that boll weevil damage would be escaped if rapidly fruiting cotton could set a harvestable crop prior to second-summer-generation boll weevil densities reaching economic thresholds (Fig. 4). Commercially used varieties of the 1960s tended to drop early blooms and exhibited a prolonged blooming period, giving boll weevils ample opportunity to infest the crop. New cultivars were needed.

Funding provided to Texas A&M University by the Texas legislature in 1960 established a cotton breeding initiative for bacterial blight resistance (L. Bird, *personal communication*). This funding leveraged an effort to obtain resistance to a wide range of pests and stresses called multi-adversity resistance (MAR) and produced resistant germ plasm that was also rapid fruiting (4,36). Profitable yield was achieved in a shorter time with fewer inputs and a dramatically reduced threat from boll weevil and late-season secondary pests. Breeders, pathologists, agronomists, economists, and entomologists pursued an interdisciplinary focus to exploit the production characteristics of these cottons. Some consultants and farmers also recognized their potential early and adopted them into their programs. Research fund-

Fig. 2. Phenology of cotton and principal insect pests in Texas. Adjustment of date of planting, cultivar, cultural practices (irrigation, fertilization, row spacing, etc.), and pesticide type and frequency of use can affect intensity and duration of particular pest problems. Modified from Bohmfalk et al. (5).

TEXAS COTTON

Fig. 3. Cotton yield per acre in Texas from 1866 to present. Cotton acreage (not shown) increased until 1926, when declining soil fertility, cotton root rot, boll weevil, and the Great Depression reduced acreage until about 1945. Oil based agriculture through mechanization, pesticides, fertilizer, defoliants, irrigation, and price supports resulted in increased acreage and yields following World War II. BW = boll weevil entering Texas 1892, R = resistance of insects to pesticides; BAC BLT = bacterial blight breeding program initiated in 1960 that led to the multi-adversity resistant (MAR) short-season cottons grown in the 1970s and 1980s and now combined with new Delta cottons. LS = long-season cotton and SS = short-season cotton.

Fig. 4. Boll weevil puncturing a one-third grown square (developing flower bud) preparatory to oviposition. This activity, commencing 40 to 50 days after planting (DAP) cotton, prevents early boll set and allows boll weevil increase to devastating densities in the next generation, some 80 to 90 DAP. (Courtesy W. Sterling)

ing from the Rockefeller Foundation, EPA, and USDA through the Huffaker Project and the Consortium for IPM funded interdisciplinary research in the MAR program from the late 1960s to the mid-1980s, especially in the Coastal Bend region of Texas, where cotton production had waned in the late 1960s. The rediversification of agriculture in this area re-established a cotton-sorghum rotation on acreage tending toward monocultural sorghum. This rotation benefited sorghum production by reducing disease problems that had been on the increase (R. Frederiksen, Texas A&M University, *personal communication*), reduced buildup of cotton pests, and allowed ground water supplies to increase during sorghum-producing years for use the following season on cotton, which demands more water. The Extension cotton IPM program provided the institutional conduit for interfacing this technology with producers (5).

The Texas Pest Management Association (TPMA), formed in 1977, provided scouting services. Data were consolidated by Extension and used in decision making by producers (2). This additional implementation and educational component of the cotton IPM program also provided feedback on the overall cotton production program because it interfaced with existing producer practices regardless of their production approach. TPMA administered scouting services on more than 260,000 ha in Texas by 1980 (2), but the expanding program had reached implementation limits with 23 county extension entomology professionals, each serving as a scout supervisor and farm advisor for 2,000 to

6,000 ha. Cotton acreage has varied from 2 to 4 million ha since 1950, and a scout supervisor is most efficient with 4,000 to 5,000 ha of responsibility (2). The proposed solutions were to train paraprofessionals to provide supervisory and scouting support, thereby freeing the county entomologist to train supervisors, scouts, farmers, and consultants in order to introduce new technologies into IPM and to encourage producers to use private consultants where IPM needs warranted it. Private consultants in Texas increased from 15 in 1972 to about 115 in 1986, and the statewide Pest Management Program has become more involved in education and technical support, with TPMA and private consultants performing scouting (14).

The MAR cottons became commercially available in the early 1970s. Their short-season characteristics ideally suited them to cultural management of boll weevil with minimum pesticide intervention. Other factors—irrigation, fertilization, row spacing, planting time, growth regulators, desiccants, and stalk destruction protocols that established a harvestable crop quickly, matured it early, and destroyed the residue before harmful pests could accumulate to overwinter and plague production the following year—were also incorporated into the cotton IPM program. Computer-based models were also developed as prediction and decision aids (MOTH-ZV, COTFLEX, and TEXTIM) (15,31) and used in conjunction with field data obtained by pheromone trapping and TPMA scouting for pests and natural enemies.

Shared experience accumulated during the 1960s and 1970s showed program pes-

ticide treatments for early-season pests, most notably boll weevil, increased vulnerability to late-season outbreaks of tobacco budworm and bollworm, so that IPM efforts focused on reducing the need for early-season program treatments (2). The advent of synthetic pyrethroids in the late 1970s initially provided spectacularly effective control of late-season pests. They were adopted because yield increases could

Fig. 5. Control of early-season pests with broad-spectrum insecticides also kills natural enemies of secondary pests like tobacco budworm and bollworm (*Helicoverpa zea* (Lepidoptera: Noctuidae)). Development of pesticide resistance by secondary pests released from natural enemies results in devastating epidemics that destroy cotton bolls.

Fig. 6. Tropical wild-type sorghums are unsuitable for commercial production using mechanized agriculture, yet contain genetic variability essential for sorghum improvement. The Sorghum Conversion Program begun in 1963 uses the sterile male technique to develop shorter, more agriculturally suitable plants (23). (Courtesy G. Teetes)

Fig. 7. Sorghum midge oviposits in flowers, and larvae prevent seed development. This multivoltine pest begins development in Johnson grass in the spring and increases in density with succeeding pest generations as long as hosts are available. Late-planted sorghum can be devastated. (Courtesy G. Teetes)

initially be obtained with a single late-season treatment. By the mid-1980s, tobacco budworm resistance to pyrethroids triggered resistance management modifications to IPM where in-season monitoring in sensitive areas allowed determination of resistance levels and likely effectiveness of pesticide treatments (28). By the late 1980s, new Delta cottons, which matured about 10 days later than the MARS but about 30 days earlier than cultivars grown in the 1960s, began to be widely planted because of yield, strength, and fiber length characteristics (10), despite their increased exposure to late-season pest problems.

There is a rough balance among risk from boll weevil (and secondary pest problems that ensue when pesticides must be used several times in the early season), length of growing season, and yield. Weather factors can also affect length of growing season by 10 to 14 days above (wet) or below (dry) the average for a given cultivar to produce a given yield. The Delta cottons have been widely adopted by producers because the average yield per acre represents an approximately 20% increase over standard MARS, and to date the increased risk inherent in the longer season has been manageable.

The cotton IPM program in Texas began with a scouting and action level effort on conventional cotton cultivars in 1972 to properly time needed pesticide treatments in a pilot program. This effort was expanded in 1975, when results indicated the approach was effective. New IPM tools and approaches were developed from new cotton cultivars, cultural controls, fertilizer, irrigation, growth regulator, desiccant, pheromone, insecticide, and better understanding of pest plant–natural enemy relationships. Crop diversification and rotation, especially with sorghum, also allowed mutual escape from pests through time and varied crop demands on the soil. These practices allowed yield increases achieved by chemical agriculture to be conserved through IPM (Fig. 3). Commercial availability of Bt transgenic cottons in 1996 and boll weevil eradication efforts in Texas have resulted in new IPM opportunities and challenges (15). Current production practices seek the highest yield possible given all constraints, and IPM has been adapted and readapted to this dynamic endeavor.

Sorghum

Sorghum, *Sorghum bicolor* (L) Moench, is believed to be native to Africa, perhaps to Abyssinia (21). It became widely planted in the United States in the nineteenth century as broom corn, durra, rice corn, and sorghum, and Sturtevant predicted it “will probably not be grown as a food grain except in arid regions.” Principal producing states today are Kansas, Texas, and Nebraska, with about 30, 30, and 15%, respectively, of the 4 to 5 million

ha currently grown for animal feedstocks. Selection and breeding has resulted in converting this tall, large-stemmed, perennial, tropical grass (Fig. 6) to some 17,000 cultivars. Selected F₁ hybrids grow to about 1.6 m in height to produce a mechanically harvestable, heat- and drought-tolerant crop in 100 to 140 days (23). Sorghum is a key low-input rotation crop with cotton and other row crops in Texas and historically a reservoir for natural enemies of many crop pests (35).

The sorghum pest complex consists of a wide range of arthropods and pathogens whose ravages have waxed and waned during the past century in Texas, primarily

in response to climatic variations and the genetic makeup of the cultivars under cultivation (13,34). Pest protection of sorghum prior to 1940 was based on trial-and-error selection of hardy cultivars coupled with planting timed late enough so soil temperature and moisture would allow germination that was rapid but early enough to escape late-summer generations of sorghum midge (Fig. 7), *Contarinia sorghicola* (Diptera: Cecidomyiidae), at harvest. Pesticides (except seed treatments) were and are used reluctantly because slim gross returns leave little margin for additional overhead. Vigorous breeding programs conducted by land grant universities,

Fig. 8. Greenbug on sorghum. The unexpected destructive appearance of this aphid in epidemic numbers on sorghum in 1968 caught scientists and producers by surprise. Greenbug devastates plants outright and also vectors *Maize dwarf mosaic virus* (34). (Courtesy G. Teetes)

Fig. 9. Sorghum resistance to greenbug allows crop production without insecticides (resistant plants on right and susceptible on left). (Courtesy G. Teetes)

USDA, and private seed companies currently screen for and incorporate resistance as a primary protection against pests.

The need for a new plant protection effort in sorghum occurred in 1968 when greenbug, *Schizaphis graminum* (Homoptera: Aphidae), a well-known pest of small grains in the spring and fall, became epidemic on sorghum (Fig. 8) in the summer months (8). This unexpected outbreak was initially met with repeated insecticide sprays. They were effective at first, but they were ecologically disruptive, expensive, and soon resulted in pesticide-resistant greenbug populations and outbreaks of other pests previously under biological control (33). The greenbug epidemics brought entomologists, breeders, plant pathologists, industry, politicians, and others together to achieve short-term answers and long-term progress. The IPM ideas of Stern et al. (32) found receptive application in sorghum with the impetus of the greenbug. By the early 1970s, the initial research and development needed to implement a sorghum integrated pest management program was available (13,33,34). This included a pest inventory, cultural controls, resistant cultivars, biocontrol strategies, economic thresholds, pesticide strategies, and a communication system to articulate results to producers. Refinements have followed.

Then and now, the program recognizes two key in-season pests, greenbug and sorghum midge, and many secondary and occasional pests. The strategies were integrated into existing disease and weed management systems and emphasized preven-

tive control measures such as crop destruction, crop rotation, good seed bed preparation, early planting, planting disease- and arthropod-resistant cultivars, and using pesticide-treated seed. Periodic monitoring of the crop was then performed on an as-necessary basis to ensure that damaging levels of pests were prevented, with pesticides as a last resort. The foundation of sorghum IPM is host-plant resistance to diseases and insects, combined with cultural control measures and back-stopped by scouting and pesticides only as justified. The resistance program emerged from the Sorghum Conversion Program begun in 1963 (23), which had developed a strong disease resistance component by 1968 (13). Insect resistance (Fig. 9) was incorporated in a rigorous way following the greenbug epidemic (34). The interdisciplinary, interagency, international research effort interfaced with Extension, seed companies, and producers to develop high-quality, high-yielding cultivars requiring minimum pesticidal protection. The disease resistance component, despite numerous genetically variable pathogens, has been remarkably reliable in providing continuous protection to farmers' fields once resistance was incorporated into commercial cultivars (13; R. Frederiksen, *personal communication*). Contingency work, however, has been done to identify new pathotypes (of downy mildew for example) and incorporate resistance to them into elite lines to ensure remedies are available should anticipatable epidemics occur. Sorghum insect resistance to greenbug has been thwarted periodically by

biotypes that require pesticide management until new resistant cultivars can be deployed. This occurred in 1968 (biotype-C), 1980 (E), 1990 (I), and 1996 (K) (29). The scouting-economic threshold components of sorghum IPM increase in importance during such periods.

Impact of sorghum IPM on producers. Sorghum producers were surveyed in 1987 (22), 1992 (24), and 1997 (35) regarding IPM practices and pesticide use. Based on stringent criteria set by IPM specialists, 87.4% of Texas sorghum growers can be classified as IPM users on an estimated 1.3 million sorghum ha in the state (35). IPM practices include tillage (85%), rotation (92%), seedbed preparation (94%), resistant cultivars (85%), scouting (81%), economic thresholds (78%), early planting (72%), and seed treatment (60%). The costs and benefits of these practices have not been calculated, but the availability and use of resistant cultivars conserves 30% of the yield potential of the crop based on disease and arthropod effects on known susceptible cultivars (27,38). The use of scouting and economic thresholds is estimated to cost \$4 to \$6/ha and to eliminate at least one insecticide treatment (\$15/ha) while ensuring that the timing of needed treatments provides maximum yield conservation. The economic portion of the crop at risk is 30% of production on 1.3 million ha (4 billion kg, valued at \$450 million) with scouting costs of \$5/ha and pesticide savings of \$15/ha or \$11.2 million in savings. A review of the value of the INTSORMIL program that included pest resistance in sorghum as a key com-

Fig. 10. Native range of pecan, A, and infrared aerial photograph, B, of mixed wild trees (top), orchard pecan (left center) and a pure stand of native pecan (right). Pecan break bud later than other trees and appear green to gray in the photograph; the river channel from upper right to lower left is blue. (Bill Hart, USDA Citrus Insect Lab, Weslaco, TX)

ponent of variety improvements concluded a net welfare gain of \$389 million to the United States (11).

Pecan

Pecan, *Carya illinoensis* Wang. (K. Koch), is indigenous to most of Texas. The wild tree still comprises some 60% of nut production, with the remainder coming from vegetatively propagated orchards (Fig. 10). The pest complex (Fig. 11) is for all practical purposes also indigenous and has evolved with the pecan (16). Some pest species have expanded their range as vegetatively propagated trees extended the range of the pecan. The wild trees are typically thinned of competing trees and brush to produce a grass understory to accommodate cattle grazing, and are rainfed. These semi-domesticated trees and their nuts are called natives. Vegetatively propagated orchards may be irrigated or rainfed. There

are about 40,000 ha of vegetatively propagated pecans, 50,000 ha of managed wild pecans, and another 50,000 to 100,000 ha of unmanaged wild pecans in Texas that may be harvested in years of high production.

Pecan habitat is typically deep, well-drained bottomland soils adjacent to rivers and streams. Trees live upward of 150 years and can reach 30 m or more in height with a 2-m trunk diameter. Wild trees in closed canopy environs bear synchronously at irregular intervals of 2 to 7 years, and orchard trees bear annually when young but tend toward biennial bearing when crowding begins to occur (18). Yields in bearing years are about 500 kg of nuts per ha, but intensive orchard management can result in 2,000 kg/ha for sustained periods. Nuts from natives are about 45% kernel and require 200 to produce 1 kg, whereas improved vegetatively propagated pecans shell out to about 55% kernel and require

100 for 1 kg. Prices vary, but native pecans usually market at about 65% of the price of improved pecans.

Integrated pest management of pecan in the Southwest began in the early 1970s with research on arthropods to determine phenology, pest status, economic injury levels, and interactions with pecan (19,30). Resulting IPM programs in vegetatively propagated orchards benefited from disease-resistant cultivars from the USDA Pecan Breeding Program (16). In Texas, a pecan IPM coordinator was hired by Extension in 1977 to facilitate implementation of IPM. This catalyzed efforts by Extension personnel (horticulture, plant pathology, entomology, etc.) from county agents to those with regional and statewide responsibilities to consider pecan IPM. The position was originally held by a horticulturist and is now occupied by an entomologist. The pecan IPM coordinator in Texas provided interdisciplinary linkage, interagency linkage into the Experiment Station research effort, and linkage to producers through the Texas Pecan Growers Association. A recent review of the economic impact of the pecan IPM program in Texas provides a more detailed context regarding how pecan pest control has evolved to the present (20).

Pecan pest complex. The principal problems on pecan are zinc deficiency, pecan scab, nut-feeding insects, and foliar

Fig. 11. Pecan and pest phenologies emphasizing critical management periods. Pecan IPM focuses on including a pesticide in the tank mix only when the crop is demonstrably at risk from a pest.

Fig. 12. Pecan nut damage caused by pecan nut casebearer in the early season, A, pecan weevil in the late season, B, and pecan scab, C.

insects and diseases (Fig. 12). Each can prevent a harvestable crop from being grown (Fig. 13). The pecan aphid complex produces honeydew residues throughout the summer that can incite growers to take action as well. Workers until the early 1970s advocated regular foliar sprays of zinc, fungicide, and insecticide to prevent damage (20). These materials were usually tank mixed even when only one material was thought necessary.

Research resulted in a better understanding of pest biology–damage relationships, and monitoring methods for use in decision making were developed that allowed better timing of needed spray decisions to be made with more confidence. The advent of the formal pecan IPM program in 1977 provided needed linkages and feedback to implement this information (7). A fundamental tenet of this program was to apply a pesticide only when a damaging pest was present in damaging numbers. This meant avoiding tank mixes unless they were justified. This approach was not initially accepted by all disciplines

or growers, and many coordinative efforts were needed to speak with one voice on this subject. In retrospect, the most convincing action to generate interdisciplinary and interagency consensus was a 5-year field research–demonstration interdisciplinary study headed by the Extension pecan IPM coordinator comparing conventional, IPM, and nutritional control treatments that showed IPM was economically competitive while drastically reducing pesticide use (20).

Impact of pecan IPM. Producer surveys conducted on four occasions from 1981 to 1997 allowed a determination of pesticide application programs during that period (20). Zinc application changed little, while fungicide and insecticide treatments were reduced significantly by conventional and IPM practitioners, with the latter consistently treating less (Fig. 14). Yield comparison between conventional and IPM producers (20) showed that the latter produced generally higher yields despite applying less pesticide. Producers in Texas reduced fungicide use 30%, insecticide use

35%, and the overall number of applications per season 9% from 1980 to 1997. The overall economic benefit to pecan producers due to the pecan IPM program in Texas was estimated to be \$6.06 million per year during 1990 to 1996 (20). This benefit would have been higher but for the loss of the insecticide phosalone (Zolone) to producers through voluntary withdrawal by the manufacturer (17). The insecticide component of the Texas pecan IPM program has been significantly reduced (Fig. 14), but remaining use is still primarily dependent upon pre-1980s chemistry (Fig. 15). This circumstance is unusual because pest resistance has rendered this old chemistry useless on most crops. Judicious use of pesticides on pecan in Texas, however, has retained its biological efficacy. The irony is that legislation and economics of pesticide production may eliminate chemical options kept viable because of IPM.

Environmental benefits that can be calculated for the pecan IPM program in Texas account for less pollution of the sensitive riparian environments where pecan are primarily grown. This is calculated from consolidated data from three surveys between 1990 and 1996 that show the average conventional pecan producer in Texas reduced fungicide sprays by 1.45 and insecticide sprays by 1.35 per season, and that IPM producers reduced fungicide sprays by 1.35 and insecticide sprays by 2.15 per season compared with 1980 (20). The average amount of fungicide and insecticide was calculated from labeled rates and adjusted for each material based on use frequency reported by producers, which results in a reduction of 8.5 kg a.i./ha per season for conventional producers and 12.21 kg/ha for IPM producers. Given 54,819 managed ha of pecan in Texas (11,547 improved under conventional management, 10,530 improved under IPM, 17,146 native-conventional, and 15,596 native-IPM, respectively), a reduction in pollution of 243,816 kg of pesticide by conventional producers and 319,056 kg by IPM producers, totaling 562,872 kg, resulted annually during 1990 to 1996.

The reduction of pesticide use also affects energy use, which was calculated to be \$381,760 in annual energy savings in 1993 (M. K. Harris and B. R. Ree, 1994, unpublished data). These savings result in less demand for nonrenewable resources and reduced rates of pollution from such sources. Decreased health risks to the operator, pesticide residue in food, pollution of soil, water, and air, pesticide resistance by target and secondary pests, and increased effectiveness of natural enemies in preventing pest outbreaks also occur but are difficult to quantify. Public benefit of IPM results from these effects and would probably be found to outweigh the economic benefits, which are presently tractable calculations.

Fig. 13. Yield losses totaling 21.5% of the overall crop from the 12 leading arthropod and pathogen pests reported by Texas pecan producers in surveys from 1989 to 1996.

Fig. 14. Pesticide applications per season reported by Texas pecan producers in 1981 compared with 1997 following IPM implementation. Producers in 1977 identified their program as conventional (CONV.) or IPM. ZN = zinc, FUNG = fungicide, and INSEC = Insecticide. This compares with about 30%.

Impact of IPM

The impact of IPM on cotton, sorghum, and pecan in Texas must recognize more than relative profitability to agricultural producers. IPM has permeated the entire society, affecting public attitudes on how we can and want to conduct plant protection. In turn, these attitudes affect the way we educate, research, and implement solutions to pest problems, the industries that serve that process, and the legislation and agencies that govern quality food production and environmental health. Nevertheless, without producer profitability, no agricultural program, however meritorious in other respects, could succeed for very long.

Economic. The cotton IPM program has been reviewed many times and in many ways. In 1976, producers were found to increase net returns by \$56/acre using IPM, and insecticide use on cotton in Texas had decreased from 19.3 million lb. in the mid-1960s to 2.3 million lb. by the mid-1970s (note this is before pyrethroids with their 10-fold rate differential became widely available in 1979 and made such comparisons more problematic [2]). Norton and Mullen (26) include 11 documented economic evaluations of Texas cotton IPM and report overall increased net returns of 10 to 387% and overall decreased pesticide use for IPM users.

The major component of sorghum IPM, host-plant resistance, has been evaluated for greenbug (9) and sorghum midge (12). Net returns without insecticides for users of greenbug-resistant sorghum were 21% higher than those of nonresistant sorghum users, and the former used 22% less insecticide than the latter (9).

The pecan IPM program has reduced insecticide use 35% and fungicide use 30% while maintaining needed zinc treatments and resulting in overall higher yields for IPM users, for an overall economic benefit to producers of \$6.06 million/year during 1990 to 1996 (20).

Interdisciplinary. Academic disciplines remain relatively autonomous, especially within our academic institutions, as organized entities for obtaining and transmitting knowledge on specific subjects. The research, teaching, and technology transfer of IPM is best served by utilizing many disciplines. The cotton, sorghum, and pecan IPM programs in Texas interface agricultural economics, agronomy, entomology, horticulture, plant pathology, and others in conducting plant protection with producers. Their respective beginnings from MAR cottons, the Sorghum Conversion Program, and interdisciplinary evaluations of pecan pest management are specific examples. The disciplinary inter-relatedness of current plant protection has been aided greatly by IPM as a focused philosophy emphasizing holistic solutions. The challenge is to present the ability to learn and progress provided by each disci-

pline while continuing to broaden interdisciplinary interactions catalyzed by IPM.

Interagency. The practice of IPM requires educated vigilance and adaptability, which depend on new students, continued research, and experienced practitioners of continuing education interacting with federal, state, and private agencies and producers. IPM has given rise to a new organization, TPMA, and served as a basis for changing curricula and organizing and implementing research. Because IPM also has a concern for environmental health and producer profitability, it serves as a common ground for debate, interagency interaction, and legislation on these issues.

Private sector. By providing a philosophical base encouraging newer, greener technology, IPM provides a receptive proving ground for selective chemicals, hormones, pheromones, plant growth regulators, transgenics, and other agribusiness wares that seek an agricultural market. IPM also encourages service industries such as private consultants whose expertise is needed to implement IPM as these technologies are introduced.

Environmental. IPM has hastened the reduced use of pesticides by: (i) more judicious application of broad-spectrum poisons, (ii) aiding development of selective

chemicals, (iii) planning reliable production systems that are less dependent upon chemicals, and (iv) implementing decision making processes that allow "no chemical needed" solutions to be made with confidence.

Academic. The first course of Insect Pest Management at Texas A&M was offered in 1974 (ENTO 401), and an interdisciplinary course in host-plant resistance (AGRO/ENTO/PLPA 610) was offered in 1975. These and courses that came later, such as Weed Ecology, resulted from the perceived need for curricula that addressed IPM. Many IPM practitioners in Texas today obtained their initial exposure to IPM through these new courses. The IPM approach impacted academia by stimulating new curricula and is now reciprocally affected as practitioners improve and extend IPM theory and practice. This important aspect of IPM has received little attention and less direct funding.

Future of IPM

IPM is a convenient descriptor for the wide range of still-evolving pest control programs that emerged from the chemical prophylaxis practiced in the 1950s. IPM theory has fostered a transition from primarily chemical control to programs tem-

Fig. 15. Pecan insecticide use frequency compared with insecticides under review by the Food Quality Protection Act (FQPA) of 1996. This act requires the Environmental Protection Agency to review older previously labeled pesticides to determine if the label should be continued. The prospect of this expensive process often results in preemptive economic decisions by industry to withdraw the pesticide irrespective of agricultural utility and ecological risks, especially where only small markets for the product remain.

pered with biological information and input tailored to each agroecosystem, crop, and pest situation in practice. Chemistry now has value-added components based on biological considerations of how, where, when, why, and which chemicals will be used. Yet many problems remain to be solved, including pest resistance to chemicals and pollution. Some fault IPM and have called for a paradigm shift in pest-management theory from managing components or individual organisms to an approach that examines processes, flows, and relationships among organisms (25). Others note IPM has far to go before theory can be put to practice (3). All seem to agree that more biological information and input are needed.

IPM has contributed much in both theory and practice. It now provides a convenient stump to engage debate on agricultural policy and practice. Public demand for high quality and quantity food and fiber, available at reasonable cost in dollars and to the environment, ensures continuing attention will be paid to how we solve pest problems to conserve valued resources. However, aggressive leadership must emerge in the land grant universities, the U.S. Department of Agriculture, and other public agencies and the private sector to maintain and extend existing IPM progress.

IPM successes have been achieved by combining a wealth of organismal-, population-, and community-based biological information (primarily gathered over the past century prior to IPM) with more recently acquired chemical technology and adding a little newly obtained biological and ecological insight. Major public funding for IPM in the 1970s provided the resources needed to establish most programs extant today. New biological research has been increasingly focused at the molecular level for the past two decades. Entomology, plant pathology, and weed science departments, the disciplinary core of IPM, have been combined into other departments at many land grant universities over the same period. Development of new fungicide and especially herbicide chemistry during this period has outpaced new insecticide chemistry and has been met with resistance and pollution problems just as entomology was previously. Transgenic plant technologies emerging as proprietary products from industry are based on excellent subcellular science but currently are deficient in the backstopping capabilities provided by scientists trained to address problems at the organismal, population, and community level, due to the erosion in their ranks already mentioned. Relying on subcellular breakthroughs achieved in the laboratory to sustain effectiveness of transgenics in production agriculture systems with minimal commodity and ecological community oriented expertise unduly risks a dependable supply of food and fiber produced safely and affordably. IPM has a role

to play in production agriculture for the foreseeable future. The question is, will it be as an afterthought addressing failures of new technologies, or as an integral component of the research and technology transfer process in production agriculture?

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