Cropping Systems and Integrated Pest Management: Examples from Selected Crops

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SUMMARY. Cropping systems have been central to managing associated pests for centuries. This treatment focuses on the history, concepts, and the integration of available Integrated Pest Management (IPM) tools/strategies into cropping systems. Pest assessments/diagnoses, IPM-decision-making aids, and examples of pest management in selected crops/cropping systems (wheat, soybean, corn, cotton, potato, and strawberry) as well as emerging opportunities and challenges are discussed. The evolving philosophy of IPM and the recently renewed emphasis on ecologically based pest management address the fact that significant levels of predation and/or parasitism are desirable insofar as they promote diversity and sustainability of agroecosystems. Thus, cropping systems are beginning to focus on soil and crop health as well as specific IPM and production goals. Although extensive efforts have been directed toward modeling the many interactions between crops, associated pests and the

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environment, the general implementation of a systems approach to integrated crop and pest management remains to be accomplished.

KEYWORDS. Agroecosystem management, biological control, chemical control

INTRODUCTION

Cropping systems have been central to managing some crop pests for centuries. An early cropping system that evolved specifically to avoid the low yields associated with the potato cyst nematodes (*Globodera rostochiensis*) in Peru included rotation and fallow (Bridge, 1996). The concept of utilizing multiple management tactics was pioneered by Kühn (1888) when he tested fumigation, rotation, and cover crops as means of controlling the sugar beet cyst nematode (*Heterodera schachtii*) (see Campbell, Peterson, and Griffith 1999). However, the term Integrated Pest Management (IPM) was first used by Smith and van den Bosch (1967) in regards to controlling insect pests. The modern concept of IPM evolved from the initial concept of "Integrated Control," as developed by Stern et al. (1959).

Many definitions of IPM have been offered. A useful definition of IPM adopted by the National Coalition on Integrated Pest Management is as follows: "A sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks" (CAST 2003a). That definition, however, loses some of the aspects contained in earlier concepts of IPM, including the use of decision rules based on ecological principles, economic/social considerations, and a multidisciplinary approach (Rabb and Guthrie, 1970; Kennedy, 2000). Two recent publications, "Ecologically Based Pest Management" (EBPM) (National Research Council, 1996) and "Ecological Management of Weeds" (Liebman, Mohler, and Staver, 2001) stressed the importance of ecological considerations in pest control. Widespread concerns about the detrimental impact of pesticides on the environment and related health issues were responsible in large part for the development of the concept of IPM (Kennedy, 2000). In fact, the publication of the book "*Silent Spring*" by Rachael Carson in 1962 ignited widespread discussion/debate on the real and potential hazards of pesticides. This still ongoing dialogue includes scientists in many disciplines, environmentalists, and policy makers. *Silent Spring* contributed much to the development of alternatives to pesticides for pest management purposes, augmented global interests in developing cropping systems that limit crop pests, and added much to the environmental movement. Diverse publications continue to re-visit Carson's 1962 landmark treatment (van Emden and Peakall, 1996; Waddell, 2000).

Several related concepts interface with IPM, including "Integrated Crop Management" (ICM), or Integrated Farming Systems (IFS) as used in a number of countries (El Titi and Ipach, 1989), "Good Agricultural Practices" (GAP), and "Sustainable Agriculture." "ICM is a whole farm management strategy that uses IPM as a component, minimizes waste and pollution, safeguards natural farm assets, enhances energy efficiency and manages crop profitability" (Carroll, 2000). ICM systems are dynamic and encompass the latest research and technology, based on expert advice and experience. GAP is defined as "efficient production of good-quality food, feed, and fiber while maintaining natural resources and optimizing crop inputs to minimize environmental impacts and ensure responsibility for the health and safety of farmers" (Carroll, 2000). The concepts of IPM, ICM, and GAP, while sharing considerably in overall goals, provide much of the infrastructure of Sustainable Agriculture (Carroll, 2000).

Fundamental to effective IPM programs is the development of appropriate pest management strategies and tactics that best interface with cropping system-pest situations. A pest management strategy is the overall plan to eliminate or minimize the pest problem. A pest management tactic, in contrast, is a method used to implement a given strategy (Barker and Koenning, 1998; Pedigo, 1999). Depending on the type of pest, some of the primary management strategies include: exclusion, eradication; reduction of pest population numbers; reduction of crop susceptibility; combination of reduced population numbers and crop susceptibility; or do nothing (Agrios, 1997; CAST, 2003a). As discussed later, a first critical step in IPM is to secure site-specific information on pest incidence/levels and soil nutrient status. In addition, an understanding of the life cycles or history and ecology of the pests as well as the epidemiology of diseases is helpful in the formulation of IPM strategies and tactics.

Additional aspects of the evolving IPM concept included: the influence of the total agroecosystem on pest problems; the recognition that only certain levels of pest infestations caused crop damage; and the philosophy that multiple tactics or methods should be used to manage single pests or pest complexes (Kennedy, 2000). Because plant pathogens and weeds have very divergent characteristics versus those of insects, IPM has often been viewed as an activity among entomologists. While population levels and economic thresholds often can be determined for insect infestations, the rather different natures of many plant pathogen, weed, and nematode communities frequently require very different assessments as discussed herein.

Estimated annual yield losses due to a wide array of pests on food and fiber crops amount to 40% in the U.S.A. and 48% worldwide (Agrios, 1997). Worldwide estimates of yield losses to the various pests range from 5 to 12% annually for plant-parasitic nematodes (Koenning et al., 1999), 12% for insects and 12% for plant pathogens, and 10% for weeds (Agrios, 1997). Recent estimates on dollar losses to weeds in the U.S.A. include $4 billion annually in direct losses and $6 billion for herbicides (Liebman, Mohler, and Staver, 2001). The magnitude of these losses emphasizes the crucial importance of effective pest management. These economic losses also have instilled into growers a high sensitivity for risks associated with crop pests. In earlier years, for many growers, limiting these risks meant high pesticide usage as crop insurance. In some countries such as the United States, crop insurance is being viewed as a means of minimizing associated production risks–including risks sometimes encountered with minimal pesticide use. In addition, IPM certification may eventually enable private insurers to offer crop protection insurance products (CAST, 2003a).

Pest population assessments, in addition to being central in minimizing the use of unnecessary pesticides, are used in decision making related to cropping systems, including appropriate crop rotations, selection of pest-resistant cultivars, or a combination of pest-management strategies/tactics. Field histories related to pests are especially important for soilborne organisms such as plant-parasitic nematodes and soil-inhabiting insects as well as fungi, bacteria, and weeds. With the advent of precision agriculture, site-specific treatments of weed infestations and other crop pests can be utilized to further limit use of pesticide applications to mini-sites in given fields where they are needed (CAST, 2003a; Renner, Swinton, and Kells, 1999). Other new technologies, especially those related to genetic engineering, identification and populations-assessment methodologies, and integrated systems are having profound impacts on IPM and related cropping systems. For example, more than 50% of the soybeans (*Glycine max* L. Merr.) and cotton (*Gossypium hirsutum* L.) currently produced in the United States are herbicide-tolerant lines. The increased use of Bt-transgenic cotton from 1995 to 1998 resulted in a reduction of some 1.1 million liters of insecticides on that crop (CAST, 2003a).

The objectives of this article are to provide a synopsis of the concepts of IPM, the integration of available strategies and tactics into selected cropping systems, and related challenges. In the U.S., progress in the development and implementation of IPM tactics in suitable cropping systems has been heavily impacted by government polices and programs. The EPA in 1993 renewed support by setting a goal that IPM practices would be implemented on 75% of the nation's cropland by the year 2000; this goal included the reduction of pesticide use and associated risks (CAST, 2003a; GAO, 2001). In 1994, the USDA announced a related initiative to facilitate achieving the 75% goal by 2000 through research, outreach, and education (Benbrook et al., 1996; CAST, 2003a; Fernandez-Cornejo and Jans, 1999; GAO, 2001; Merrigan, 2000). The objectives of the UDSA 1994 IPM Initiative grouped various related farming practices (similar to those listed in Tables 1 and 2) into four categories: Pre-

TABLE 1. Cropping systems and other strategies and tactics used in IPM

Management practice[a]	Options	Utility per pest group[b]			
		Insects	Weeds	Pathogens	Nematodes
Crop Rotations	Continuous	0/--	+/--	0/--	0/--
	2-year	++/--	+/--	+/-	+/-
	≥ 3-year	++/--	+/-	++/-	++/-
Fallow	-	?	--	++/-	++/-
Cover crops	-	+/--	+/0	+/0	++/0
Refugia	-	+/0	NA?	0/-	NA
Tillage	No-Till	+/--	+/--	0/--	+/-
	Chisel	0/-	0/-	+/-	+/-
	Moldboard	+/-	+/-	++/-	-?
Planting Date	Early	0/--	+/-	+/0	+/0
	Late	0/--	+/-	+/-	+
Plant Population	Low	0/-	-	+/-	NA
	High	0/-	+	+/-	NA
Row Width	Narrow	+/0	+/0	0/--	NA
	Conventional	0	0/-	+/0	NA
Cultivation	Early	0	+/-	0	+/-
	Late	0	+/-	0	+/0
Pesticides	Foliar	++/--	++/-	++/-	+/NA
	Seed	?	++/0?	++/0	+/0
	Soil	++/NA	++/0?	++/NA	++/-
Sanitation	-	+/0	+/0	++/0	++/0
Resistant varieties	-	++/NA	++/NA[c]	++/-	++/-
Biological controls	-	++/NA	+/NA	+/NA	+/NA
Soil amendments	-	+/0?	+/0?	+/0	+/0
Field size and Borders	Small/borders	+/-	NA	0/--?	NA
	Large w/o borders	0/-	NA	0/--?	NA

[a] In part, adapted from Cavigelli et al. (2000).
[b] Symbols codes as follows:
0 = No or little effect on pest risks
\+ = Limits pest risks
++ = Greatly limits pest risks
\- = Slight increase in pest risks
– = Strong increase in pest risks
NA = Not applicable.
? = Definitive information lacking
[c] Herbicide tolerant crop cultivars can greatly limit weed risks.

TABLE 2. Pest management practices, field crops, 1996 (adatped from Fernandez-Cornejo and Jans, 1999).

Cultural techniques are the leading pest management practice for field crops

Item	Corn	Soybean	Cotton	Fall potato	Winter wheat	Spring wheat	Durum wheat
				Percent of planted acres			
Biological Techniques							
Considered beneficial insects in selected pesticides	8	5	52	29	10	4	12
Purchased and released beneficial insects	*	*	*	0	*	*	0
Used pheromone lures to control pests	na	*	7	2	*	1	0
Used *Bacilllus thringiensis* (Bt)[2]	2.4	1.6	4.1	*	*	0	0
Cultural Techniques							
Adjusted planting or harvesting dates[3]	5	6	25	7	19	11	13
Used mechanical cultivation for weed control	51	29	89	86	na	na	na
Used a no till system	19	33	na	na	3	4	7
Crop rotations[4]							
Continuous[5]	18	11	67	2	42[11]	14	10
Rotation with other row crops[6]	54[8]	63[9]	15	2	2	2	0
Other[7]	28	26	18	96[10]	56[12]	83[13]	90[14]
Pesticide Efficiency							
Alternated pesticides to control pest resistance	31	28	41	69	13	38	32
Monitoring							
Used pheromone lures to monitor pests[1]	1	*	33	3	*	4	1
Used soil biological testing to detect pests such as insects, diseases, or nematodes	2	3	9	46	2	0	0

[1] For corn, pheromone lures were used to monitor black cutworm.
[2] Percent of insecticide-treated acres for Bt.
[3] Adjust planting dates only for corn.
[4] Crop rotations include 3 years 1994, 1995, and 1996. Column crop heading is for crop planted in 1996.
[5] The same crop was planted in 1994, 1995 and 1996.
[6] A crop sequence, excluding continuous same crop, where only row crops (corn, soybeans, sorghum, cotton, and peanuts) were planted for three consecutive years.
[7] Other excludes continuous same crop and rotation with row crops and includes fallow or idle.
[8] 49 percent of corn-planted acres were in rotation with soybeans.
[9] 56 percent of soybean-planted acres were in rotation with corn.
[10] 26 percent of potato-planted acres were fallow in 1994 and 1995, and 70 percent were in rotation with other crops or fallow in 1994 or 1995.
[11] Continuous same crop for winter wheat were for two years 1995 and 1996, for winter wheat planted in fall 1994 and winter wheat planted in fall 1995.
[12] 40 percent of winter-wheat-planted acres were fallow in fall 1994 and had winter wheat in fall 1995.
[13] 23 percent of spring-wheat-planted acres were fallow in 1994 and had spring wheat in 1995, and 60 percent were in rotation with other crops or fallow in 1994 or 1995.
[14] 24 percent of durum-wheat-planted acres were fallow in 1994 and had durum wheat in 1995, and 66 percent were in rotation with other crops or fallow in 1994 or 1995.

na = not available or not applicable. * Less than 0.5%. (Original source: NASS/ERS 1996 ARMS survey.)

vention, avoidance, monitoring, and suppression (PAMS) (GAO, 2001). For example, avoidance practices encompass cropping system components such as rotation, adjusting planting dates, and use of pest-resistant crop varieties. The percentages of acerages for various field crops utilizing these diverse IPM practices in 1996 are summarized in Table 2 (after Fernandez-Cornejo and Jans, 1999). Overall, the USDA has estimated that some IPM practices have been followed in about 76% of U.S. cropland, but biologically-based IPM practices were often less than 20% (GAO, 2001). A second major federal program now affecting IPM in the U.S. is the 1996 Food Quality Protection Act (FQPA) (CAST, 2003a; EPA, 1996; Ragsdale, 2000). This act will limit the use of a number of pesticides and likely foster the implementation of IPM, as discussed briefly under “Emerging Opportunities and Challenges.”

IPM TOOLS, STRATEGIES, AND TACTICS

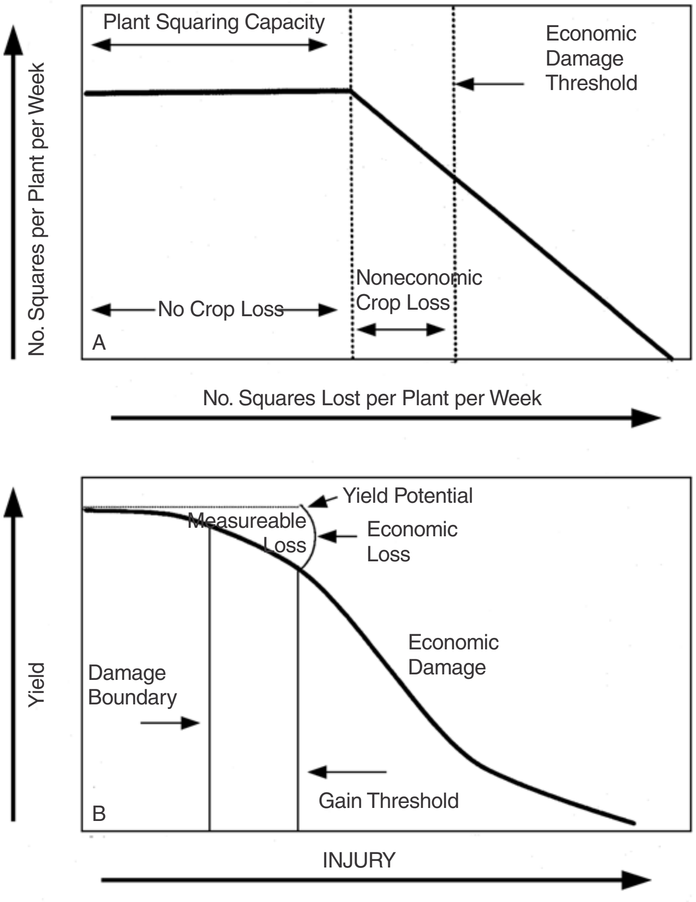
Pest Assessments and Diagnostics

Reliable identification of pests and diagnosis of related problems is a cornerstone for minimizing losses caused by insects, weeds, and plant pathogens. Assessment and monitoring of pest populations and/or damage as well as yield losses are becoming increasingly important to growers as they strive to limit production costs and unnecessary application of pesticides. In addition to the classical methods of pest identification, recently deployed molecular- and computer-based diagnostic technologies now offer much to IPM. Today, advanced DNA sensors and sensor arrays for direct, genetic analysis of pathogens are under development for human pathogens (Henkens et al., 2000). Already in use in some cropping systems, Global Positioning Systems (GPS) and Geographical Information Systems (GIS) offer a means of identifying site-specific pest-management needs within given fields.

Insect Infestations

Monitoring of insect infestations generally interfaces closely with the use of economic thresholds (Figure 1) as well as regulatory programs. However, assessments of insect populations in given insect-crop combinations often go beyond scouting and diagnosis by a skilled specialist (Pedigo, 1999). For example, methods for detecting pesticide-resistance in insects include biochemical, immunochemical, molecular, and bioassay procedures (Roe et al., 2000). This area of IPM, while especially important in detection and monitoring of insecticide resistance, is crucial to augmenting the durability of many pesticides. Due to the extremely dynamic nature of many insect pest populations, routine systematic sampling over substantial portions of the growing season (“scouting”)

FIGURE 1. Relationships of crop injury/damage and economic damage caused by insects. (A) Effects of cotton boll set of plant capacity and insect injury (Adapted from Smith and van den Bosch, 1967); (B) General relationships between the damage boundary and the gain threshold (Adapted from Pedigo, 1999).



are better developed and more widely used for arthropods than for other pests (Kennedy, 2000).

Information on insect activity is fundamental to their management. This includes surveillance data on their invasion of crops, long-distance migration, local movement, feeding, and reproduction (Kennedy and Storer, 2000; Pedigo, 1999; Southwood, 1978). Surveillance of insect and other pest activities receives much effort via local, state, and national government agencies. In the

U.S.A., the Animal and Plant Health Inspection Service (APHIS) monitors for introductions and spread of invasive pests.

Weeds

Agricultural fields usually are infested with large numbers of seeds of highly diverse weed species which sharply contrasts to the dynamic spatial dispersal of most other plant pests (Liebman, Mohler, and Staver, 2001). Thus, weeds pose an ongoing and obvious threat to crops for which growers may use a combination of cultural and herbicide-management strategies/tactics to limit yield losses. Assessment of the weed-seed banks in given fields can be very effective, but costs involved may be very high (CAST, 2003a). Although such data are essential for utilizing the concepts of an economic threshold or action thresholds, the costs for assessing weed seed kinds and numbers may be prohibitive even for small units. As a result, scouting fields for weed seedlings in most crops is not done in a systematic manner. Since given fields typically contain five or more dominant weeds with rather specific image signatures that differ from the crop, efforts to automate weed seedling counts by remote sensing with specialized cameras have met with some success. Site-specific application of herbicides of weeds, as determined by soil sensors, also is under evaluation (Hall, 2000). The concept of "time-density-equivalent" also offers a new approach for weed assessments over a growing season (CAST, 2003a; Gunsolus et al., 2000).

Pathogen Detection and Diagnoses

Plant-disease assessments often encompass crop-pathogen field histories, assessments of environmental conditions that favor or limit epidemics, and in some instances data on likely disease progression. A "disease-progress curve" for a specified pathogen-crop cultivar is thus developed. A number of plant parasites frequently may be encountered on one plant or crop although only one pathogen is causing the primary disease problem. In this regard, "detection" concerns establishment of the presence of a particular target organism within a sample, whereas "diagnosis" involves identification of the nature and cause of an observed disease problem (Louws, Rademaker, and deBruijn, 1999). Both detection and diagnosis are very important for effective IPM programs.

The choices of diagnostic procedures for plant pathogens have increased greatly in recent years. Immunological diagnostic tests are now available for viral and bacterial pathogens, and a number of tests are becoming available for fungal pathogens (Stewart, 2000). Laboratory-oriented tests also have been developed for plant-parasitic nematodes. ELISA (enzyme-linked immunosorbent assay) is the primary method utilized for the detection and diagnosis of virus problems on a number of crops, especially for greenhouse ornamentals (Dinesen and van Zaayen, 1996). Detection kits also are available commercially for given groups of viruses such as the potyviruses. Still, bioassays using susceptible hosts often are needed to confirm negative ELISA results. A number of polymerase chain reaction (PCR)-based protocols such as rDNA-based PCR, and others, have been devised and adapted to enhance both the detection and identification of plant pathogenic bacteria (Louws, Rademaker, and debruijn, 1999). These protocols have been utilized widely in research programs and are resulting in the development of fundamental information on the ecology and population dynamics of bacterial pathogens, but remain to be applied in IPM programs. Additional protocols used for identifying bacteria include immunofluorescence and staining, the ELISA procedure, and immunobinding assay (Dinesen and van Zaayen, 1996). Currently, the use of these methods is limited largely to research programs and diagnostic laboratories. However, commercial ELISA kits are now available for fungi such as *Septoria nodorum*, *S. tritici* (Stewart, 2000), *Rhizoctonia solani*, and *Fusarium*, *Pythium* and *Phytophthora* species.

Nematode Diagnostics

Most plant-parasitic nematodes have very limited capacity for active dispersal. Therefore, field history and soil characteristics along with population data and damage or economic thresholds serve as the key parameters for their management. Assessment of population data and diagnoses of related problems rely on soil and tissue sampling, a range of extraction procedures, and identification by various methods (Barker and Davis, 1996). Nematode morphology and differential hosts have been the primary basis for identification of nematode species and host races. Protocols that use immunology, protein electrophoresis, isoelectric focusing, and a range of DNA-based protocols are still limited to laboratory and research programs (Barker and Davis, 1996; Fleming and Powers, 1998). For IPM purposes, the presence of nematode-specific symptoms (galled roots for root-knot nematodes or root lesions for lesion nematodes) and signs of nematodes (the pear- or round-shaped cysts of the cyst nematodes, etc.) as well as the typical spotty growth patterns of a given crop in an infested field are good indicators of nematode problems. Precise identifications of nematode species, however, continue to be done primarily by nematode advisory programs and research laboratories.

Elimination of Pathogens

The importance of pathogen-free plant material is sometimes overlooked in modern as well as subsistence agriculture. Still, interest in this area is increasing due to the need to reduce pesticide usage in response to environmental and health issues. Meristem culture, which has been in use for almost 50 years, has been employed on many crops as a method of eliminating virus infections (Dinesen and van Zaayen, 1996). This procedure may also free plants from bacteria, fungi, viroids, phytoplasmas, and nematodes. Although meristem culture has been used intensively on ornamentals, the technology has much potential for other crops. For example, Pesic-van Esbroeck and associates (personal communication) have a major ongoing program at North Carolina State University in which this protocol is utilized to free strawberry (*Fragaria chiloensis* Duchesne), sweet potato (*Ipomoea batatas* (L.) Lam.), and other crops from associated virus pathogens. This procedure also is invaluable for limiting virus problems on potato (*Solanum tuberosum* L.).

Decision-Making Aids

As indicated earlier, effective IPM depends on accurate diagnosis of pest problems, quantification of the infestations, and information on related population dynamics, or dispersal of pests over time (CAST, 2003a) as well as decision rules (Kennedy, 2000). Thus, general decision-making aids include pest-population monitoring; field histories; various models, including those based on experience, crop-loss models for given pests, and more comprehensive mathematical models; and weather-based advisories. Information on the rate of overwintering of soilborne insects and nematode pests is essential for management decisions before the establishment of susceptible crop. Fields with high infestations of given fungi or other soilborne pests frequently are planted to non-host crops, especially where no other effective management tactic is available or where treatment costs are excessive. For some of the highly damaging vegetable root rots, avoiding high-risk fields has saved the industry millions of dollars over the last 3 decades (CAST, 2003a).

The compilation and interpretation of pest-population data, beneficial organisms, distribution of weeds, field histories and the appearance and development of plant diseases serve as the infrastructure of many IPM programs. Although labor and data intensive, the resulting regional and national IPM programs provide improved pest control as well as reductions in pesticide usage, and enhanced profitability for the grower. IPM service-advisers generally provide a range of services, including pre-season pest and soil-nutrient assessments, and crop monitoring during the growing season for pests/diseases, nutrient status, collection of weather data, and application of these data via pest-prediction models to aid in management decisions (CAST, 2003a). An additional pre-harvest sampling for some pests and other variables can facilitate estimations of yield and the need for monitoring for post-harvest, or storage, pest problems. Reliable weather data and their interpretation serve as important variables for prediction of the appearance and development of a number of crop pests. This information is applied via models that then impact management decisions. Weather-based IPM advisories are available for field crops such as peanuts (*Arachis hypogea* L.) (Phipps, Deck, and Walker, 1997), potato, and certain vegetables (CAST, 2003a; Main et al., 2001).

While population levels and economic thresholds (Figure 1) can be determined for many insect infestations, most threats posed by plant-pathogen infestations are assessed by symptomology, environmental/weather conditions, and field history (Campbell and Benson, 1994). Projections of disease development can be offered via various "models," including those driven by environmental parameters, especially temperature and relative humidity. "Disease-progress curves" (Figure 2) that characterized disease on specific cultivars are useful in that regard.

Choice of appropriate crop rotations, selection of pest-resistant cultivars, or a combination of pest-management tactics/strategies are often based on pest diagnostics. In addition to resources such as traditional pest-resistant cultivars, cultural practices, and pesticide options, other new technologies, especially those related to genetic engineering, and precision agriculture are having an impact on IPM and related cropping systems.

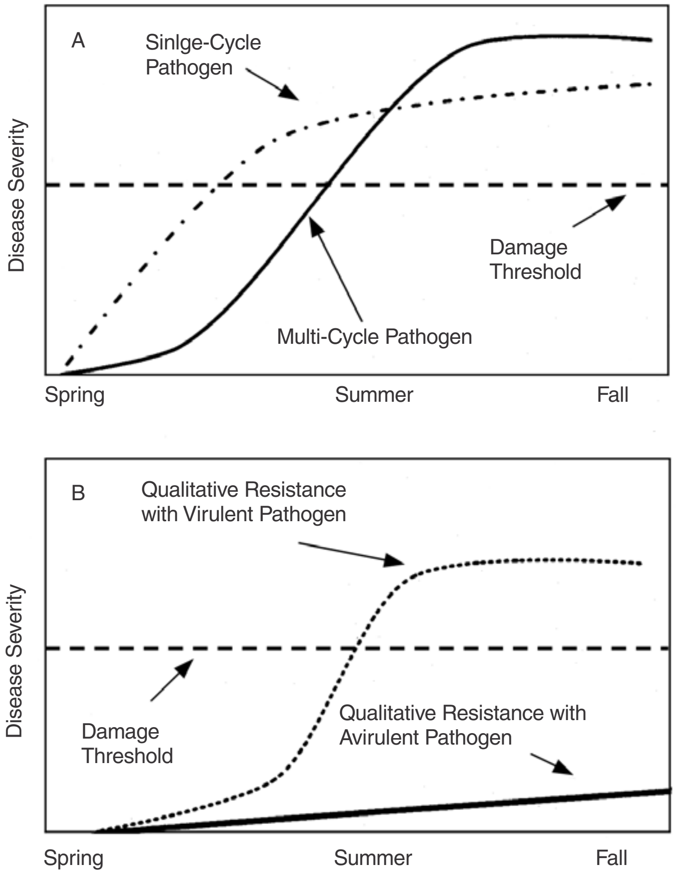
SPECIFIC IPM TOOLS USED IN CROPPING SYSTEMS

A synopsis of the wide range of cropping components and other practices for managing crop pests, including their relative effectiveness, is given in Table 1. Cropping components include: rotation, fallow, cover crops, manipulating pest refugia, tillage, row width, type of cultivation, soil amendments, and field size and borders. These and other practices such as pesticide usage, plant populations, sanitation, and resistant varieties are discussed as follows.

Rotation/Cultural Practices, and Habitat Management

The growing interest in IPM and sustainable cropping systems has generated renewed emphasis on cultural methods of pest management (Cavigelli et al., 2000; Kennedy and Sutton, 2000; Madden, 1992). As indicated in Table 1, many cultural practices have proven to be effective for managing a wide range of pests. Key facets of cultural pest control include polyculture, crop diversification, destruction of residual roots of certain crops with a perennial growth habit, minimal tillage, and biological/environmental manipulation that lead to biological diversity (Altieri, 1994). Polyculture may include the use of "refugia" to maintain and enhance populations of natural enemies of some arthropod pests (Altieri, 1994; Landis, Wratten, and Gurr, 2000). Crop rotation provides for diversity in time and space and often is the preferred means of management for soilborne pests such as plant-parasitic nematodes. The benefits of rotation

FIGURE 2. Disease progress curves. (A) Comparison of single-cycle (one generation, usually soilborne parasite) and multi-cycle (multiple generations, usually foliage parasites) plant pathogens; (B) Rapid disease development induced by a virulent pathogen on a qualitatively resistant crop versus minimal disease with an avirulent pathogen (in large part, adapted from Cavigelli et al., 2000).



are derived from the destruction of given crop pathogens and often other pests by natural enemies or "sanitizing organisms" while other unrelated crops are grown (Cook and Veseth, 1991). Rotation, however, may be of limited value for pests that have a wide host range or are highly mobile. Furthermore, the need to rotate crops varies with given pest populations and location. Corn (*Zea mays* L.) can be grown continuously in some locations, whereas soilborne pests such as nematodes can cause serious yield losses to this crop in some regions (Barker and Koenning, 1998). In contrast, soybean (*Glycine max* L.), a crop highly susceptible to nematodes and other soilborne pathogens, is routinely rotated with corn and other crops to prevent related yield losses and to prolong the durability of resistant cultivars. Many intensively managed crops that are susceptible to numerous pathogens and nematodes often encounter severe disease and other pest problems under monoculture. Rotating crops such as tobacco (*Nicotiana tabacum* L.) with fescue (*Festuca arundinacea* L.) limits pest activity, improves soil structure and water-holding capacity, and enhances crop yield. Plants directly antagonistic to certain pests also can be used in crop rotations. *Crotalaria* species may function as trap crops for root-knot nematodes, and the African marigold (*Tagetes erecta* and other *Tagetes* species) provide excellent nematode control under certain conditions (Barker and Koenning, 1998). As discussed under potato, effective rotations are central to nematode and pest management of this high-value crop.

Effective use of cultural practices in a crop management system requires a considerable database (CAST, 2003a). Features of the cropping system that can be manipulated to retard pest activity while enhancing biological control should be central. This situation may call for the integration of a range of management practices such as rotation, minimal tillage, soil amendments, and the use of a cover crop (El Titi and Ipach, 1989; Zwart et al., 1994). To provide optimum returns, information on the impact of such management practices on beneficial organisms and crop pests is essential.

The use of cover crops or green manure crops between primary crops offers many benefits (Table 3). When utilized as green-manure or cover crops, a number of selected clovers, velvet bean [*Mucuna deeringiana* (Bort.) Merr.] and joint vetch (*Aeschynomene americana* L.) have considerable potential for augmenting soil health and crop production (Barker and Koenning, 1998; Kloepper et al., 1992). Benefits of using these legumes encompass enhanced soil nitrogen (N), promotion of soil populations of plant-growth-promoting rhizobacteria, and direct or indirect negative effects on a spectrum of plant pests (Magdoff and Van Es, 2000). A range of legume cover crops, including castor bean (*Ricinus communis* L.), sward bean [*Canavalia ensiformis* (L.) D.C. Bean], and velvetbean greatly enhance the numbers of plant-growth promoting rhizobacteria such as *Burholderia cepacia* and *Pseudomonas gladioli.* Both cyst and root-knot nematode populations are suppressed when soybean followed any of these cover crops (Kloepper et al., 1992). Certain rhizobacteria may induce systemic acquired resistance to foliage pathogens such as *Pseudomonas syringae* pv. *lacrymans* and *Colletotrichum orbiculare* on cucumber as well as provide some nematode control (Wei, Kloepper, and Tuzun, 1996). Other soilborne bacteria designated as "deleterious rhizobacteria," including certain strains of *Pseudomonas flourescens*, have potential as biological controls of weeds (Liebman, Mohler, and Staver, 2001).

TABLE 3. Effects of selected grass and legume cover crops on soil and associated pests/beneficials (adapted from Bowman, Shirley, and Cramer, 1998).

Cover crop	Loosen soil	Allelopathic	Benefits/risks per pest group[a] weeds	pathogens	Nematodes	insects	Beneficial insects
Annual ryegrass	++++[a]	++	++++/----	++/-	++/-	-	+
Barley	+++	+++	+++/---	+/---	+/---	---	++
Oats	+++	+++	++++/0	++/-	●/--	--	0
Rye	++++	++++	++++/----	++/-	++/--	--	+
Wheat	+++	+	+++/--	+/---	+/---	---	+
Buckwheat	+++	+++	++++/----	●/0	+/-	-	++++
Sorghum-Sudan	++	++++	++++/--	+++/0	+++/-	-	++
Berseem clover	+++	+	+++/0	●/-	●/--	--	++
Cowpeas	+++	●	+++/0	●/-	●/--	--	+++
Crimson clover	++	+	++/--	++/-	+/----	----	+++
Field peas	+++	+	+++/0	+++/---	++/--	--	+++
Hairy vetch	+++	++	+++/--	++/0	+/--	--	++++
Medics	+	+	+++/--	++/0	++/---	---	+
Red clover	++	++	++/--	+/-	+/---	---	+++
Sweet clovers	++++	+	++/---	+/0	+/---	---	+++
White clovers	+++	++	+++/--	●/-	●/--	--	++

a Symbols for benefits

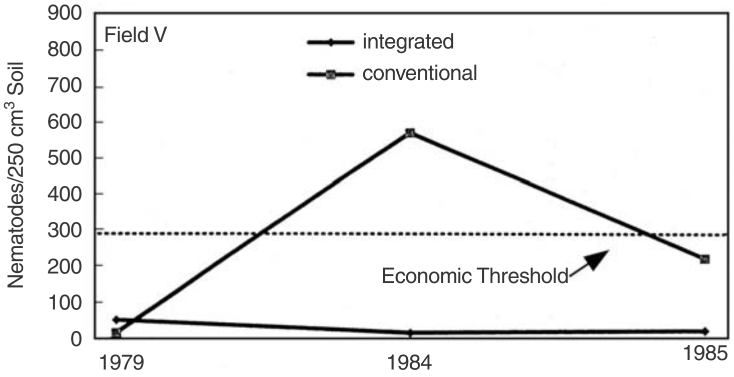
● = Poor
\+ = Fair
++ = Good
+++ = Very good
++++ = Excellent

Symbols for increased pest risks

0 = rarely becomes a problem
\- = occasionally a problem
-- = can be a minor problem
--- = can be a moderate problem
---- = can be a major increased pest risks

Various tillage and cropping options may differentially affect soil organisms and crop pests (Table 1). In an IFS, beneficial earthworms made up 17.6% of the total soil microflora/fauna whereas they may be absent in a conventional system (Zwart et al., 1994). Bacteria comprised 94% of the biomass in the conventional production systems versus 75% in the integrated system. Figure 3 shows that IFS that included altered soil tillage, a clover cover crop, organic manure, and reduced pesticide usage, resulted in highly suppressed populations of two nematode species (*Heterodera avenae* and *Ditylenchus dipsaci*) on cereals versus those in conventional cropping (El Titi and Ipach, 1989). For health management of crops such as wheat (*Triticum aestivum* L.), a key goal is to limit tillage as much as possible (Cook and Veseth, 1991).

FIGURE 3. Relative infestation levels by the cereal cyst nematode, *Heterodera avenae*, in integrated and conventional farming systems [expressed as the mean number of eggs + juveniles per 250 cc soil; differences are highly significant, according to Wilcoxon Test ($P = 96\%$)] from 1984 onwards (Adapted from El Titi and Ipach, 1989).



Soil organic matter (SOM) can play a multi-faceted role in IPM and cropping systems. Magdoff and Van Es (2000) concluded that good SOM is the very foundation for a sustainable and thriving agriculture. Objectives in all cropping systems should include an annual goal of returning as much or more organic matter to the soil than is withdrawn (Cook and Veseth, 1991). Bowman, Shirley, and Cramer (1998) provide general ratings on the capacity of various cover crops to suppress the activity of weeds, pathogens, nematodes, and insects (Table 3). Certain cover crops such as buckwheat (*Fagopyrun esculentum* Moench) and hairy vetch (*Vicia villosa* Roth) are very effective in attracting beneficial insects. Most grass cover crops serve to "loosen" the soil but can have allelopathic effects on subsequent crops. Although legume cover crops provide many benefits, including increased soil N, some can enhance pest/pathogen problems (Table 3). In addition to increased biological activity and diversity in the soil, organic matter improves soil quality through increased aggregation, pore structure, tilth, and water-holding capacity (Magdoff and van Es, 2000). These many benefits, although not providing a high level of control of all crop pests, are undoubtedly partly responsible for the rapid annual growth of 20 to 30% in the organic production industry (USDA, 2001).

Host-Plant Resistance/Tolerance

Crop resistance, carried in the seed or propagation materials, is an ideal tactic in IPM with the deterrent to the pest being inherited. The heritable trait that limits the normal host-pest interaction restricts associated damage and yield loss, compared to susceptible varieties (CAST, 2003a). Since crop resistance involves little or minimal input costs, it is an ideal tactic for managing a wide range of pests, including bacteria, fungi, viruses, insects, mites, nematodes, mammalian herbivores, and other plants (through allelopathy) (see Tables 1 and 3). Although pest-crop resistance requires minimal management input, its durability is heavily dependent on the manner in which it is deployed (CAST, 2003a). Continuous use of a given resistance source in the same fields often results in the development of biotypes of pests that overcome the impact of the resistance genes. Except for this important problem, resistance has a low-management requirement as compared to many management-intensive IPM tools. In addition to the classical pest resistance developed through traditional plant-breeding programs, genetically engineered crop lines or cultivars with resistance or tolerance to major pests are being widely deployed as indicated earlier. Examples of these types of resources are discussed under given cropping systems.

Biological Control

Among numerous definitions of biological control, Hoy (2000) provided a succinct description: "Biological control of arthropod pests and weeds is a method of pest management that employs parasitoids, predators, pathogens, and entomophilic nematodes (natural enemies) to reduce pest populations." A broader concept of biological control was given by Cook (1987): "The use of natural or modified organisms, genes, or gene products, to reduce the effects of undesirable organisms (pests) and to favor desirable organisms such as crops, trees, animals and other beneficial insects, and microorganisms." Biological-control products are also being used in IPM. They are differentiated from biological-control agents as follows: "Biological-control organisms are living organisms that can be used to manage arthropods (mites and insects), weed, and plant (bacteria, fungi, viruses, and nematodes) pests and pathogens"; "genes or gene products derived from living organisms that kill, disable, or otherwise regulate the behavior of plant pests are biological-control products" (National Research Council, 1996). Our increasing understanding of the basis for biological control is bringing new pest-control products to the market as well as advancing ecologically-based IPM (Kennedy and Sutton, 2000).

Pesticides

Pesticides have traditionally been an important component of cropping systems. Ecologically-based IPM is our most promising option for reducing the negative effects of pesticides on our environment while contributing to the sustainability of our societies (CAST, 2003a). Still, pesticides continue to be essential to feed and protect the ever-increasing world population. IPM programs have helped stabilize pesticide usage in the U.S. since the mid-1980s, whereas their use in rapidly growing economies such as those of the Pacific Rim is increasing at about 8% per year (CAST, 2003a). The niche for pesticides in crop production differs greatly with the cropping system, associated pests per region or site, weather and economics. Examples are given in the cropping systems presented herein, but usage continues to evolve as new IPM options are developed, changes in pest situations, and changes government regulations (CAST, 2003a; Kennedy and Sutton, 2000; Main et al., 2001).

EXAMPLES OF PEST MANAGEMENT IN MAJOR CROPS OF THE U.S.

Cropping systems vary along a continuum from very low intensity, low input, high acreage systems to high intensity, high input, low acreage systems. Pest management efforts and inputs vary along this continuum as well. In general, pest management in low value, extensive cropping systems must rely on inexpensive management strategies/tactics (i.e., many cultural practices and host-plant resistance). This situation results from the equilibrium points of many pests in these systems routinely falling well below economically justifiable pesticide-based, thresholds. Pest management in high value crops generally is far more intensive because the value of the crop dictates lower tolerance for production loss and therefore lower thresholds. Since pesticides are typically highly efficacious but often expensive (both in terms of direct costs of application and collateral impact) and temporary in effect, the intensity of pesticide use may be a strong indicator of the intensity of the overall pest management program in a given commodity. However, the potential for much greater economic return in high-value crops also provides opportunity to integrate high intensity, non-pesticidal tactics as well.

In the following, we discuss examples of cropping systems along the continuum from low value, extensively farmed crops to high-value, intensively farmed crops and the typical pest management options and considerations in each. Alternatively, crops intensively managed in one region may be grown with minimal inputs elsewhere. For example, potatoes are grown with minimal inputs in much of the developing world, while European and North American production is intensive. Likewise, wheat in the U.S. and Australia receives few pesticide inputs, whereas production in Europe usually is greatly intensified.

Wheat

Wheat occupies approximately 26 million ha in the U.S. This area includes winter wheat, durum, and spring wheat. Average yields in the U.S. in 1998 and

1999 were approximately 2,350 kg ha^{-1} with an average gross return of about \$247.00 ha^{-1} (USDA/NASS, 1999a; 2000a). Significant weed pests of wheat include both grasses and broadleaves. Tillage is an important management tactic for all weeds, although demands for soil conservation now limit its use on wheat (Cook and Veseth, 1991). About 30-40% of area under wheat is treated with one or more herbicides annually; the most frequently used material is 2,4-D, which provides control of broad-leaved weeds (USDA/NASS, 2001c). Important insect pests of wheat in the U.S. include the Hessian fly (*Mayetiola distructor* Say), the Russian wheat aphid (*Diuraphis noxia*) and other aphids, the cereal leaf beetle (*Oulema melanopus* L.) in eastern North America, and chinch bug (*Blissus leucopterus* Say). Typically less than 10% of the area under wheat receives an application of insecticide over the course of the growing season. Insect management in wheat relies on non-insecticidal tactics. Hessian fly management is dependent on two main strategies: host-plant resistance and the use of a "fly-free" planting date (ensuring that most adult flies have died by the time the crop emerges). Cereal leaf beetle management over much of the area where it occurs depends on introduced parasitoids.

Infectious wheat diseases may be caused by bacteria, fungi, nematodes, viruses, and flowering plants (Wiese, 1987). Some pathogens can cause more than one disease on this crop. For example, *Fusarium graminearum* and related species, in addition to inducing seedling blights and foot rots, also cause a major disease, "scab," on wheat. This disease often is especially severe when wheat follows corn as the pathogen overwinters in corn stalks. The emerging spores are windborne and infect heads of wheat at flowering. While this disease is common in the Great Lakes states and other regions, it is limited to fields receiving pivot irrigation in the Pacific Northwest (Cook and Veseth, 1991). In addition to suppressing wheat yields, infected grain may contain mycotoxins that impact the health of cattle.

Cook and Veseth (1991) provide a comprehensive, holistic approach to wheat health management or IPM. They document the benefits of crop rotation and maintaining SOM/soil structure. Additional principles for managing wheat include: an understanding of the production limits of the cropping system; using well-adapted, pest and disease resistant varieties; choosing high quality, disease/weed-free seed; minimizing environmental and nutrient stresses; maintaining or enriching populations of beneficial insects and microorganisms; and scouting for pests and treating, when necessary, with pesticides. While promoting rotations and augmented organic matter, these authors view tillage as a prime means of destroying organic matter and enhancing soil erosion. A combination of increased organic matter and reduced tillage can suppress pathogens such as the cereal cyst nematode (*Heterodera avenae*) (El Titi and Ipach, 1989) while enhancing populations of beneficial organisms, including earth worms (Zwart et al., 1994). With the foliage pathogens, however, host resistance continues to be invaluable in wheat. In the U.S.A., wheat cropping systems included rotations in about 83 to 90% of the area in 1995 (Table 2). To minimize the development of resistance, pesticides were alternated in about 30 to 38% of area under wheat (Table 2). An average of 0.25 kg ha^{-1} of pesticides was used in U.S. wheat in 1998. Of this, about 98% was herbicide (USDA/NASS, 1999c).

Soybean

Soybean is grown on approximately 28 million ha in the U.S. Average yields across the U.S. in 1998 and 1999 were approximately 2130 kg ha^{-1} with an average gross return of about $450.00 ha^{-1} (USDA/NASS, 1999a, 2000c). Weeds are significant pests of soybean, and shifts over the last 15-20 years towards reduced-tillage systems have increased reliance on herbicide use in soybeans. Approximately 95% of the soybean acreage in the U.S. received at least one application of herbicide in the 1998 and 1999 growing seasons (USDA/NASS, 1999c, 2000c). The development of transgenic, glyphosate-resistant soybean cultivars has been a major development in weed management in this crop. Approximately 60 to 70% of the U.S. soybean crop is planted to these cultivars (S. R. Koenning, personal communication). Another significant cultural development over the last 15-20 years has been the shift towards narrow row spacings; narrower rows close the plant canopy quicker and give the crop a competitive advantage over weeds (Howe and Oliver, 1987).

While a large number of insect species feed on soybean, and occasionally cause economic damage (Higley and Boethel, 1994), two significant arthropod pests of soybean are the corn earworm (*Helicoverpa zea* Boddie) and the bean leaf beetle (*Cerotoma trifurcata* Foster). Insecticides currently play a very small role in soybean since less than 5% of the area under soybean in the nation received an insecticide application in the 1998 and 1999 growing seasons. This represents a rather dramatic shift from the situation 20-25 years earlier, when as much as 40-50% of the acreage may have been treated with an insecticide. Several factors contributed to the decline in insecticide use in soybean. The profitability of soybean has declined as prices dropped to less than 50% (taking inflation into account) of what they were at their highest in the late 1970s. This has elevated the economic injury levels of many of the insects, previously regarded as serious soybean pests, to points well above the equilibrium points for those species. The bean leaf beetle is both an early season and mid-season defoliator and pod-feeder; however, because of prevailing economic conditions, only very high populations warrant treatment (Pedigo, Zeiss, and Rice, 1990). Furthermore, cultural strategies for managing the most significant soybean pests have been developed. The importance of the corn earworm dropped dramatically with the adoption of narrow row spacing and the increase in double-cropping. Narrow rows close the crop's canopy much earlier making soybean less attractive to ovipositing female earworm moths; double-cropping results in asynchrony between ovipositing moths and the most attractive phenological stage of the soybean plant (Bradley and Van Duyn, 1979).

An array of diseases caused by nematodes, fungi, bacteria, and viruses is well documented for soybean (Hartman, Sinclair, and Rupe, 1999). Among these pathogens, the soybean cyst nematode (*Heterodera glycines*) causes the greatest yield losses which amount to billions of dollars annually. Severe stunting of plants by high infestations of this nematode also can result in greater weed and insect problems on the crop (Alston et al., 1991). In recent years, disease and nematode management in soybeans have been pursued largely through the development of resistant cultivars and the identification of appropriate cultural tactics. Bradley and Duffy (1982) documented the economic value of disease resistance on this crop via an economic analysis. The cost of developing one cyst-root-knot nematode resistant cultivar "Forrest" was \$1 million, whereas the return to growers (avoiding losses) over a 6-year period amounted to \$401 million. Statistical models also may be useful for predicting soybean as well as corn yields for specific soils and regions (Garcia-Paredes, Olson, and Lang, 2000).

Key cropping systems for IPM in soybean in the U.S. include rotation (89%), no-tillage (33%), mechanical cultivation for weeds (29%), and alternating pesticides (28%) (Table 2). An average of 1.23 kg ha^{-1} of pesticides was used in U.S. soybean in 1998. Of this, 99% was herbicide (USDA/NASS, 1999c).

Corn

Field corn is planted on approximately 28.3 million ha in the U.S. Across the country, annual gross returns over the 1998 and 1999 growing seasons were approximately \$630.00 ha^{-1} on yields of approximately 8,000 kg ha^{-1}. As in the earlier examples, weed competition can significantly compromise corn production (USDA/NASS, 1999a, 2000a). Weed management in corn historically relied on tillage and cultivation. However, over the last 30 years, herbicides have assumed a much larger role in weed management in corn. Currently, virtually all corn acreage receives at least one application of one or more herbicides; the most widely used active ingredient is atrazine (USDA/NASS, 1999c). Again, pressure to conserve agricultural soils has increased adoption of reduced tillage production systems. As with soybean, herbicide tolerant corn varieties are being developed and deployed.

The major arthropod pests of corn are the European corn borer, *Ostrinia nubilalis* Hubner and the corn rootworm complex composed primarily of the western corn rootworm, *Diabrotica virgifera*, and the northern corn rootworm, *Diabrotica longicornis barberi*. Many other arthropods feed on corn and are occasional pests; however, these three drive corn pest management over much of the country. The European corn borer is an introduced moth found throughout the eastern half of the U.S. Over much of this area, two generations per year attack corn. In most areas, the first generation is well suppressed by host plant resistance bred into most hybrid corn lines (Chiang and Hudon, 1976). This resistance dissipates before the onset of the second generation. Second-generation management has been quite problematic due to the large size of the plant during this part of the growing season and the boring habits of the larvae. Recently, transgenic corn varieties containing *Bacillus thureingensis* (Bt) toxins effective against European corn borer have been developed; however, social concern over this technology may limit its utility (CAST, 2003a).

The corn rootworm complex has, until recently, been managed through a combination of cultural and chemical tactics. These two species are univoltine, and most populations have traditionally laid their eggs in cornfields. The eggs over-winter and hatch in the spring about the time corn roots become available. This life cycle has made this complex susceptible to management through rotation to a non-host crop. Within the last decade, however, populations of western corn rootworm have been identified which remain in diapause for two years (Krysan, Jackson, and Lew, 1984), and populations of north corn rootworms have been found which oviposit in soybean fields, the most frequent rotational crop (O'-Neal, Gray, and Smyth, 1999). Transgenic corn hybrids containing genes coding for rootworm-active Bt toxins have been developed and hold great promise for management of the rootworm complex if societal concerns over the technology are resolved.

Numerous diseases often affect the yield and quality of corn (White, 1999). Except for pathogenic nematodes, disease management in corn has depended on the identification of resistant or tolerant germplasm and incorporation through conventional plant breeding, together with cultural disease management strategies. Reliance on a limited pool of genetic material for hybrid development has, in the past, caused crises in corn production; the most notable example of widespread failure of this nature was the southern leaf blight, caused by *Cochliobolus heterostrophus* (Drechs.) Drechs. (*Bipolaris maydis* (Nisik.) Shoem.), epidemic of the mid-1970s. Although corn is somewhat tolerant to several nematode species, the lesion nematode (*Pratylenchus* spp.), stubby-root nematode (*Paratrichodorus* spp.), needle nematode (*Longidorus* spp.), and the sting nematode (*Belonlaimus* spp.) can inflict extensive damage, especially in sandy soils.

More recently, concerns over mycotoxin contamination have complicated corn production (CAST, 2003b). Aflatoxin in corn is most serious during years with droughts and other conditions favorable for the causal fungus, *Aspergillus* spp. Although prevailing environmental conditions in the southeastern U.S.

result in frequent aflatoxin problems, the impact of this toxin in midwestern corn would be much greater as 75% of U.S. corn produced in the North Central States. Thus, any major aflatoxin problems in that region can limit the availability of clean corn for export as well as domestic use. A comprehensive treatment of aflatoxins is forthcoming (CAST, 2003b). Fungicide use is negligible in corn.

Corn cropping IPM systems in the U.S. for 1996 included rotation (82%), mechanical cultivation (51%), and no-tillage (19%) (Table 2). An average of 3.16 kg ha^{-1} of pesticides was used in U.S. corn in 1998. Of this, about 93% was herbicide (USDA/NASS, 1999c).

Cotton

Cotton is produced annually on approximately 5.4 million ha in the U.S. Cotton is a frost-intolerant perennial managed as an annual, and production is concentrated in the southern states from Virginia through California. Annual gross returns to the producer over the 1998 and 1999 growing seasons were approximately U.S. \$830 ha^{-1} on production of ca. 690 kg ha^{-1} of lint (USDA/NASS, 1999a, 2000a). Since cotton is initially not very competitive and is typically grown in warm climate areas with either abundant rainfall or substantial irrigation, weed management is a significant production issue. On average, in excess of 95% of the crop receives at least one application of herbicide; typically, two or three herbicides will be applied. Weed management also typically involves two or three cultivations, although the advent of transgenic, herbicide resistant cotton varieties and the development of reduced tillage systems for cotton have reduced the frequency of cultivation.

Cotton fruits are present and are vulnerable to attack by arthropod pests for approximately 70 days during the growing season; this, together with the wide diversity of insects attacking cotton, elevates the importance of insect management. Significant arthropod pests in cotton include the bollworm complex [*Helicoverpa zea* (Boddie) and *Heliothis virescens* F.], the pink bollworm [*Pectinophora gossypiella* (Saunders)] (restricted to the Southwest), thrips (Thysanoptera), stink bugs [*Acrosternum hilare* (Say), *Nezara viridula* (L.), and others] and plant bugs (*Lygus* spp.), and in a rapidly declining area in the mid-south and Texas, the boll weevil [*Anthonomus grandis* (Boheman)].

Insecticide use has been reduced in those areas where the boll weevil has been economically eradicated. Foliar applications of insecticide have declined from about 12 per season to about 4 per season in these areas (Bacheler, 1991) (other factors, including the advent of plant growth regulators and short-season varieties, have also contributed to this decline). However, the eradication program has been and continues to be expensive. Approximately 6% of total insect management costs are for eradication and the maintenance of eradication in areas were the insect has been extirpated (Williams, 1999).

Insect management for cotton often includes advanced strategies and tactics. Computer programs such as TEXCIM, a software package that focuses on costs of pests, benefits of management tactics, and crop value is used in southern Texas. Frequent, systematic sampling of insect pests is routine in cotton, and much of this activity (42% in 1996) is conducted by paid crop consultants (Williams, 1999) (Table 2). Most cotton areas are examined at least weekly for insect pest problems. Foliar insecticide use is more intense in cotton than in any of the crops discussed earlier. An average of 4.3 foliar applications of insecticides was applied to the 1998 crop (Williams, 1999); approximately half of this targeted the bollworm complex. In addition, approximately 54% of the acreage received an at-planting application of insecticide, primarily for thrips control. Total average costs of insect pest management in 1998 were U.S. \$155.80 per ha^{-1}.

While disease management is also an important consideration in cotton, many diseases are of limited, regional importance (Kirkpatrick and Rothrock, 2001). Key pathogens of cotton include seedling parasites, nematodes and wilt fungi. Cottonseed is treated with a fungicide prior to planting for control of seedling diseases, and a small fraction of the total area also receives a foliar fungicide. The Columbia Lance nematode (*Hoplolaimus columbus*), occurs only in the southeastern U.S. Other important cotton diseases are managed through a combination of cultural strategies, host plant resistance, and soil-applied chemicals.

Monoculture was the choice cotton-cropping system in 1996 (67%), and mechanical cultivation was used for weed control in 89% of the area (Table 2). With the widespread use of herbicide-tolerant cotton, mechanical cultivation likely has diminished. An average of 3.55 kg ha^{-1} of pesticides was used in U.S. cotton in 1998. Of this, approximately 40% was insecticide and 59% was herbicide. In addition, each hectare also received about 1.12 kg of other agricultural chemicals, primarily plant-growth regulators and harvest aids (USDA/NASS, 1999a, 1999c). To aid in limiting the development of resistance, pesticides were alternated in 41% of U.S. cotton in 1996 (Table 2).

Potato

Potatoes are grown on approximately 565,000 ha in the U.S. Annual gross returns to potato producers over the 1998-1999 growing seasons averaged approximately \$4,900 per ha^{-1} on average production of 39,300 kg ha^{-1} (USDA/NASS, 1999b, 2000c). Because of the value of this crop and the impact of its many pests, comprehensive or holistic management-production plans are available (Rowe, 1993). This program includes guidelines in establishing long-term rotations at least a year before growing potatoes and following definitive practices at preplant, all growth stages of the crop, and at harvest and storage. Rigorous disease/insect scouting is interfaced with highly developed IPM Programs (CAST, 2003a; Rowe, 1993). Weed management in potatoes is achieved through fairly intense herbicide use and frequent mechanical cultivation through the first half of the growing season. Approximately 95% of the potato hectarage receives at least one application of a herbicide, and a substantial portion of the land receives more than a single herbicide (USDA/NASS, 1999b).

The most significant insect pests of potato are the green peach aphid [*Myzus persicae* (Sulzer)], in the northern production regions, and the Colorado potato beetle (*Leptinotarsa decemlineata* Say), in the eastern and central production regions. The green peach aphid is an important vector of viral diseases of potato, particularly potato leafroll virus (PLRV), the causative agent of net necrosis in potato tubers. Green peach aphid management is based on the use of systemic insecticides at planting and early season foliar insecticides to limit the incidence of this disease. Field sanitation and the use of virus-free tubers are also important components of the management of PLRV (CAST, 2003a).

The Colorado potato beetle is most significant in areas where two generations develop per year. While crop rotation and tillage can reduce Colorado potato beetle populations, management of this insect relies on the use of insecticides. Due to heavy insecticide use, some populations of the Colorado potato beetle have developed resistance to virtually all classes of insecticides (Forgash, 1985). On average, in excess of two foliar insecticide applications are made to potato crops annually for all foliar pests.

Disease management in potato is critically important; several fungal, nematode, and viral diseases can seriously compromise potato yield and quality. Two foliage diseases, early blight (*Alternaria solani*) and late blight (*Phytophthora infestans)* can defoliate potato plants, resulting in low yields and quality. Frequent monitoring is crucial in managing these diseases. A number of forecasting models [HYRE system, WALLIN system, BLIGHTCAST system], based on temperature and moisture and/or humidity, have been developed (Rowe, 1993). "Early dying" is a soilborne disease complex caused by the lesion nematode (*Pratylenchus penetrans*) and *Verticillium dahliae*. Late-summer soil sampling in fields preceding spring planting can help growers assay for infestation levels of both pathogens and plan cropping systems appropriate to the pest hazard. Options could involve rotations with a nonhost crop or fumigation (Rowe, 1993).

Sanitation and certification of disease-resistant planting stock are important components of potato disease management, as is vector management. However, fungicides are the key disease management tools in this crop, and crops may receive seven or more applications of these materials over the course of a growing season. An average of 16.9 kg ha^{-1} of pesticides was used in potatoes in the U.S. in 1998. Of this, about 82% was fungicide (USDA/NASS, 1999b). Pesticide rotation is used (69% in 1996–Table 2) to minimize the development of resistance. Rotation is followed in about 98% of potato hectarage (Table 2). Rotation 'crops' include Sudan grass hybrids (*Sorghum bicolor* L. Moench) which give good control of *M. chitwoodi* on potato, but are not effective for lesion nematodes (MacGuidwin and Layne, 1995). Hybrids of sorghum-Sudan grass also control *Meloidogyne chitwoodi* but these plants must be grazed with care as they synthesize high concentrations of dhurrin, which is toxic to cattle (Mojtahedi, Santo, and Ingham, 1993). A federal quarantine has been very effective in limiting the spread of the highly damaging golden nematode (*Globodera rostochiensis*) in the U.S. (Marks and Brodie, 1998). In addition to using a carefully developed rotation system and certified, high quality tubers of resistant cultivars, fields heavily infested with soilborne pathogens should be avoided (Rowe, 1993).

Strawberries

Strawberry is a perennial, herbaceous vine grown commercially as an annual. A total of approximately 19,400 ha of strawberries are grown for commercial fresh market sales and processing annually in the U.S. (many additional ha are planted for "pick-your-own," purchaser-harvest operations). Average yields on commercial plantings in 1999 were approximately 32,300 kg ha^{-1} with gross returns to producers of about \$34,600 ha^{-1}. Approximately 80% of commercial strawberry production in the U.S. is in California (USDA/NASS, 2000d).

Commercial cultivation of strawberry is extremely intensive due to the high value of the crop and demand for high quality. Because of these key issues, IPM plays a limited role in producing this crop as compared to potato and many field crops. Also, weed and pathogen management usually must be implemented as preventatives rather than eradicatives. Strawberry fields are typically fumigated prior to planting; the material of choice has been a mixture of methyl bromide and chloropicrin (Maas, 1998), but this chemical is being phased out through federation and international regulation (EPA, 2001). On most commercial fields, plastic sheet mulch is applied either before or after planting for moisture, weed/pest, and soil-temperature management. Drip or sprinkler irrigation is usually supplied; sprinkler irrigation systems may be installed purely for frost protection purposes. Supplemental N and other nutrients (in some areas) are supplied.

Strawberry crops are confronted by even more suites of pests than most other crops. While damage thresholds are not available for weeds (Maas, 1998), management of these pests is far more integrated in this crop than in any other we have addressed previously. Pest control is largely effected by the fumigation of planting beds, the implementation of the plastic mulch, some use of herbicides, and hand labor. The shift from perennial culture of strawberries to annual culture, including preventative treatments, also simplifies weed management.

The most important arthropod pests of strawberry are mites. The spider mites (*Tetranychus* spp.) are managed through intense monitoring and applications of miticides. The cyclamen mite [*Steneotarsonemus pallidus* (Banks)] is managed primarily through rotation and destruction of old production beds. Other arthropods, including several species of aphids, *Otiorynchus* root weevils, and several species of stem and foliage feeding beetles and moths infest strawberry plantings and are managed through the use of insecticides and rotation with other crops. Vacuum insect extractors have been used in strawberries as well (Vincent and Lachance, 1993). For the southeastern U.S., the imported fire ants (*Solenopsis invicta*) can pose problems due to their large mounds and the painful stings inflicted on pickers (Maas, 1998).

A number of disease agents threaten strawberry production, and, indeed, disease management drives much of the culture of the crop. While direct sampling for pathogens is not practical, disease diagnosis and pathogen identification along with an understanding of related etiology, epidemiology and life cycles of the pathogens are fundamental to producing profitable crops. Basic control practices for strawberry pathogens include: use of certified, disease-free planting stock; sanitation; host resistance where available, rotation, and chemical treatments. Soil fumigation is done in large part to manage all soil-inhabiting pests. Host plant resistance has also been heavily exploited, but resistance can be complicated by interactions between pathogens, the host, environment, and the presence of vectors for some parasites. Also, some cultivars have resistance to only certain races of given pathogens such as *Phytophthora fragariae* var. *fragariae* (Maas, 1998). Sanitation and certification of planting stock are also critically important in strawberry disease management as a number of pathogens, including viruses and nematodes, can be introduced with poor plants. Recently, meristem propagation techniques have been adopted to help insure disease free planting stocks.

An average of approximately 335 kg ha^{-1} of pesticides were applied on strawberries the U.S. in 1999 (USDA/NASS, 2000d). Of this total, approximately 98% were fumigants used for broad-spectrum pest control with almost all acreage in California receiving a preplant treatment of methyl bromide-chloropicrin (Maas, 1998). Currently, much effort is being directed toward the development of alternatives to this biocide. Potential detrimental effects of the high usage of pesticides on this crop have received only limited attention. More effective linkage of IPM and carefully developed sustainable cropping systems that include strawberry could minimize these negative effects. Presently, however, the short-term economic benefits of current IPM programs fail to justify the associated costs (Maas, 1998).

Several beneficial organisms often are important in strawberry production. For example, more than 130 species of Mycorrhizal fungi are associated with this crop. These obligate symbionts benefit their hosts by facilitating nutrient update and may provide a level of resistance or tolerance to some pathogens such as root-knot nematodes *Meloidogyne* spp. (Barker and Koenning, 1998). However, highly effective biological control agents for most strawberry pests remain to be identified and exploited.

EMERGING OPPORTUNITIES AND CHALLENGES

Much progress has been made in characterizing the many interactions between crops and associated pests, including the development of simulation and other models. This includes the characterization of pest interactions on given crops (Abawi and Chen, 1998; Alston et al., 1991). Nevertheless, one of the greatest shortcomings of current IPM programs is the limited use of a systems approach (Merrigan, 2000)–an area in need of intensive research. The integration across pest types for specific crops and the overall production system continues to be a major challenge for IPM.

The recent advances in the development of IPM tools through biotechnology and other technologies pose new opportunities as well as weighty questions for IPM and cropping systems in agroecosystems (Bridges, 2000; CAST, 2003a; Ellsbury et al., 2000; Kennedy and Sutton, 2000). Unknown effects of genetically modified organisms (GMOs) on nontarget pests and associated organisms remain to be determined. A number of U.S. genetically engineered or transgenic crops with agronomic crop improvements such as insect resistance and/or herbicide tolerance have been economically successful. However, as 'Starlink' corn proved recently, the deployment of transgenic crops requires a number of special and complex considerations, including guidelines for production, harvesting, storage and marketing and processing. For long-term stability of these new tools, biointensive IPM-copping systems approaches will be essential. This includes industry support, monitoring of pest communities, rotation systems, judicious pesticide applications where needed, and a truly integrated crop production-IPM system (Kennedy and Sutton, 2000).

In addition to integrated systems and transgenic organisms, precision farming tools offer an option for site-specific IPM (CAST, 2003a). While precision farming provides tools for application of the appropriate amounts of inputs at the ideal time and areas in given fields, the required information and equipment are not readily available for most pests/crops and production regions. As more biotechnology and information-intensive products and related information are used, crop-oriented industries likely will have a greater impact in the development of cropping and IPM systems. For example, industry-developed crop-pest-management packages or systems are becoming available (Carroll, 2000). The focus of these types of packages is on large-acreage, high-value crops. These developments will likely impact the traditional technology-transfer systems that are provided by governmental agencies and Universities.

Another rapidly developing phenomenon is the growth of "Organic Farming" as a food-production system in a number of countries. Since the Final Rule in the U.S. prohibits the use of GMOs and greatly restricts the use of traditional pesticides (USDA/AMS, 2001), will our new technologies eventually be accepted by the organic-products communities? Clearly, the growth rates of 20 to 30% annually for organically produced foods in the U.S. and Europe will pose ongoing challenges for adaptations in IPM-cropping systems.

Increased global travel and trade have accentuated a bioinvasion of our agroecosystems and natural habitats. This problem is so severe in the U.S. that a national "Invasive Species Council" was established via a Presidential Order in 1999 (CAST, 2003a). Invasive pests clearly are bringing new challenges to IPM and cropping as well as animal systems. For example, widespread development of aggressive invasive pests, especially weeds, often greatly suppresses the activity of the normal fauna/flora, including microbes, and thereby reduces the biodiversity so important in ecology-based IPM (Altieri, 1994).

The ongoing development of pesticide resistance in numerous types of pests constitutes another huge barrier in IPM. With more than 700 pests already having acquired resistance to pesticides (CAST, 2003a), cropping systems should include "resistance-management plans." Government polices currently are having an increasingly important impact on IPM and related cropping systems. The international phase-out of methyl bromide offers one of the greatest challenges encountered by growers and agricultural scientists (EPA, 2001). The impending loss of this biocide has necessitated the development of alternative treatments for the control of an array of crop pests as well as altered cropping systems in many instances. Growers in the U.S. are faced with an equally difficult problem with the implementation of the "Food Quality Protection Act (FQPA)" (EPA, 1996; Ragsdale, 2000). This act redefines how pesticides are regulated and the act may limit the availability of organophosphates and carbamate insecticides and other older classes of pesticides. The FQPA encourages the adoption of IPM, and thus will affect many cropping systems. Ragsdale (2000) suggested that the FQPA could result in decreased availability of a wholesome and affordable food. Still, the FQPA is especially relevant to small acreage crops such as fruits and vegetables that comprise much of the diets of children.

As suggested by a call for new solutions for pest control through "ecologically-based pest management," there is a need for increased emphasis on the ecological facets of IPM and crop-production systems (National Research Council, 1996). While "Ecologically Based Pest Management" should not replace the well-established concepts of IPM, the critical needs for greater focus on ecological and other environmental factors cannot be ignored. As a recent GAO (2001) report and other assessments (CAST 2003a, Kennedy and Sutton, 2000) indicate, many other needs must be accommodated to facilitate further development and use of IPM. One of the greatest challenges for IPM is the development of truly integrated IPM-crop-production systems.

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