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Review

Integrated pest management in practice — pathways towards successful application

M.J. Way[a,*], H.F. van Emden[b]

[a]*Biology Department, Imperial College of Science, Technology and Medicine, Silwood Park, Ascot, Berks, SL5 7PY, UK*
[b]*School of Plant Sciences, University of Reading, Whiteknights, Reading, Berks, RG6 2AS, UK*

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Abstract

Examples from perennial and annual crops in temperate and tropical conditions are used to illustrate the research and development approaches that have contributed to use and integration of host plant resistance and biological, cultural and chemical controls. The evidence shows how successes in IPM have depended upon classical experimental approaches continually responding to changing constraints and to novel discoveries, which are being applied increasingly efficiently and intelligently to farm practice. Future developments are discussed in the context of past experience and new technologies. Recent developments of important new approaches that could help revolutionize management of some pest complexes, in particular genetic engineering, semiochemicals and bioinsecticides, are discussed. Much attention has been devoted to strategic modelling in the IPM context which aims to provide novel insights, but there is little evidence of its value to practical IPM; instead it could be used unwisely to encourage accumulation of unnecessary information. In contrast, tactical models are proving increasingly valuable in forecasting the need for and timing of applied controls. Whilst there have been some outstanding developments in practical application of IPM in many developed countries where the ultimate goal is to decrease over-reliance on conventional insecticides, evidence shows that in many developing countries, where the goal is an ecologically sound mix of non-chemical and chemical methods, there remains a crucial need for much more appropriate research and implementation, especially in small farm conditions. © 2000 Elsevier Science Ltd. All rights reserved.

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> In framing an ideal we may assume what we wish, but should avoid impossibilities.
>
> Aristotle, 4th Century BC

1. Introduction

A burgeoning literature on insect pest management (IPM) has arisen since 1959 when the term Integrated Pest Control was defined (Stern et al., 1959). Most has dealt with theory and research results, much only distantly related to what is happening on farms. So, one question posed by this review is, how much has this output been productive, directly or indirectly, in helping farmers to utilize "the best mix of control tactics for a given pest problem in comparison with the yield, profit and safety of alternative mixes" (Kenmore et al., 1985), or "an adaptable range of pest control methods which is cost effective whilst being environmentally acceptable and sustainable" (Perrin, 1997). Such definitions of IPM are pragmatic, and are not as demanding as the conceptually attractive ones which can also be irrelevant or misleading for the practitioner. We use historical case studies to examine how far the evolutionary pathways of basic, strategic and applied research, and of development work, have been useful or otherwise. We ask which approaches have been productive at any one time and how far the different approaches have responded to new discoveries and to the ever changing needs and constraints imposed by society. "Success" is never more than temporary. Furthermore, there will be totally different opportunities and constraints in, for example, large scale developed country arable systems when compared with small farmer developing country systems. Experience has provided crucially important guidelines for future research and development work, but these guidelines now need to be reconsidered in relation to new inputs from fashionable biotechnologies that are currently given high priority.

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[*] Corresponding author.

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Another IPM related and expanding occupation is strategic modelling based on the contention that the computer can provide "insights" where conventional thought has proved inadequate. Have strategic and tactical modelling justified the time devoted to them? Can national and international funding be put to a more balanced use, particularly in the implementation of true IPM, rather than the relentless generation of biological data and the somewhat isolated development of management tools?

2. Case histories

2.1. Apples

Early developments in apple pest management are reviewed excellently (Blommers, 1994; Croft and Hoyt, 1983; Hardman, 1992; Pickett, 1958; Prokopy and Croft, 1994; Solomon, 1987; Thwaite, 1997; Whalon and Croft, 1984). These developments over the last 80 yr are outlined below:

From the early 1920s lead arsenate was used to control major Lepidoptera pests but winter washes against over-wintering pests destroyed natural enemies causing outbreaks of hitherto harmless species, notably the European red mite *Panonychus ulmi* (Massee, 1958). Then from 1940 onwards organochlorine insecticides (OCs) replaced lead arsenate. Very serious outbreaks of spider mites were not controlled by OCs or by organophosphates (OPs) which were temporarily effective but virtually eliminated all natural enemies (Pickett, 1958). Pioneering integration of chemical and biological controls was done in parts of Nova Scotia using selective ryania instead of OCs and OPs (Pickett et al., 1958). Codling moth *Cydia pomonella* and some leafrollers became resistant to DDT and serious problems with spider mites continued even in Nova Scotia where the relatively ineffective ryania had been replaced by broad spectrum synthetic chemicals (Whalon and Croft, 1984).

In 1960–1970 a wide range of new summer acaricides was developed for control of spider mites, including *P. ulmi*, which quickly became resistant to most of these (Cranham and Helle, 1985; Pree, 1990). However, by the 1970s, mite predators of European red mite, e.g. *Typhlodromus pyri* had also become resistant (Hoyt, 1972; Solomon and Fitzgerald, 1984; Whalon and Croft, 1984). The use of native and introduced OP and carbamate resistant predatory mites was a breakthrough in practical integrated control and became the trigger for more biologically based IPM research (Blommers, 1994; Prokopy and Croft, 1994; Solomon, 1987; Whalon and Croft, 1984). Refinements in the use of predatory mites continued (e.g. Blommers, 1994; Croft and Thompson, 1975; Hardman et al., 1995; Solomon and Fitzgerald, 1993) including development of more selective fungicides. This use of resistant mite predators was fortuitous IPM that was economically highly acceptable. In the early 1980s very effective and cheap pyrethroids were introduced against many orchard pests. Their use was soon discontinued in western Europe because their toxicity to beneficial species was associated with outbreaks of red spider. Elsewhere, predatory mites were sometimes disregarded in favour of chemical acaricides plus pyrethroids, partly because of OP resistance in some Lepidoptera. Bt mixed with very low pyrethroid dosages was less harmful to the predatory *T. pyri* (Hardman and Gaul, 1990). Selection and evaluation of pyrethroid resistant *T. pyri* continued in New Zealand, North America and Europe (Hardman et al., 1995; Markwick, 1986; Solomon and Fitzgerald, 1993), including ecologically selective uses of pyrethroids (Hardman, 1992). More work is needed on effects of different acaricides on the complex inter-relationships between predatory and phytophagous mites. For example, fenpyroximate is harmless to the key predator *T. pyri* but kills the other mites including the predatory *Zetzellia mali* which could act as vital alternative food for maintaining *T. pyri* when phytophagous mites are scarce (Greatorex and Solomon, 2000).

Recently, studies have concentrated on more biologically based PM, extending into "second level IPM practices" (Prokopy and Croft, 1994; Prokopy et al., 1996). Emphasis was placed on phasing out broad spectrum insecticides toxic to natural enemies of pests such as aphids (Blommers, 1994; Easterbrook et al., 1985) and Lepidoptera (Blommers, 1994). Selective alternatives, including microbials and especially insect growth regulators (IGRs), led to large decreases in summer fruit tortrix which had become a major pest in The Netherlands (Blommers, 1994). Interest was renewed in mating disruption pheromones, a technique first examined in N.America in the 1960s and 1970s but found not economic (Whalon and Croft, 1984). For example in Washington State, mating disruption pheromone was used on about 40,000 acres in 1998, having increased by 40% per year for the past four years (T. Alway, 1999, pers. comm.), though 86% of growers used supplemental sprays on some border areas. Evidence of resistance to OP insecticides has also encouraged increased use of mating disruption, e.g. in California against multivoltine codling moth (H. Riedl 1999, pers. comm.). Developments of organic (no synthetic pesticides) apple pest management are based on natural enemies, biological pesticides, mating disruption, other behavioural control technologies and cultural controls (e.g. Wearing et al., 1994). In general there was renewed emphasis on cultural controls as part of biologically based strategies (Prokopy and Croft, 1994), although some pests reappeared that had become insignificant during the OC and OP regimes (Easterbrook et al., 1985). IGRs kill earwigs, *Forficula auricularia*, which prey on woolly apple aphid *Eriosoma lanigerum*, and summer fruit tortrix *Adoxophyes orana* (Blommers, 1994; Easterbrook et al., 1985). Changes to smaller apple trees often grown in trellises have been associated with major improvements in pesticide application (Matthews, 1999).

Monitoring in apple orchards has permitted large decreases in applied pesticides during and since the early chemical-based regimes (Solomon, 1987; Whalon and Croft, 1984); for example amounts used in The Netherlands have halved (Blommers, 1994). Biologically based PM may include monitoring predators (e.g. Croft and Thompson, 1975; Solomon, 1986). Comprehensive orchard management schedules, (e.g. Craig et al., 1997) and associated fact sheets in Nova Scotia are widely available from government agricultural services in many apple growing regions. Pheromone traps and phenology models are increasingly used to assess the need for, and timing of, insecticide applications against tortricids (T. Alway, 1999, pers. comm.; Blommers, 1994; Brunner et al., 1982; Prokopy and Croft, 1994; Solomon, 1987), for example, by 94% of advisors in California (Flint and Klonsky, 1989). In general, selective controls demand more monitoring than "supervised" use of broad spectrum chemical controls (Blommers, 1994; Easterbrook et al., 1985), and the costs of monitoring in England were once estimated to be greater than savings when compared with scheduled spraying (Fenemore and Norton, 1985). However in practice, as in New Zealand, savings from pesticides have since proved notably greater than costs of monitoring which has intensified (J.T.S. Walker, 1999, pers. comm.).

Like PM of other crops, apple pest management has attracted pest management modellers (e.g. Croft et al., 1976; Hardman, 1989; Whalon and Croft, 1984). According to the available case history evidence, strategic models, mostly designed to provide "insights", seem to have contributed no more than would conventional wisdom in pointing to gaps in knowledge, and have not been useful to the apple grower. In contrast, a phenology model has been used to link the need for and optimum timing of insecticide application to overwintering egg populations of *T. pyri* (Rogers, 1992). Similarly, computer generated farmer support systems have been greatly aided by temperature driven computerized systems especially in control of key insect species such as codling moth (T. Alway, 1999, pers. comm.; R. Prokopy, 1999, pers. comm.; Solomon, 1995). Second level IPM, involving multiple management of biologically based tactics for all pests (Prokopy et al., 1996), has a positive image for growers and the public (Prokopy et al., 1995), but so far in practice has been too complex, even for advisers. Instead, apart from codling moth control, growers and many advisers seem to use experience-based relatively qualitative estimates of thresholds, for example, they may just relate percentage leaves with spider mite and percentage with predatory mites as a basis for assessing need for a acaricide (R. Prokopy, pers. comm.).

In conclusion, the practical impact of much elegant research has been limited in most major apple growing regions, and PM has continued to need broad spectrum OPs and sometimes pyrethroids, but with OP resistant predatory mites as the positive highlight. Even in IPM-pioneering-Nova Scotia, pest management depends heavily on broad spectrum chemicals because, as elsewhere, they are convenient, cheap and require less decision-making. Moreover, in selective chemical regimes, some "forgotten" pest species previously controlled by broad spectrum chemicals have reappeared. In Europe and USA, registration withdrawals have caused phasing out of environmentally unacceptable organophosphate insecticides and are forcing change, as in The Netherlands where the selective IGR's are replacing organophosphates against tortricids, though their future is threatened by evidence that they might harm Crustacea in waterways (L.H. Blommers, pers. comm.). Moreover, pest resistance remains a continuing problem in European fruit. For example, induced resistance of codling moth to the selective acyl urea, diflubenzeron, and to the newer ecdysone mimic tebufenozide in France (Sauphanor and Bouvier, 1995) has forced reversion to OPs, leaving mating disruption and virus diseases as more expensive and difficult-to-manage alternatives. In these circumstances there is an expanding future for microbial pathogens and pathogenic nematodes (Cross et al., 1999). In California mating disruption is being used increasingly following development of local resistance to OPs by the multivoltine codling moth (H. Riedl, 1999, pers. comm.).

In future, apple pest management will be increasingly set within an overall farming systems framework, as in Western Europe where the emphasis is on Integrated Fruit Production (IFP) and quality labelling or quality assurance (QA), both already adopted in about 50% of the production area (Cross et al., 1996). IFP provides continually evolving guidelines for production of healthy crops in economically and ecologically healthy farms and environments (Blommers, 1993; Cross and Dickler, 1994). It is anticipated that the IFP/QA labels will enable apples to be sold at a premium. More importantly, the market is increasingly demanding such labelled products, as is already evident from safety criteria demanded by some supermarkets. A similar programme, also involving much decreased pesticide use, is being adopted by the New Zealand NZIFP Pipfruit Programme to involve all growers by the year 2000 (Batchelor et al., 1997; Walker et al., 1997). Australia has the same objectives (Thwaite, 1997). All these programmes seek decreasing use of toxic chemicals and increasing biologically-based PM (Blommers, 1993), but their ultimate success may depend on whether similar constraints on broad spectrum chemicals are adopted in other major apple producing regions, notably the USA where greater EPA restrictions on use of OPs are impending. In these circumstances, an enlarging USA market will enhance the economic viability of chemical industry investment in biologically based PM. As regards adoption by farmers, several countries, including The Netherlands, Great Britain and New Zealand, have established the necessary interactive education programmes and discussion groups with the enthusiastic participation of growers, advisers and research workers (Batchelor et al., 1997; L. Blommers, M.G. Solomon, J.T.S. Walker, pers. comms.). They emphasize that such close collaboration is crucial for success.

2.2. *Tropical irrigated rice*

The pathways towards practical rice IPM in Southeast Asia provide a classic example of procedures that are also relevant to many non-rice small farmers elsewhere (Matteson, 2000). The initial break-through was by Kenmore (Kenmore et al., 1984) who demonstrated the commanding role of a natural enemy complex that was locally obliterated by Green Revolution technology involving new cultivars and intensive use of insecticides in the 1970s, which led to catastrophic outbreaks of pests, notably brown planthopper (Bph). In 1990, Farmer Field Schools (FFS) were set up under FAO *aegis* (Matteson, 2000) aimed at empowering farmers to make their own decisions based on appreciation of crop agronomy and appropriate knowledge of the key pests, and of natural enemies hitherto not recognized by them as beneficial (Kenmore, 1996; Ooi, 1996). FFS have been very successful where adopted, particularly in parts of Indonesia and Vietnam, although their sustainability has been questioned (Eveleens et al., 1996). In China an experiment on the FFS approach demonstrated that it was more effective in decreasing insecticide applications than the conventional procedure of basing pesticide usage on economic thresholds (Mangan and Mangan, 1998).

The approach of Kenmore et al. (1984) depended on relevant field ecological research and its application. Subsequently, insecticides against early season defoliating pests have been proved unnecessary in parts of the equatorial tropics because the rice compensates for damage, so preserving the early arriving natural enemies that are crucial for later biological control (Way and Heong, 1994). This finding stimulated participatory experiments, whereby farmers compared yields of conventional spraying with no-early spraying in halves of fields (Heong and Escalada, 1997). In Vietnam the successful outcome led to practical uptake by the official advisory services and quickly reached 92% of twelve million farmers in the Mekong Delta (Huan et al., 1999). As with FFS trained farmers, insecticide use greatly decreased, and profits increased (e.g. Anon, 1993). In terms of sustainable pest management the shortcut approach, stemming directly from research, was criticized for failing to empower farmers with necessary knowledge that enables them to make their own informed decisions on interventions with insecticides and agronomic inputs based on the state of the crop. However, it exemplifies an important step-by-step IPM pathway towards success, characterized by other case histories such as apples and glasshouse crops (van Lenteren, 1995) where, like irrigated rice, biological controls are critically important. In contrast, the FFS approach is holistic, implying that, with experience, some programme components could be omitted or simplified. Some simplification of the FFS approach is seemingly needed because, in the last ten years, it has reached only about one million of the 19 million farming families in Indonesia (Oka, 1996) and perhaps less than 1% of Asia's 300 million rice farmers. It is hoped that the FFS impetus will snowball through IPM farmers' clubs (Kenmore, 1996) and with the development of programmes whereby farmers train other farmers through their own community based activities (Eveleens et al., 1996; FAO, 1997, 1998). However, this will require well organized effort and incentives, especially as it remains difficult to prevent farmers from reverting to the conception that many insects need to be chemically controlled (Heong and Escalada, 1999). A penetrating review (Eveleens et al., 1996) points to the need for greater research-extension and research-farmer linkages, for strengthening farmers' capabilities, and particularly for follow-up programmes to ensure sustained practices.

2.3. *Cotton*

Cotton PM has been reviewed in detail (El-Zik and Frisbie, 1985; Frisbie et al., 1989, 1992, 1994; Matthews, 1997; Matthews and Tunstall, 1994; Smith and Reynolds, 1972). Despite early disasters, as in Peru (Barducci Boza, 1972), created in the 1940s by overuse of inappropriate insecticides, these early warnings were not always heeded, for example in Northern Australia where cotton production ceased after more than thirty insecticide applications per season failed to control bollworm (Hearn, 1975), and in India and Pakistan where there is much uncontrolled overuse of insecticides (Matthews, 1997). In China, during the cultural revolution, outstanding IPM programmes were developed within communes by enhancing native natural enemies and by production and mass release of *Trichogramma* and insect pathogens (Ma-Shih-chun, 1976; Hussey, 1978; Way, 1978). Such procedures, using natural enemies bred in each commune, continued until the centrally managed systems were broken up when unrestricted use of insecticides created resistance problems and localized disasters (Matthews, 1997). Similarly, in Peru the classic Canete Valley success in the 1950s, when insecticide applications were decreased from 16 to 2–3 per crop (Barducci Boza, 1972), has degenerated. In Peru, including the Canete Valley, the area planted to cotton has more than halved in the last ten years, associated with Agrarian Reform involving the "break-up" of large estates, loss of credit facilities for the small farmers and pressure from pesticide salesmen "who are the dominant influence" (A. De La Rosa, 1999, pers. comm.) IPM is still practised on a few farms, including about 300 ha of organic cotton in the Canete Valley (S. Barbosa, 1999, pers. comm.). Nor has the message been heeded in the Californian Imperial Valley, where the cotton area had declined by 85% due to pest control costs escalating to $400 per acre (Frisbie et al., 1994). Overall, more than half of the world's cotton area is still treated intensively by insecticides.

2.3.1. *Large scale production*

In the USA, unlike Peru, farm size for cotton production has increased markedly, facilitating a more centralized homogeneous IPM approach to pest management (Frisbie et al., 1992). This has created greater opportunities for area-wide pest management based on IPM educational programs by Extension Services (Frisbie et al., 1994) and has enhanced the role of professional consultants with expertise in biological and cultural controls, together with need-based use of insecticides. The more biologically-based improvements in the USA since the 1960s (Frisbie et al., 1992) include multi-resistant cultivars and scouting-based timing of insecticide application sometimes using phenology models and pheromone traps with special emphasis on minimizing early season treatments that harm natural enemies (El-Zik and Frisbie, 1985; Wilson et al., 1998). There is good evidence of economic benefits (Norton and Mullen, 1994). Advances in resistance management include the Australian system of restricting when pyrethroids are applied (Forrester et al., 1993) though this has not reversed resistance development. An outstanding highlight is the community-wide eradication campaign against boll weevil using trapping of males and females with aggregation pheromone together with appropriate area-wide applications of insecticide to short season cultivars which have enforced planting and harvesting dates (Frisbie et al., 1994; Smith and Harris, 1994). This has already succeeded on four million acres of cotton in several States where insecticide use has declined by 60–75%. Another success has been the regional use of a pheromone confusion technique against the pink bollworm in Egypt (Critchley, 1991). This is under central control and has decreased insecticide applications per crop from five to less than two. As in China, the programme could fail with increasing privatization, as might the centralized successful pheromone trap-timed mass release of parasitoids against bollworm in Uzbekistan where privatization is impending (Matthews, 1997). Decentralization is also anticipated in the Sudan Gezira, where effective IPM by host plant resistance with cultural, physical and legislative controls lasted from about 1910 to the 1940s (Dabrowski, 1997; El Amin, 1997). Then groundnuts and wheat replaced bollworm-dislocating fallows and the pest-diversionary *Dolichos lablab* (Way, 1987). Pest incidence greatly increased and a programme of sole dependence on insecticides was introduced by package deals with the chemical industry. This created more pest problems and was terminated in 1981 (El Amin, 1997). Subsequently there was 80% reduction in insecticide inputs, following FAO programs based on renewal of some non-chemical controls (El Amin, 1997). Now, the application of IPM to the Gezira cropping system is being strengthened by the Global IPM Facility's participatory Farmer Field Schools (FFS) (Dabrowski, 1997). However, much applied ecological research is still needed on biologically based controls linked to cultural practices and use of insecticides (Dabrowski, 1997).

2.3.2. *Small-scale tropical production*

In Central Africa, small farmer cotton production is usually part of a mixed cropping system, and, unlike in India, foreign exchange controls have limited insecticide imports. In Zimbabwe, research since the 1960s, and a longstanding farmer training school have highlighted use of resistant cultivars, pest monitoring and the manipulation of insecticides and acaricides for pest resistance management (Matthews, 1996). Scouting provides a yardstick for insecticidal control, but such decision making is said to have been largely replaced by more qualitative experience-based judgments by the farmer or by trained assistants.

In Zimbabwe, cotton yields have not altered since the 1970s (G.A. Matthews, 1999, pers. comm.) although much production has changed from large scale to small farms that now produce more than half of the crop. Small farmers, like large commercial farms, apply 6–10 insecticide sprays per season, yet bollworms, for example, have not developed insecticide resistance. This can perhaps be attributed to unsprayed maize which is an important source of bollworms (Pearson, 1958) so is a large refuge of susceptible bollworms. This augurs well for success of Bt cotton once Bt cultivars with jassid resistance become available. Elsewhere, in Francophone West Africa, calendar spraying has created bollworm and spider mite resistance in circumstances where cotton adjoins sprayed horticultural crops, though decision based chemical controls are now being developed (Ochou et al., 1999).

In Zimbabwe, preliminary work with small farmers by the Global IPM Facility suggests that the number of insecticide applications can be decreased. The Facilities' FFSs plan to involve 50,000 participating farmers in the next four years, based on improved agronomy and much needed applied ecological research notably on natural enemies. This might benefit from techniques used by enthusiasts of organic cotton production (Myers and Stolton, 1999). Unlike the large commmercial farms, serious logistic constraints for small farmers need to be overcome, for example, long distance transport along inadequate roads, and, especially, soil infertility.

In conclusion, despite abundant evidence from IPM improvements beginning in the 1950s, IPM is not practised on much of the world's cotton area which still remains dependent on intensive insecticide applications, e.g. 14–30 applications in some areas of India and China. Amongst reasons for this failure are cheapness of insecticides, pressures from salesmen, poorly educated smallholders and inadequate work on natural enemies and on their integration with other controls notably insecticides that have lost efficacy against bollworm (Armes et al., 1994) and are being badly applied (Matthews, 1997). The future will include more use of pheromone based controls, and of strategies to delay breakdown of transgenic and other host plant resistance to pests. There is a potentially important future for transgenic Bt cotton especially against *Helicoverpa* spp in the tropics. Transgenic crops themselves should also help to reduce selection pressure for resistance to conventional insecticides and, together with increasing use of neonicotinoid seed treatments, should enhance the prospects for strengthening natural controls. Small farmer systems, as in sub-Saharan Africa, present the most serious problems because pest management requires a much improved infrastructure, in particular better overall agronomy to raise the yield potential needed to justify costs of pest control inputs (Dabrowski, 1997). This is the basis for present work by the Global IPM Facility.

2.4. Arable food crop systems

We contrast IPM in two extreme situations: developed country farming in Western Europe, and developing country small farmer systems in sub-Saharan Africa. The contrast is between a temperate climate and the dry tropics, between high and low inputs, between relatively simple and mostly complex systems, between sustainable and risky crop production (Chambers et al., 1989), and between priorities to decrease and to increase production (Beets, 1990).

2.4.1. Western Europe

IPM practices involving combinations of physical, biological and chemical controls were recommended as early as 1860 in a classic book on Farm Insects (Curtis, 1860). Crop rotations, used in China 3000 yr ago (National Research Council, 1996), and other traditional pest controlling practices remained important until the late 1940s when the European "Green Revolution" package of early sown higher yielding crop varieties, fertilizers and pesticides, created large yield increases of in-demand crops. Prophylactic pest control became part of "factory" production for individual crops. For example, in the Netherlands, annual soil fumigation made it rewarding for farmers to grow successive potato crops which otherwise need 3–5 yr rotations. Much more insecticide was used, as against cereal aphids which became economic to control at very low pest thresholds (Way and Cammell, 1979). Mechanization and new varieties demanded radical changes. For example, precision drilling of new monogerm sugar beet made protection from seedling pests essential for the first time, and it also enhanced spread of aphid-transmitted sugar beet yellows virus (Jepson and Green, 1983). In spite of much research, forecasting the need for aphicide against vectors of yellows virus proved unreliable, so chemical controls continued to be routine for risk averse sugar farmers (Mumford, 1981) or based on crop sampling (Dewar and Smith, 1999). The situation has recently been transformed by imidacloprid as a prophylactic seed dressing which also protects against yellows (Dewar and Asher, 1994). This requires only about 10% of the active ingredient needed for prophylactic soil applied granular insecticides (Heijbroek and Huijbregts, 1995), but its already widespread use is a recipe for induced resistance.

Field beans provide a contrasting example of how new chemicals have altered the status of the severely damaging *Aphis fabae*. This periodically caused catastrophic damage to spring sown field beans and a widely effective forecasting scheme was developed in Southern England to determine need for, and timing of, aphicide application (Way et al., 1977). However, new fungicides enabled farmers to switch mostly to the higher yielding autumn-sown beans which generally reach a growth stage that is unattractive at the time of *A. fabae* immigration (Way, 1967). The forecasting scheme therefore became redundant.

Many examples show that the objective of high yields of desirable crops led to much greater use of pesticides, often applied prophylactically. Subsidies based on the Common Agricultural Policy (CAP) of the European Union (EU) encouraged pesticide overuse and embarrassing surpluses of some major agricultural products. The rational outcome, foreseen in 1979 (Way and Cammell, 1979), was legislation against unnecessary use of environmentally hazardous insecticides and improved decision making on insecticide usage within an integrated farming framework. These objectives are being pursued aggressively in Europe, for example taxes on pesticides in Denmark, legislation in some countries to cut pesticide usage, initially by 50%, and increasing restrictions on emission of pesticides to the air, soil and waterways (Matteson, 1995). There is also renewed support for work on cultural and biological controls together with compatible pesticide usage (Matteson, 1995; Wijnands, 1997). IPM, as a component of integrated farming, must now be compatible with priorities for other desirable land uses including leisure and preservation of wild life (Rabbinge et al., 1994). The key outcome is that much previously used pesticide has proved unnecessary (Anon, 1998a; Wijnands et al., 1995). Any small yield reductions have been more than offset by decreased costs, for example by 60% through decrease of insecticide use, and where farm prices for cereal grains have fallen, integrated practices have become even more profitable (Anon, 1998a).

In Western Europe, major developments in arable crop pest management were initiated by a cooperative research network comparing conventional with less intensive integrated and also sometimes "organic" farming systems in government institutions and farmers' fields (e.g. Jordan et al., 1995). In the UK, programmes on such integrated farming are also supported by an "Alliance" of growers, government and industry concerned with research, farm practices and environmental issues (Anon, 1998a). The EU programme on sustainable agriculture (Anon, 1998a), benefiting from IOBC initiatives (Boller et al., 1998), is associated with guidelines for integrated production of arable crops (Anon, 1998b; Boller et al., 1997) and is supported by awards of "green labels" which enhance the value of the crop. Such quality requirements are now being demanded by supermarkets (Proost and Matteson, 1997) which are becoming leading instigators particularly for horticultural crops. Moreover, in the USA at least one large-scale grower is successfully applying its low pesticide IPM practices (National Research Council, 1996). Cooperative work has emphasized changes from monocrop, pesticide dependent, farming towards preservation of natural enemies and appropriate rotational cropping integrated with need-based use of environmentally acceptable pesticides (Minks et al., 1998; Wijnands, 1997). However, impending Common Agricultural Policy changes under "Agenda 2000" have proposed cuts in subsidies for cereals and particularly for most alternate "break" crops. The key question therefore is how will IPM, as we define it, be applied to what might become virtual monoculture wheat in some regions? The opportunities and constraints are exemplified by the two major insect problems of wheat in Northern Europe: First, wheat bulb fly, *Delia coarctata*. This is not a pest in wheat monocultures because paradoxically it is fallows and some rotational crops that attract ovipositing females in summer. Larvae cause severe damage to winter wheat sown in such fields after mid-October, the time when traditional wheat varieties used to be sown. However, modern high yielding varieties are mostly sown much earlier and reach a growth stage which can largely compensate for wheat bulb fly damage where it occurs. Nevertheless wheat bulb fly remains a serious pest where wheat, of necessity, cannot be sown early, e.g. after a sugar beet crop. In these circumstances, low-cost prophylactic seed treatment is usually the best financial option (Young and Ellis, 1995). Otherwise, damage is avoided if a non-host crop is grown or if wheat is sown in spring after the February-early March egg hatch. Early sown winter wheat, though it can compensate for damage, becomes a breeding ground for abundant good quality flies, thereby increasing potential damage by the next generation. This has been partly and incidentally countered by EU over-production, since farmers have been subsidized to "set-a-side" fallow areas which can act as powerful oviposition traps. A mixture of IPM practices based primarily on a range of cultural controls as well as insecticides targetted at eggs, larvae or adults provides a choice of IPM "menus" (Young and Ellis, 1995).

Secondly, cereal aphids, particularly vectors of Barley Yellow Dwarf virus (BYDV). BYDV was unknown until the 1950s when it became the most serious pest problem of wheat and barley following early sowing and hence early emergence of seedlings which attracted viruliferous aphids from infected grasses. Farmers adopted cheap prophylactic chemical control, especially after the failure of a forecasting scheme. Pyrethroids have, in particular, proved very cost effective with no evidence of pyrethroid resistance since first used in the late 1970s (Port, 1983; McKirdy and Jones, 1996). However, much work continues on practical forecasting, notably on an ambitious decision support system – DESSAC, which includes a BYVD control module (Harrington et al., 1998).

Wheat bulb fly and BYDV exemplify insecticides with cultural controls as the present basis for wheat IPM. Attempts to increase the contribution of natural enemies (Barbosa, 1998), especially against aphids, have focussed on the wild plant verges of arable fields that are reservoirs of wheat aphid parasitoids and some predatory Coleoptera. Pollen producing verge plants can also attract Syrphidae, parasitoids and Coccinellidae which oviposit in the adjoining crop (van Emden, 1965). So, in the UK, the Ministry of Agriculture's Arable Stewardship Scheme subsidizes farmers to undertake environmental practices that favour wild life and also highlights "Conservation Biological Controls" by natural enemies. The outcome has been larger areas of grasses with other plants in field corners. Farmers interested in game birds may also leave a herbicide-untreated spray-boom width for graminaceous birds around field edges. However, so far there is little evidence that strips and verges enhance biological controls or that aphid control by cheap natural enemy-killing insecticides is impaired (Gurr et al., 1998). Much work still needs to be done to understand and enhance the role of relevant predators and parasitoids (Gurr et al., 1998; Powell et al., 1998; Wratten and Van Emden, 1995), for example, on the value of non-inversion tillage which, unlike conventional ploughing, preserves active (Glen, 2000) and diapausing (Way et al., 1969) natural enemies within fields. Unfortunately field verges benefit some pests (van Emden, 1965), and flowering plants, whilst attracting parasitoids, can induce more damage by pests in the adjoining crop (Gurr et al., 1998). This poses a startling dilemma. Wild habitats such as field verges are environmentally desirable, as is rotational cropping. Yet for wheat, such habitats are the source of viruliferous aphids and other pests, whereas rotational cropping creates the wheat bulb fly problem and can exacerbate nematode and slug damage (Glen, 2000).

Intensive wheat monocultures with minimal wild plant areas might therefore be adopted in localities given priority for high yield production (Way, 1966). This should minimize pesticide pollution but also destroy wildlife habitats. However, elsewhere, localities could be designated for subsidized environmental priorities (Way, 1966); there are other possible scenarios (Rabbinge et al., 1994) which recently include tiered EU subsidies for integrated and organic farming. The need for profitable food production alongside environmental care in rural areas has now spawned the fashionable concept of "Integrated Crop Management" (ICM) of which IPM is one sub-set of "a whole farm policy aiming to provide the basis for efficient and profitable production which is economically viable and environmentally responsible" (Anon, 1998a). It is fortunate that Western Agriculture has the luxury of balancing these two objectives in physical and political climates that are reasonably stable and predictable.

2.4.2. Dryland arable food crops in small farmer Sub-Saharan Africa

About 80% of farmer families practise mostly subsistence agriculture on poor soils with uncertain rainfall. Unable to afford significant inputs, theirs is a risk strategy often buffered by growing a diversity of intercrops which can provide insurance against those that fail (Beets, 1990). Yet between 1990 and 2020 the human population is expected to double, so exacerbating a situation where yields have increased in total but decreased *per capita* since the 1970s. So far, the increased productivity has come from increasing the cropped area at the expense of traditional bush fallows that aid fertility and pest control. This is in striking contrast to Western Europe where the population has stabilized and there are larger yields from smaller areas of cropped land.

In Sub-Saharan Africa, very large grants have been allocated to work on developing IPM of basic food crops during the last 30–40 yr. They include the CILSS project in the Sahel costing almost $30 million which failed in its objective of farmer application (Zethner, 1995). Reasons for limited practical developments have been forcefully discussed (Goodell, 1984; Morse and Buhler, 1997). Fundamentally, the key constraint in most situations is that of unpredictable crop yields due to uncertain rainfall and poor soil fertility. The crucial need, therefore, is to make the low input agriculture more sustainable (Chambers et al., 1989; Pretty, 1996). Otherwise, many IPM inputs may be irrelevant. The significance and feasibility of food crop IPM in dryland conditions throughout much of the developing world and particularly in Sub-Saharan Africa has been questioned (Goodell, 1984; Morse and Buhler, 1997) on the assumption that it is usually complex and relatively costly. However, this is based on the flawed importation of methods developed in western agriculture and is not assumed in our concept of IPM (Kenmore et al., 1985; Perrin, 1997) or from evidence of "natural pest control inventions" in Central America (Bentley et al., 1994).

Staple tropical dryland crops such as maize, sorghum, pearl millet and grain legumes have been by-passed by the Green Revolution and have remained unfashionable to donors, though the Global IPM Facility has just begun work on some of them. Ideally, for resource-poor farming, pest management should require no extra cash from the farmer, as exemplified by classical biological control against accidentally introduced exotic pests or the yet-to-be realized potential for use of exotic natural enemies against indigenous pests. Another farmer friendly control is host plant resistance. Here, there have been a few successes in dryland food crops, e.g. against cassava mosaic, but limited progress against Lepidoptera which are the most damaging pests of these crops (ICIPE, 1991; Sharma, 1993). Otherwise there are vital opportunities to help the resource-poor farmers to build upon the array of traditional control practices that they have devised. Such methods were reviewed by Perrin (Perrin, 1977, 1980) and listed (Altieri, 1993, 1995; Bentley et al., 1994; Mohamed and Teri, 1989; Richards, 1985; Sanou, 1984; van Emden and Peakall, 1996), but, surprisingly, there seems to be little interest in supporting appropriate research and development work with the farmers. There appear to be only two case histories to exemplify significant IPM advances in Sub-Saharan Africa:

2.4.2.1. Cassava. Introduced from South America, this is worldwide the fourth most important human calorie food and is vital because it can withstand drought. The first PM breakthrough was the development in the 1930s of cultivars with stable resistance to the insect-vectored cassava mosaic disease (Yaninek and Schultess, 1993). Research on a local grasshopper pest in West Africa led to a recommendation for clearance of specific oviposition sites, though farmers were aware of these and were already controlling the pest by digging up the eggs (Richards, 1985) as well as by protective intercrops (Atteh, 1984). In the early 1970s, the accidentally introduced cassava mealybug threatened catastrophic damage throughout the cassava belt, but was effectively diminished by classical biological control using parasitoids from its native South America (Herren and Neuenschwander, 1991). Another exotic pest, the green mite, has also reached Africa and attempts are being made to control it by introduced predators and by host plant resistance (Zethner, 1995).

2.4.2.2. Mixed arable cropping — cereals and legumes. This is a long-standing ICIPE research project (Chitere et al., 1998; ICIPE, 1991). The IPM work has been based on cultural practices, using evidence of decreased stemborer attack in intercropped sorghum or millet with cowpea but increased attack in mixed maize and sorghum crops; also in interplanted millet and sorghum, millet responds by compensatory tillering if intercropped sorghum is killed by shootfly (Jackal and Daoust, 1986). Early planting, disposal of infested crop residues and some cultivar resistance were also integrated with intercropping, all within an integrated crop production framework. Crop yields were notably increased, though pest management appeared to contribute less than other practices (Zethner, 1995). The almost infinite array of mixed cropping tactics provide exciting opportunities for work on the improvement and application of different IPM menus for different situations. There now seems to be sufficient knowledge to begin testing a combination of IPM practices for Sahelian millet and sorghum based mainly on early sowing, tolerant cultivars and destruction of overwintering borers (van Emden and Peakall, 1996). However, until very recently, funding for essential experiments with participating farmers seems to have been neglected.

In Sub-Saharan Africa, relatively little insecticide is used by resource-poor farmers and a low value crop such as millet grown in semi-arid conditions in Mali does not justify expenditure on insecticides (Jago, 1991). Elsewhere in Africa, in more sustainable and more productive cropping conditions, they could become a necessary IPM component (van Emden and Peakall, 1996; Wightman, 1998) following the example of present and anticipated practices on dryland cotton in Southern Africa. Future work could learn from problems of Asian overuse (Raheja, 1995; Wightman, 1989) with insecticides applied 10–20 times per season on some grain legumes, but not raising yields, which have remained stagnant for decades (Wightman, 1989). Little IPM development work involving farmers' use of insecticides seems to have been done even in Asia where the international research institute with the mandate for dryland crops is sited. This is partly explained by the crusade amongst some donor organizations and NGOs for totally pesticide-free management systems, ignoring the potential value of judicious insecticide application where none currently exists. An Indian example of possible opportunities is the success of cultural controls plus natural insecticides in farms which yielded as well as, or better, and were $> \times 6$ more profitable than insecticide-dependent farms (Katre, 1996). Here, the main constraint seems to be the subsidy needed during transfer to the IPM practices.

In conclusion, the developed and developing country systems represent opposite pathways towards a common goal of successful IPM. The developed country agribusiness approach was initiated using top-down pesticide inputs, which contrast with developing country pest controls based on farmers' trial and error applied ecology. In EU countries, the constraints on pesticides have renewed interest in the use of ecologically based cultural and biological controls. These can now benefit from a much greater knowledge base than was available to the farmers of the pre-pesticide era who, like their African counterparts, had first developed their own controls empirically (Curtis, 1860). Nevertheless, EU arable agriculture still remains dependent on pesticides, with IPM mostly represented by considerable reduction and refinement of their use to minimize harm to natural enemies and to the environment. Novel formulation, e.g. microencapsulation, and delivery, e.g. precision placement, will enhance the sophistication and safety of chemical use in the future. In Southern Africa where relatively little insecticide is used on food crops (van Emden and Peakall, 1996), it is recognized that IPM should be developed from farmers' traditional practices with priority work aimed at a greatly improved knowledge base (Herren, 1996). There are certainly opportunities for use of selectively acting insecticides to increase yields of some tropical food crops (Kogan, 1998).

The above case histories mostly discuss research and IPM roles of conventional control methods in widely differing crops and conditions. There is now increasing interest in relatively novel biotechnological methods, and also in the use of computers in systems analysis using models as aids to IPM research and field application. Their roles as parts of the IPM "tool box" are examined below.

3. Biotechnology

3.1. Host plant resistance by genetic engineering

Conventional plant breeding for enhancing host plant resistance is being revolutionized by techniques for transferring resistance genes from unrelated plants, animals and micro-organisms (Carozzi and Koziel, 1997; Gatehouse et al., 1992; Hoy, 1996; Khush and Toenniessen, 1992). Such techniques are faster, more precise and allow access to a vastly greater array of desirable genes than traditional methods (Snow and Palmer, 1997). They include plant genes that encode toxic proteins such as lectins, proteinase inhibitors, trypsin inhibitors, cytokinins and chitinases (Carozzi and Koziel, 1997; Hilder and Boulter, 1999; Hoy, 1996; van Emden and Peakall, 1996). The method has the potential for creating stable resistance by multiple gene transfers, and though there are currently few examples (Hilder and Boulter, 1999), encouraging developments are impending, including combining portions of genes for broader pest spectrum efficacy, and "stacked" or "pyramided" genes from different Bt strains and "hybrids" which have different pesticide profiles from those of the parents e.g. Greenplate et al. (1999). "Gene shuffling" is another future possibility for creating truly novel insecticidal proteins. Bt cotton is foreseen as the basis for eradication programmes of pink bollworm for example, as well as use of antagonistic transgenics against plant virus diseases and for eliciting alarm pheromones by plants. It is even suggested that improved natural enemies could be created by transferring appropriate genes from insecticide-resistant pests (Hoy, 1996). The prospects present a fascinating challenge for the third millenium. The intensive work on transgenic Bt toxins expression has led to commercialization and exemplifies some opportunities and problems.

3.1.1. Bt crops

Toxins from many Bt strains, themselves genetically modified and differing in selectivity (Gould, 1998; Tabashnik, 1998)) are being enthusiastically transferred to many major crops, especially against lepidopterous pests. About 70% is Bt cotton in some States of the USA, though in many other countries all Bt crops are at present restricted to experimental conditions. This is because there are problems ranging from ethical and environmental concerns to those connected with its longer-term efficacy (Gould, 1998; Mellon and Rissler, 1998; van Emden, 1999). The reservations include declining efficacy as Bt plants mature (Fitt et al., 1998) and that, at least theoretically, there is the potential for "yield drag" involving an energetic cost to the plant (Hilder and Boulter, 1999; van Emden, 1999). This is most likely with stacked genes and raises the issue of how many genes for insect and disease control plus "quality" traits can be grouped (R.M. Perrin pers. comm.). Another uncertainty is harm to biological control agents based on effects on natural enemies (Birch et al., 1999; Hilbeck et al., 1998), although the evidence to date gives a false impression. The meaningful comparison is with other control measures rather than no control at all, and by this standard Bt is far more selective than commonly used synthetic chemical alternatives. The most serious efficacy hazard is selection for tolerant pest strains comparable to what has happened with many conventional insecticides, and including sprayed Bt (Gould, 1998; Tabashnik, 1998; van Emden, 1999). Such tolerance must be expected with Bt crops planted over large areas and there is currently controversy as to whether the tolerance that has appeared is natural or has been selected in the field (Hilder and Boulter, 1999) though natural inherited tolerance does exist (Sumerfield and Solomon, 1999). Moreover, the development of tolerance to Bt crops could accelerate pest tolerance to Bt sprays used importantly, for example, by organic growers. Despite the concerns, transgenic Bt was licensed for farm use on some crops in the USA with the immediate introduction of recommendations for delaying the onset of tolerance, based on theory that implies a high dose strategy. The recommendation, assuming random mating between tolerant and susceptible individuals, was for the use of unsprayed non-Bt refuge areas comprising about 20% of a cotton crop (Gould, 1998; Mellon and Rissler, 1998), but requirements are already changing, e.g. 50% legally enforced non-Bt maize where it is cropped with cotton. Moreover, Bt tolerant and susceptible pink bollworms develop at different rates so decreasing interbreeding which could speed tolerance development (Crawley, 1999; Liu et al., 1999). USDA "virtual resistance management centers" will be set up in the USA to handle complexities of regional strategies. Large refuge areas are also envisaged in Australia (Dillon et al., 1998) including other host crops in a rotation (Caprio and Suckling, 1998). The complexities of adult dispersion and mating behaviour (e.g. Dillon et al., 1998), about which so little is known, will determine how well any non-Bt area can serve to maintain resistance alleles at low frequencies in the population. So the "suck it and see" approach in the USA represents an empirical experiment of the kind that otherwise would need to be done over large areas to be meaningful. It is imperative that the outstanding properties of transgenic Bt toxins are preserved, especially on grounds of safety and efficacy, since the present alternative transgenes are orally much less toxic to insects, for example Bt is 1000–10,000 times more active than lectins (RM Perrin, pers. comm.). Enhanced expression systems may partly overcome intrinsic deficiencies but commercialization in elite crop varieties appears somewhat remote (R.M. Perrin, pers. comm.). Much of the private R&D in biotechnology is now focussed on quality traits and enhanced yield rather than crop protection, 'but even these modifications, which include "unnatural" fruiting patterns and crop architectures, have implications for pest population dynamics and the ability to use conventional controls.

In the longer term, and in relation to present recommendations for delaying pest resistance, it is recognized that a transgene such as Bt must be envisaged as part of an IPM mix (Hoy et al., 1998) including other transgenes (Fischhoff, 1996) and especially conventional biologically based and chemical controls against pests unaffected by the transgenics. This includes pests that previously had been suppressed incidentally by broader spectrum insecticides (Hoy et al., 1998), for example heteropterous pests of Bt cotton in China, Australia and USA. In the IPM context, the presently chosen high kill strategy using Bt, for example, may be feasible given stable resistance to some target pests, but Bt only gives partial control of others. That the crops may now receive less total insecticide provides an opportunity for supplementing the mortality with biological control. This has implications for van Emden's (van Emden, 1966) concept of synergism between partial host plant resistance and natural enemy action. With the Bt example, biological control will then be added to a level of plant resistance already used by farmers. In these circumstances, the addition of biological control might theoretically hasten adaptation by the target pests to the Bt gene (Gould et al., 1991), although their model, which suggests this, was based on a simple one allele — one plant resistance mechanism system. This however seems irrelevant to the field situation which involves different mixtures of controls against an array of pests including natural enemies which may also benefit from non-Bt refuges (Chilcutt and Tabashnik, 1999). Indeed, experiments combining transgenic Bt, natural enemies and conventional insecticides (Hoy et al., 1998) have given encouraging results, as has field work on compatibility with conventional host plant resistance and natural enemy action (Cuong et al., 1997). Moreover, in a comparable IPM situation involving sprayed Bt and a parasitoid, theory suggested that a low dose strategy is better than a high dose strategy (Chilcutt and Tabashnik, 1999). This indicates that IPM realities require a more critical appraisal of Gould et al.'s (1991) basic theory. In present circumstances it is becoming increasingly evident that correctly timed conventional insecticides, notably pyrethroids, are needed on USA Bt cotton, not only to control a new spectrum of pests such as stink bugs but also against bollworm (Capps et al., 1999). This therefore requires continual scouting to determine when such "over-sprays" are needed (Bell et al., 1999). Fewer over-sprays are needed than for non-Bt cotton, though not invariably, e.g. Layton et al. (1999).

Selective and safe transgenes could transform IPM of some very serious pests of tropical food crops. In these circumstances transgenes could replace no controls, or control by natural enemy-killing insecticides, as components of IPM of important tropical dryland crops such as pulses, maize, sorghum, millet and also cotton. There is criticism of multinationals tying up genes and preventing their use in the developing world. So, the patenting and licensing of these evolving technologies needs to be resolved. Some governments could fund their own transgenic programmes as in China. Otherwise, international organizations including NGOs should fund means of supporting preliminary collaborative work with developing country governments on selected small farmer transgenic dryland tropical cultivars, as is now beginning at the International Rice Research Institute. Despite present fears of transgenes regarding farm ecology and human dietary risks, are the dangers comparable to those of the older hazardous insecticides that are being over-used in much of the tropical world? Potential dangers are that crops could become invasive weeds and that transgenic resistance could be transferred from crops to related weeds (Snow and Palmer, 1997). These could be much less easily reversible in contrast to merely stopping use of a harmful conventional chemical, but present evidence indicates no risks (Crawley et al., 1993; Prins and Zadoks, 1994). A key issue here is what is considered "safe" and "environmentally friendly" and who decides between conflicting ethical and more pragmatic viewpoints. In Europe the public remains deeply suspicious of GM crops being introduced in the wake of various food health scares. This has slowed the adoption of insect- and herbicide-tolerant crop varieties compared with the USA and, in the short term, it is doubtful if any scientific data or argument can instil confidence in this novel technique (Crawley, 1999). Past experience with toxic pesticides has made many developing countries similarly fearful, and there is now "increasingly vocal concern" in the USA about GM products (Anon, 1999a).

3.2. *Semiochemicals*

These are mostly highly specific (Minks and Kirsch, 1998) so theoretically have ideal environmental and IPM qualities. Here we outline promising uses:-

3.2.1. *Pheromones*

There is renewed interest in mass trapping and male confusion techniques as specific alternatives to broader spectrum conventional chemicals in integrated and organic crop production e.g. against moth pests of apples (T. Alway, pers. comm.; Wearing et al., 1994). At least 46 different pheromones are available commercially (Copping, 1998) and overall, about 300,000 ha of different crops were treated by mating disruption in 1996 including 80,000 ha against pink bollworm on Egyptian cotton (Minks and Kirsch, 1998) in a programme which preserves important biological controls. A both-sexes lure and kill aggregation pheromone is proving outstandingly successful as part of an eradication programme against boll weevil in the USA (see earlier). However, the most widespread use of sex pheromones is in monitoring to assess need for use and timing of pesticide application as mentioned in several of the case histories. Recent research promises expanding future applications (Cardé and Minks, 1997; Schlyter and Birgersson, 1999).

3.2.2. *Allelochemicals*

Apart from their natural roles in host plant resistance, synthetic equivalents have been developed to manipulate the behaviour of pests and beneficial insects in relation to each other and to the host plant (Pickett et al., 1997; Ridgeway et al., 1990; van Emden and Peakall, 1996). Naturally occurring allelochemicals can attract natural enemies to a host and to its host plant, which suggests that plant variety selection and modification could be used to manipulate natural enemies (Bottrell et al., 1998). Moreover, allelochemicals are no doubt involved in the attraction of some pests from at-risk to diversionary crops (Khan et al., 1997; Pearson, 1958; Way, 1977, 1987). Synthetic allelochemicals are envisaged as IPM components (Pickett et al., 1997), but it remains to be demonstrated whether they will prove both effective and economical, except possibly as transgenes which might potentially be used to elicit alarm pheromones or other semiochemicals against pests.

3.3. Bioinsecticides

We define these as mass produced products that are usually non-replicable microbial alternatives to conventional chemical insecticides. Most bioinsecticides, such as Bt, have desirable properties of safety and specificity (van Emden and Peakall, 1996) so they have important IPM uses in some circumstances (Bateman, 1999; Bateman and Thomas, 1996), notably for some horticultural pests and in forests and rangelands where conservation is important. Elsewhere their safety and specificity can also make them important natural enemy-benign alternatives to chemicals in organic crop production and in resistance management strategies (Bateman and Thomas, 1996), but there are weaknesses such as slow speed of kill, relatively poor storage capacity and possible allergic effects (Bateman, 1999). Interest has accelerated from an unpromising situation about twenty years ago, especially following increasing pressure against use of some synthetic insecticides and also the introduction of transgenic bioinsecticides. New delivery systems are making some inadequately persistent pathogens much more effective (Bateman, 1999), and capable of self renewal in the field, for example, the fungus *Metarhizium anisopliae* against locusts and grasshoppers (Bateman and Thomas, 1996). The future of bioinsecticides as selective alternatives to conventional insecticides in IPM programmes will depend on possibilities of self renewal (Waage, 1996a, b) and on industry's competitive success in developing selective conventional synthetic chemicals and also on the success of engineered bioinsecticides other than Bt which has already captured a large market. There are, for example, more than 1600 known baculoviruses from over 1100 insect and mite species (van Emden and Peakall, 1996) some of which have already been genetically engineered against cotton Lepidoptera (Heinz et al., 1999; Treacy and Rensner, 1999). Constraints and other problems in use of insecticides, for example in apple pest control, should trigger more work on many inadequately studied entomopathogens (Cross et al., 1999). In the IPM context there may be a future for pathogens of intermediate effectiveness (Waage, 1996a, b). As with synthetic insecticides, there are concerns about development of pest resistance, already experienced with sprayed Bt; also possible harm to some non-target organisms. Besides their use as transgenics, bioinsecticides will probably have a small but increasing niche market helped by fast track registration of biologically based technologies in the USA (Waage, 1996a, b). Apart from transgenic Bt, they have been envisaged as mere substitutes for conventional chemicals and hence limited by the same constraints as those on the big chemical companies. However smaller organizations are better equipped to produce bioinsecticides, as they already do successfully for the glasshouse industry. Such industries could be encouraged initially by public/private sector initiatives as exemplified by collaboration in the LUBILOSA locust control project (Bateman, 1999). Large-scale agriculture and forestry could also produce their own, as once in China (Hussey, 1978).

4. Systems analysis

We define this as providing an appropriate framework to help understand and perhaps manipulate a system and, for IPM, to provide guidelines or insights for the development of improved pest management strategies and tactics. Methodologies may range from qualitative conceptual "soft technique" models (Norton and Mumford, 1993; Rossing and Heong, 1997) to complex mathematical analyses (Dent, 1991). In the context of this review we recognize three kinds of mathematical model – fundamental, strategic and tactical. The first are aimed at understanding general principles of dynamics of animal populations (Hassell, 1978; May, 1975); May and Hassell, 1988) that can be relevant to theory of biological control and for example to dynamics of GM based host plant resistance (Crawley, 1999). However, in this review we are concerned with mathematical modelling that is more directly targetted to IPM. So, we regard strategic models as specifically aimed at providing novel insights and guidelines for IPM research, whereas tactical models are intended to be directly applicable to farm practice.

4.1. Strategic models

There is now a huge literature where such models have been used for two main purposes — to simulate real world situations particularly in biological control (Barlow, 1983; Ruesink, 1976), and to help provide understanding of a pest system. The latter include simulation and analytical models but, most notably, they aim to examine insect/plant interactions such as analytical combination models of population dynamics of the pest and the growing crop (Rabbinge, 1983).

Models have been very widely used, particularly in relation to biological control, and some are reviewed by Barlow (Barlow, 1998). The object is usually to mimic relationships already examined in the field in the hope that the model will add novel insights or will be developed as a predictive tactical model. It is implicit in these models, however, that the output can only reflect the input, and therefore the model cannot provide any insight which is non-deductable from simple additivity or other prescribed function of these inputs. Although strategic models can be a shortcut in suggesting outcomes for testing by experiment, they cannot be a substitute for empiricism. Models unfortunately cannot predict the unpredictable, whereas experiments can for example reveal important and often unexpected synergism or compatibility between control methods as shown by our case histories. Some relatively early simulation models were discussed by Way (1973). For example, field work in England defined proportional losses of winter moth caused by different mortality factors, including parasitism, which was shown to be of negligible importance. Yet, contrary to the English evidence, parasites were introduced into Canada where they proved spectacularly successful through "mere good fortune" (Embree, 1971). Modelling in hindsight (Hassell, 1969, 1978) then helped explain the contradiction. Another classical biological control example began with experiments on two introduced parasites which indicated that one had much better attributes (Huffaker, 1970), but this prediction failed in the field until release of the other parasitoid compensated for poor performance of sole use of the first. This situation was then simulated (Huffaker, 1970). There are many assertions that strategic models are, or will be, valuable in IPM (e.g. Dent, 1991; Huffaker, 1970; Rabbinge, 1983; Rabbinge et al., 1989; Sutherst and Maywald, 1985). However, since the time of Ruesink (Ruesink, 1976) when there was already an "incredible quantity of literature on biological models", have they provided insights or pointed to important gaps in knowledge that were not evident from the original research (Barlow, 1983, 1998)? Some models have aimed to provide guidance for classical biological control but, in practice, no introductions have been based on novel information from models, all of which have so far been retrospective simulations. This is borne out by conclusions in reviews (Barlow, 1998; Ruesink, 1976; Ruesink and Onstad, 1994). Yet, as in 1970 (Huffaker, 1970), optimism is still being expressed (Waage and Barlow, 1993). Other strategic models include insect/plant interactions (Rabbinge, 1983), for example on cotton (Gutierrez et al., 1975), and cassava (Gutierrez et al., 1993). These are relatively complex models of trophic interactions involving many assumptions (Barlow, 1998) and the inclusion of questionable evidence from the field. For example, apparently unreplicated plots with no error limits (Gutierrez et al., 1975) resulted in the claim that bollworm loss in a particular treatment would be 0.0004 of a cotton bale! Other comparable models (e.g. Xia Jingyuan, 1997) are more safely based on sound field work and appropriate error estimates. Yet even this work simulates conclusions already evident from field results and previously demonstrated by conventional research on other related species, e.g. delayed density dependent predation, and self regulatory mechanisms. Many complex models, particularly on cotton, have been devised, for example SIMCOT and GOSSYM. These require large amounts of data, computer inputs and time, and do not appear to have been validated by experiment (El-Zik and Frisbie, 1985). It is claimed that, as research tools, they can be useful for evaluating different scenarios (Gutierrez and Curry, 1989; Gutierrez and Wilson, 1989). It is also claimed that such models force users to think more about the various factors in the ecosystem and thereby provide a better understanding of IPM. Consequently the value of such strategic models should be evident from their role in the last 20–30 yr of improvements in cotton IPM which has been modelled more than any other crop (Mumford and Norton, 1994). However, there is no evidence from successful IPM developments on cotton (Frisbie et al., 1994; Matthews, 1997) or from our other case histories that they have offered new IPM "insights" additional to those that stem directly from the cerebral cortex! Are good field experimentalists sufficiently impaired to need modelling as a "crutch" (Ruesink and Onstad, 1994)? Moreover, whether or not modelling is a preferred tool to devise an IPM strategy, it is ultimately economics, convenience and legislation that drive uptake of new developments by growers. Barlow (1983, 1998) concludes that lack of progress with strategic models is because they have been too abstract, or over complicated, or inappropriate, or because the author's interest has been in publication, not application; to this should be added uncritical editors and readers who seem to accept such models as an end in themselves. It is advocated that, in future, a more "pragmatic approach using fairly holistic models should be adopted" or that they should be "constrained to particular aspects" (Waage and Barlow, 1993). This is exemplified by one study in classical biological control (Godfray and Waage, 1991) in which easily measurable life history parameters were used as independent confirmation of conclusions concurrently shown by in-field effects of the release. Although this shows what might be possible with predictive modelling, it is still far removed from proving its value for use in natural enemy introductions, especially as the coincidence of model output with "real world" output cannot be assumed and requires confirmation more than real-world evidence requires independent confirmation from a model.

Sometimes progress by experiment has to be limited by the large scale of the field experiments that may be necessary. Two examples indicate how modelling can then be useful pointers to likely effective control measures, especially in making it easy to add an economic dimension to combinations of interactions compiled from current knowledge. One relates to a comparison of prototype arable systems (see Arable Farming case history) a comparison which cannot feasibly be reproduced throughout all of the site-specific areas (Rossing et al., 1997). Research on losses caused by aphids and other pests of wheat in one region, combined with other survey data, were used to explore economic returns to indicate years when pesticide use would be justified. A model "crop simulator" based on the farmer's decision rules then indicated bottlenecks in existing wheat-based systems (Rossing et al., 1997) and offered options for testing through prototype site-specific experiments. This seems a valuable role for models, that they can help justify and prioritize what experiment is needed.

A strategic approach is also being used for minimizing development of resistance to transgenic Bt in cotton and other crops. Here the models, of necessity, have been based on the results of small scale laboratory tests and theoretical assumptions on insect dispersion, genetics and mating behaviour (e.g. Gould and Tabashnik, 1998). The model speeds up the calculation procedure for estimating the proportions of unsprayed non-Bt crop refuges needed to prevent or delay induced pest resistance. Like more complex models, e.g. Storer et al. (1999) involving two crops, it remains to be validated in different field situations.

Besides their value in information technology, models may have other educational roles (Mumford and Norton, 1994). For example, in a dialogue between environmentalists and flower bulb producers they helped to explain that environmental aspects could be improved without economic penalties; this then prompted jointly designed on-farm experiments (Rossing et al., 1997). In this context models can be especially valuable for the economic analysis of IPM practices (Croft et al., 1976; Mumford and Norton, 1984; Norton and Mullen, 1994; Waibel and Fleischer, 1998).

We conclude that the wrong balance of time and funding has been devoted to strategic modelling vis à vis relevant field research, especially as modellers are always wanting more field data of the kind that might divert from imaginative experimental approaches (see later).

4.2. *Tactical models*

Expert Systems aim to prescribe action by the farmers unlike Decision Support Systems that provide the information needed for farmers to make their own decisions depending, for example, on the extent to which they are risk-averse. The classic example of an Expert System, EPIPRE, was for pesticide application that proved experimentally successful for about 600 farmers in the Netherlands (Zadoks, 1981). That it was not subsequently adopted was attributed to farmers learning to make their own decisions (Dreuth et al., 1989). Decision Support models may aim to provide advice on some or all aspects of crop production and protection. These consist essentially of a "framework" to which relevant IPM specific modules can be attached. Such a model proved impractical for apples in the Netherlands, but Orchard 2000 is seemingly being adopted in New Zealand (Laurenson et al., 1994). In cotton, SIRATAC was adopted by about 25% of Australian farmers on 40% of the acreage in the early 1980s (L.T. Wilson, pers. comm.), but adoption tailed off with the cessation of government finance. In the USA, usefulness has been claimed for some complex cotton models (Gutierrez and Wilson, 1989) including TEXCIM (Sterling et al., 1993), though this was not reported in recent reviews of cotton IPM (Frisbie et al., 1994; Matthews, 1997) and so far has proved too sophisticated to be accepted by extentionists and farmers (W.L. Sterling 2000 personal communication). Simpler user-friendly expert systems (e.g. Goodell et al., 1991; Plant and Wilson, 1986) are considered valuable for consultants and farmers, at least in the future (Frisbie et al., 1994). Perhaps the most ambitious model is DESSAC which is being developed to cover all aspects of arable farming in the UK, including, for example, a BYDV control module for wheat and barley (Harrington et al., 1998). It is aimed at large computerized farms and consultants, and will be a test of whether such complex futuristic models will be practicable.

So far there has been a "low level of uptake by farmers" in the UK (Knight, 1997), because they and advisers have not yet adopted the necessary computer technology and because some models are not sufficiently relevant. The most widely practised use of tactical models is where real time forecasting of need and time of insecticide application are critical, such as the temperature driven models used in pheromone monitoring of many pests, notably codling moth. In the USA such computer-based models, like those based on weather and other historic information in California since the 1950s (F. Zalom, 1999, pers. comm.), are widely used (Flint and Klonsky, 1989; Giese et al., 1975; T. Alway, H. Riedl, pers. comms.); similarly in the UK (Finch et al., 1996), though some horticulturists use personal weather stations (Collier, 1997). Climate driven models can be used for judging the potential for success of invading species, including forecasting in relation to climate change (Sutherst and Maywald, 1985).

In conclusion, as far as we can ascertain, complex Expert and Decision Support Systems for farmers seem to be little used, though they, together with the already widely used simpler monitoring and forecasting models, will undoubtedly become increasingly available and used in developed country agriculture and horticulture. In developing countries they could be used for industrialized crops and perhaps elsewhere when decisions can be made over large areas such as in rice bowls. Similarly, for small farmer cropping systems, forecasting models may help against plague pests such as locusts and army worms (Day et al., 1996).

5. Discussion

The case histories provide evidence of progress that reflects a diversity of motives among those concerned, as well as the effects of evolving opportunities and constraints. Motives include national policies to decrease pesticide use (Netherlands and Scandinavia), adoption of IPM in the broadest sense (USA), exploiting new market opportunities (European fruit), encouraging sustainable agriculture (UK) and being "safe", "green" or "environmentally friendly" (individual growers). For example, in apples since the 1920s, there have been frequent changes, some mistaken, some positive, towards the elusively changing goal of successful IPM, the criteria for which have become increasingly stringent in response to induced pest resistance, to registration withdrawals of undesirable chemicals, and to introduction of new insecticides and methodologies. The work on apples has involved imaginative empirical and experimental work notably in applied ecology combined with a highly innovative chemical industry, improvements in pesticide application technology and increasingly enlightened farmers and advisers; yet, in terms of idealized IPM, the major highlight is the use of pesticide resistant predaceous mites, with insecticides still predominant, albeit need based and more selective. The changes in Western European arable IPM are similar though complicated by a greater variety and rotation of crops, and benefiting from many opportunities for cultural controls. Importantly, IPM is now well recognized as a component of integrated farming not only in developed countries but critically in tropical small farmer arable cropping especially where improved pest management must depend on simultaneously raising the basic yield potential. The evolving IPM pathways for cotton in much of the USA are an outstanding example of developed country practical IPM based on mixes of pheromones, transgenic Bt and biologically based controls particularly cultural controls, as well as conventional synthetic insecticides. These have benefited from a rich history of research on single pest control components, first motivated by the absence of easy insecticide solutions and later in response to problems that those solutions created. However, elsewhere in the world $>50\%$ of cotton production still depends on, and suffers from, overuse of synthetic insecticides. IPM success in tropical irrigated rice cropping systems stems from applied ecological research that demonstrated the crucial role of natural enemies. Outstandingly, the successes of natural or introduced biological controls in tropical rice, and in protected tomato crops (van Lenteren, 1995) and soya beans (Moscardi and Sosa-Gómez, 1996) arose from failures, sometimes catastrophic, of chemical controls.

The key question is: what are the research and development approaches that have succeeded? It has often been asserted since the 1970s that improved IPM will depend on "a sophisticated understanding of the ecology of the ecosystem involved" (Doutt and Smith, 1971), and on "depth of understanding of agroecosystem structure and dynamics" (Kogan, 1998). This approach can make impossible demands on the field ecologist because, even in one system, the complex interactions in a food web, of for example irrigated rice with potentially 9000 trophic links between 645 taxa (Cohen et al., 1994) differ in time and space. Cohen et al. (1994) used step-wise multiple regression analysis to simplify the complexity and to identify 3–5 species from selected food elements that mostly correlated with pest abundance in a single rice crop season. However, that the same correlates can be used to predict abundance in other seasons and sites would need to be critically verified before the regression can have the claimed predictive value. The call for sophisticated understanding of the agroecosystem as a basis for successful IPM typifies the Baconian procedure of accumulating information which it is hoped will "eventually fall into place", an approach which has "always been singularly unproductive" (Wigglesworth, 1955). There is a danger that, misleadingly, it might be encouraged by a powerful advocacy of "Ecologically Based Pest Management" (National Research Council, 1996). An example is a massive ecological study on spruce budworm which did not advance practical control (Way, 1973). In contrast, the experimental approach for testing ideas and hypotheses is of proven value throughout science as postulated by Aristotle (4th century BC), classically exemplified for applied ecology in the 1940s by Ulyett (1947) and highlighted by Kenmore et al.'s (1984) work on tropical irrigated rice and by our other case histories. In the IPM context this approach necessitates hands-on field experience which has mostly been hindered by the work of many IPM theorists who have inadequate appreciation of reality; also by ecologists funded to work on IPM who are primarily interested in fundamental ecology. A broad knowledge of ecological principles is however needed, including a healthy scepticism of some concepts. For example, it is still being postulated that stability is positively linked to diversity and hence that agroecosystems create problems through lack of diversity. Yet monocultures can minimize problems as exemplified by our European arable crops case history. It is not diversity per se that is significant in pest management, rather it may only be the presence or absence of one or a few functional links (Way, 1977). For example, at the 2–3 trophic level a single predatory species effectively controls a spider mite pest amongst the diverse arthropod community in an apple orchard, and it seems likely that biological control of tropical irrigated rice pests may depend on relatively very few natural enemy species rather than on the hundred or so that have been identified (Way and Heong, 1994). Such a hypothesis can be tested by experiment as has been shown by our case histories. At the 1–2 trophic level the removal of a single crucial host plant requirement for the pest can make it ineffective, for example in our Western European arable crops case history, the removal of a linking host plant or change in sowing date of the at-risk crop. So, potentially there is an important and realistic future for IPM in the practical exploitation of key functional elements of diversity (van Emden and Peakall, 1996; Way and Heong, 1994). The importance of the experimental approach is evident from the plethora of vital IPM questions that need answering by critical field experiments.

They include questions about the value of interactions, positive or otherwise, between IPM components (van Emden and Peakall, 1996) and also on improvements in the role of individual components, for example how can natural enemy-enhancing traits contribute to biological control (Bottrell et al., 1998)? The really valuable contributions have frequently been made by dedicated workers with applied appreciation, often through individual pieces of work that have happened to fit socio-economic realities of crop production.

The future of transgenic controls is in danger of being jeopardized by lack of experimental work on their role as IPM components partly because they were promoted initially as "magic bullets". In the IPM context there are intriguing opportunities. For example, herbicide tolerant sugar beet, grown without weed control at the start of the season, can later be treated, so diverting natural enemies from the killed weeds to the young crop (Dewar et al., 2000). Experiments will show whether this is useful. Similarly for small farmers in Africa, cotton is traditionally grown with maize which could be an excellent "refuge" for susceptibles of bollworm attacking Bt cotton. In summary, the experimental approach is endangered by Baconian demands of some "strategic" modellers. Yet such models will always be "at best caricatures of reality" (May, 1975); also there is virtually no critical evidence that these models have helped progress along the IPM pathways towards success that are exemplified by our case histories. Instead, many are a distraction, especially as they seem to have been done for their own sake without verification or because their value has been uncritically assumed.

The most important message from this review is that priority should be given to application of the right kinds of applied ecological and associated behavioural work in real situations in the field. At present, the balance is wrong, with too high priority given to fashionable technologies. Good applied ecology also suffers because it has low status and usually involves time consuming hands-on work often in difficult field conditions. Furthermore, dedicated applied ecologists have often been frustrated in their attempts to translate experimental results into farm practice. For example, with irrigated tropical rice it has taken about twenty years for proven IPM practices to reach only about 1% of the farmers in Asia. The problem is particularly acute in developing countries where the bias towards biotechnologies is draining the very limited funding from critically needed basic biological work and its application (Herren, 1996). Hopefully, the Global IPM Facility and associated research heralds correction of this imbalance.

At the turn of the millennium it has been customary to "crystal ball-gaze" for example on the role of synthetic insecticides. Present views on their future are mostly too highly polarized (Perrin, 1997). We anticipate that, beyond and despite Silent Spring (van Emden and Peakall, 1996), appropriate conventional synthetic insecticides will remain as important IPM components in many crop systems for the foreseeable future, as is evident from their continuing vital roles in some of our case histories. In view of exposure hazards to operators, there will undoubtedly be a continuing decrease in use of broad spectrum organophosphates. Pyrethroids, despite risks to biological controls and fish, have the important attributes of safety to birds and mammals. In practice, they are active at extremely low dosages and, properly used, can have minimal undesirable side effects as an ultimate weapon. Novel chemical groups will be developed, and already include neonicotinoids that have valuable selective seed dressing and systemic action. Their use is expected to grow to about 15% of the total world insecticide market by 2003 (Anon, 1999b). The rate of development of such novel chemicals has recently accelerated and, for IPM compatibility, a resistance management strategy is now part of their registration process (R.M. Perrin, 1999, pers. comm.). Although transgenically pesticidal plants have a potentially great future they cannot provide the total solution for some important crops especially those with a large pest complex. The transgenic approach is also being used to provide desirable traits such as extended fruiting cycles and climate tolerance. These changes will influence pest management in ways that cannot yet be foreseen. IPM requires the practical integration of transgenic technology with other appropriate technologies, including biopesticides. However, industry faces ever-growing registration costs which, despite incentives, could mitigate against the development of niche products like baculoviruses or entomopathogenic fungi. These can still be economically attractive to smaller private pest control companies, and may yet become part of the bundles of technology which large companies will be able to offer customers at prices affordable by agribusinesses. Indeed, as agribusinesses become vertically integrated in the food chain, owning seed companies at one end and wholesales or retails at the other, they will become less sensitive to the costs of crop protection and more concerned with regular supplies of high quality produce (R.M. Perrin, pers. comm.). The threatened de-registration of the older toxic organophosphates and carbamates provides another impetus for more expensive selective compounds and alternative non-chemical technologies. It must be remembered that even so-called "selective insecticides" are never entirely so. However, for these as well as for more broad spectrum insecticides it is their "risk" in the field when properly used as part of an IPM programme that is important, and not their "hazard" as shown in laboratory tests (Perrin, 1997). In this context we stress the many opportunities for making some broad spectrum insecticides ecologically selective (Metcalf and Luckmann, 1994), now including lure and kill and precision placement as well as the older concepts of seeking selectivity by formulation, decreased dosage, timing of application and selectivity in space such as alternate row spraying. In summary, insecticides will continue to be widely used for the foreseeable future, but more as relatively expensive stilletos, never again as cheap panaceas.

Host plant resistance is the theoretically ideal control method (van Emden and Peakall, 1996), so in the past has often been given paramount priority, for example by the CGIAR international research institutes, with emphasis on seed based technology including crop protection requirements. The implementation of this approach, however, has been limited by the inability to develop adequate stand-alone host plant resistance in most key crops and against many pests, coupled with the lack of interest by plant breeders in releasing cultivars with partial resistance. Where stand-alone resistance has succeeded initially, the development of virulent strains of a pest has jeopardized its value, especially because it has only been belatedly realized that host plant resistance must be used as just one component of an IPM mix. This is best exemplified by the notorious brown planthopper (Bph) of Asian tropical rice where, for the Green Revolution, the disastrous mix of "resistant cultivars" with single gene resistance and intensive broad spectrum insecticide controls quickly selected resistant breaking pest strains against all new resistant rice cultivars (Way and Heong, 1994). Yet now, with preservation of the natural enemy community, some of the rice cultivars are retaining useful resistance (Cuong et al., 1997) despite the continuing potential of Bph to overcome single gene resistance mechanisms. It is significant that, in their plant breeding policies, international institutes such as IRRI no longer trade stability for intrinsic yield (IRRI, 1996). The resistance of Bt crops, based on antibiosis, is similarly linked to a single gene; hence the urgency of present attempts to avoid selection of resistance breaking strains. Whilst we now foresee the potential for multiple genetic manipulation to create durable host plant resistance, we presently give priority to IPM practices that can retain otherwise non-durable resistance such as that of Bt plants, and equally important, the retention of conventional resistance mechanisms in an IPM framework.

This review has concentrated on IPM research and its application, but we also recognize the key role of social and institutional practices. For example, EU and individual country policies are shaping environmentally safe Western European IPM as shown by our arable crops case history. Unfortunately, and particularly for developing countries, there are often serious social and organizational obstacles to be overcome locally, governmentally and internationally. These have been discussed frequently (e.g. Goodell, 1984; Heong, 1999; Kogan, 1998; Perrin, 1997; van Emden and Peakall, 1996; Wearing, 1988). Indeed in much of Africa, prospects are particularly "bleak" if such constraints remain unresolved and if proper commitment is not made by international organizations and by the countries themselves (Metcalf and Luckmann, 1994). Specific constraints include political bias on policies for research and development, and lack of appreciation of realities and priorities in tropical developing countries (e.g. Barfield and Swisher, 1994). For example, transgenic technologies might be especially valuable for the tropics but must be built on IPM research which will help determine the circumstances where this technology will be useful and safe (Cohen, 1998; Waage, 1996a, b). There is a real danger that biotechnology in general will drive changes in agricultural practice that fail to accommodate the implications for pest management, as did pesticides initially overshadow many valuable and timeless cultural controls.

It is apparent to us in writing this review that the same principles, though with different relevance, apply to the two contrasting scenarios of the technologically developed and the small farmer developing world as in Southern Africa. In the former, these principles are being applied systematically to decrease over-reliance on conventional insecticides: in the latter there will be increased ecologically compatible use of some conventional insecticides and also bioinsecticides, including transgenics. In both scenarios the top priority is the relevant application of the right kinds of much needed applied ecological research. The IPM tool box has never been fuller. The ultimate practical challenge is farm level ability to select menus of appropriate tools and to employ them cost-effectively.

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