Developing sustainable pest management strategies for a changing future:

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Worldwide, agricultural pests destroy 30-40% of crops before the harvested food reaches human consumers or our livestock. These huge losses continue each year, despite $6 billion being spent globally on synthetic pesticides in an attempt to control pest problems on crops. It is estimated that each year insects consume the quantity of crops which would feed one billion people. The impact of crop losses due to pests is exacerbated by the rapid increase in human populations and the depletion of natural resources globally.

Plant breeding for pest-resistant crops Breeding for host plant resistance to insects has been a successful strategy deployed by SCRI's plant breeders and entomologists together with other research centres over 40 years Breeding resistance into crops has reduced, and must continue to reduce, the need for insect control based on synthetic agrochemicals. However, breeding is a long-term approach (e.g. 10-15 years for new pest-resistant varieties to reach farmers), throughout which pest insects and mites are constantly adapting and overcoming plant resistance genes in a co-evolutionary "arms race". This interactive process between insects and plants has been occurring for thousands of years, but has speeded up due to intensification of agriculture, e.g. use of fewer crop varieties and genotypes being deployed, grown in monoculture rather than as a mix of genetically variable landraces. This means the pest resistance 'targets' for plant breeders and biotechnologists are constantly moving, allowing no time to rest on past laurels and successes. Recent examples of pests' counter-adaptations to introduced pest resistance genes are seen in SCRI's crop varieties. These include red raspberry varieties which were formerly resistant to the main aphid and virus vector pest, *Amphorophora idaei* (the large raspberry aphid), and most recently in blackcurrant varieties resistant to galling and virus-transmitting *Cecidophyopsis* mites (e.g. blackcurrant gall mite). In both cases, many years of careful plant breeding is being overturned by rapid counter-adaptation in genetically variable pest populations see fig 1. This process typically occurs through co-evolution

Fig 1 The use of pest-resistant crop varieties by growers to help control insects and mites inevitably creates selection pressure for counter-adaptation in the pest populations. SCRI scientists a new research programme are studying this "co-evolutionary battle" in (Host Parasite Co-evolution), using virus-transmitting blackcurrant gall mites and raspberry aphids as examples. The aim is to maximise the durability of pest resistance genes used in SCRI's current and future crop varieties.

between pest and plant, particularly if the crop is put under intense selection pressure from the target pest (e.g. subjected to very high pest densities). This pest adaptation process may take as little as one third of the time taken to breed a pest-resistant variety, so the "arms race" is generally skewed in favour of the counter-adapting (-) pest, not the plant breeder.

Moving targets and fewer weapons against pests Consumers, environmentalists, farmers, supermarkets and government policy makers are demanding more sustainable and ecologically-friendly approaches to crop protection. As a result, many of the older and broader spectrum pesticides are currently being withdrawn in the U.K. and in Europe. For example, three years ago, UK brassica growers had nine insecticides available to control cabbage root fly on vegetable crops. Soon growers will be left with only one pesticide to control root flies, which cause at least £25 million damage per year with the current level of pesticide-based control (HDC News, June 2002). Farmers are increasingly being faced with gaps in their armoury of approved insecticidal weapons against crop pests. In addition, pests under strong selection pressure from existing pesticides are constantly counter-adapting to widely used synthetic chemicals, as well as to pest-resistant crop varieties. For example, some formally very effective insecticides are now much less effective against important UK pests like the peach-potato aphid, *Myzus persicae*. This aphid, which causes more than £100 million losses to UK agriculture each year, now has three different types of resistance (i.e. metabolic over-production of certain carboxylesterase enzymes; and target site - MACE and kdr) to several commonly used insecticides, including pirimicarb, aldicarb and deltamethrin. Perhaps the time is now right to start applying more widely the many years of IPM-related ecological research SCRI and other UK institutes have been developing.

Can pest-resistant GM crops help? Biotechnology has the potential to offer new solutions to agricultural crop protection, in the form of pest-resistant GM crops (for background see SCRI Annual Report for 1996/7, p68). Several types of genes from plants and microbes (e.g. *Bacillus thuringiensis* toxins, lectins, enzyme inhibitors, anti-metabolites) can now be routinely expressed in a wide range of crops to confer added pest resistance and thus reduce pesticide applications. However, until various environmental and health-related regulatory questions have been addressed and the public's concerns are answered, it is unlikely that these solutions will be widely available to UK and EU farmers in the near future. If GM crop varieties are approved for use in the UK and Europe it will be important to maximise their durability, since pests have the ability to rapidly adapt to resistance genes unless they are used in a carefully planned way as part of an integrated approach to pest management.

Selecting complementary strategies to fill the armoury gap What then are the viable options for European farmers in the short to medium term (i.e. the next 10 years), faced with fewer pesticides, fewer pest-resistant crop varieties and few immediately usable biotechnology solutions? Organisations including 'LEAF' (Linking Environment and Farming – see www.leafuk.org for details) and 'DEFRA' (Department for Environment, Food and Rural Affairs) are actively promoting Integrated Farm Management (IFM) systems These give increased emphasis to the consideration of environmental factors, through minimising the reliance on synthetic crop protection chemicals (pesticides). Unlike organic farming codes of practice (e.g. the organic codes of practice under UKROFS, the UK Register of Organic Food Standards and by EU legislation), IFM allows careful use of more selective pesticides, while at the same time promoting careful selection and deployment of any available resistant (or partially resistant) crop varieties in carefully planned crop rotation systems. IFM is promoted by LEAF and other similar organisations as a "win-win" solution for farmers and consumers and aims for affordable, quality produce achieved with responsibility to the environment. During 2002, SCRI scientists have initiated research projects with LEAF, to develop these ideas scientifically, bringing in new research findings for testing on the experimental farm at SCRI and then around the U.K. on leaf demonstration farms.

Organic farming – good for consumers and pests? Potentially, organic farming systems have certain advantages that could be more fully researched and compared with IFM and high input, intensive farming. A recent 21 year comparative study by Swiss scientists (*Science* 296, May 2002) shows that although mean yields of organic crops are lower than conventional farming systems, there are net energy gains because of greatly reduced inputs of fertilizers and pesticides, as well as increased biodiversity on organic farms. In this recent study, average activity density of beneficial carabids, staphylinids and spiders (important natural predators of insect pests) were almost twice that of the conventional treatments. In the EU, only 3% of farms are currently organic, but numbers are increasing by 25% each year. Surveys indicate that many consumers in the EU are willing to pay 10-30% more for organic produce. However, organic agriculture still produces food for a limited niche market, that can only be sustained by a majority of more conventional farmers in the larger regional landscape. Pest populations on organic farms are, to an uncertain degree, suppressed indirectly, by use of insecticides and other pest control strategies on the surrounding conventional farms. It is unclear therefore, whether pest problems would be controllable if Organic farming were the only or the dominant form of farming in a region. Moreover, in perennial crops, such as raspberry, the option for Organic production may be more difficult, due to the build up over several years of the pest burden and disease inoculum. Whatever the furture of organic and GM farming in the UK and EU, there will be increased need for research to support IFM-based systems over at least the next ten to twenty years. How will the UK agricultural landscape look and function ecologically in the future, if we have a patchwork of organic, IPM-based and conventional fields and farms (with future GM crops potentially adding to the complexity)? This question requires a knowledge of how different fields and farming systems interact at a landscape scale, which is a challenge mathematical modellers are currently starting to address.

Understanding agro-ecosystems – the key to sustainable and 'greener' farming Concerns about the environmental impact of pest-resistant GM crops have necessitated novel methods of risk assessment. In addition, accessibility to more powerful computers in recent years has allowed the employment of computationally intensive individual-based modelling methods. At SCRI we have developed a tri-trophic, individual-based, mathematical model with which we can explore the possible impacts of pest-resistant crops (including conventional and GM crops) on their associated arthropod community. Individual insects in the model have common traits but are parameterised differently, to allow for different strategies regarding resource foraging and resource acquisition, dispersal, temperature responses, and reproductive strategies. Different pest-resistant GM crops act in different ways on target and non-target pests (e.g. lectins as distinct from *Bt* toxins). Such differences at the plant-pest interface and consequences for the pest-natural enemy interface can be incorporated in to the model, to explore their effects on system properties, such as crop yield (efficacy), arthropod diversity (community structure), and sustainability of deployment (pest counter-adaptation).

Our models have recently been used to predict the time taken for pests to counter-adapt to the introduction of a new crop variety having conventional or GM resistance to the pest. The ability of a pest to get round the plant's resistance genes occurs naturally in a pest population but in extremely low frequency, for example 1 individual in a million. We have moved beyond existing models to include factors such as disturbance in arable and horticultural systems, variation in crop growth rate, and the arrangement of resistant and susceptible varieties in different planting configurations (see also the article on canopy heterogeneity). The model, funded by DEFRA, is now available with a 'user-interface' to enable other researchers to explore counter adaptation and tri-trophic interactions.

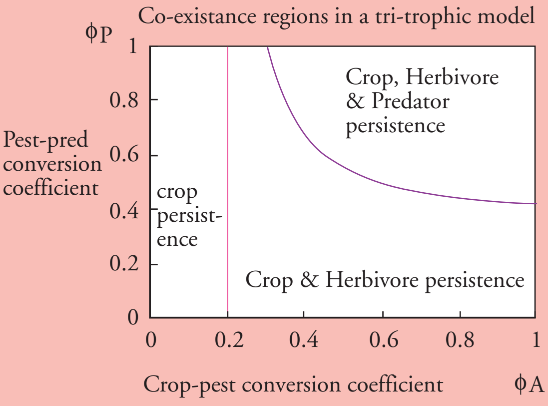


Figure 2 SCRI's tri-trophic models allow scientists to predict the effects of plant traits (e.g. insecticidal toxins) that reduce pest numbers but allow predators to co-exist within a sustainable IPM framework.

Chemical ecology of pest-plant interactions – fundamental knowledge leading to future crop protection tools Practical developments in pest control can also be achieved through understanding the subtle plant chemical signals (semiochemicals) that insects use to select or reject a plant as a host for feeding or egg laying. Three SCRI studies based on the chemical ecology of pest-plant interactions have been developed from fundamental research through technology transfer to a stage where successful and end-user application is possible in the near future.

Raspberry beetle attractants from host flowers Several years of research at SCRI have led to the development of chemically-enhanced traps for monitoring and trapping raspberry beetles (see SCRI Annual Report for 1995, pp144-148). These traps release specific flower volatiles and can enhance the visual com-

Figure 3 Insects use specific plant-produced chemicals (e.g. plant odours) to locate suitable host plants to attack. Chemical ecology studies involving SCRI scientists and international collaborators identified the key flower volatile chemicals and reflected wavelengths from raspberry flowers that raspberry beetles are attracted to when searching for egg-laying and feedng sites. Specially enhanced white traps are now being evaluated in the U.K. and U.S.A for their potential as monitoring tools in Integrated Crop Management. Such traps could allow growers to reduce synthetic pesticide applications in conventional soft fruit production and may also have potential in organic production.

ponent (white colour, mimicking raspberry flowers) by a factor of x10 or more. These traps have now been field-tested in several countries under EU CRAFT funding (see fig 3). Most recently, the Horticultural Development Council have funded a new 3 year PhD project at SCRI, to develop the practical deployment of these traps for UK growers and to study how they affect other pests and beneficial insects. The chemically-enhanced traps are also being evaluated against N. American pests of raspberry by collaborating partners.

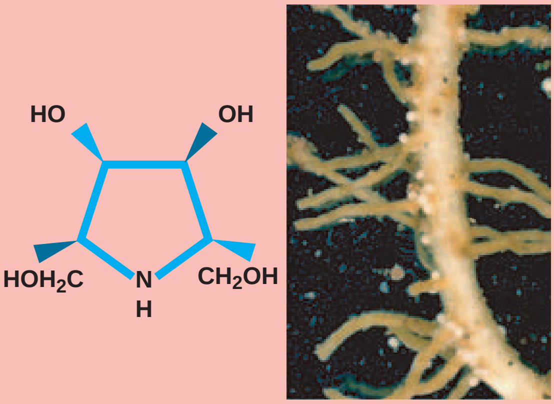


Figure 4 A plant-derived chemical called DMDP, which was isolated from tropical legume seeds, was found by scientists from SCRI and the Royal Botanic Gardens Kew to have systemic activities against root-feeding nematodes. This technology is now patented in key territories worldwide. The British Technology Group (BTG) have recently undertaken commercial evaluations of this natural plant product on a range of tropical, sub-tropical and temperate crops, including coffee, bananas, soybeans, tomato and potatoes. Commercial licences are also currently being sought by BTG to exploit this discovery.

Pesticidal plant compounds from South American legumes Similar approaches, based on the chemical ecology of pest-plant interactions are leading to other new ideas for environmentally-benign pest control. We have developed a plant-derived pesticide from tropical legumes in collaboration with with the Royal Botanic Gardens, Kew and InBio in Costa Rica (see fig 4). This research was funded and patented by the British Technology Group. The plant natural product devel-

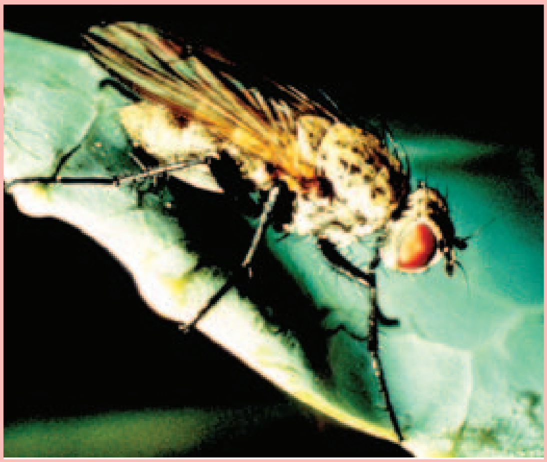


Figure 5 Cabbage and turnip root flies are major pests of vegetable and forage brassica crops. Pesticides which are currently used to control root flies are being withdrawn, due to environmental hazards. SCRI scientists working with collaborators in Switzerland have identified the key plant chemicals on the leaf surfaces of crop and wild crucifers which either stimulate or deter these pests from laying their eggs. These plant-derived chemicals could provide valuable components of alternative control strategies in the future, replacing the increasing list of banned pesticides for these crops in the U.K. and Europe.

oped in this collaborative project is now undergoing final field trials in several countries, as a new anti-nematode treatment for tropical and temperate crops including coffee and potato. This SCRI discovery is already generating income for SCRI's commercial arm, MRS Ltd through a successful technology transfer.

Stimulants and deterrents affecting egg laying by the cabbage root fly from wild crucifers In previous studies at SCRI with Swiss collaborators (see SCRI Annual Report 1993; *Grower* March 28, 2002, pp 20-21) we discovered that specific leaf surface chemicals triggered the sequential egg laying behaviour of the cabbage root fly (see fig 5). Some wild (non-cultivated) crucifer species related to the normal host plants of this pest (cabbages, swedes, turnips, broccoli) were later found to be avoided as sites for egg laying. Recent chemical analyses of leaf surface extracts from 18 wild Crucifer species, which varied in their attractiveness to this pest, showed a wide range of glucosinolate structures (characteristic plant secondary compounds from Cruciferae) on their leaf surfaces (see text box). A clear relationship was detected between different classes of leaf surface glucosinolates and egg laying preference by the pest. This study also confirmed the presence of other classes of chemical deterrents to egg laying in leaf surface extracts from wild Crucifers. Such discoveries open up new possibilities to push the pest away from crops using natural deterrents and also attract the pest to trap crop areas sprayed with the stimulant compounds. This pest control strategy, based on selective use of behaviourally-active natural compounds, is

IOBC and EU funded GM Crop Biosafety Guidelines Projects initiated during 2002 The GMO Guidelines Project was launched in 2002 by a group of scientists, the Global Working group on Transgenic Organisms in IPM and Biocontrol. The project is funded by the Swiss Federal Agency for Development and Cooperation and organised by the International Organisation for Biological Control (IOBC). The project aims to 'establish international, scientifically sound, conclusive and acceptable guidelines for assessing the environmental risks posed by GMOs.'

The Project's first workshop was held in Nairobi in November 2002 and concentrated on Bt maize in Kenya as a case study. The workshop was attended by around forty scientists, half from Africa. The aim was to draft scientific guidelines for the assessment of risk posed by GMO cultivation in Kenya, using insect-resistant (maize stem borer species) *Bt* maize as the case study.

SCRI staff (Nick Birch, Ron Wheatley) led workshops on Non-target impacts of *Bt* maize and on Soil ecosystem function. Other international scientists from ICIPE Kenya, KARI Kenya , University of Minnesota USA, Ohio State University USA, Swiss Geobotanical Institute, CSIRO Australia led linked workshops on Plant characterisation, Gene flow, Resistance management and on African agricultural systems. Finally, workshop outputs were presented at a Public Day, attended by Kenyan stake holders, policy makers and press agents. The next workshop will be held in Brazil and will be hosted by EMBRAPA.

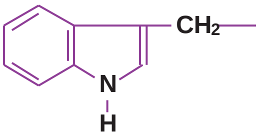
Further information on the IOBC GMO Guidelines Project can be obtained at www.gmo-guidelines.info

SCRI staff (Bryan Griffiths, Nick Birch) are also involved in a second new project, 'ECOGEN', which is funded by the European Union. This project is investigating ecological and economic impacts of using *Bt* and herbicide-tolerant GM crops on soil organisms and functions at various experimental scales (laboratory to field). It involves scientific partners from Denmark, France, Netherlands and Slovinia and also includes various end-users from the biotechnology industry and from European policy-making organisations. Further information is available from www.ecogen.dk

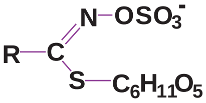
Figure 6 Pest-resistant GM crops could offer potential economic and ecological benefits to farmers in developing countries, where pest problems can be severe and food shortages are common. However, some GM traits could cause adverse environmental effects (e.g. on non-target insects which are beneficial or on the soil ecosystem). Each GM variety needs to be assessed on a "case-by-case" basis, to measure potential risks and benefits to local agricultural systems. SCRI scientists recently co-led IOBC workshop sessions in Kenya which evaluated the potential ecological impacts of Bt maize. This GM trait protects the crop from several important stem borer pests. Further IOBC workshops are planned in Brazil and S.E Asia during 2003.

know as the ‘stimuli-deterrent’ or ‘push-pull’ strategy and has already been used successful to reduce insect attack in African millet and maize.

Generalised Glucosinolate Structure

Trivial name	R =
sinigrin	$CH_2=CH-CH_2-$
progoitrin	$CH_2=CH-CH(OH)-CH_2-$
glucoberteroin	$CH_3S-CH_2-CH_2-CH_2-CH_2-CH_2-$
glucoraphanin	$CH_3SO-CH_2-CH_2-CH_2-CH_2-$
glucobrassicin	

Examples of common brassica derived glucosinolates



International Guidelines for GM crops SCRI’s expertise in integrated management and modelling is finding a range of applications throughout the world, notably where GM technology is being developed to solve problems of crop production in severe environments. In 2002, SCRI staff were involved in setting up the GMO Guidelines Project and contributing to its first workshop, which was held in Nairobi, Kenya (See text box opposite and fig 6).