

SESSION 6A

**EFFECTS AND FATE OF
PESTICIDES IN WATER AND
THE ATMOSPHERE**

CHAIRMAN DR V. EDWARDS

SESSION
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INVITED PAPERS

6A-1 to 6A-4

LOSS OF PESTICIDES FROM PLANT AND SOIL BY VOLATILIZATION

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ABSTRACT

During and after application of pesticides two important pathways for the transport into the atmosphere can be found. Beside the translocation by drift downwind from the treated area there occurs an aerial flux of organic chemicals in the ambient air above the treated surface. Therefore drift and volatilization are important factors for the simulation of dispersal and fate of pesticides and the estimation of environmental risks caused by field applied pesticides.

An volatilization apparatus is presented in which the loss of pesticides by volatilization from different surfaces, from soil as well as from leaves, can be determined under laboratory conditions. During the experiment the important microclimatic factors (windspeed, air and soil humidity, temperature) can be held constant over each of the 15 samples in the chamber. Under comparable conditions losses of the herbicides pendimethalin, triallate and trifluralin are measured from drying liquid films, soil and plant surfaces.

INTRODUCTION

Pesticides reach soil or leaf surfaces either intentionally, by direct application, or unintentionally through spillage and by dry and wet deposition (Renner *et al.*, 1990; Schomburg *et al.*, 1991). As with many pollutants of the environment side effects occur in both cases. Great efforts have been made in past years to examine the effects of pesticides on the build-up of residues in plants and on the soil of the tillage zone. In the last 10 years more and more attention has been paid to adjacent compartments for example aquifer and atmosphere. In this connection the persistence of a pesticide in a specifically defined compartment of the environment is of great importance. A compartment is one phase of the environment, i.e. soil, water, air, plant or animal (Figure 1) and its description must include all the environmental factors which affect the residence time of a chemical (Greenhalgh *et al.*, 1980). Measurements of the overall degradation rate of a pesticide and all the various processes such as sorption, degradation and losses affecting its disappearance from the relevant compartment defines persistence in either specific or comparative terms (Pestemer *et al.*, 1988).

Pesticides may enter soil, crops, and forests by the process of drift during application (Maas & Krasel, 1988; Maas *et al.*, 1988) and by volatilization of residual deposits after application. The latter describes a process by which a chemical vaporizes into the atmosphere from other environmental compartments, e.g. soil, plant and water surfaces. This is an important mechanism for the loss of pesticides and their transfer to the air.

For estimating probable exposure and/or movement of chemicals comparative information is needed about the relative behaviour of different chemicals tested under similar conditions. Therefore short term laboratory tests as well as field studies are useful prerequisites to evaluate the environmental distribution and transport of chemicals.

Various factors influencing the volatilization and the complexity of interrelationships between physico-chemical properties of the active ingredient (a.i.) and environmental parameters are known. Particularly under field conditions atmospheric flux can change rapidly and over a wide range.

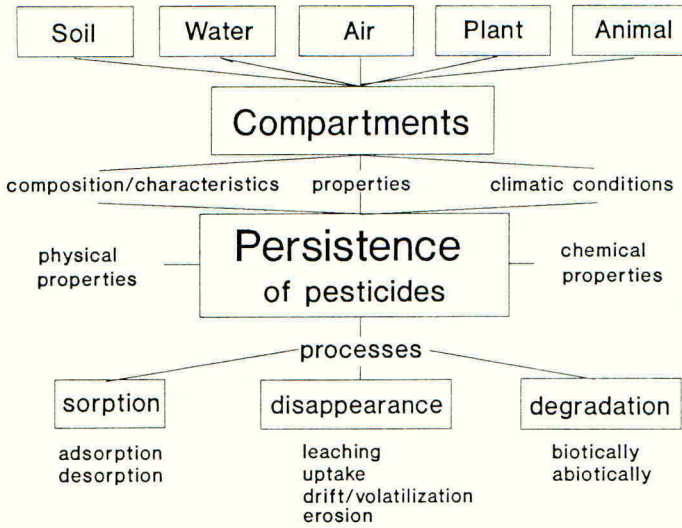


Figure 1: Important factors and processes influencing the persistence of pesticides in different compartments of the environment (from Pestemer *et al.*, 1988)

For this reason a volatilization chamber (Figure 2) has been developed which allows the control of all environmental conditions and the behaviour of pesticides can be determined by manipulation of individual environmental parameters (Krasel *et al.*, 1992).

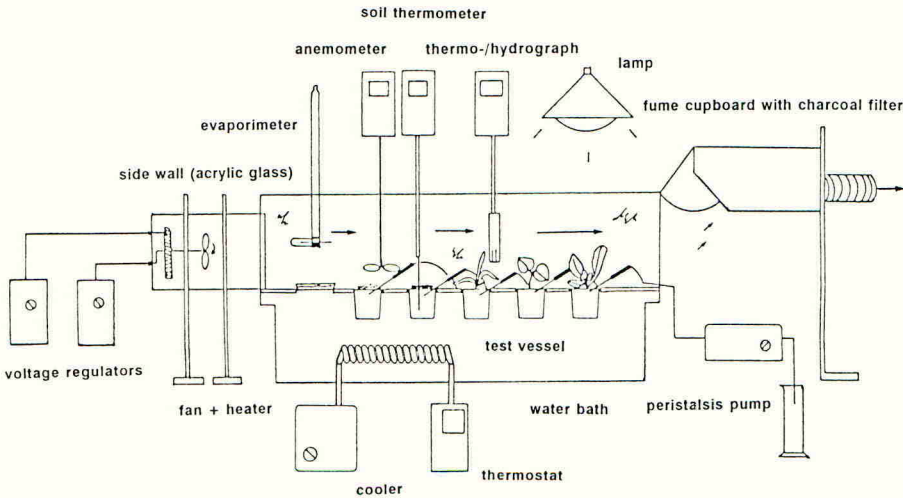


Figure 2: Experimental design for the measurement of volatilization of pesticides

This paper describes investigations determining the loss of pesticides from plant and soil surfaces under laboratory conditions with the above mentioned experimental design.

IMPORTANCE OF SELECTED PHYSICO-CHEMICAL PROPERTIES ON LOSS PROCESS

Volatilization of surface deposits from both soil and leaf are influenced by physico-chemical properties of the a.i. and their formulations. In this connection the physical properties (vapour pressure, but also molar mass, water solubility, polarity, acidity, sorption, diffusion coefficients, fugacity) and the biotic and abiotic degradation rates are the most important ones influencing their interactions with air, water soil and biota and their flux through the plant/water/soil-air interface as well as their distribution in the atmosphere (Scheunert *et al.*, 1985). For the herbicides pendimethalin, triallate and trifluralin - selected physico-chemical data are given in table 1 - the relationship between the Henry's Law coefficient H and volatilization is of prime importance.

Table 1: Physico-chemical data of three herbicides (Perkow, 1988)

Physico-chemical data	pendimethalin	triallate	trifluralin
molar mass [g/mole]	2,81E+02	3,05E+02	3,35E+02
solubility in water [mg/l]	0,3 (20 °C)	4,0 (20 °C)	1,0 (27 °C)
vapour pressure [hPa]	8,4E-05 (25 °C)	1,6E-04 (25 °C)	2,6E-04 (29,5 °C)
Henry Constant [Pa m ³ /mole]	8,00E-02	1,00E-02	9,00E-02

The Henry's Law coefficient H is defined as the ratio of partial vapour pressure of the dissolved compound at saturation in air to the equilibrium water concentration (Thomas, 1982). This air-water partition plays a critical role in determining the environmental dynamics of pesticides, especially the volatilization of pesticides from water:

- Temperature affects volatilization mainly through its effect on H via its influence on vapour pressure.
- Vapour pressure influences H only in relation to water solubility. If the solubility and vapour pressure have low values, H and therefore also the volatilization of non-volatile substances is high.
- Since H only describes the partial pressure of dissolved chemicals the actual H will be lower than the total concentration in water if the molecules are sorbed or bound by solvent ingredients such as detergents, emulsified materials or organic matter. These effects influence solubility and thus change the H-value.
- In this connection high values ($H > 10^{-2}$ hPa m³/mole), e.g. as in the case of triallate (Figure 3) favour volatilization whereby chemicals with a low H-values may persist in soil- plant- or water-residues, solid surfaces and liquid solutions.
Since H-values control the fugacity of each chemical the transfer of pesticide a.i. between soil, plant and water is influenced as well as the process of dry and wet deposition and volatilization (Suntio *et al.*, 1988; Mackay *et al.*, 1986)
- Models for predicting volatilization from soil consider a high boundary layer resistance for chemicals with very low H-value. Because of such low partition coefficients these molecules establish only low concentrations in soil air which in turn causes slow fluxes across the stagnant boundary layer over the soil-atmosphere-interface (Jury *et al.*, 1984).
- An analogous modelling approach can be used to predict the volatilization from water surfaces. The two film model assumes well-mixed bulk phases - water body and air - which are separated by two thin boundary layers - a liquid and a gas film. The relative resistance encountered by the transport across water to air through these film is controlled by the magnitude of H (Liss & Slater, 1974).

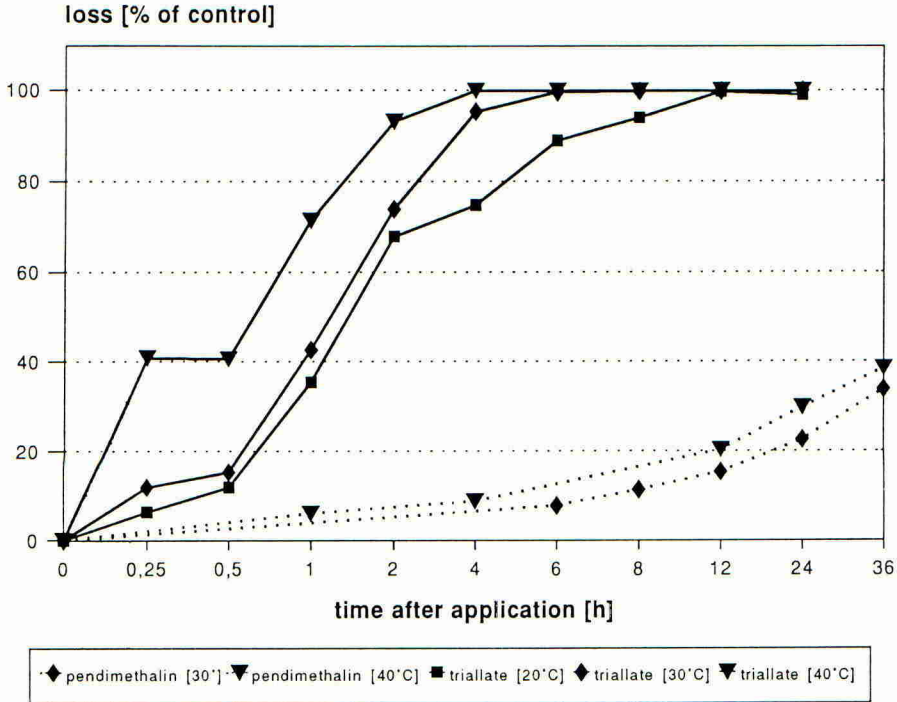


Figure 3: Volatilization of pendimethalin and triallate from aqueous solution at different temperatures

VOLATILIZATION FROM SOIL

The rate at which a chemical volatilizes from soil is influenced by environmental conditions like air temperature and air velocity measured directly over the soil surface. But the volatilization process is also affected by the chemical properties of the pesticide involved in this process and e.g. by the concentration of the chemical, soil water content, mass transport in soil by wick effect, temperature, porosity, diffusion, and soil sorption.

All these factors controlling the mechanisms involved in the distribution between soil surface and air can be described by three processes:

- transport to the evaporating surface, especially for incorporated pesticides (diffusion and wick effect)
- vapour density of the chemical in air over the boundary layer (surface deposit, desorption)
- movement away from the evaporating surface into the air (diffusion through the stagnant boundary layer and by turbulent transport in the atmosphere).

Soil sorption properties have an important influence on volatilization because adsorption reduces the chemical activity, especially the vapour concentration in soil air. The volatilization rate falls below that of the potential volatilization losses because sorption coefficients are directly related to

surface area of the soil and its organic matter. In the case of triallate the loss of this volatile herbicide from a soil with 13,5 % organic matter can be reduced to about 20 % after 24 hours after application (Figure 4).

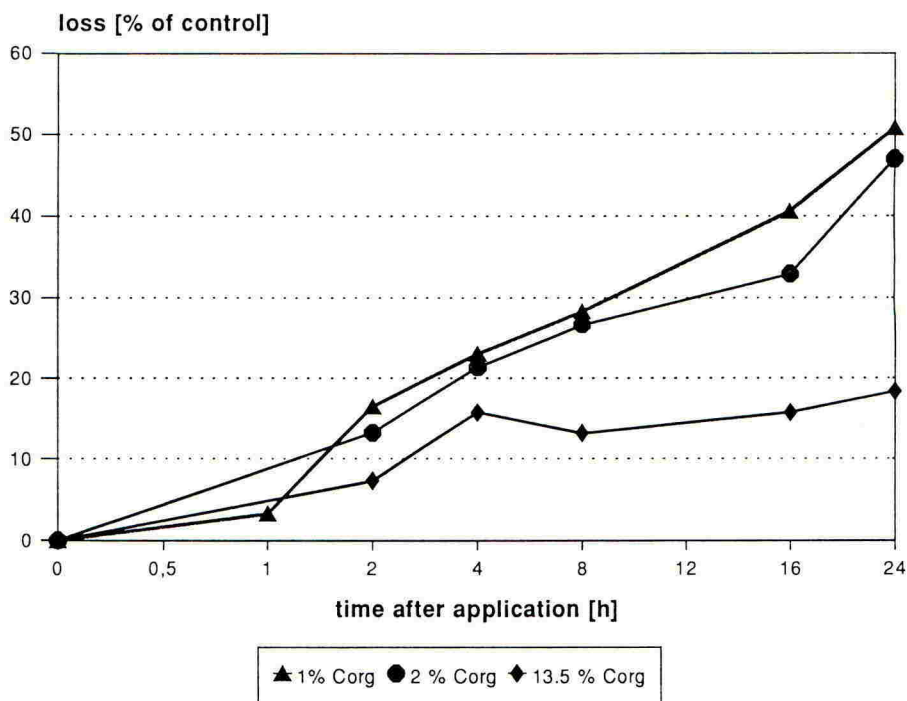


Figure 4: Volatilization of triallate from soil surfaces at different organic carbon contents

While for more polar ionic chemical molecules clay mineral plays a major role in adsorption, for weakly polar non-ionic organic substances, like many herbicides the amount of organic matter in soil is an important factor controlling adsorption (Figure 4) which in turn influences pesticide losses from soil.

Volatilization of soil incorporated chemicals depends (in addition to the factors influencing the volatility from soil surfaces) on their rate of transport from deeper soil layers to the evaporating surface (Spencer & Cliath, 1975). The magnitude of upward transport of compounds partitioned between soil water, soil air and soil particles depends on water solubility and sorption properties as well as water content of the soil, for example the loss of triallate increases from 35 % at 40 % m.w.h.c. to about 55 % at 90 % m.w.h.c. (Figure 5). In case of bulk flow of the solution up to the capillaries (wick effect) the value of upward transport increases. As long as water rising to the surface moistens the soil surface the volatilization process is accelerated (Thomas, 1982).

Incorporation of pesticides also decreases the concentration of active ingredients at the evaporating surface and thereby decreases volatilization below the value of surface applied chemicals. In the case of the volatile compound triallate e.g. volatilization decreases to about 10 % one day after application (Krasel & Pestemer, 1991).

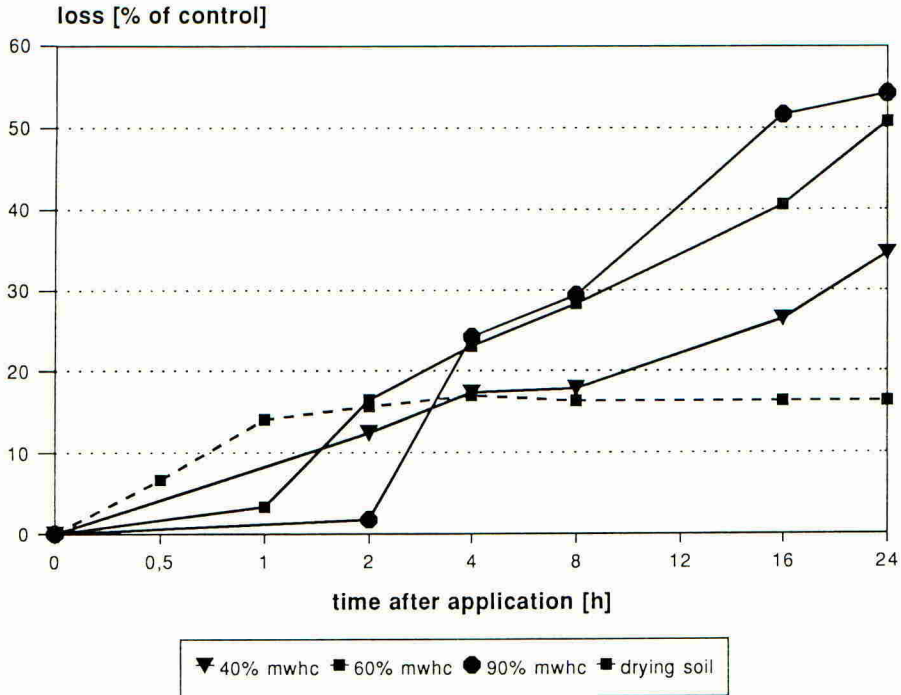


Figure 5: Volatilization of triallate from soil surfaces at different soil moistures

Measurements of vapour pressure in soil at various water contents demonstrated that volatilization from wet soils is greater than from dry soils because weakly polar pesticides were displaced from soil water which compete for adsorption sites (Spencer *et al.*, 1969). All described processes are very much influenced by temperature.

VOLATILIZATION FROM PLANT SURFACES

Pesticide disappearance from foliage and fruits by volatilization immediately after application can be rapid and losses may be substantial (Willis *et al.*, 1985). This important pathway of atmospheric contamination by pesticides occurs from foliar applied pesticides and by deposition of pesticide vapour or dust (Scheunert, 1985). The length of time that chemical residues persist on foliage affects not only the efficacy of the pesticide but also its pollution potential, e.g. transfer to non-target areas by volatilization (Riederer, 1990).

Not only is geometrical distribution important but also pesticide formulation, weather conditions like humidity and wind, properties such as the nature of pesticide, adjuvants, surfactants, acidity, droplet size and surface roughness. Figure 6 gives an example for triallate volatilization from plants at different physiological stages (2- and 4-leaf-stage), from species (french bean, sunflower), from different concentrated herbicide deposits with and without an emulsifier (Triton X 100).

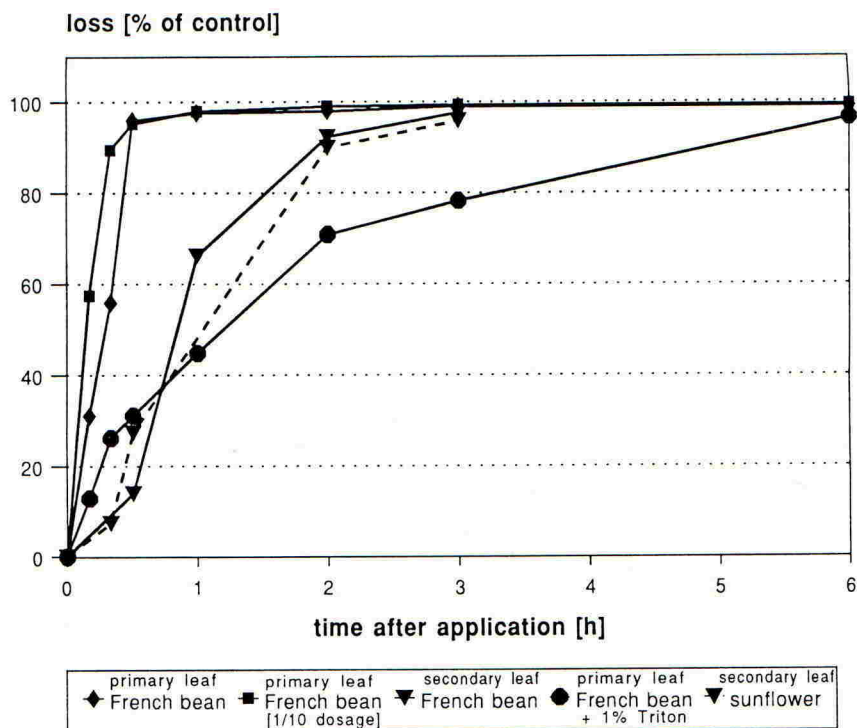


Figure 6: Volatilization of triallate from plant surfaces at different growth stages, of plant species, from initial deposits and after addition of a surfactant

Volatilization is a function of vapour pressure which is reduced by adsorption or by dissipation in leaf waxes and oils. This process results in decreased volatilization. Since only a small fraction of the applied pesticide would be in direct contact with the leaf surface the initial deposit vaporizes at a rate closely resembling a complete covering of pure material (Taylor, 1978). Later the pesticide loss rates may be interpreted by the decreasing coverage of leaf surfaces by pesticide layers which form discontinuous islands filling leaf irregularities.

The affinity of leaf surfaces for water based sprays is also influenced by the amount of leaf wax, its chemical composition and physical configuration on the surface. Wax surfaces affect leaf wetting and the contact angle between spray droplet and leaf surface influenced by adhesion forces (Bayer & Lumb, 1973).

For estimating the partitioning and transport of organic chemicals in the foliage atmosphere a fugacity based model using octanol/water- and cuticle/water-partition coefficients, solubility and vapour pressure assesses the potential for volatilization of organic chemicals from leaves (Schönherr & Riederer, 1990). The calculated tendency of high pesticide losses directly after application can be seen under field conditions as log concentration losses. Linear losses are subsequently established (Nash, 1989).

Figure 7 shows an example where the volatilization of three herbicides from frenchbean-leaf-surface is compared. In this connection it should be noted that the volatile compounds trifluralin and triallate are not applied on plants in practice.

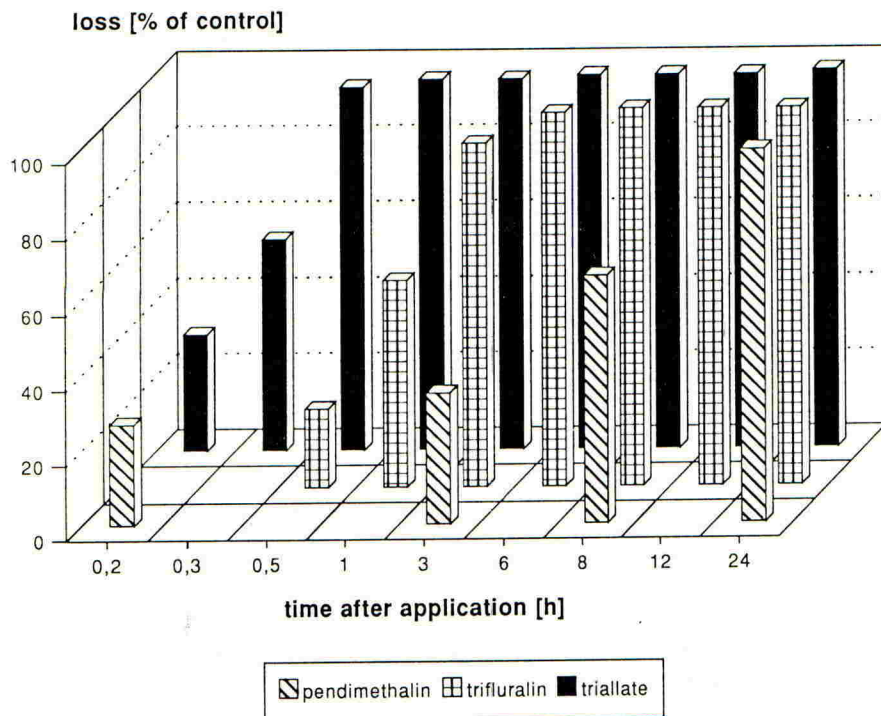


Figure 7: Comparison of the volatilization of different herbicides from plant surface (French bean).

CONCLUSION

In the case of volatilization, which is difficult to measure experimentally the availability of a predictive model would be an important development. Based on physico-chemical properties as well as models validated in laboratory and field studies pesticide use can be regulated through maximizing economic pest control and thereby posing minimal risks to the environment.

For this purpose agrochemicals must be carefully applied under field conditions. In Figure 8 the volatility behaviour of triallate from different surfaces is compared with the loss after incorporation into the soil. About 100 % is volatilized after 1 hour from plant surfaces whereas losses from incorporated triallate are significantly reduced.

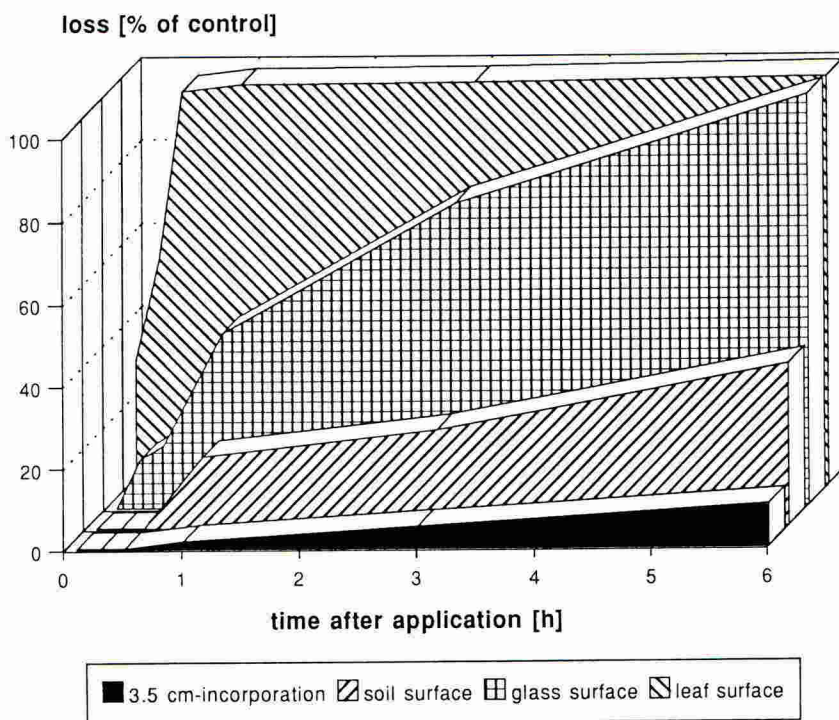


Figure 8: Comparison of triallate volatility from different surfaces and after soil incorporation

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PHOTOCHEMICAL PROCESSES AFFECTING THE FATE OF PESTICIDES IN THE ATMOSPHERE

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ABSTRACT

Pesticides with liquid phase vapor pressures $>10^{-4}$ Pa can undergo volatilization into the atmosphere, where they are subjected to a number of physical and chemical removal and/or transformation processes. These atmospheric removal and transformation processes are briefly discussed and examples given.

INTRODUCTION

At equilibrium, chemical compounds are distributed between soil, water, sediment, air (in the gas and particle phases) and biota depending on the soil-water, air-water, gas-particle (in the atmosphere) and biota-water partition coefficients (Mackay, 1991). These partition coefficients can be calculated from the physical properties of the chemical, namely the saturated vapor pressure, liquid-phase vapor pressure, aqueous solubility and octanol-water partition coefficient (Mackay, 1991). Many pesticides have physical properties such that at equilibrium they distribute at least partially into the atmosphere. Following, or during, the application of pesticides to soils, crops or bodies of water, these pesticides can then be volatilized into the atmosphere.

Based on ambient air measurements and theoretical considerations of gas/particle partitioning (Bidleman, 1988) and air-water-soil partitioning (Mackay, 1991), chemicals with liquid-phase vapor pressures $>10^{-4}$ Pa, Henry's law constants of $H > 1 \text{ Pa mol}^{-1} \text{ m}^3$ and octanol-water partition coefficients, K_{ow} , of $K_{ow} < 10^3 H$ (with H in $\text{Pa mol}^{-1} \text{ m}^3$ units) are expected to undergo significant volatilization from soil and water to the atmosphere, where they will initially exist primarily in the gas phase. Since the vapor pressure, and hence the Henry's law constant, of a chemical is highly temperature dependent, then the rate of volatilization will be temperature dependent and vary with time of day, season and latitude (see, for example, Woodrow *et al.*, 1990; Hoff *et al.*, 1992). Since volatilization is the reverse process to wet deposition, then wet deposition of gases from the atmosphere is not highly efficient for values of $H > 1 \text{ Pa mol}^{-1} \text{ m}^3$. The volatilization of pesticides from soils and water to the atmosphere has been experimentally observed in numerous studies (see, for example, Spencer & Cliath, 1990; Woodrow *et al.*, 1990).

ATMOSPHERIC LOSS PROCESSES FOR PESTICIDES

After volatilization into the atmosphere in the gas-phase, pesticides can undergo a number of removal and/or transformation processes which are applicable to all gas-phase chemicals (Atkinson, 1988a). These include wet and dry deposition, photolysis and chemical reaction of the gaseous pesticide, gas/particle partitioning, and wet and dry deposition, photolysis and chemical reaction of the particle-associated pesticide.

The overall lifetime of a pesticide, τ_{overall} , in the atmosphere in the gas or particle phase is given by the equation

$$(\tau_{\text{overall}})^{-1} = (\tau_{\text{physical}})^{-1} + (\tau_{\text{chemical}})^{-1}$$

where τ_{physical} is the lifetime due to physical loss processes such as wet and dry deposition, and τ_{chemical} is the lifetime due to chemical loss processes. For a gas-phase pesticide, these chemical loss processes are photolysis and reaction with OH radicals, NO_3 radicals and O_3 , and

$$(\tau_{\text{chemical}})^{-1} = (\tau_{\text{photolysis}})^{-1} + (\tau_{\text{OH}})^{-1} + (\tau_{\text{NO}_3})^{-1} + (\tau_{\text{O}_3})^{-1}$$

where each individual lifetime corresponds to the lifetime due to that removal/transformation process. For the reactions with O_3 , OH radicals and NO_3 radicals, then the lifetimes are given by, for example,

$$\tau_{\text{OH}} = (k_{\text{OH}}[\text{OH}])^{-1}$$

where k_{OH} is the rate constant for the reaction of the pesticide with the OH radical, and $[\text{OH}]$ is the tropospheric OH radical concentration. In general, the concentrations of ozone, OH radicals and NO_3 radicals are temporally and spatially variant (see below).

Furthermore, chemicals can be distributed in the atmosphere between the gas and particle phases, depending on the liquid-phase vapor pressure at the ambient temperature of the air parcel (Bidleman, 1988), with the partitioning towards the particle phase being favored by lower temperatures. As a generalization, chemicals exist to a significant extent in the gas phase for liquid-phase vapor pressures (at the ambient temperature) of $>10^{-4}$ Pa (Bidleman, 1988).

Atmospheric removal processes of particle-associated pesticides

The wet deposition of particles, and hence of particle-associated chemicals, is very efficient and every precipitation event will lead to essentially complete removal from the atmosphere (Bidleman, 1988). Dry deposition of particles depends on the particle size, being a minimum for the particles of size range 0.1-5 μm typically present in the troposphere, leading to a lifetime of particle-associated chemicals due to dry deposition of ~10-15 days. To date, little is known about the photolysis and chemical reactions of particle-phase or aerosol-phase pesticides, and the lifetime due to dry and wet deposition of the host particles can be taken as an upper limit to the pesticide lifetime. A lifetime of 10-15 days is sufficient for long-range atmospheric transport (several thousand kilometers) to occur.

Atmospheric removal processes of gas-phase pesticides

These involve the physical loss processes of wet and dry deposition (Bidleman, 1988; Atkinson, 1988a), photolysis and gas-phase reaction with the hydroxy (OH) radical, the nitrate (NO_3) radical and ozone (O_3) (Atkinson, 1988a). Dry deposition of gas-phase chemicals with high Henry's law constants is generally of minor significance, but wet deposition could be important if a pesticide is transported to lower temperature locations, leading to a lower value of the Henry's law constant at that location.

For photolysis of a pesticide to occur in the troposphere, the compound must absorb radiation at wavelengths ≥ 290 nm (the lower limit due to absorption of solar radiation by the stratospheric ozone layer) and have a

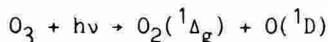
non-zero quantum yield for chemical change. Because of the difficulties in working with low volatility chemicals, few data exist concerning the absorption cross-sections and photolysis quantum yields for gas-phase pesticides. For organic compounds present in the gas phase, the most important atmospheric loss processes involve photolysis and chemical reaction with OH radicals, NO₃ radicals and O₃. The atmospheric formation and concentrations of O₃, OH radicals and NO₃ radicals are briefly discussed below, followed by a discussion of the literature data base concerning the gas-phase atmospheric reactions of pesticides.

Tropospheric ozone

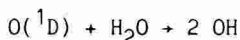
Ozone is transported downwards from the stratosphere into the troposphere, with destruction (dry deposition) at the Earth's surface. In addition, ozone is produced and removed by photochemical processes in the troposphere (Logan, 1985), with the formation versus destruction of tropospheric ozone by these photochemical processes depending on the NO concentration. In the "clean" troposphere, the lower tropospheric ozone mixing ratios show relatively little diurnal or seasonal variation and are in the range (10-50) x 10⁻⁹. A typical tropospheric ozone concentration may be taken to be ~7 x 10¹¹ molecule cm⁻³ (Logan, 1985).

Tropospheric hydroxyl radical

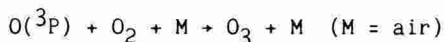
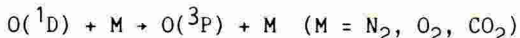
In the clean troposphere, OH radicals are formed from the photolysis of ozone at wavelengths <319 nm:



with the O(¹D) atom reacting with water vapor



in competition with deactivation to the ground state O(³P) atom and reformation of ozone

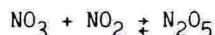


At room temperature and 50% relative humidity, every O(¹D) atom formed leads to 0.2 OH radicals. In polluted urban areas, the photolysis of nitrous acid (HONO) and aldehydes (primarily formaldehyde) also lead to the net production of OH radicals (Atkinson, 1988a).

As expected from the mode of formation of the OH radical, its concentration exhibits a diurnal and seasonal variation, with maximum concentrations around solar noon and very low concentrations during nighttime. To date, there are few reliable direct measurements of OH radical concentrations in the lower troposphere (Eisele & Tanner, 1991; Hofzumahaus *et al.*, 1991; Mount & Eisele, 1992), and these indicate peak daytime OH radical concentrations of several x 10⁶ molecule cm⁻³. A diurnally and annually averaged global tropospheric OH radical concentration can also be derived from the emissions of methylchloroform (CH₃CCl₃), the atmospheric concentrations of methylchloroform and a knowledge of its reaction rate constant with the OH radical (its major atmospheric loss process), and Prinn *et al.* (1992) have obtained a 24-hr average concentration of 8 x 10⁵ molecule cm⁻³, corresponding to an average 12-hr daytime OH radical concentration of 1.6 x 10⁶ molecule cm⁻³.

Tropospheric nitrate radical

The formation of the NO_3 radical and N_2O_5 occurs from the reactions



However, because of the rapid photolysis of NO_3 (with a lifetime due to photolysis of ~ 5 s at solar noon), NO_3 radical concentrations remain low during daylight hours, but often rise after sunset to concentrations ranging from $< 5 \times 10^7$ to 1×10^{10} molecule cm^{-3} (Atkinson *et al.*, 1986). As this range of measured NO_3 radical concentrations implies, the nighttime NO_3 radical concentration at any given time or place is highly uncertain. Atkinson (1991) has suggested use of a 12-hr average nighttime NO_3 radical concentration of 5×10^8 molecule cm^{-3} (uncertain to a factor of 10).

Laboratory studies of gas-phase reactions of pesticides

To date, laboratory studies to determine the rate constants for the potentially atmospherically-important reactions have been carried out for only a few in-use pesticides; these being cis- and trans-1,3-dichloropropene (Tuazon *et al.*, 1984), 1,2-dibromo-3-chloropropane [DBCP] (Tuazon *et al.*, 1986) and the thiocarbamates EPTC and cycloate (Kwok *et al.*, 1992). Additionally, the atmospheric chemistry of several trialkyl phosphorothioates, dimethyl phosphoramidates and dimethyl phosphorothioamidates has been studied (Tuazon *et al.*, 1986; Goodman *et al.*, 1988a,b; Atkinson *et al.*, 1988), with these compounds serving as volatile "model" compounds for in-use organophosphorus pesticides. The room temperature rate constants for the gas-phase reactions of these compounds with OH radicals, NO_3 radicals, and O_3 are given in Table 1. For these particular compounds, no evidence for photolysis was observed.

These measured rate constants for reaction with OH radicals, NO_3 radicals and O_3 can be combined with the ambient tropospheric concentrations of OH radicals, NO_3 radicals and O_3 to calculate the lifetimes of these compounds with respect to each individual reaction pathway and to calculate the overall tropospheric lifetimes with regards to gas-phase reactions. For the pesticides and pesticide-related compounds studied to date, the OH radical reactions are calculated to be the dominant gas-phase removal process, as is the case for the vast majority of organic compounds studied, irrespective of chemical class (Atkinson, 1988a).

As noted above, rate constants have been measured for only a very few in-use pesticides, in large part due to the experimental difficulties of working with low-volatility chemicals. To date, apparently reliable kinetic studies can be carried out at room temperature only for chemical compounds with vapor pressures $> 10^{-2}$ Pa. Accordingly, rate constants have been measured for simple, and volatile, model compounds such as $(\text{CH}_3\text{O})_3\text{PS}$, $(\text{CH}_3\text{O})_2\text{P(S)NHCH}_3$ and $(\text{CH}_3)_2\text{NC(O)SCH}_3$ for use in the development of estimation techniques which allow the OH radical reaction rate constants to be calculated for organic compounds for which experimental data are not available (Atkinson, 1988b).

The estimation of OH radical reaction rate constants for gaseous organic chemicals is described in detail by Atkinson (1988b), Kwok *et al.* (1992) and Atkinson & Aschmann (1992). This estimation method uses the

TABLE 1. Measured rate constants at room temperature for the gas-phase reactions of pesticides and structurally-related organophosphorus compounds and thiocarbamates.

Compound	Rate constant, $k(\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1})$ for reaction with		
	OH	NO_3	O_3
$\text{CH}_2\text{BrCHBrCH}_2\text{Cl}$	4.4×10^{-13}		$<3 \times 10^{-20}$
<u>cis</u> - $\text{CH}_2\text{ClCH=CHCl}$	8.4×10^{-12}		1.5×10^{-19}
<u>trans</u> - $\text{CH}_2\text{ClCH=CHCl}$	1.4×10^{-11}		6.7×10^{-19}
$(\text{CH}_3\text{O})_3\text{PO}$	7.4×10^{-12}		$<6 \times 10^{-20}$
$(\text{CH}_3\text{O})_2\text{P}(\text{O})\text{SCH}_3$	9.3×10^{-12}	$<1.1 \times 10^{-15}$	$<2 \times 10^{-19}$
$(\text{CH}_3\text{S})_2\text{P}(\text{O})\text{OCH}_3$	9.6×10^{-12}	$\leq 2.4 \times 10^{-15}$	$<1 \times 10^{-19}$
$(\text{CH}_3\text{O})_3\text{PS}$	7.0×10^{-11}	$<1.6 \times 10^{-14}$	$<3 \times 10^{-19}$
$(\text{CH}_3\text{O})_2\text{P}(\text{S})\text{SCH}_3$	5.6×10^{-11}	$<2.8 \times 10^{-14}$	$<2 \times 10^{-19}$
$(\text{C}_2\text{H}_5\text{O})_3\text{PO}$	5.5×10^{-11}		
$(\text{CH}_3\text{O})_2\text{P}(\text{O})\text{N}(\text{CH}_3)_2$	3.2×10^{-11}	$<3.6 \times 10^{-14}$	$<2 \times 10^{-19}$
$(\text{CH}_3\text{O})_2\text{P}(\text{S})\text{N}(\text{CH}_3)_2$	4.7×10^{-11}	3.2×10^{-14}	$<2 \times 10^{-19}$
$(\text{CH}_3\text{O})_2\text{P}(\text{S})\text{NHCH}_3$	2.3×10^{-10}	3.1×10^{-13}	$<2 \times 10^{-19}$
$(\text{CH}_3\text{O})_2\text{P}(\text{S})\text{NH}_2$	2.4×10^{-10}	4.0×10^{-13}	$<4 \times 10^{-19}$
$(\text{CH}_3)_2\text{NC}(\text{O})\text{SCH}_3$	1.3×10^{-11}	7.1×10^{-15}	$<4 \times 10^{-20}$
$(\text{CH}_3\text{CH}_2\text{CH}_2)_2\text{NC}(\text{O})\text{SC}_2\text{H}_5$	3.2×10^{-11}	8.9×10^{-15}	$<1.3 \times 10^{-19}$
$\text{C}_2\text{H}_5(\text{c-C}_6\text{H}_{11})\text{NC}(\text{O})\text{SC}_2\text{H}_5$	3.5×10^{-11}	3.2×10^{-14}	$<3 \times 10^{-19}$

fact that the OH radical reactions can proceed by four pathways: H-atom abstraction from C-H and O-H bonds, OH radical addition to $>\text{C}=\text{C}<$ and $-\text{C}\equiv\text{C}-$ bonds, OH radical addition to aromatic rings, and OH radical interaction with N, S and P atoms [or combinations thereof, as for the $>\text{NC}(\text{O})\text{S}-$ structural unit in the thiocarbamates (Kwok *et al.*, 1992)]. The overall OH radical reaction rate constant is then the sum of the rate constants for these four processes (not all of which may occur for a given pesticide).

The calculated tropospheric lifetimes for a series of organophosphorus, organochlorine and thiocarbamate pesticides, using the OH radical, NO_3 radical and O_3 concentrations given above, are given in Table 2. The organophosphorus and thiocarbamate pesticides are clearly reactive, with calculated lifetimes due to gas-phase reaction with the OH radical of less than one day for those shown (any partitioning to the particle phase may lead to a longer overall lifetime, depending on the lifetime of the particle-associated pesticide). In contrast, several of the organochlorine pesticides, such as hexachlorocyclohexane (Lindane) and hexachlorobenzene, have much longer calculated gas-phase lifetimes, measured in days or tens of days and being sufficiently long for long-range transport to occur.

TABLE 2. Calculated tropospheric lifetimes due to gas-phase reaction with the OH radical for a series of pesticides

Pesticide	Lifetime
<u>Organophosphorus Compounds</u>	
Malathion	3 hr
Ethoprophos	3 hr
Methamidophos	~7 hr
<u>Organochlorine Compounds</u>	
Dieldrin	1.1 days
Lindane	~7 days
Hexachlorobenzene	~2 years
<u>Thiocarbamates</u>	
EPTC	6 hrs
Cycloate	5 hrs
Molinate	6 hrs
Triallate	5 hrs

CONCLUSIONS

As is the case for other organic compounds, atmospheric reactions of pesticides present in the gas phase are expected. The interplay between gas-phase chemical reactions, wet and dry deposition and gas/particle distribution, all of which are a function of temperature, determine the overall atmospheric lifetime of a pesticide released into the atmosphere. At one extreme, truly gas-phase pesticides will undergo photolysis and chemical reactions with OH radicals, NO₃ radicals and O₃, and may have lifetimes of the order of a few hours or less, and therefore will impact only the local areas around their point of application.

At the other extreme, certain of the organochlorine pesticides have low reactivities towards gas-phase atmospheric reactions and/or may be of sufficiently low volatility that they can become particle-associated with the attendant physical loss processes of wet and dry deposition of the particles, resulting in the potential for long-range atmospheric transport and/or what has been termed a "distillation" process from warm summertime areas to cold wintertime areas (see, for example, Bidleman *et al.*, 1989; Oehme, 1991; Cotham & Bidleman, 1991).

Clearly, a complete understanding of the physical and chemical properties of a given pesticide is necessary to assess its atmospheric lifetime and potential range of impact. Furthermore, although not discussed here, the atmospheric transformation products of pesticides need to be investigated and understood, since these transformation products can be more or less toxic than the parent pesticide. Lastly, but not least,

experimental methods need to be developed to allow the experimental study of gas-phase reactions of low volatility pesticides, since the present methods can deal only with chemicals which have vapor pressures some two orders of magnitude higher than occur in the gas phase in the atmosphere.

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PESTICIDE APPLICATION AND DEPOSITION - THEIR IMPORTANCE TO PESTICIDE LEACHING TO SURFACE WATER

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ABSTRACT

The aerial transport and deposition of several pesticides has been investigated as part of a study examining factors influencing pesticide contamination of surface waters. Measurements were made on two agricultural herbicides, simazine and isoproturon, the amenity herbicide atrazine, and the organochlorine insecticides, lindane (γ -HCH), α -HCH and aldrin. The near surface transport of isoproturon and simazine was examined in one season during spraying of land just sown to winter wheat and beans respectively. Early data have shown low background concentrations of the target compounds in bulk rainwater samples and ambient air. In mid-winter 1991, concentrations above 0.1 $\mu\text{g/l}$ for simazine, atrazine and lindane were detected in rainwater. Examination of near surface transport of pesticides showed that, even under controlled conditions, up to 0.7% of the applied spray was displaced outside the target area. The initial results suggest that large atmospheric movements can contribute to the aerial transport and deposition of pesticides in the environment and may influence the detection of some pesticides in surface waters.

INTRODUCTION

As agriculture in the United Kingdom (UK) has become more intensive, agrochemical usage has increased and several agricultural pesticides have been widely detected, albeit at relatively low concentrations, in surface watercourses. Until recently transport mechanisms, and the relationships between applications of pesticides and consequent leaching, were little understood, especially for clay soils which are dominant in surface water supply catchments. Recent studies in discrete catchments in predominantly rural areas have looked at these issues and have found contamination of river systems relatively common. However, the source of some pesticides has not been determined. Also the importance of spray drift or aerial transport and deposition of pesticides has not been fully examined.

This paper presents results from a study where the aerial transport and deposition of three commonly used herbicides and two organochlorine

insecticides have been studied. The autumn application of two of the herbicides applied with commercial farm machinery was also monitored to estimate the amount reaching the target under controlled conditions. The detection of some of these herbicides in drainage water in this study and the source of some pesticides identified in surface waters are suggested.

EXPERIMENTAL DETAILS

Plot design

The work was carried out on field clay plot lysimeters at the Brimstone Farm site (Fig. 1) described by Bailey *et al.* (1992). The plot lysimeters have provided the ideal testing ground for examining the interaction between applied pesticides and losses to surface waters. The hydrological isolation of the 0.2ha plots enabled drainflow and depth to the water-table to be monitored and correlated with losses of agrochemicals carried through the drainage system. Meteorological data were obtained from two on-site weather stations and the nearby Meteorological Office station at Brize Norton.

Pesticide Active ingredients

The active ingredients analysed in the aerial transport and deposition study were the triazines, simazine and atrazine, the urea isoproturon, plus the organochlorines lindane - gamma hexachlorocyclohexane (γ -HCH), the isomer alpha hexachlorocyclohexane (α -HCH) and aldrin (Table 1). Simazine and isoproturon are widely used agricultural herbicides which have been identified in UK surface waters whereas atrazine was most commonly used as an industrial herbicide. Lindane (γ -HCH) continues in use as an organochlorine insecticide, whereas the isomer of lindane, (α -HCH) has been identified as a constituent of technical grade HCH, and also as a photodegradation product of lindane in the environment (Bidleman *et al.*, 1987). Aldrin was included as an example of persistent organochlorines no longer licenced - its approval was withdrawn in 1989, although it has not been used extensively for 20 years. The determination of spray drift and pesticide residue leaching to drainage water was limited to the herbicides simazine and isoproturon.

Pesticide applications

Pesticides used during the experimental trial at Brimstone Farm were applied according to their respective label recommendations and limited to those in typical agricultural usage to conform to Good Agricultural Practice guidelines. They included simazine to winter and spring beans, and autumn and spring isoproturon to winter wheat crops. The timing of applications is given in Table 2. Atrazine was not applied. For the test sprays in autumn 1990, applications were made by a standard hydraulic nozzle sprayer with a 10m wide boom (standard for the site) which was operated in accordance with the appropriate Control of Pesticides (COP) and Control of Substances Hazardous to Health (COSHH) Regulations.

Pesticides in the atmosphere

Air samples were collected in an open grassed area to the south of the main trial (Fig. 1) in standard High Volume equipment for 24-48 hour periods collecting approximately 1000m³ every 24 hours. Particulates, collected on a Whatman EPM2000 glass fibre filter, and vapours, collected on three polyurethane foam plugs below, were Soxhlet extracted for 24 hours in

dichloromethane (DCM). The extracts were filtered, evaporated and stored in hexane prior to analysis by gc-ecd for the organochlorine compounds. After these analyses, the extracts were evaporated and redissolved in acetonitrile/water for analysis by reversed phase hplc for the triazines and isoproturon. Limits of detection of 5 pg/m³ were obtained.

TABLE 1. Active ingredients selected for analysis

Component	Analysis period	Active ingredient	Vapour pressure μPa at 20°C, ¹
Water	autumn 1989-1992	isoproturon	3.3
		simazine	0.8
Atmospheric (Rainwater and air)	winter 1991/92	simazine	0.8
		atrazine	40.0
		isoproturon	3.3
		lindane (γ -HCH)	5600.0
		(α -HCH)	c.5000.0 ²
Spray drift	autumn 1990	aldrin	8600.0
		isoproturon	3.3
		simazine	0.8

¹ Source Worthing & Walker (1987)

² Biddleman *et al.* (1987)

TABLE 2. Applications of target pesticides from harvest year 1988 - 1991.

Application date	Mean wind speed km/h	Pesticide applied	Rate g/ha	Plots treated
15/11/89	13.01	isoproturon	2488	All plots except 1,15
11/03/90	No data	isoproturon	1625	All plots except 1,15
08/10/90	11.04	isoproturon	2448	Plots 2,3,6,10,11,13,14,17,19,20
16/10/90	8.74	simazine	1150	Plots 4,8,12,18
10/04/91	10.73	isoproturon	1625	Plots 2,3,6,10,11,13,14,17,19,20
10/04/91	10.73	simazine	216	Plots 5,7,8,16
09/10/91	9.63	isoproturon	2448	All plots
05/04/92	11.30	isoproturon	1625	All plots

Bulk precipitation samples included wet and dry deposition collected in 5 litre bottles beneath an open topped PTFE funnel (0.6m diameter), located adjacent to the High-Volume sampler. Between January 1991 and March 1992, 22 samples were collected; each was divided into two and liquid/liquid extracted, in turn, into hexane (for gc-ecd analysis), and DCM followed by acetonitrile/water (for hplc analysis). Limits of detection of 2 ng/l for

the triazines and isoproturon and 0.25 ng/l for the organochlorines were obtained. In addition, from autumn 1991, equipment was designed to collect 'wet only' event driven rainfall; a rectangular 0.5m² stainless steel funnel, with an electrically operated sliding cover was exposed to rainfall only when a sensor detected both impact from rainfall and conductivity from moisture. A 30 second delay was set before automatic closure of the cover.

The analytical data for rainwater and air samples determined by the Birmingham laboratory have not been subject to the same degree of quality assurance work as other sample types analysed by the Cambridge and Harpenden laboratories and must consequently be interpreted with some caution.

Spray drift

Pesticide spray drift was examined on 8 October 1990 for isoproturon and on 16 October 1990 for simazine (Table 1). The prepared solution in the tank was checked before spraying for each active ingredient against a calibration solution. Site conditions at the time of application were recorded. Three methods of measuring deposition were undertaken for each spraying carried out around midday:

- 2.1m lengths of 50mm wide Whatman No.1 Chromatography paper were attached to lengths of untreated wood laid on the ground within the target area together with 85mm diameter discs of Whatman No.3 paper in pre-washed petri dishes. The experiment was laid out between the tramlines (wheelings) on each plot immediately before the application of the pesticides to avoid cross contamination from adjacent plots.
- At ground level up to 8m immediately downwind of the target area, further 2.1m lengths of 50mm wide Whatman No.1 Chromatography paper were laid out, again attached to wood strips.
- Airborne drift was assessed from 2mm diameter polythene tubing suspended from carbon fibre masts, 11m high, and erected 8m downwind of the edge of the sprayed area.

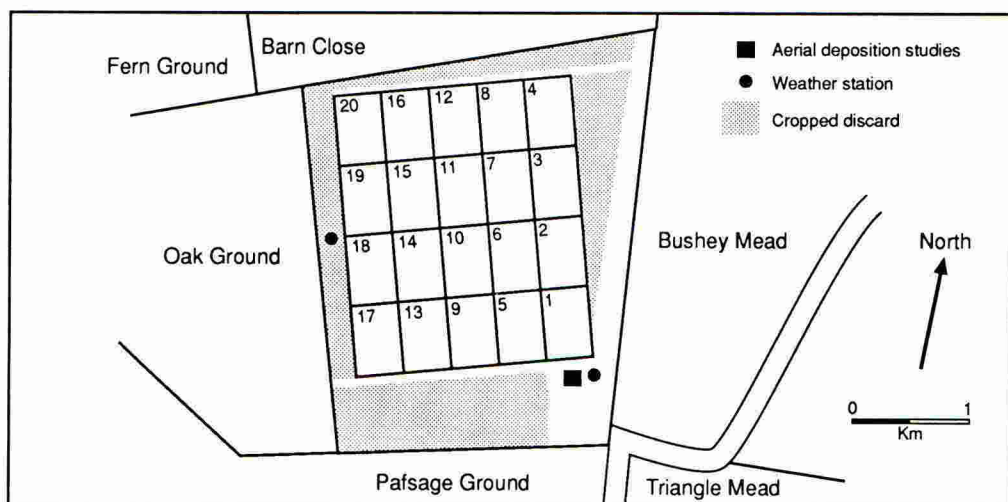


Fig 1. Layout of site plot lysimeters, discards and adjacent fields

The various sample media were extracted into solvent and the extracts analysed at the Cambridge laboratory by either reverse phase hplc using a diode array detector (isoproturon and simazine) or by gc-npd (simazine only); limits of detection were 0.1 µg/ml. The analytical data were subject to a similar degree of quality assurance work as the drainage water samples. A number of the extracts, re-analysed for isoproturon at the CSL Harpenden laboratory, provided very good agreement.

Pesticides in water

Initially most samples for pesticide residue analysis were bulked from the smaller samples collected by automatic water samplers. This meant that few data were available on the variations within individual rain events such as the initial response, the period near the peak of the event and the recession period. This baseline monitoring was extended in the winter 1990/91 and in subsequent seasons to include detailed sampling in storm periods. Sampling times were recorded on data loggers and related to the drainflow for each plot. The analytical procedures used by the Cambridge laboratory and the supporting quality assurance procedures, such as confirmatory analyses, recovery experiments and sample storage stability studies have been fully described by Harris *et al.* (1991). Limits of detection of 0.1 µg/l for both isoproturon and simazine were sufficiently sensitive for this type of sample.

RESULTS

Aerial transport and deposition

Concentrations in bulk rainwater samples of atrazine, simazine and isoproturon are given in Fig. 2 and concentrations of lindane (γ -HCH), α -HCH and aldrin in Fig. 3. The frequency of sample collection varied, as it was dependent on sufficient rainfall to collect a sample, but the data show peaks when apparent 'flushes' of the pesticides occurred. These higher concentrations were different for different active ingredients and if the differences are real then they imply that different air masses are involved. In particular, the peaks for simazine were detected in January/February 1991 and in February 1992 (maximum of 0.23 µg/l). Isoproturon peaks were detected in March/April 1991 (maximum of 0.13 µg/l) and February 1992. These concentrations exceeded 0.1 µg/l, the EC Directive limit for potable water (Anon. 1980), providing opportunities for direct contamination of shallow surface water sources. Similar high concentrations of up to 0.5 µg/l were seen for lindane in early winter 1991 and 1992. There was less variation in concentration for the organochlorines observed than for the other herbicides.

Results from the High Volume air samples are given for all active ingredients in five periods sampled in Table 3. In general summer samples showed greater vapour phase concentrations for all compounds. Spring samples indicated highest levels of currently applied triazines and isoproturon. Lindane (γ HCH) was found to be on average three times higher than α HCH.

Spray drift

The mean wind speed at 2m height during each test (midday) was 12.5km/h (direction 315° ± 20°) for isoproturon and 11.1 km/h (direction 227° ± 10°) for simazine. This compared with mean daily wind speeds of 8.7 km/h and 9.5 km/h respectively. Under the controlled test conditions and dry, sunny

weather, the deposition of pesticides on the target plots was distributed evenly indicating that very little boom bounce and yaw occurred. The range of pesticide deposition in the target area showed no significant difference between mean results from the two types of sampling, ie. using 2.1m lengths of chromatography paper and 85mm diameter Whatman paper discs. Combined sample means for each herbicide treatment are given in Table 4; there was no statistical difference in the deposits under the three sections of the boom.

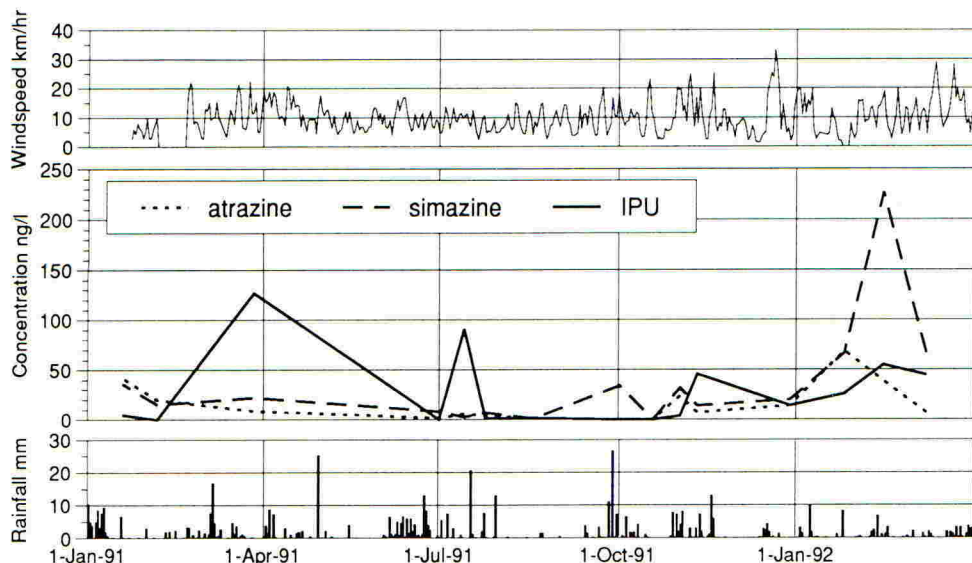


Fig. 2. Concentrations of atrazine, simazine and isoproturon detected in bulk rainwater samples.

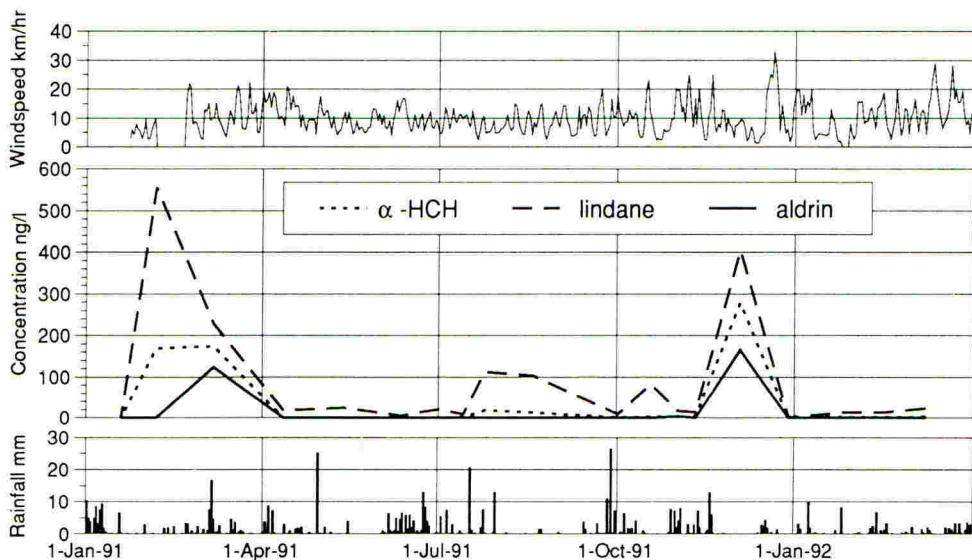


Fig. 3 Concentrations of lindane (γ -HCH), α -HCH and aldrin detected in bulk rainwater samples.

The results showed, however, that even with an accurate spray placement as described, some displacement occurred immediately outside the target area. This displacement was considered to come from a single swath of spray closest to the edge of the target area. 0.4% to 0.7% of the applied spray was displaced, with 0.07% to 0.35% of the applied spray remaining airborne 8m from the edge of the sprayed area (Table 5).

TABLE 3. High Volume samples for organochlorines, triazines and isoproturon
Total collected - vapours and particulates (pg/m³)

Sample period	Wind speed km/h	γ-HCH	α-HCH	aldrin	atrazine	simazine	isoproturon
16-18/1/91	No data	270	41	164	262	27	32
26-28/6/91	6.59	4787	1311	825	260	288	90
7- 9/8/91	10.96	4457	1565	705	127	51	5
17-18/12/91	21.94	1015	187	56	71	14	5
2- 3/4/92	8.12	1061	776	523	707	211	145
Mean data	-	2318	782	455	285	118	55

TABLE 4 Comparison of applied tank formulation with that detected by ground samplers

Plot no.	Formulation	Application rate (l/ha)	Spray solution a.i (mg/ml)	Amount of a.i. (mg.m ²)		
				Expected from calibration	Found Mean	SD
6	isoproturon 81.6% ww	199	12.36	246	230	28.8
4	simazine 500 g/l	199	6.16	123	107	22.2

Pesticide residue leaching

The herbicide isoproturon was detected in bulk water samples from Plot 6 at a peak concentration of 26 µg/l. This compared with losses in the range 10 to 50 µg/l from other plots at Brimstone Farm. The total quantity of isoproturon leached in the winter following this application was estimated at less than 1% of autumn applied isoproturon (Bailey *et al.*, 1992). In winter 1990/91, the more comprehensive sampling undertaken demonstrated that a flush of pesticide residues occurred in the first drainflow event of the season. This was observed to occur before a water-table was established in the sub-soil and was considered to result from rapid flow through the soil

profile in macropores and cracks (Bailey *et al.*, 1992). Under these conditions, the peak loss for isoproturon detected on Plot 6 was nearly 50 µg/l and the peak for simazine (Plot 4) was 25 µg/l.

TABLE 5 Deposition of spray immediately downwind of sprayed area

Location	Tramline	Pesticide	Amount pesticide - mg/m ²				total mg per 1x8m strip
			0-2m	2-4m	4-6m	6-8m	
Plot 6	upper	isoproturon	6.91	0.95	0.72	0.23	17.62
	lower		4.02	1.42	0.49	0.49	12.84
Plot 4	upper	simazine	0.95	<0.24	<0.24	<0.24	0.95
	lower		1.19	0.71	0.48	<0.24	4.76

DISCUSSION AND CONCLUSIONS

The presence of pesticides in rainwater and ambient air suggests that these should be considered in assessing losses to UK surface waters. The data from Brimstone Farm have indicated concentrations in bulk rainwater samples for atrazine, simazine and isoproturon at 0.04 µg/l, 0.23 µg/l and 0.05 µg/l respectively in February 1992, which are close to or above the EC limit for potable water (0.1 µg/l for a single pesticide). Results for the organochlorines showed peak concentrations in bulk rainwater up to 0.5 µg/l for the more volatile lindane. Photoisomerisation of lindane (γ-HCH) has been reported elsewhere as a source of α-HCH; (α-HCH in technical grade HCH is also a possible source). Knap & Binkley (1988) described the ratio of α/γ as a measure of the age of an air mass; data reported from remote areas have ratios greater than 1, whereas the data reported here, supported by other European data (Villeneuve & Cattini; 1986, Turnbull, 1989) suggest ratios less than 1. This might indicate a local source from recent use of lindane.

Little data for the existence of triazines or isoproturon in wet and dry deposition exist. However, Braun *et al.* (1990) detected all three in rainfall in their study in Germany. More data will be required to allow further interpretation of the UK results.

In cracking clay soils, such as those at Brimstone Farm, it has been demonstrated that rapid water movement through the soil can occur in early winter in the absence of a water-table. In such circumstances little soil-water contact may occur and opportunities arise for pesticides in rainfall to be carried rapidly to drainage waters or for direct input into shallow water sources. However, in the small plots at Brimstone Farm the losses detected for simazine and isoproturon, following autumn applications, completely overshadowed any influence that inputs in rainwater might have. However, atrazine is only occasionally used as an agricultural pesticide but has been found widely in rural surface waters. Many sources have been suggested, in particular its use by Local Authorities on roadside verges and on railway tracks to limit weed problems. These are probably the major contributors, although Harris *et al.* (1991) identified atrazine, and subsequently simazine, leaching from road aggregate derived from dis-used railway ballast. Analysis for atrazine in drainage water from Brimstone

Farm was not included in the study reported here. However, in parallel work on the same site, Moore (personnel communication) found atrazine in surface runoff in September 1991 at 0.04 $\mu\text{g}/\text{l}$ (Plot 14) in one of four samples taken. Neither atrazine, nor the organochlorines examined, had been applied to this site for at least 15 years.

However, localised spray drift, following herbicide applications of isoproturon and simazine, both representing low volatile compounds, showed that considerable drift could occur. The work at Brimstone Farm demonstrated that even under good conditions up to 0.35% of the applied spray remained airborne as lateral drift, 8m downwind from the sprayed edge. This applied to low volatile active ingredients which are likely to be initially transported as droplets. Similar findings were reported by Elliot & Wilson (1983) who indicated that a buffer of at least 10m may be necessary to prevent damage to adjacent crops, depending on localised wind conditions.

Spray drift into the experimental area from neighbouring fields was also assessed as these could be a possible source of some of the herbicides or organochlorines in the bulk rainwater and ambient air samples. Most of the surrounding fields were in grassland during the study period. Exceptions were Pafsaage Ground to the south and Bushey Mead to the east (Fig. 1). Although both fields were in winter wheat in harvest years 1991 and 1992, it is felt that drift from Pafsaage Ground was unlikely as there is a dense 7m high, 15m wide tree and shrub barrier separating this field from the Brimstone Farm site. Bushey Mead however, was only separated from the site by a 1.5m high, narrow hedge. It was confirmed that the only applications of the target pesticides to Bushey Mead were isoproturon at label rates in the weeks beginning 19 November 1990 and 24 October 1991. Detections of isoproturon in rainwater samples in the latter period were extremely low.

The information from neighbouring fields confirmed that nearby pesticide applications were unlikely to have contributed to the higher concentrations seen in the rainwater samples (Fig. 1). This suggested that the pesticide deposition observed, with the exception of aldrin, which was withdrawn from use in spring 1989, resulted from larger scale atmospheric movement of pesticides following applications further afield. In April 1991 and February 1992, when the herbicide concentrations were higher, the wind direction although variable was predominantly south westerly. In February 1991, when the organochlorine concentrations were higher, the wind direction was predominantly north-easterly.

The initial results from this work suggest that large atmospheric movement can contribute to the aerial transport and deposition of pesticides in the environment and may influence the detection of some pesticides in surface waters. In particular, for atrazine this is more likely to be linked to its use as a total weed control (industrial usage) throughout the year, than as an agricultural treatment, the major crop use being to maize in April/May and other minor crops in February to April. For simazine, the major use to winter beans in November did not correlate with the timing of the detection of the higher concentrations, although its use to other agricultural crops (spring beans, fruit, hops and forestry) in February to May may be more important. Isoproturon is almost exclusively applied to winter cereals, with typically 90% applied between October and December each year and the remainder in spring. The higher concentration detected in late March/April 1992 (0.13 $\mu\text{g}/\text{l}$) may have resulted from general agricultural applications at this time. Lindane is used for both crop and non-crop uses at all times of the year. The predominant peak crop use tends to be spring

and autumn. This did not correlate well with the higher concentrations seen in February 1991 (0.56 µg/l) and November/December 1992.

Further work will assess variations between years; data are also being collected at a second site in Herefordshire.

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LABORATORY METHODS FOR EVALUATING THE IMPACT OF PESTICIDES ON WATER/SEDIMENT ORGANISMS

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ABSTRACT

Laboratory test methods for assessing the effects of pesticides in sediments are reviewed with respect to their relevance to the field situation and their use in generating data for hazard assessments. If environmental fate and toxicity data indicate potential for effects on benthic communities then this could be investigated in a relatively simple laboratory test. It is proposed that a freshwater, static, water/sediment system to determine chronic toxicity to *Chironomus riparius* is suitable for the development of a standard test, with the pesticide applied directly to the sediment prior to introducing the test organisms.

INTRODUCTION

Laboratory testing of pesticide effects on aquatic organisms has, to date, concentrated on organisms which live in the water column, with standard regulatory tests on various fish species, *Daphnia* and algae. Recognised regulatory procedures exist to determine the acute and, if necessary, chronic effects on these organisms in laboratory tests so that hazard assessments can be made. On the basis of these assessments, it can be determined whether further testing in the field is required. There are no similar well-defined procedures for testing the effects on representatives of the sediment in-fauna. These organisms first appear in the regulatory process at the field testing stage.

The use of sediments in laboratory tests of the toxicity of pesticides to aquatic organisms, however, does have a long history and it has been demonstrated that certain pesticides have their acute toxicity "reduced" simply by the addition of sediments to the test system. For example, Wilson and Bond (1969) reported a 96-hour LC50 for diquat to *Hyalella azteca* of 0.048 mg/l. In the presence of "pond mud", diquat was over 100x less toxic with a 96-hour LC50 of 6.8 mg/l. Similar reductions have been reported for the toxicity of pyrethroid insecticides to fish and aquatic invertebrates (Hill, 1985, 1989). In these earlier studies, little consideration was given to the sediments themselves and they concentrated on reduction of toxicity in the water phase. The results were expressed as nominal concentrations of the chemical in the water phase, and as few details of the sediment are given, calculations of the concentration of the pesticides in the sediment are not possible. More recently, interest has focused on the concentrations of chemicals in sediment. Aquatic sediments can act as a "sink" for hydrophobic pesticides and it has become apparent that, for some of these, low concentrations may be relatively persistent, degrading only slowly. Therefore a method for assessing the possible effects of such pesticides on benthic organisms is required in order to

carry out hazard assessments for benthic communities. One proposed method is the development of a relatively simple, "standardised", laboratory sediment toxicity test. Such a test would be triggered by environmental fate data concerning estimated entry rates of a pesticide into aquatic environments, adsorption to and likely persistence in aquatic sediments, which linked to data on toxicity to water column organisms (fish and *Daphnia*) indicate the potential for effects on benthic organisms. At present it is not possible to predict to what extent products adsorbed to and persistent in sediments will be bioavailable. The results of the laboratory sediment tests will contribute to assessments to screen out those compounds which would present no hazard in the environment, in order to focus resources on products which warrant further evaluation by laboratory or field testing. It will, in general be unnecessary to study hydrophilic products in laboratory water/sediment tests as their adsorptive properties are limited and tests in water alone will provide sufficient data for environmental assessments.

Toxicity testing of sediments has been comprehensively reviewed by Burton (1991 and 1992). This paper describes the potential problem of pesticides in sediments, proposing methods which are appropriate for the laboratory testing of toxicity to benthic organisms in order to generate data that could subsequently be used to aid environmental hazard assessments.

TEST METHOD

Test System

A variety of test systems have been employed for the testing of chemicals, including pesticides, in marine and freshwater sediments. For example, the American Society for Testing and Materials (ASTM, 1991) have published standard test methods for assessing the toxicity of sediments to benthic organisms. Clark *et al.* (1989) investigated the acute toxicity of fenvalerate and cypermethrin to mysid, pink and grass shrimp in static and flow-through water/sediment systems, Adams *et al.* (1985) determined the acute and chronic toxicity of Kepone to *Chironomus tentans* again using both static and flow-through methodology. In Germany, a Biologische Bundesanstalt für Land- und Forstwirtschaft/ Industrieverband Agrar e.V. (BBA/IVA) *ad hoc* working group are considering a test method using a static system to determine the chronic toxicity of pesticides to *Chironomus riparius*.

Although a large amount of work has been carried out on the toxicity of marine sediments, freshwater systems are more suitable, when considering standard procedures for testing pesticides, due to the use patterns of these products and the much greater dilution factors in estuarine and marine environments. In addition, static systems are likely to present a more severe test of exposure than flow-through where test chemical may be lost to the outflow water. Clark *et al.* (1989) demonstrated that both fenvalerate and cypermethrin were more toxic in static than flow-through water/sediment systems. Static test systems are easier to set up and control and they represent the best option for defining standard laboratory water/sediment toxicity testing methods (providing the test organisms will survive in such a system).

Test Phase

There are a number of approaches for assessing the toxicity of chemicals to benthic organisms, all of which have been used with some degree of success. They involve testing different phases of water/sediment systems or whole systems, as listed below:

- (i) spiked water alone
- (ii) interstitial (pore) water from treated/contaminated sediments
- (iii) elutriates (water extractable phase) of treated/contaminated sediments
- (iv) organo-extractable phase of treated/contaminated sediments
- (v) spiked water/sediment systems
- (vi) bioassay of field sediments.

In order to choose a test-phase suitable for the laboratory testing of pesticides in sediments, it is necessary to consider what the requirements of a test should be. If a test is to be a part of the standard regulatory procedure it should be robust and reproducible so that different laboratories conducting it will obtain similar results. In addition, the test should have some relevance to the "real-life" field situations so that results can be used as part of an assessment of the risk to organisms in the field. Therefore, it is necessary to consider the field exposure of organisms before deciding which test methodology is appropriate.

Benthic organisms can be exposed to the toxicant in the field by three routes; in the overlying water, the interstitial water and through ingestion of contaminated sediment. Therefore, a test should include all of these routes of exposure. Thus (i) - (iii) above are unsuitable, as they test only the water phase of any water/sediment system. Phase (iv) is also unsuitable as it has no sediment present and the chemicals extractable with organic solvents may not, in practice, be available to the organisms. In addition the absence of sediments in (i)-(iv) might stress the benthic organisms concerned and in chronic toxicity testing may affect their growth and development. Bioassay of field sediments (vi), by sampling and bringing back to the laboratory may be of value in dealing with some specific situations. However it can be difficult to attribute any effect to a specific product. Furthermore, for new products, testing would normally be done prior to their widespread field use. Thus we are left with spiking of a water/sediment system as the most appropriate method for standard, regulatory tests. This test system has two major variables: (a) the water/sediment and (b) the spiking. Other important factors include the period of the test and the test organism.

Test Water/Sediment

The most important criterion is that the selected water/sediment should enable the survival and normal growth and development of the test organism for the duration of the test. A range of water types from different sources and with different physico-chemical parameters should satisfy the above criterion, but the choice of water phase is much less critical than that of sediment. However, in the interests of consistent test methodology a standard, defined water with respect to hardness, for example might be chosen. The choice of sediment is by far the more

important of the two components of the system. The following options exist:

- (i) a natural aquatic sediment sampled and tested so as to preserve its integrity
- (ii) a natural aquatic sediment, prepared by sieving, mixing etc
- (iii) a sediment prepared from field soil
- (iv) an artificial sediment.

Of the above, the use of whole natural sediments has its attractions in that it must be closest to the natural situation. However, taking samples of field sediments and maintaining their integrity, physically, chemically and microbiologically, is likely to be very difficult. Furthermore, natural sediments, as sampled, are not homogeneous and the use of separate field-collected samples in laboratory tests would introduce another variable within and between tests other than test chemical concentration. In addition natural sediments which satisfy the criterion of being able to support the test organism are almost certainly going to contain indigenous organisms, possibly affecting the test organisms. The majority of published work on pesticides has been done with natural sediments which have been prepared for testing by mixing and sieving in order to produce a homogeneous substrate. This method allows within-test standardization of the sediment, whilst still retaining some of the features of a natural sediment, although the problem of indigenous organisms can still exist. Work in the author's laboratory on the toxicity of pyrethroid insecticides has been performed using sediments which were field soils. These were sieved and mixed to produce a homogeneous preparation prior to use. Artificial sediments, which could support the test organisms and be prepared in the laboratory (provided they were not too dissimilar to natural sediments) could eliminate much of the variation between tests and between testing laboratories, with respect to sediment. This method could be an acceptable option, although a large amount of work would be necessary to define and test a suitable artificial medium. Whichever method is chosen it is important that the sediment is characterised, and particle size distribution and percent organic matter reported.

The type of sediment chosen may have a significant effects on the result of any toxicity test with benthic organisms. Toxicity of a chemical will depend on its bioavailability through the three possible routes of exposure to benthic organisms; via overlying water, interstitial water and ingestion. The concentration of a toxicant in the overlying water and interstitial water will vary substantially depending on the sediment, particularly for those compounds with high K_{oc} values, which are those most likely to adsorb to bottom sediments and so may require this sort of testing. Table 1 shows how the difference in the organic matter can theoretically affect the concentration of permethrin and parathion, chemicals with K_{oc} values of 100000 and 5000, respectively (Wauchope *et al.* 1992), in the water phase in water/sediment systems using sediments at 100 μg pesticide/kg with different organic matter contents. It is assumed that the system is at equilibrium, thus the pesticide concentration in the water and sediment phases will depend on K_{oc} values and the water:sediment ratio.

TABLE 1. Theoretical concentration of permethrin and parathion in water phase of water/sediment systems

Sediment organic matter (%)	Concentration in water phase ($\mu\text{g}/\text{l}$) ^a , for water:sediment ratios					
	permethrin			parathion		
	4:1	10:1	25:1	4:1	10:1	25:1
1	0.171	0.169	0.165	3.03	2.56	1.85
5	0.034	0.034	0.034	0.671	0.645	0.588
10	0.017	0.017	0.017	0.340	0.333	0.317

$$^a C_w = C_s / (R + K_d)$$

where C_w is concentration in water phase ($\mu\text{g}/\text{l}$)

C_s is concentration in sediment phase ($\mu\text{g}/\text{kg}$)

R is the water:sediment ratio (ml/g)

K_d is the soil adsorption coefficient ($[K_{oc} \times \text{om}\%]/172.4$; ml/g)

The data in Table 1 indicate that there is a 10-fold decrease in the concentration of permethrin in the water phase as the organic matter content of the sediment correspondingly increases from 1 to 10%. For parathion, a less hydrophobic compound, the correlation is not as good, but there is still a decrease in the water phase of between 6- and 9-fold with increasing organic matter. The data also demonstrate that for compounds with high K_{oc} values, the water:sediment ratio makes little difference to the concentration in the water phase. This is certainly the case for permethrin with a K_{oc} of 100000 and even for parathion with a K_{oc} of 5000 there is still a factor of <1.5x difference in water concentrations as the water:sediment ratio changes from 4:1 to 25:1. If toxicity to the test organisms is due to exposure to the toxicant concentration in the interstitial water or overlying water, then the lower the organic matter content, the higher the exposure to the organisms. Alternatively, if the toxicity were due to ingestion of the pesticide adsorbed to organic matter in the sediment then exposure is potentially higher in systems with sediment of high organic matter content. However, Di Toro *et al.* (1991), claim that, in equilibrated systems, the route of exposure is not significant and that for hydrophobic (high K_{oc}) chemicals any biological effects can be predicted from the concentration of the chemical in the sediment organic carbon content, together with effects in water-only exposures. Reviewing published studies concerning the toxicity of hydrophobic organic chemicals to benthic organisms, they show the data to support this hypothesis and that toxicity to benthic organisms can be predicted from equilibrium partitioning between the water and sediment phases. Studies done on the acute toxicity of the pyrethroid insecticides permethrin, cypermethrin and tefluthrin in the author's laboratory also support this (see Table 2), as do the studies of Clark *et al.* (1989) with fenvalerate and cypermethrin. However, at present, only limited data exist and it is not possible to determine whether this conclusion that bioavailability is dependant on soil organic matter holds for all types of pesticides.

TABLE 2. Toxicity of the pyrethroid insecticides permethrin, cypermethrin and tefluthrin to *Asellus aquaticus* in water only and in a water/sediment system

Chemical	EC50 in water only ($\mu\text{g}/\text{l}$)	EC50 in water/sediment system ($\mu\text{g}/\text{kg}$)	Calculated conc. in water at water/sediment EC50 ($\mu\text{g}/\text{l}$) ^a
Permethrin	0.085	281	0.107
Cypermethrin	0.009	42	0.016
Tefluthrin	0.16	375	0.13

^a assuming equilibrium between the sediment and water and calculated using the following data; for both permethrin and cypermethrin water:sediment ratio (WS) = 15:1, sediment organic matter (OM) = 4.5% and $K_{oc} = 100000$; and for tefluthrin WS = 25:1, OM = 5%, $K_{oc} = 100000$

Spiking of the Test System

The test chemical can be applied to the test system in different ways. Most fundamentally it can be applied to (a) the water or (b) the sediment. Both of these have their merits and can be appropriate to particular situations. However, when investigating the possible effects of pesticides in sediments under laboratory conditions, there are problems with application to the water phase as follows:

- (i) initially all the available test compound will be in the water phase and toxic effects could occur prior to the adsorption of the compound to the sediment, possibly overestimating the sediment toxicity
- (ii) many compounds will adsorb to surfaces other than the soil in the test system. Pre-determined concentrations in the sediment phase could be difficult to achieve, leading to variation between replicate treatments.

In many cases the route of entry of the chemical to the sediment in field situations is via the water phase (following spray-drift deposition) and regulatory tests already exist to establish the possible effects of the chemical in the aqueous phase. In order to truly assess sediment toxicity, a method is needed to assess the potential effects of pesticides when they are in the adsorbed state. The type of compound for which this assessment would be most likely needed will only be in the water phase in significant concentrations transiently. They would rapidly be adsorbed by bottom sediments or in many cases they will already be adsorbed onto soil particles when they enter aquatic environments, through run-off.

Studies concerning the acute toxicity of the soil pyrethroid insecticide tefluthrin to bluegill sunfish (*Lepomis macrochirus*), and three aquatic invertebrates (*Daphnia magna*, *Cloeon dipterum* and *Asellus aquaticus*) have been carried out by the authors in water and water/sediment systems with three methods of application of the test chemical:

- (i) treated water alone
- (ii) treated water above a layer of untreated sediment
- (iii) treated sediment (4 hours incubation), flooded with untreated water.

The sediment used was a sandy loam soil with an organic matter content of 5% and the ratio of water:sediment in each system was 25:1. Test systems were prepared just prior to addition of the test organisms. The results, given in Table 3, show that whilst the toxicity expressed in terms of the nominal concentration in the water was less in both water/sediment systems than in water alone, the toxicity was 12-38x lower when applied to the sediment phase than when applied in the water phase of a water/sediment system. The chemical was of similar toxicity to all the test organisms, even though three out of the four organisms are not benthic and presumably only exposed to tefluthrin in the overlying water. The fourth, *Asellus*, is a benthic organism, exposed to the interstitial water and the treated sediment. This suggests that for this compound toxicity is due to the concentration in the interstitial/overlying water phases. This would seem to be confirmed from calculations of the concentrations of tefluthrin in the water phase of the systems, which show that, after application to the sediment (method iii above), at the EC/LC50 in the water/sediment system, the calculated concentration in the water phase is very similar to the toxicity in water alone (method i).

TABLE 3. Toxicity of tefluthrin to aquatic organisms in water and water/sediment systems.

Organism	72hr EC/LC50 values in test system ^a				
		$\mu\text{g/l}$ water ^b		$\mu\text{g/kg}$ sediment ^c	
	(i)	(ii)	(iii)	(ii)	(iii) ^d
<i>D.magna</i>	0.41	1.4	53	35	1325(0.45)
<i>C.dipterum</i>	0.25	0.62	8	16	200(0.07)
<i>A.aquaticus</i>	0.16	0.62	15	16	375(0.13)
<i>L.macrochirus</i>	0.18	0.69	16	17	400(0.14)

^a (i) water alone, (ii) treated water + untreated sediment, (iii) treated sediment + untreated water

^b calculated assuming all the test chemical was evenly distributed in the water phase

^c calculated assuming all the test chemical was evenly distributed in the sediment phase

^d the figure in brackets is the calculated concentration in water assuming the system is at equilibrium (water:sediment ratio = 25:1, sediment organic matter = 5%, K_{oc} = 100000)

Other workers have also reported differences in results where application has been to water or sediment phases of water/sediment systems. Lydy *et al.* (1990) reported a reduction in the toxicity to *Chironomus riparius* larvae of several highly hydrophobic compounds in the presence of sediments, but no difference between spiking the sediment or water phases. However in this case organisms were introduced into the test systems after 24 hours equilibration, following application of the test chemical to the test system, by which time both the test systems would be at or close to equilibrium and so therefore no differences in toxicity would be expected. However for less hydrophobic compounds, including parathion, carbaryl and aldicarb (K_{oc} 5000, 300 and 30, respectively; Wauchope *et al.* 1992) tested using the same methods, Lydy *et al.* (1990) showed that toxicity was lower in systems where the compound was applied to sediment, possibly indicating

that these chemicals take longer than the hydrophobic compounds to equilibrate in the system.

The objectives of the study, together with consideration of the field situation and differences that can arise from the application method, suggest that pesticide treatments of the test system should be to the sediment. The application method should be chosen to give an homogenous distribution throughout the sediment phase (for example, using a rolling mill or application in a solvent other than water, depending on the test chemical). This allows the toxicity of the chemical in its adsorbed state to be assessed, in a system which is at or close to equilibrium, without complications from constantly changing concentrations between the water and sediment phases.

Acute or Chronic Toxicity Testing?

Methods exist for conducting both acute or chronic sediment toxicity tests to a variety of benthic organisms. If the environmental fate data on persistence and degradation for a chemical indicate only short term concerns, then acute tests in water alone, on standard water column test organisms will generally provide adequate information for hazard assessments. However if it is anticipated that chemicals may be persistent in sediments, at least over the life-cycles of the organisms which are of concern, then we are least interested in setting sediment toxicant concentration criteria using acute toxicity levels from short term tests. As with all persistence problems, what is needed is to determine chronic toxicity levels and to define NOECs for the organisms concerned. Acute sediment toxicity tests may have a place, but only in setting exposure levels for subsequent definitive chronic tests. Conducting chronic as opposed to acute tests would probably necessitate the use of sediment or some other substrate as the organisms may not grow and develop normally in its absence. The design and end-point of any chronic sediment toxicity test will depend on the chosen test organism.

Test Organisms

Many studies have been carried out to determine the toxicity of chemicals in freshwater sediments using the standard test organisms for assessing toxicity in water alone, such as fish and *Daphnia*. These have the advantage of being readily available along with the biological test methodology. However, these are not benthic organisms and whilst *Daphnia* may feed off the sediment surface they are not exposed to interstitial water nor do they ingest sediment organic matter. In order to assess the possible impact of pesticides on benthic communities, a benthic organism should be used in order that all possible routes of exposure are included. A variety of organisms have been tested in freshwater sediment toxicity assays, most commonly used among aquatic invertebrates are the oligochaetes (*Tubifex*), amphipods (*Gammarus*, *Hyalella*), isopods (*Asellus*) and insect nymphs and larvae (*Chironomus*, *Hexagenia*). *Chironomus* and *Hyalella* are established in standard test methodologies for chronic toxicity tests (ASTM, 1991), they can be easily cultured in the laboratory and have relatively short generation times allowing the completion of chronic tests within a relatively short time (<28 days). *Chironomus riparius* is well established as a test organism, both in Europe and the USA, and, as such, would be a favoured organism for a standard sediment test. However, work

is necessary to define standard chronic test methodology, particularly with respect to life-stages tested and end-points.

CONCLUSIONS

A method is required to assess the possible impact of pesticides on sediment in-fauna (benthic) communities. It is possible that for hydrophobic pesticides, environmental fate data and toxicity to other aquatic organisms could be used to predict effects on the basis of equilibrium partitioning, however there is insufficient data at present to prove this. If there is a potential for effects on benthic organisms then another way this may be investigated is using a standard laboratory test. This should be a static, freshwater test of the pesticide applied to a sediment, investigating the chronic effects on a suitable benthic organism, for example *Chironomus riparius*. Further work is necessary to define "standard" procedures with respect to the water/sediment, the organisms used and chronic end-points.

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SESSION 6B

ADVANCES IN IPM IN FRUIT AND VITICULTURE

CHAIRMAN PROFESSOR C. C. PAYNE

SESSION
ORGANISER MR S. C. GORDON

INVITED PAPERS 6B-1 to 6B-2

RESEARCH REPORTS 6B-3 and 6B-4

THE ROLE OF INTEGRATED PEST MANAGEMENT IN INTEGRATED PRODUCTION OF VITICULTURE IN EUROPE

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ABSTRACT

Modern Integrated Pest Management (IPM) in viticulture is removed from its former isolation and put into the broader context of Integrated Production as defined by IOBC. After a short conceptual overview we identify the key pests and diseases occurring in all European viticultural areas. The present state-of-the art of IPM is presented and discussed.

INTRODUCTION

Integrated Pest Management (IPM) in Europe is intimately linked with the activities of IOBC (International Organisation for Biological Control and Promotion of Integrated Systems). In viticulture we can trace back the first attempts of an international collaboration in this field to the establishment of an IOBC Working Group on "Integrated Protection in Viticulture" in 1974 when entomologists from France, Germany, Italy, Spain and Switzerland decided to start a mutual exchange of information and to develop concepts and methods of IPM. Today the group still exists and has grown into a broad interdisciplinary programme that operates 6 subgroups dealing with sucking pests, chewing pests, diseases, physiological deficiencies, weeds and side-effects of pesticides. A 7th subgroup handles the aspect of Integrated Production synthesising the results of the different disciplines in an interdisciplinary systems approach where IPM is put into the larger context of Integrated Production (IP). The objectives and principles of IP have been defined by IOBC in March 1992 (IOBC,1992a) and provide the overall conceptual framework and guidelines for the orientation of IPM as one of the major components of Integrated Production (IOBC,1992b). Other key elements in the IOBC charter are a low input sustainable agriculture, the agro-ecosystem, natural resources and regulating mechanisms, and the entire farm as basic unit. It is evident that modern IPM has been removed from its former isolated status as it became more and more evident that plant protection involved more than repairing damages caused by a multitude of inadequate farm operations (e.g. fertilisers, cultural practices, training and pruning systems). Summarising the general idea of IPM we can say that emphasis is placed on prevention rather than curative therapy, on systems-oriented solutions rather than isolated and linear therapeutic measures.

The information generated by this working group is one of the major sources for those wishing to gain a comprehensive overview on current trends and the state-of-art in the field of IPM and IP in viticulture - information that has to be compiled otherwise from the many excellent scientific and more practical publications scattered in the relevant literature. A gold-mine in this respect are the proceedings of the bi-annual meetings with original contributions on research in progress that will often find their final place in the professional literature several years later (published as Bulletins of IOBC/WPRS). Another important source of recent origin are the Proceedings of a joint CEC- IOBC symposium on "Plant-protection problems and prospects of integrated control in viticulture" held in 1988 at Lisbon/Portugal (Cavalloro, 1990).

PESTS, DISEASES AND WEEDS

Table 1 provides an overview of the major problem species in European vineyards. A number of pests and diseases occur in all European viticultural areas (Cabezuelo, 1990). They provide the hard core of problems taken into consideration during the planning of a generalised European IPM concept. Other problems are of local or sporadic nature and require the regional adaptation of IPM programs.

TABLE 1. The most important viticultural pests and diseases in Europe.

Key-problems in most countries	Important regional problems
Mites: <i>Panonychus ulmi</i> <i>Tetranychus urticae</i> <i>Calepitrimerus vitis</i>	Mites: <i>Eotetranychus carpini</i>
Lepidoptera: <i>Lobesia botrana</i> <i>Eupoecilia ambiguella</i>	Leafhoppers: <i>Scaphoideus titanus</i> <i>Empoasca vitis</i>
Diseases: <i>Plasmopora viticola</i> <i>Uncinula necator</i> <i>Botrytis cinerea</i>	Lepidoptera: <i>Sparganothis pilleriana</i>
	Diseases: <i>Pseudopeziza tracheiphila</i> <i>Guignardia bidwellii</i> <i>Eutypa lata</i> , Esca. <i>Flavescence doree</i> (Virus)

With this inventory we proceed to the examination of the available preventive and ecologically sound therapeutic measures for the category of key-problems fitting into a modern IPM programme.

OPTIONS AVAILABLE TO-DAY FOR THE PREVENTION AND CONTROL OF KEY-PROBLEMS IN EUROPEAN VITICULTURE

General approach

The general approach taken according to the IOBC concept is the ecological diversification of the agro-ecosystem "vineyard" and the maintenance of its ecological stability by minimising potential disturbing factors. An important first step is the reduction of chemical inputs (especially nitrogen and unselective pesticides) to protect and enhance the natural regulating mechanisms. A second step is the establishment of a permanent or temporal flora (green cover) in viticultural areas with annual precipitations above 700 mm that transform the traditional monoculture into an agro-ecosystem of increasing ecological diversity and stability (Boller, 1990; Jörger 1990; IOBC 1992 b). This flora functions as a major ecological "turn-table" within the ecosystem as it activates and influences 3 other important key components: the complex of general antagonists (insect predators, parasitoids), the predatory mites, and the nitrogen cycle (Fig.1) (Boller, 1990).

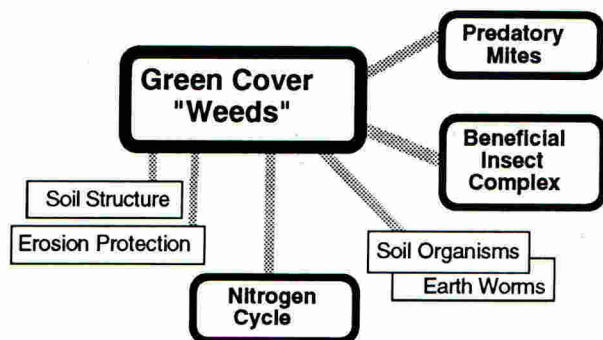


Fig.1. The 4 important ecological turntables of a diversified agro-ecosystem "vineyard" (after Boller, 1990)

This important role of the green cover can be enhanced by an alternating mowing regime producing a constant supply of flowering plants on 50% of the surface increasing dramatically the faunistic diversity of the vineyard (Remund *et al.*, 1989). A recent faunistic survey carried out in Switzerland on 21 vineyards has shown a significant correlation between botanical and faunistic diversity (Fig.2) (Remund *et al.*, 1992).

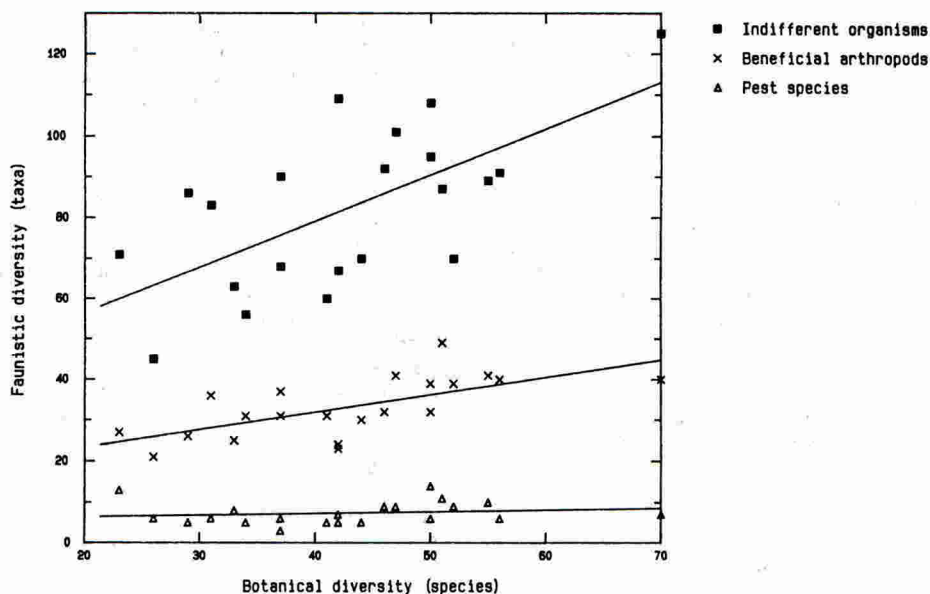


Fig.2. Influence of botanical diversity on faunistic diversity in 21 vineyards investigated in eastern Switzerland (Remund *et al.*, 1992).

Interesting is the observation that with increasing numbers of plant species insect pests remained at a low level with respect to abundance and number of species. On the other hand we observed a significant increase in beneficial arthropods and indifferent phytophages serving partly as alternate food and hosts for important predators and parasitoids. We observed 104 different plant species in our experimental vineyard at Walenstadt and estimate that about 2000 different arthropod species occur in this diversified agro-ecosystem (Remund *et al.*, 1989).

Another important point is the availability of excellent documents with respect to the side-effects of viticultural pesticides on beneficial arthropods including standardised test methods under laboratory, semi-field and field conditions (e.g. Anonymous, 1987; Boller *et al.*, 1989; Hassan *et al.*, 1985).

IPM solutions for individual problems

Spider mites

The actual damage caused by the main spider mite species is presently reviewed in order to redefine the present empirical tolerance levels on the basis of a scientific analysis of the physiological reaction of the grapevine to increasing stress caused by increasing mite densities. The stress physiology of the grapevine is a current topic of a research project in Switzerland that investigates the compensation potential of the plant depending on increasing mite-loads (Candolfi, 1991). The investigations confirm that the impact caused by *Tetranychus urticae* is much greater than the effect of *Panonychus ulmi*. The grapevine is most sensitive to stress from bud-break till 2 weeks after bloom and can afterwards easily tolerate relatively high spider mite populations. With *P. ulmi* no significant reduction of the photosynthesis, of diagnostic growth parameters nor yield and quality could be observed during a 4 year investigation at mite densities 50 times higher than the actual tolerance levels of 5 mites per leaf. We investigate presently the physiological effects of a combined stress imposed by mite feeding and sub optimal water supply and investigate the long-term effect of spider mite stress on the carbohydrate reserves of the plant that could influence yield and quality in the following year. Only with these data at hand we can consider a modification of the actual threshold levels and revise our current IPM programmes. Several research projects in Europe address the question of sampling methods (e.g. Baillod *et al.*, 1989; Arias & Nieto, 1990; Kast, 1990).

Prevention: The reduction of N input is a first and important step to reduce spider mite populations. IP guidelines fix the maximum N input to 50 kg/ha and many IP-farms in northern countries operate at a 0-20 kg level of N fertilisation. The avoidance of certain herbicides (e.g. paraquat, diquat) that trigger an emigration of *Tetranychus urticae* from weeds to the grapevine is another preventive measure (Boller et al. 1984).

Biological control: Effective biological control can be achieved by the natural occurrence or inoculative releases of predatory mites that are considered a key component of an IPM programme (Baillod, 1984). *Typhlodromus pyri* is the dominant species in cooler areas, whereas *Amblyseius andersoni* and *A. aberrans* are the most effective species in the south (Duso et al., 1990). A large scale release of *T. pyri* was completed two years ago in Switzerland covering some 40 ha of vineyards (Boller & Remund, 1991) and release programmes are under way in most European countries, including eastern Europe. Pollen supplied by a flowering vineyard flora has been identified as important nutritional component of *T. pyri*, apparently the only important species that can survive and reproduce in the absence of animal prey (Eichhorn & Hoos, 1990; Engel, 1990). There is a controversy over the ecological justification of organophosphor-resistant strains occurring and being propagated in certain regions (Caccia et al., 1985). This approach allows the continued use of unselective OP insecticides without destroying the important predatory mites. It is, however, incompatible with the emphasis placed by modern IPM on a diversified and stable agro-ecosystem.

Chemical control: There are many selective acaricides available for IPM programmes. Resistance problems may arise after repeated use of ovicides such as clofentezine, hexithiazox and flufenoxuron (Delorme & Dacol, 1989).

Eriophyid mites:

This is a problem area without entirely satisfactory solutions. Predatory mites are often not effective enough to keep the pest populations below damaging densities. Wettable sulphur (2%) and oleo-endosulfan applied before bud-break are presently the only chemicals without negative side-effects on OP-sensitive predatory mites. Economic thresholds and sampling techniques are in an early stage of research.

Grape moths:

Grape moth larvae at moderate population densities cause minor mechanical damage to grapes (3-5 berries damaged per larva) and could be dismissed as minor pests in grapes produced for vinification (Kast & Munder, 1990) However, they are of economic importance because their feeding damage of ripening grapes greatly facilitates the development of *Botrytis cinerea* (Schruff, 1983). Therefore, grape moth control can be considered a prophylactic measure against that important disease.

Forecasting systems based on temperature summation are well established in Germany and Switzerland (Boller 1976; Schruff 1990). A method of risk assessment based on weekly catches in pheromone traps has been introduced in 1983 in eastern Switzerland but found no wider use in other countries (Boller & Remund 1983; Roehrich & Boller, 1991).

Biological control: The application of *Bacillus thuringiensis* (BT) is presently the only true biological control method, available for many years but used with moderate enthusiasm in most countries. An exception is a longer tradition of BT use in Switzerland where several commercial products (with addition of 1% sugar) show an effectiveness of over 90% in *Lobesia botrana* and about 80-90% in *Eupoecilia ambiguella* (Schmid et al., 1977; Boller & Remund, 1981; Charmillotet et al., 1991) and has become an important part of IPM programmes. However, various chemical companies are currently intensifying research on more efficient serotypes and several improved BT preparations have been registered lately or are expected to be registered in the foreseeable future.

Parasitoids are presently not available in practice but research has been intensified on the potential use of the egg parasitoids *Trichogramma* spp. as most promising antagonist of the grape moths. One possibility pursued in Germany (Kast & Hassan, 1986; Castaneda, 1990) focuses on the mass-rearing and inundative release of *Trichogramma*, an approach that failed and has been abandoned in Switzerland (Remund & Bigler, 1986). Another possibility is the enhancement of naturally occurring *Trichogramma* spp. by exposing sterilised grape moth eggs in vineyards (Schade & Sengonca, 1990) and/or by a diversification of the perennial flora within the vineyard - an approach taken in Switzerland (Remund & Boller, 1991). Experiments in progress show cases of high egg parasitism in the first generation of *Eupoecilia* that is significantly reduced during the second generation (Fig.3).

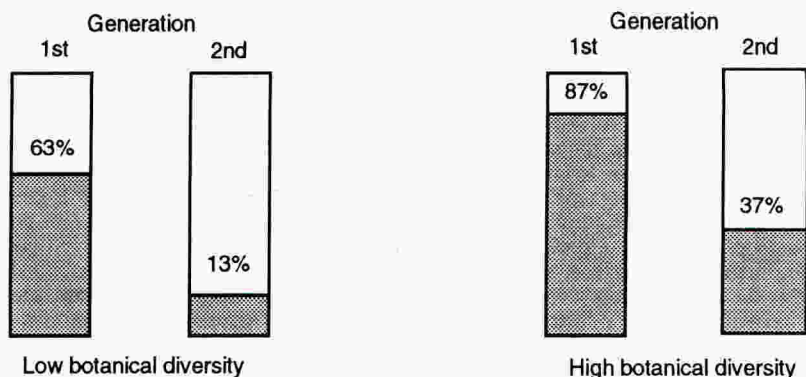


Fig.3. Parasitism of grape moth eggs by *Trichogramma* spp. during the first and second generation in vineyards exhibiting a low and high botanical diversity, respectively. (Remund & Boller, 1991).

So far we can only speculate about the causes of this decline. Besides unverified negative side-effects of fungicides (sulphur ?) it is possibly the lack of adequate alternate lepidopteran hosts in the green cover that allow the parasitoid to bridge the gap between the two flights of the grape moths. A list of potential lepidopteran hosts and their host plants has been established and is presently being investigated in the field.

Biotechnical methods: The mating disruption technique with sex pheromones against *Eupoecilia ambiguella* developed by BASF is so far the only case where this technique is successfully applied in practice (Schmid, 1989). This novel technique has been registered so far in Austria, Germany and Switzerland. Five hundred pheromone dispensers are applied per ha in spring and cover both generations. There is no doubt that this approach is the first choice from the ecological point of view and would certainly find even wider acceptance if the costs of Sfr. 290.- per ha decreased. The mating disruption technique was applied successfully in 1992 on 25% of the entire viticultural surface in northern Switzerland where *Eupoecilia* is the predominant species. For *Lobesia botrana* the method is in an advanced stage of experimentation but often produces erratic results (Neumann, in press).

Another option is the application of insect growth inhibitors (acting on the process of chitin synthesis) that are relatively harmless for key antagonists (e.g. Fenoxycarb, flufenoxuron, teflubenzuron). The necessity of an early application shortly after the beginning of flight makes it a prophylactic type of pest control without prior risk assessment.

Most conventional insecticides available for grape moth control are detrimental to the beneficial fauna. The application of such pesticides should be minimised and those used exhibit a rapid degradation.

Diseases

Unlike arthropod pests, diseases provide fewer opportunities to reduce chemical control measures or to replace chemical control by biological alternatives. While insecticides, acaricides and herbicides can constantly be reduced in modern IPM programmes we have to accept for quite a while that fungicides will be applied regularly and frequently. Entomologists are grateful to their colleagues in phytopathology that the vast majority of fungicides are harmless for their beneficial fauna. An exception to this rule is the group of dithiocarbamates destructive to predatory mites. However, recent investigations in Germany (Englert, in press) seem to indicate that the detrimental side-effects of the dithiocarbamates are greatly reduced if applied by helicopter.

Despite this situation there are preventive measures that can help to reduce the infection pressure and the number of fungicide treatments. The parsimonious use of nitrogen and the defoliation of the grape bearing part of the vine are successful measures to reduce *Botrytis cinerea*. The importance of an efficient control of grape moths as an indirect control measure of *Botrytis* has already been

mentioned. The selection of grape varieties with loose grape bunches is another option supporting an IPM programme.

Major progress has been achieved in recent years in epidemiological modelling and the development of prognostic tools that might lead to a reduction of fungicidal treatments against *Plasmopora viticola* and possibly against *Pseudopeziza tracheiphila* (Clerjeau, 1990). Different types of modelling are being developed in various countries to improve the prognostic precision taking into consideration the different climatic conditions of the respective regions (Strizyk, 1983; Hill, 1989; Blaise & Gessler, 1990). Various devices which measure physical parameters and calculate the critical data for primary infestations by *Plasmopora viticola* are available now and are being tested in the field (Kast & Hauser, 1990). No adequate fungicides with a sufficient curative efficacy, however, are available to be successfully used under practical conditions after an infection has occurred. Suction devices operated by solar panels have been developed to capture ascospores of *Pseudopeziza tracheiphila* that facilitate the decision when the first treatments have to be applied (Schüep, unpublished).

Since chemical control remains the major weapon in the near future it is of utmost importance to develop and recommend active ingredients with negligible risks for man and environment. A safe pesticide management can be ensured by using highly specific fungicides with minimum impact on non-target organisms. The experience has shown, however, that pathogens can generally build-up resistance to molecules with specific mechanisms of action. Therefore, investigations on resistance mechanisms, resistance monitoring and resistance management are of great importance at the present time.

Less advanced are the areas of biological control and of induced resistance. The use of *Trichoderma harzianum* as antagonist of *Botrytis* still remains in the experimental stage (Garibaldi *et al.*, 1990). Induced resistance is under investigation but has so far not yet passed beyond the experimental stage (Pezet & Pont, 1990).

Remains to be mentioned that research and field experimentation have been intensified in the area of interspecific varieties being resistant to *Plasmopora viticola* and producing promising wine qualities. Although these new hybrids would achieve a reduction of fungicide treatments it is probably unwise to speculate that these new varieties will eventually replace the traditional *Vitis vinifera* varieties.

Weeds

The world of herbology is divided in two parts, being separated by the border of annual precipitation of approximately 6-700 mm. Herbologists in cooler climates and working mostly in German speaking countries are in the process of deleting the term "weed" from their vocabulary. What were considered as noxious plants some 20 years ago have turned into a beneficial flora, into a natural green cover to be managed according to agronomic and ecological considerations. The flora is recognised as a key element in a new type of activity appropriately described as habitat management. In the interdisciplinary development of modern IPM programmes and integrated production strategies, herbologists have become the closest allies of the entomologists.

The scenery changes drastically when we cross the borderline of critical precipitation of < 700 mm. There, weed control with all its ramifications, is the major preoccupation of the herbologists. We refer to the excellent review given by Moreira (1990) the acting chairman of the IOBC subgroup on weeds. However, there are increasing tendencies in semi-arid areas to establish a green cover during the winter months to reduce erosion and nutrient loss by leaching.

CONCLUSIONS

IPM in viticulture has reached an advanced stage in Europe and meets most of the requirements defined by the IOBC charter. Integrated production in viticulture has matched and partly surpassed the pioneering achievements in integrated fruit production especially with regard to concepts and originality of implementation. IOBC will open in 1993 a certification procedure for organisations meeting the European standards set by IOBC and wishing to obtain IOBC recognition and labels. There is no doubt that many IP organisations in viticulture will do their best to reach that goal.

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APPLE PEST MANAGEMENT IN NORTH AMERICA: CHALLENGE AND RESPONSE

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ABSTRACT

Because of the scarcity of registered alternatives, especially insect growth regulators and insect pathogens, North American apple growers remain largely dependent on broad-spectrum pesticides. In many orchards pest populations are monitored and economic thresholds are used in control decisions, yet problems continue with pesticide resistance and outbreaks of secondary pests. Solutions to these problems include ecologically selective use of broad-spectrum pesticides and development of a number of alternatives to pesticides including biological, cultural and behavioural controls. Second-stage IPM, which blends ecologically selective use of pesticides up to mid-June followed by alternative controls thereafter has given promising results in orchards trials.

INTRODUCTION

Use of broad-spectrum pesticides in apple orchards has a number of harmful side effects besides the more obvious concerns about environmental contamination and human safety (Metcalf & Luckmann, 1982; Croft & Hoyt, 1983). Induction of resistance in target and non-target pests often leads to more frequent applications or higher dosages. Harm to natural enemies leads to outbreaks of secondary pests such as mites, aphids, leafminers, and leafhoppers. This problem may be specially acute when pest resistance forces growers to switch to a new class of compound for which the natural enemies have no resistance. There are two main solutions to these problems: to use broad-spectrum pesticides in an ecologically selective fashion, so as to conserve natural enemies; and to develop alternatives to conventional pesticides, e.g., biological controls and behavioural controls.

In this paper I will use a few examples mostly from Nova Scotia, Canada to illustrate current IPM practices in North American apple orchards, detail the problems which arise from continuing reliance on broad-spectrum pesticides and describe the solutions which are being developed for these problems.

CURRENT PRACTICES OF PEST MANAGEMENT

The pest management program most widely used in North American apple orchards has been described as 'supervised control' in Europe and as 'first-stage' IPM in North America (Prokopy *et al.*, 1990). First-stage practices focus on pest monitoring to predict first appearance, rate of development, and abundance of pest and beneficial arthropods, which leads to recommendations of the least-toxic, properly-timed pesticides as the sole tactic of controlling pests not effectively suppressed by beneficials. Unfortunately, growers often do not use the least toxic alternative, either because the alternative is more expensive or is thought to be less effective. The methods of monitoring pests and the economic thresholds currently used in Nova Scotia are given in Table 1. With codling moth (*Cydia pomonella*) there is an added refinement: the dosage of organophosphate insecticide recommended depends upon the number of male moths caught in the pheromone traps. In most orchards either growers do not need to spray, or only the 1/4 rate of insecticide is required (e.g., 425 g of phosmet per ha). In a 1980-1983 survey of orchards under this regime, there was an average of 2.5

insecticide applications and 0.5 acaricide applications per orchard block per year. Total insect injury averaged 2.3% of harvested fruit (Hardman *et al.*, 1987).

TABLE 1. Economic thresholds and methods of sampling major pests in apple orchards in Nova Scotia, Canada.

Pest	Economic threshold
Green fruitworm (<i>Orthosia hibisci</i>)	1 larva per 15 limbs
Winter moth (<i>Operophtera brumata</i>)	2-3 larvae per 20 clusters per 5 trees
Rosy apple aphid (<i>Dysaphis plantaginea</i>)	1.5 colonies per metre of tree height
Apple brown bug (<i>Atractotomus mali</i>)	8 bugs per 20 limb taps
mullein bug (<i>Campylomma verbasci</i>)	
White apple leafhopper (<i>Typhlocyba pomaria</i>)	1 per leaf (1st generation) 2 per leaf (2nd generation)
Apple maggot (<i>Rhagoletis pomonella</i>)	1 adult per baited yellow trap
Spotted tentiform leafminer (<i>Phyllonorycter blancardella</i>)	1 live mine per leaf
European red mite (<i>Panonychus ulmi</i>)	20 mites plus eggs per leaf (June) 10 mites plus eggs per leaf (July) 15 mites plus eggs per leaf (August)
Codling moth (<i>Cydia pomonella</i>)	40-99 per trap 1/4 rate 100-199 per trap 1/2 rate 200+ per trap full rate

PROBLEMS WITH CURRENT PEST MANAGEMENT PROGRAM

A 1985-1986 survey of commercial apple orchards in Nova Scotia indicated an average of 3.1 insecticide applications, 0.7 acaricide applications and 13.1 fungicide applications per orchard per year (Hardman *et al.*, 1991). Both published and local data indicated that most of the frequently applied insecticides were harmful to insect predators and parasitoids as well as to the phytoseiid mite *Typhlodromus pyri*. Many of the acaricide and fungicide applications were either moderately harmful or harmful to *T. pyri*. Growers used broad-spectrum organophosphate and pyrethroid insecticides because of the absence of registered narrow-spectrum alternatives, notably pathogens and insect growth regulators. With few exceptions (see below), there has been little improvement since the time of the survey in the mid-1980's.

The cause of the current scarcity of narrow-spectrum agents to control insects in Canadian and US apple orchards is the registration process. Just when more selective alternatives such as insect growth regulators and insect pathogens were being tested in the 1980's, the safety and environmental requirements became so expensive that registration was effectively blocked. (Fortunately, *Bacillus thuringiensis* var. *kurstaki* was registered before costs became prohibitive). The situation is now improving. In the USA costs of registering insect pathogens have become much less than for chemical pesticides. Canada is now moving to ease requirements for pathogens. In the US, pheromone dispensers are now registered for mating disruption of *C. pomonella*. Canadian registration is expected for 1993.

I shall use examples from Nova Scotia and Ontario in Canada to illustrate problems with pest resistance and outbreaks of secondary pests. In Nova Scotia, populations of the

winter moth (*Operophtera brumata*) had by the late 1970's become resistant to organophosphate insecticides (Hardman *et al.*, 1988). At that time there was also an outbreak of the spotted tentiform leafminer (*Phyllonorycter blancardella*). A 1980-1983 survey of commercial orchards indicated that use of pyrethroids to control winter moth or *P. blancardella* led to higher counts of *P. ulmi* and *A. schlechtendali*, more severe leaf bronzing by mites and more frequent applications of acaricides (Hardman *et al.*, 1988). These effects were probably due to suppression of populations of *T. pyri*, the principal natural enemy of *P. ulmi* and *A. schlechtendali*. A later survey (1985-1986) confirmed that pyrethroids were strongly associated with outbreaks of phytophagous mites, but fungicides and other insecticides also suppressed *T. pyri* and induced outbreaks (Hardman *et al.*, 1991).

In southern Ontario the spotted tentiform leafminer is now a major pest in apple orchards (Pree, 1990). Organophosphate treatments for control of key pests such as codling moth, mullein bug, apple maggot and plum curculio (*Conotrachelus nenuphar*) first suppressed populations of parasitoids such as the braconid, *Pholetesor ornigis*, which would otherwise control populations of the leafminer (Trimble & Pree, 1987). Populations of the leafminer then had to be controlled with organophosphates. By 1975-1977 many growers switched to pyrethroids or to methomyl because the leafminer had become resistant to organophosphates. Pyrethroid resistance and control failures appeared within 5 yr of annual use to control the leafminer. By the 1980's there were also populations that were resistant to the carbamates, methomyl and oxamyl (Pree, 1990).

Both pyrethroids and methomyl are highly toxic to the phytoseiid mite, *Amblyseius fallacis*, which had until then effectively controlled *P. ulmi* and *T. urticae*. Within three seasons of pyrethroid use, acaricide use increased from one application needed per season to 3-4 applications. Heavy use of acaricides led in turn to acaricide resistance. By 1981 the first failures were noted in efforts to control *P. ulmi* with cyhexatin. Within a few years there was also widespread resistance to dicofol (Pree, 1990).

RESPONSES TO THE CHALLENGE

Efforts to improve pest management in apple orchards have proceeded along two main lines 1) ecologically selective use of broad spectrum pesticides; and 2) development of alternatives to conventional pesticides. In Massachusetts, these approaches have been combined in a season-long program that Prokopy and colleagues have labelled 'second-stage IPM' (Prokopy *et al.*, 1990).

Ecologically selective use of broad-spectrum pesticides

Ecological selectivity is the judicious use of pesticides based on critical selection, timing, dosage, placement and formulation of broad-spectrum pesticides (Hull & Beers, 1985). The requirements for this judicious use include development of appropriate sampling techniques, determination of economic thresholds and quantitative knowledge of the biology of pests and their natural enemies.

In Nova Scotia the most extensive recent work on monitoring and economic thresholds was done by private pest monitoring companies. Armed with data on pest counts, pesticide treatments and levels of injury to foliage and fruit, they adjusted sampling methods and refined economic thresholds in the light of extensive practical experience in commercial orchards. Less extensive work was done in greater depth by the provincial entomologists and by federal scientists at the Kentville Research Station (KRS).

Work on *P. ulmi* illustrates the interactions that occurred among the three groups. Hardman *et al.* (1985), using regression analysis, found that the accumulation of mite-days (motile mites) to 15 July was a better predictor of yield than earlier or later accumulations, indicating the economic importance of mid-season injury. For that reason, the pest management company gradually lowered its June economic threshold from 40 mites plus eggs

per leaf in 1983 to 20 per leaf by 1990, while raising the August threshold from 10 per leaf to 15 per leaf. The equation relating yield to cumulative mite-days was included in a model simulating the effects of weather and acaricide applications on densities of *P. ulmi* and on apple yields (Hardman, 1989). This model indicated possible risks in delaying mite assessments until June when *P. ulmi* can be counted on leaves. If the initial density of *P. ulmi* winter eggs is high enough, then application of miticide would be too late to prevent significant yield losses in the current year, a high population of winter eggs by late summer, and reduced yield the following year. Partly as a result of this analysis, the provincial entomologist encouraged growers to use mineral oil which had previously seldom been used for mite control. He also developed a sampling scheme based on counts of *P. ulmi* winter eggs on "spurs"—3 cm of wood (at least 2 yr old) around a spur or bud (Rogers, 1992). In this scheme the recommended treatment depended on egg abundance (Table 2).

TABLE 2 Treatment thresholds based on counts of *P. ulmi* winter eggs on spurs of apple trees (after Rogers, 1992).

Mean score	Recommendation
0	No treatment
0.1	Superior oil concentrate, 17 litres/ha, at silver tip to tight cluster stage
1.0	Superior oil, 65-100 litres/ha, at silver tip to green cluster stage
2.0+	Clofentezine, 150 g (a.i.)/ha, at pink bud stage

Scores: 0, 0 eggs on 10 spurs from each of 3-10 trees per orchard; 1, 1-10 eggs per spur; 2, 11-50 eggs; 3, 51-100 eggs; 4, > 100 eggs per spur.

Other collaborations to enhance sampling are ongoing with the apple maggot (*R. pomonella*) and with fruit-stinging mirids. In 1991, at the instigation of R. F. Smith, KRS, the pest monitoring company began attaching a vial of synthetic apple volatiles to their yellow protein-baited sticky boards used for sampling *R. pomonella*. The new trap proved more sensitive and reliable in detecting fly populations. Smith is also testing traps with improved dispensers so the protein bait may be released over the total month-long flight period of *R. pomonella*.

The mullein bug (*C. verbasci*) and the apple brown bug (*Atractotomus mali*) remain troublesome pests because of the difficulty in sampling populations (currently by tapping nymphs onto a canvas sheet) and in timing insecticide applications for optimal control. To overcome these difficulties, Smith and researchers from Simon Fraser University, British Columbia, isolated and synthesized the sex pheromone for *C. verbasci*, determined the relationship between fall catches of the mirid in traps baited with the female and density of nymphs the following spring, and determined the thermal requirements for egg hatch and nymphal development in the spring (Smith & Borden, 1990, 1991; Smith *et al.*, 1991). A private firm, Phero Tech of British Columbia, is now manufacturing *C. verbasci* pheromone in research quantities with the intention of commercial production in the near future. Similar work is now underway with *Atractotomus mali* to identify components of the pheromone blend, to synthesize pheromone, to determine thermal requirements for phenology prediction and to develop economic thresholds based on pheromone-trapping.

Tactics for ecological selectivity

Efforts have been made in Nova Scotia to reduce the harmful side effects of pyrethroids. Data from a 1980-1984 survey of commercial orchards indicated that preblossom applications of permethrin were less likely than post flowering applications to cause higher counts of phytophagous mites. However, the advantage of prebloom applications was less apparent with the more disruptive pyrethroid, fenvalerate (Hardman *et al.*, 1988). Accordingly, growers were advised to avoid post flowering use of pyrethroids and to use permethrin instead of fenvalerate.

In a later study Hardman and Gaul (1990) found counts of *P. ulmi* varied according to the pyrethroid applied, from cypermethrin as emulsifiable concentrate (EC) (lowest count), to cypermethrin wettable powder (WP), to permethrin EC, to deltamethrin EC (highest count). Indeed, fewer mite-days were accumulated to 14 July with the full recommended rate of cypermethrin EC (50 g/ha) than with 1/10th the recommended rate of deltamethrin (i.e., 0.75 g/ha). For this reason, cypermethrin is recommended where pyrethroid, either alone at recommended rate or mixed at the 1/10th rate with *Bacillus thuringiensis*, see below) is necessary to control winter moth. This same study also indicated that mixtures of *B. thuringiensis* (B.t.) and 1/10th the recommended rates of pyrethroids were as effective in preventing fruit injury caused by winter moth, pale apple leafroller (*Pseudexentera mali*) or obliquebanded leafroller (*Choristoneura rosaceana*) as pyrethroids at the full recommended rate. Counts of the mites, *P. ulmi* and *A. schlechtendali*, were lower and populations of their principal natural enemy, *T. pyri*, were detected more frequently in plots treated with B.t./pyrethroid mixtures than in plots treated with pyrethroids at half or full rates. Mixtures of B.t. (1/4 full recommended rate) with cypermethrin EC or WP (1/10th full rate) were particularly compatible with integrated mite control and are the recommended treatments in commercial orchards where the winter moth infestation is light to moderate.

Analysis of data from an extensive 2 yr survey of commercial orchards confirmed that data on the toxicity of pesticides to *T. pyri* from Europe and the USA were largely valid for Nova Scotian populations (Hardman *et al.*, 1991). The survey also indicated varying levels of organophosphate resistance among Nova Scotian populations of *T. pyri*. The authors advocated use of a Modified Spray Program (MSP) which would allow growers to conserve this valuable predator while obtaining effective control of insect pests and apple scab. They also recommended introducing an organophosphate-resistant strain of *T. pyri* in most commercial orchards. The MSP includes sterol-inhibitor fungicides (e.g., myclobutanil), dichloro and captan for scab control, the B.t./cypermethrin mixture for all but the highest winter moth populations, and insecticides that are less toxic to *T. pyri* (azinphos-methyl, phosmet and pirimicarb) to control other insect pests such as aphids, leafhoppers, codling moth and apple maggot. Mineral oil, clofentezine and propargite are used to control mites. Many growers now use elements of the MSP in their orchards.

In Ontario, federal researchers are investigating ways to conserve *P. ornigis*, the principal natural enemy of the spotted tentiform leafminer, to reduce the need for disruptive treatments with pyrethroids or toxic carbamates (e.g. methomyl or oxamyl). First, they developed a method to sample adult *P. ornigis* to determine dates when adults of each of three generations of the parasitoid are active (Trimble, 1988). Then they did orchard trials over a 3 yr period where they tested two methods of conserving *P. ornigis*: 1) by using 1/2 the recommended rates of phosmet or azinphos-methyl to control codling moth and apple maggot; and 2) by altering the dates of application of full recommended rates to avoid times of adult activity of *P. ornigis* as indicated by captures in yellow sticky traps. (Sprays were applied earlier than or just after periods of activity, which generally lasted 2 weeks). The first strategy resulted in the same low level of parasitism found in the control block where treatments were applied according to usual commercial practice (i.e., full recommended rates of organophosphate timed according to trap catches of codling moth or apple maggot). The second approach, altered timing, resulted in much higher levels of parasitism but no increase in injury to fruit caused by *C. pomonella* or *R. pomonella* (Trimble, unpublished data). There are also prospects for conserving *P. ornigis* by using the least disruptive insecticides to control

key pests (Trimble & Pree, 1987).

In North America the apple industry is changing from large trees and low numbers per hectare to smaller trees at a higher density. With this change and advances in low volume spraying it is often feasible to use the tree-row volume concept to reduce the dosage per hectare (Hull & Beers, 1985). In Nova Scotia, the provincial entomologist has recently begun training growers in adjusting dosages according to tree-row volume in their orchards.

Baits and traps offer prospects for reducing dosages of insecticides. Discovery of apple maggot in many habitats near orchards in the western USA has led to an eradication and containment program. This program largely depends upon repeated applications of azinphosmethyl or phosmet. However, for urban areas malathion, offers the advantages of mammalian safety and short residual activity. Malathion mixed with Nulure bait (Miller Chemical and Fertilizer Corporation, Hanover, Pa.) was significantly more effective than malathion alone in reducing the percentage of apples with apple maggot injury (Mohammad & AliNiazee, 1989). In Massachusetts, researchers have obtained promising results with interception traps to control apple maggot. Red sticky spheres baited with synthetic apple odour (butyl hexanoate) were placed at 5 m intervals along the outer rows of each orchard. While the method was effective and relatively inexpensive, growers had serious reservations about the labour of cleaning debris off traps and reapplying sticky material. So Prokopy and colleagues are now investigating a method that involves ringing an orchard with non-sticky spheres, leaving the spheres permanently in place (except when affected by tree pruning), annually attaching a fresh vial of butyl hexanoate near each sphere, and once or twice annually treating each sphere with a mixture containing a contact fly feeding stimulant, pesticide, and an agent that extends residual effectiveness of feeding stimulant and pesticide (Prokopy *et al.*, 1990).

Development of alternatives to broad-spectrum pesticides

In North America, some of the best prospects for biological control involve use of phytoseiid mites. Populations of *Metaseiulus occidentalis*, *Amblyseius fallacis* and *T. pyri* are now resistant to a number of organophosphate insecticides and, in the case of *T. pyri*, to carbaryl (Hoy, 1985). Recent evidence suggests that an organophosphate/pyrethroid resistant strain of *T. pyri* (Markwick, 1986) which we imported from the Department of Scientific and Industrial Research in New Zealand has successfully colonized in a small research orchard in Nova Scotia (Hardman & Bent, 1992). The mites arrived in July 1988 and were cultured on potted apple trees in an insectary until 24 August. At that time we placed shoots from potted trees onto four cv. 'Cortland' apple trees. The four release trees and several rows of adjacent trees had been sprayed with cypermethrin 10 June and with methomyl 17 August to eliminate the native pyrethroid-susceptible strain of *T. pyri*. From 1989 to 1991 the release trees and adjacent rows were treated with a modified spray program that included the fungicide, captan, and the insecticides phosmet, malathion, pirimicarb and a mixture of B.t. and cypermethrin EC (5 g a.i./ha). In 1989 the maximum count of motile *P. ulmi* in the four release trees was 10.2 mites per leaf by late August. On that same date there was 0.1 *T. pyri* per leaf. Counts of *P. ulmi* in adjacent trees reached 36 per leaf (Fig. 1).

In 1990 and 1991 maximum counts of *P. ulmi* on the release trees were 0.6 and 0.5 per leaf, respectively. Counts in adjacent trees also showed a downward trend (6 in 1990, 2 in 1991) whereas counts of *T. pyri* were usually higher than in 1989 (up to 0.2 per leaf), suggesting that the predator had dispersed to neighbouring trees. In 1991-92, 24 h slide-dip trials were run with adult female *T. pyri* from the New Zealand release trees and with *T. pyri* from trees at the other end of the orchard. Survival of mites from the release trees dipped in the full field rate of cypermethrin EC (14.8 ppm) was 76.4%, similar to survival of the New Zealand strain (90.7%). Conversely, mites from the non-release trees only had 28.4% survival when dipped in 10% of the field rate (1.48 ppm). Thus both laboratory bioassays and three years of orchard trials suggest that the New Zealand *T. pyri* have colonized and provided season-long suppression of *P. ulmi* in plots. The stage is now set for release and testing of this strain in commercial orchards.

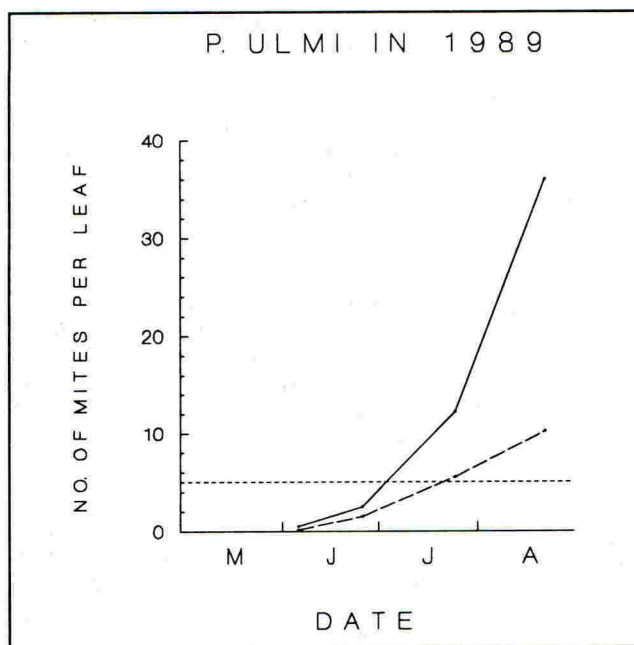


FIG 1. Mean number of fruit-tree red spider mite per leaf in 1989 on trees where the New Zealand strain of *T. pyri* had been released (broken line) and on control trees (solid line)

At the Agriculture Canada Research Station, Vineland, Ontario H.M.A. Thistlewood has placed successive generations of *A. fallacis* in petri dishes coated with increasingly concentrated residues of the pyrethroid permethrin. LC50's have increased over 600-fold from an initial level of 5 ppm. Mites were released in August 1990 in an orchard previously treated with permethrin. Counts of *P. ulmi* were reduced in the release trees compared with non-release trees. Pyrethroid-resistant predators were recovered from release and adjacent trees both in the year of release and the following season. Large-scale orchard trials are being conducted in 1992.

There has also been progress with use of pheromones for mating disruption of *C. pomonella*. Biocontrol Limited, an Australian company, has obtained registration in the USA for ISOMATE pheromone dispensers for mating disruption. Several thousand hectares of apple orchards are being treated in Washington State in 1992. The application for Canadian registration was submitted in 1991 and registration is likely to be in time for use in 1993. Three years of trials in Nova Scotia indicate this method is just as effective as the standard organophosphate treatments (J. M. Hardman, R. F. Smith & E. Bent, unpublished data). Preliminary trials were also carried with protein-baited yellow sticky boards to trap out apple maggot. These traps are less effective at capturing maggot than the red sticky spheres used in Massachusetts but are cheaper and do not require cleaning and reapplication of sticky material.

Second stage IPM

Second-stage IPM practices include pesticidal control of early season arthropod pests and behavioural, cultural and biological control of mid and late season arthropod pests

(Prokopy *et al.*, 1990). Six commercial apple orchards in Massachusetts under second-stage IPM were compared with six blocks under first-stage IPM. The behavioural approach consisted of ringing the perimeter of six apple orchards (each ca. 1 ha) with sticky-coated red spheres baited with synthetic apple odour to intercept immigrating *R. pomonella* flies. The cultural approach focused on removing unmanaged host trees (apple, pear, hawthorn and quince) within 100 m of the perimeter of the orchards to prevent entry of *C. pomonella* and red-banded leafroller (*Argyrotaenia velutinana*) females. The biological approach emphasized buildup of natural enemies of foliar pests in an environment free of insecticide and acaricide use after mid-June.

In the second yr (1988) of second-stage IPM the 6 test blocks had a mean level of 0.6% of harvested fruit injured by apple maggot and all other pests active after mid-June. Six nearby blocks under first-stage IPM received 0.4% combined injury from these pests. Unbaited apple maggot traps within orchards showed that comparatively few *R. pomonella* flies penetrated the ring of perimeter traps placed 5 m apart even though catches on perimeter traps indicated heavy fly pressure. Beneficial predators of pest mites and aphids were nearly twice as common in second-stage as in first-stage IPM blocks. Higher labour costs in second-stage blocks offset savings in pesticide use, so both IPM systems had similar overall costs.

In Nova Scotia we compared mite counts and insect injury to fruit for 3 years in two orchards with adjacent plots under first-stage and second-stage IPM (J. M. Hardman, R. F. Smith & E. Bent, unpublished data). Pests were monitored as described in Table 1. The first-stage regime involved applications of materials recommended in the MSP (described above). The second-stage regime was the same as first-stage except for the following: diflubenzuron was used for control of winter moth; codling moth granulosis virus or pheromone dispensers for mating disruption were used to control *C. pomonella*; and yellow sticky boards baited with protein bait or apple volatiles were used to trap out *R. pomonella*. No chemical insecticides were applied after mid-June. Winter moth injury was < 2.8 % of the fruit in all plots and was consistently < 1.9% where B.t./cypermethrin was used for control. Codling moth granulosis virus allowed more injury than the standard phosmet treatment, but mating disruption was at least as effective as the insecticide. In one orchard with a heavy fly infestation, baited yellow sticky traps distributed within the orchard caused a gradual reduction in *R. pomonella* infested fruit from initial high levels to economically tolerable levels over a period of 3 yr. In the other orchard, trapping out was as effective as the standard phosmet treatment from the first year of use. In one of the orchards, in the third year of the study fewer apples had injury caused by rosy apple aphid (*Dysaphis plantaginea*) in the second-stage plots than in the first-stage plots. It is not known whether this was due to greater activity of natural enemies, as was noted in Massachusetts (Prokopy *et al.*, 1990). In both orchards, counts of motile *P. ulmi* stayed below the economic threshold in second-stage plots. In one orchard, mite counts in 1989 and 1990 rose above the threshold in the first-stage IPM plots except for those trees where the New Zealand *T. pyri* had been released in 1988.

CONCLUSIONS

A blended approach such as second-stage IPM, where insecticides are used only before mid-June, offers the best prospects for addressing environmental concerns and minimizing harm to natural enemies. We are continuing trials with this system in Nova Scotia and shall test new tactics (biological agents, behavioural controls) as they become available to observe their performance and compatibility with other IPM tactics. Successive years of substituting pesticides with alternatives should result in a gradual buildup of beneficial predators and parasitoids and reduction in levels of insect and mite resistance to pesticides.

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IMPLEMENTATION OF IRAC ANTI-RESISTANCE GUIDELINES WITH IPM PROGRAMMES FOR BELGIAN APPLE AND PEAR ORCHARDS

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ABSTRACT

Recent papers presenting the IRAC Fruit Crops Working Group strategy for resistance management in mites on top fruit have been criticised as being too chemically focused and being insufficiently cognisant of the grower's need to control a range of pests and diseases within his orchards.

The Gorseme Research Institute is at the centre of the Belgian Fruit growing area and has been actively involved in the introduction of IPM programmes for the past 10 years. The paper describes how, in apple and pear orchards, the IPM approach has been implemented and the IRAC guidelines on mite control incorporated.

Pear orchards are all managed within an IPM framework which allows populations of anthocorids to build up and control Psylla. The build up of natural predator populations is also encouraged in many apple orchards and in some is supplemented by release of Typhlodromus for mite control.

Customer preference for fruit finish can have significant influence on the rate at which IPM can be implemented in apple orchards.

INTRODUCTION

At the 1988 Brighton Conference, R W Lemon on behalf of the Insecticides Resistance Action Committee (IRAC), Fruit Crops Working Group (FCWG) presented a paper entitled 'Resistance Monitoring methods and Strategies for Resistance Management in Insect and Mite Pests of Fruit Crops' (Lemon, 1988). He introduced the paper by explaining IRAC's role in providing expert advice to the International Group of National Agrochemical Manufacturers (GIFAP), in co-ordinating industry's efforts to prolong the life of pesticides by defining appropriate technical strategies, and in developing research relationships on resistance matters with non-industrial institutions.

He then stressed the need for standardised resistance monitoring methods and put forward guidelines for the use of acaricides, together with a grouping of chemicals based on known or expected cross-resistance patterns, although he conceded that knowledge of cross-resistance patterns was incomplete and considerable research required. He also emphasised that resistance management strategies should be based on consideration of all methods available for control of the pest including

- the use of mixtures of acaricides subject to different resistance mechanisms.
- alternation/rotation of acaricides
- moderation of use by, for example the use of reduced rates in conjunction with biological control, a reduction in the frequency of application as a result of the adoption of damage/population thresholds and improved pest scouting, and the leaving of refugia.

In short - Integrated Pest Management

In an attempt to validate the proposed groupings of acaricides a research project was initiated at Cornell University comparing the responses of an unselected and six field selected strains of Tetranychus urticae to 17 commercially available acaricides. (Dennehy, 1991)

Despite the complexity of a programme involving 101 chemical/strain combinations, it was accepted that it would not be possible to differentiate between strains exhibiting cross resistance conferred by a single mechanism and those with multiple resistance with two or more independent but co-existing mechanisms. The primary goal of the study was, therefore, to identify putative cases of cross resistance that could subsequently be studied in more depth. Nevertheless, the results suggested that two further groups should be included in the listing of acaricides and this, together with discussions within the FCWG subsequent to the 1988 Conference, led to a re-statement of the guidelines in a paper presented at the 'Resistance 1991' Conference held at Rothamsted in July 1991. (Leonard, 1991)

During discussions following the presentation of this paper the FCWG was criticised for being too chemically focused in their "strategy" for spider mite resistance and for ignoring the requirement of growers to control pests other than mites in their orchards.

The purpose of this paper is to partially redress the balance by looking at the potential problems of adopting the guidelines in practical orchard conditions and ways of overcoming these problems, and then to show how the 'chemical' guidelines can be successfully integrated into a pest control strategy.

RESISTANCE PROBLEMS IN BELGIAN FRUIT ORCHARDS

History

The first resistance problems in Belgian fruit orchards arose in the late sixties and early seventies when the fruit tree red spider mite (Panonychus ulmi) became resistant to organophosphates. However, enough acaricides were available at that time to overcome this situation. A major problem arrived in 1983 when control of the pear sucker (Psylla pyricola) became locally impossible with synthetic pyrethroids, organophosphates, chlorinated hydrocarbons and carbamates. Only two compounds remained more or less active; amitraz and diflubenzuron.

In the middle eighties, the apple rust mite (Aculus schlechtendali) became resistant to synthetic pyrethroids and organophosphates.

Pear sucker

Until 1983 the pear sucker was a minor problem in Belgian pear orchards. Most compounds, including synthetic pyrethroids, organophosphates, chlorinated hydrocarbons and carbamates were very effective against this pest. Even when insecticides were applied against key pests such as the summer fruit tortrix moth (Adoxophyes orana) or against aphids (TABLE 1), excellent control of pear sucker populations was also achieved.

TABLE 1. Typical levels of control of pear sucker achieved with summer applications of insecticides over the period 1970 - 1982.

Compound	Formulation (g/litre)	Dose rate (g AI/100 litres)	% Control (*)
flucythrinate	100 EC	20.0	99
deltamethrin	25 EC	1.25	100
endosulfan	350 EC	52.5	92
methidathion	400 EC	80.0	98
amitraz	190 EC	38.0	94

$$(*) \left(\frac{\text{Number of pests on untreated} - \text{Number of pests on treated}}{\text{Number of pests on untreated}} \right) \times 100$$

In 1983, problems arose with the control of pear sucker in some orchards in the Hageland, an important fruit growing area in Belgium. The spraying scheme of one of the fruit growers against this pest consisted of several treatments with synthetic pyrethroids (8 x), organophosphates (5 x) and chlorinated hydrocarbons (3 x) (TABLE 2) without any effect on the pear sucker population. Uncontrolled by insecticides, the pear sucker population developed to such an extent that the crop became unmarketable due to the growth of mould on honeydew secreted by the sucker nymphs and the consequent black deposits on fruit.

TABLE 2. Typical spray programme used by Hageland grower in 1983.

Date	Compound	Formulation (g/litre)	Dose rate (g AI/100 litres)
20/04/1983	methidathion	400 EC	40.0
09/05/1983	cypermethrin	100 EC	2.0
11/06/1983	cypermethrin	100 EC	2.0
13/06/1983	deltamethrin	25 EC	0.5
18/06/1983	methidathion	400 EC	40.0
22/06/1983	cypermethrin	100 EC	2.0
24/06/1983	flucythrinate	100 EC	2.0
28/06/1983	methidathion	400 EC	40.0
02/07/1983	methidathion	400 EC	40.0
06/07/1983	endosulfan	350 EC	35.0
12/07/1983	deltamethrin	25 EC	0.5
14/07/1983	endosulfan	350 EC	35.0
23/07/1983	methidathion	400 EC	40.0
04/08/1983	flucythrinate	100 EC	2.0
11/08/1983	flucythrinate	100 EC	2.0
13/08/1983	endosulfan	350 EC	35.0

A trial carried out in the same region during the summer of 1983 against a heavy infestation of a range of larval stages of pear sucker clearly showed most compounds to be ineffective, even at higher dose rates. TABLE 3 shows the efficacy of treatments assessed on the basis of larvae surviving two weeks after treatment.

TABLE 3. Levels of efficacy against pear sucker from a representative trial in Hageland during 1983.

Compound	Formulation (g/litre)	Dose rate (g AI/100 litres)	% Control
flucythrinate	100 EC	4.0	20
deltamethrin	25 EC	1.5	27
endosulfan	350 EC	52.5	44
methidathion	400 EC	80.0	37
amitraz	190 EC	38.0	95

These results were confirmed several times in other trials in the following years. Within a few years, pear suckers in the whole of this area showed the same degree of resistance. Even successive treatments with amitraz, diflubenzuron or mixtures of both were mostly unable to control the population.

As a result of this problem, together with infections of fire blight (*Erwinia amylovora*), the area of commercial pear orchards temporarily declined in Belgium.

Apple rust mite

Before 1985 apple rust mites were unknown to the Belgian fruitgrower. Every treatment against other pests resulted in good control of these Eriophyid mites (TABLE 4).

TABLE 4. Typical levels of control of apple rust mite achieved in trials during the period 1968 - 1985.

Compound	Formulation (g/litre, g/kg)	Dose rate (g AI/100 litres)	% Control
parathion	250 EC	17.5	99
azinphos-methyl	250 WP	37.5	100
dimethoate	500 EC	50.0	99
omethoate	500 EC	75.0	99
chlorpyrifos	250 WP	50.0	99
deltamethrin	25 EC	0.5	100
tau-fluvalinate	240 EC	7.2	100
azocyclotin	250 WP	25.0	99
amitraz	190 EC	38.0	100
bromopropylate	500 EC	50.0	99

The situation changed within a few years and serious damage was seen in several orchards. If the rust mite population is high, leaves turn brown, the size and colouring of fruit is insufficient, certainly for the main variety Jonagold, and russetting of apples may even occur. In a number of trials resistance to pyrethroids, even to those with good acaricidal activity, was clearly demonstrated, as it was to organophosphates. In contrast to the pear sucker situation however, a number of compounds were still very effective, as shown by the results obtained in an experimental orchard at the Gorse Research Station (TABLE 5). Two applications of each treatment were made to each plot, the first pre-blossom in April and the second in mid-June. Counts of living rust mites were made in early June and August. The continued effectiveness of at least some compounds made resolution of the rust mite problem less urgent than had been the case with pear sucker.

TABLE 5. Typical values for the efficacy of pre- and post-blossom treatments from a trial against apple rust mite in 1988.

Compound	Formulation (g/litre, g/kg)	Dose rate (g AI/100 litres)	% Control (August)
parathion	250 EC	17.5	5
azinphos-methyl	250 WP	37.5	57
dimethoate	500 EC	50.0	27
omethoate	500 EC	75.0	-11
chlorpyrifos	250 WP	50.0	67
deltamethrin	25 EC	0.5	55
fluvalinate	240 EC	7.2	53
azocyclotin	250 WP	25.0	93
amitraz	190 EC	38.0	99
bromopropylate	500 EC	50.0	100

These results were confirmed several times in other trials during the following years.

STRATEGIES FOR RESISTANCE MANAGEMENT IN BELGIAN ORCHARDS

The problem with pear suckers, and to a lesser extent, apple rust mites, clearly showed the need for acaricide and insecticide resistance management. It was agreed with the IRAC Fruit Crops Working Group that strategies should be based on consideration of all methods available for control of the pest and the use of these methods in the best possible way to minimise the risk of resistance. Therefore, in cooperation with the Fruit Crops Working Group and the Ministry of Agriculture in Belgium, the Zoology department of the Gorse Research Station developed strategies for pear sucker control in pear orchards and for spider mite and rust mite control in apple orchards. This has finally led to the introduction of Integrated Pest Management in Belgian pear orchards during the last decade, and to the adoption of anti-resistance guidelines against mites and the introduction of the predatory mite, Typhlodromus pyri in apple orchards.

Anti-resistance strategy for pear orchards

This strategy is based on the use of selective compounds for the control of the key pests in pear orchards. The main problem, besides the pear sucker, was the summer fruit tortrix moth (Adoxophyes orana). With the arrival of fenoxycarb on the Belgian market, IPM became possible. The system is based on fenoxycarb against summer fruit tortrix and codling moth (Cydia pomonella), diflubenzuron against wintermoth (Operophtera brumata), noctuids and codling moth, pirimicarb against aphids and endosulfan against pear leaf midge (Dasineura piri). With the exception of phosalone, which is required for the control of apple bud weevil (Anthonomus piri), no synthetic pyrethroids or organophosphates are allowed. If no selective insecticide is available, a broad spectrum insecticide with a very short persistence is used. This is, for

instance, the case for propoxur against the common green capsid (*Lygocoris pabulinus*), the broad-spectrum effects of this compound being additionally mitigated by limiting applications to the lower branches of trees. The use of all registered acaricides (clofentezine, hexythiazox, azocyclotin, bromopropylate, pyridaben, fenpyroximate) is allowed for treatments against spider mites and/or rust mites, but amitraz is strictly reserved for pear sucker control to avoid over use of this indispensable product.

As a result of the use of selective insecticides and acaricides, the predatory Anthocorid bug, *Anthocoris nemoralis*, is able to move into the orchards and to control the pear sucker population in a very efficient way, decreasing the number of amitraz treatments to one or less a year, instead of the four to six applications required during the first years of resistance. The success of this strategy can be judged by comparing the list of treatments applied for pear sucker control in orchards managed "classically" or following IPM recommendations in 1987 and 1988. (TABLE 6)

TABLE 6. Differences between treatments against the pear sucker in an IPM and a classically treated orchard in 1987 and 1988.

Application Time	Treatments Applied	
	Classical pear orchard	IPM pear orchard
<u>1987</u>		
Winter	DNOC	-
Pre-blossom	deltamethrin	-
June	diflubenzuron	diflubenzuron
	azinphos-methyl	-
	endosulfan	-
	amitraz	-
July	amitraz	-
August	diflubenzuron	-
	amitraz	amitraz
<u>1988</u>		
Winter	parathion	-
Pre-blossom	azinphos-methyl	-
Post-blossom	methidathion	-
	endosulfan	-
	amitraz (x2)	-
July	amitraz	amitraz
August	amitraz	-

To promote the integrated approach, the Gorse Research Station started a course for growers and advisors in 1987, consisting of ten lessons of three hours during the winter and two guided tours in summertime. The main topics covered are biology of pests and natural

predators, selective compounds, anti-resistance strategies, fungicidal schemes in IPM-orchards, IPM in practice and an introduction to Integrated Fruit Production (IFP). More than 1000 fruitgrowers have followed this course to date and almost all Belgian pear growers are at the moment cultivating their fruit in an integrated way with excellent results. The need for anti-resistance strategies with both old and new chemical compounds is still very high because of the increased importance of a great number of formerly minor pests like the codling moth, different species of tortricids, the leopard moth (*Zeuzera pyrina*), the apple clearwing moth (*Synanthedon myopaeformis*), the apple bud weevil and the pear leaf blister mite (*Eriophyes pyri*).

Anti-resistance strategies in apple orchards

Control of spider mites and rust mites in Belgian apple orchards is still possible with chemical compounds and most orchards are regularly treated with acaricides. However, by the end of 1992 about 1000 of Belgium's 15000 ha of apple orchards will have been artificially infested with *Typhlodromus pyri* to control spider mites and rust mites. Chemical and integrated control systems are discussed separately below.

Chemical control of spider mites and rust mites

In order to prevent resistance, the guidelines developed by the Fruit Crops Working Group were adapted to accommodate the needs of Belgian fruit growers. Rust mites are at the moment more important pests than spider mites in Belgian apple orchards. The available acaricides were grouped according to known or expected cross-resistance patterns, resulting in the following list (TABLE 7).

TABLE 7. Effectiveness of groups of acaricides against spider mites and rust mites.

Group	Active ingredient	Spider mite control	Rustmite control
Organotins	fenbutatin oxide	insufficient	good
	azocyclotin	good	good
Ovo-larvicidal acaricides	clofentezine	good	insufficient
	hexythiazox	good	insufficient
Bridged diphenyls	bromopropylate	good	good
Pyrethroids	bifenthrin	good	insufficient
	fenpropathrin	good	insufficient
	tau-fluvalinate	good	insufficient
Miscellaneous *	amitraz	good	good
	pyridaben	good	good
	fenpyroximate	good	insufficient

* Unrelated compounds, each of which may be used once in a season.

This list was provisional because knowledge of cross-resistance patterns was incomplete. Only those products which were frequently used in apple orchards and/or which were still available on the Belgian market were included, leaving out dicofol and flubenzimine. The pyrethroids are mainly recommended against insects and preferably in mixture with other acaricides to avoid problems with rust mites.

Guidelines for use with the above product groups were as follows:

- not more than one compound from any one group should be applied in the same season.
- any one compound should be used only once per season.
- alternation is preferred over mixtures.
- where a mixture of compounds is required to control a mixed population of spider mites and rust mites, then the compounds used should be selected from different groups.
- compounds should be applied at times when they can be targeted at the mite life stages they control best.

The implementation of this strategy seems to have been quite successful. Mite populations are monitored regularly in 35 'pilot' orchards distributed throughout Belgium and when the damaging threshold of 3-4 mobile stages per leaf is approached, warnings are sent out to every fruit grower by the Gorseme Research Station in cooperation with the Belgian Ministry of Agriculture. Growers thus receive detailed and timely spraying schemes based on the above guidelines. What is more, several marketing organisations, and certainly the most important ones, adopted this strategy, putting these ideas into their annual spraying calendars. Contacts were also made between the agrochemical industries and the Gorseme Research Centre leading to 'gentleman's agreements' on advice and use of their respective compounds. Furthermore, the dutch version of the GIFAP video-film 'The Paradox of Resistance' was shown on many occasions, reaching most of the Belgian fruitgrowers.

It is very difficult to prove that the fruitgrowers actually follow these guidelines, but a survey about their spraying habits was made before the anti-resistance campaign started in 1990 and will be repeated within a few years.

It is even more difficult to prove that this strategy worked well in the field. However, one can point to the fact that, in Belgium, no signs of clofentezine or hexythiazox resistance have been found. Every rumour about resistance is directly checked in the field by the Zoology department of the Gorseme Research Station. The gentleman's agreement between Schering Belgium and BASF Belgium regarding using clofentezine or hexythiazox only once a year seems to work well, in contrast with the experiences in surrounding countries where both products have locally lost their activity due to over use.

Integrated Pest Management in apple orchards

Although there are still very effective acaricides available, many fruitgrowers are interested in putting out predatory mites in their orchards. This follows the good results obtained in pear orchards with IPM, and the call for a reduction in the use of chemicals on fruit.

In 1985 the first predatory mites, an OP- and carbamate resistant strain from the Netherlands, were introduced into Belgian apple orchards. After a few years they were able to control red spider mites and, to a lesser extent, apple rust mites. Despite these results, only 1000 ha will have been infested with predatory mites by the end of 1992. This is partly due to the fact that, in contrast to the situation in pear orchards, there is no urgent need for change, but mainly the result of problems with fungicide regimes.

The main apple variety in Belgium is Jonagold, and the required fruit finish for this apple is a red blush on a green background. To preserve abundant populations of predatory mites in the orchards, only a limited number of fungicides, notably captan and dithianon, can be used in summer against scab (Venturia inaequalis). Both are well known for promoting a faster ripening of the fruit, giving fruit with a yellow rather than a green background. Such fruit is unwanted by the market and thus much less valuable. Until this problem is solved, the introduction of predatory mites in Belgian apple orchards will be rather limited and the implementation of IPM will progress only slowly.

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PLANT BREEDING STRATEGIES FOR INTEGRATED PEST MANAGEMENT IN SOFT FRUIT CROPS

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ABSTRACT

The status of traditional breeding and genetic engineering for pest resistance in soft fruit is reviewed, in relation to major and minor pests including virus vector aphids, beetles, midges and mites. The timescale for producing pest-resistant plants should greatly decrease using new technology. To fully utilise genetic resistance in IPM and to maximise its durability against virulent biotypes, the mechanisms of resistance are being studied. Recent advances in analytical chemistry linked to sensitive behavioural and electrophysiological bioassays are aiding in the complex task of identifying resistance factors. Diagnostic tests using DNA probes are also being developed to detect virulent pest biotypes so that the use of resistance genes in plants can be effectively managed. Although IPM strategies for soft fruit pests are not yet fully developed in the UK, fundamental studies of natural enemies in crop ecosystems and ways of increasing their effectiveness are now in progress. The aim is to develop environmentally benign pest control programmes by minimising pesticide inputs.

INTRODUCTION

The growing trend towards reduced pesticide inputs on soft fruit crops and the continuing withdrawal of important pesticides has led to increased damage by several pests and a need to appraise the means of control left available to the horticultural industry. Whilst the investigation of spray timing regimes and the action of new, environmentally safer agrochemicals is of great importance in the immediate future, the development of commercially acceptable cultivars containing genes conferring improved pest resistance represents the best prospects for future growing strategies. In this paper we will address the techniques and developments that have or will take place in plant breeding and result in raspberry, strawberry and blackcurrant cultivars with inbuilt genetic resistance to many of the important arthropod pest species.

PEST RESISTANCE GENES

Raspberry aphids

The incorporation of aphid resistance genes into red raspberry through conventional plant breeding has been one of the most successful examples of pest control using host plant resistance. Resistance to the large raspberry aphid (*Amphorophora idaei*) controls both aphid numbers and the viruses transmitted by this vector (Birch & Jones, 1988). However, since some of these aphid resistance genes have been in commercial use for more than 40 years it is not surprising that populations of virulent aphid biotypes able to break specific resistance genes have developed. In 1965 Briggs identified

four biotypes of *A. idaei* in a survey of UK raspberry aphid populations. At that time the three virulent biotypes were uncommon within the wild population. Since then, the major resistance gene, A_1 , from *R. idaeus*, has been widely used in the breeding of resistant raspberry cultivars, offering resistance against some biotypes (Table 1). Resistance to *A. idaei* from the American black raspberry (*Rubus occidentalis*), based on the A_{10} gene (Knight *et al.*, 1959; Keep & Knight, 1967), is currently effective against all present strains of the aphid, and has been incorporated into breeding programmes.

TABLE 1. Relationship between *A. idaei* biotypes and resistance genes in red raspberry

Genetic source of resistance	<i>A. idaei</i> biotype			
	1	2	3	4
Minor gene	r	r	-	-
A_1	R	S	R	S
A_{10}	R	R	R	R

s = susceptible; r = partially resistant;
R = completely resistant; - = not tested

The incorporation of these resistance genes into raspberry cultivars has substantially reduced spread of many viruses transmitted by *A. idaei* (Jones, 1988). In the United Kingdom, 80% of the crop has some form of resistance to this aphid (Birch & Jones, 1988). Existing tests to identify *A. idaei* biotypes are based on differential colonisation of a range of resistant raspberry cultivars and are too slow and laborious for monitoring large numbers of aphid samples from field surveys.

We are currently developing a rapid diagnostic test. This uses molecular probes to detect differences in DNA content of individual aphids from field samples compared with laboratory clones of each *A. idaei* biotype. Initial results indicate that this approach has great potential for rapid biotype diagnosis (Birch *et al.*, 1992). We have already found DNA probes which detect differences between the most common *A. idaei* biotypes. Within a clone all aphids were the same but *A. idaei* populations sampled from raspberry hosts with different genes for aphid resistance had distinct Restriction Fragment Length Polymorphism (RFLP) patterns. The RFLP patterns of *A. idaei* populations from different raspberry growing regions in the UK confirmed our belief that virulent biotype 2 is now widespread, due to adaptation to resistance gene A_1 . The results also indicated that at least one new biotype is now common, adapted to two cultivars, Glen Moy and Glen Prosen, bred at SCRI and widely grown throughout the UK (Figure 1).

There are several implications of the findings from using DNA diagnostics to the future control of *A. idaei* using genetic resistance. It is evident that in the last 25 years the frequency of virulent aphid

populations has greatly increased. The discovery of a new biotype indicates that this selection for virulence in aphid populations is accelerating with increasing selection pressure. The resistance gene A_{10} currently provides protection against all known *A. idaei* biotypes but so far has had only limited exposure to *A. idaei* populations. An understanding of the mechanisms of aphid resistance conferred by the different major and minor genes should allow us to predict which resistance genes operate additively and so help to delay selection of aphid virulence. It appears from analytical studies of Robertson *et al.* (1991) that the A_{10} gene for resistance to *A. idaei* affects the chemical composition of the leaf surface which, in turn, interferes with the initial settling behaviour of the aphid. An understanding of the genetics of biotype formation in aphid populations, using molecular markers, should also help in the design of control strategies for using resistance genes which minimise selection pressure for pest virulence.

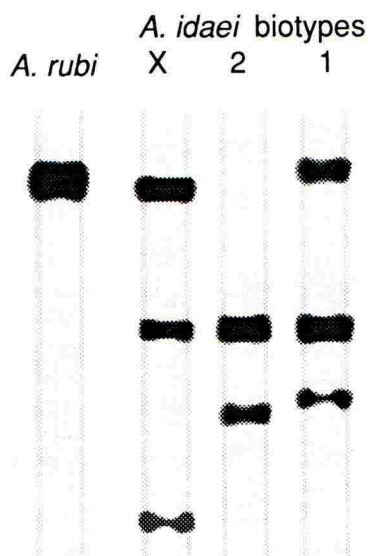


FIGURE 1. RFLP patterns of digested DNA from the blackberry aphid *Amphorophora rubi* and three biotypes of large raspberry aphid *A. idaei*

The situation is less promising for the other important virus vector species, the small raspberry aphid (*Aphis idaei*). Some *R. idaeus* cultivars reportedly have resistance to this aphid, but the results have been inconsistent (Rautapää, 1967). However, spread of raspberry vein chlorosis virus, transmitted by this aphid, may be restricted by breeding cultivars immune to infection by using *R. idaeus* var. *strigosus* and *R. occidentalis* as parental material (Jennings & Jones, 1986).

Strawberry aphids

Resistance to the strawberry aphid (*Chaetosiphon fragaefolii*) has been found in about 40 genotypes of over 4000 *Fragaria chiloensis* clones collected on the Pacific coast of the USA. The incorporation of such resistance from species material into cultivars of commercial value is likely to be long term and could take 20-30 years for strawberry.

Raspberry beetle

The raspberry beetle (*Byturus tomentosus*) is a major pest. Larvae on the fruit can cause damage, but the mere presence of the pest can lead to the condemnation of an entire fruit consignment. Control mainly depends on the application of an insecticide in the interval between petal fall and the first pink fruit stage, but this is becoming increasingly unacceptable.

Sources of resistance to raspberry beetle exist in various wild *Rubus* species (Briggs *et al.*, 1982), but the breeding effort has been mainly confined to the exploitation of resistance from *R. phoenicolasius*, *R. crataegifolius* and *R. coreanus*. As yet no commercial cultivars are available but promising genotypes are undergoing field evaluation. However, the purple raspberry cv. Glencoe, (a *R. idaeus* x *R. occidentalis* hybrid), has shown low levels of beetle infestation in field trials where adult beetles have been confined in sleeve cages.

Raspberry cane midge

Raspberry cane midge (*Resseliella theobaldi*) is an important pest of raspberry in Europe. Available chemical controls require precise timing of application to be effective. Adult midges lay eggs in splits and wounds in the bark at the base of canes in May or early June and the resultant larvae feed and develop *in situ*. These feeding sites can then become infected by a range of fungi (Gordon & Williamson, 1984) resulting in death of the canes in the following winter and spring. *Rubus crataegifolius* and *R. crataegifolius* x *R. idaeus* hybrids possess a strong ability to rapidly repair natural splits and wounds in the bark with suberised and lignified cells, and hence the new tissues from this wound periderm prevent the peeling of the bark and preclude serious midge attack (McNicol *et al.*, 1983). Where oviposition does occur the midge larvae become totally encapsulated at the wound site and are unable to develop fully and escape.

The genetic control of this resistance mechanism remains unclear, but it appears to be a continuously variable character in the F₁ and F₂ progenies from *R. crataegifolius* x *R. idaeus*. The nature of the resistance would suggest that only a major life cycle modification by the pest would overcome it.

Mites

Sources of resistance have not been identified for the two important mite species that attack raspberry, the two-spotted spider mite (*Tetranychus urticae*) and the raspberry leaf and bud mite (*Phyllocoptes gracilis*), but there are major differences in cultivar susceptibility, possibly due to morphological characters (Gordon & Taylor, 1976; Labanowska, 1978).

In strawberry there exists considerable variation in the reaction of various cultivars to infestation by the two-spotted spider mite. The Californian cultivar Chandler is a good example of mite tolerance, but there are others like EMR25 and EMR28 from Horticulture Research International (East Malling), England.

Luczynski *et al.* (1990a,b) attributed the resistance in *Fragaria chiloensis* and cultivated strawberry to the density of glandular and non glandular trichomes and the concentrations of total and catechol-based phenolics.

Blackcurrant gall mite

The blackcurrant gall mite (*Cecidophyopsis ribis*) is the most important pest of blackcurrant worldwide. Apart from inducing the characteristic galled bud response ('big bud'), this mite is the only known vector of blackcurrant reversion, which causes complete sterility of the bush within two years (Adams & Thresh, 1987). The actual agent of reversion has not been identified. Control of the mite in fruiting plantations relies on repeated applications of endosulfan, throughout the spring and early summer, together with rigorous roguing of infested bushes. It has become increasingly evident that the available chemical controls are of limited efficacy and have come under increased scrutiny on environmental grounds. As a consequence, resistance to *C. ribis* and reversion are accorded a high priority in most *Ribes* breeding and genetics programmes.

No commercial cultivars currently available in the UK offer resistance to the mite, but sources of resistance exist elsewhere in the genus *Ribes*. The European gooseberry (*R. grossularia*) has been used as the main donor for mite resistance in UK breeding, containing the single dominant gene *Ce*, and resistant backcross material of *R. nigrum* x *R. grossularia* is presently being evaluated for potential commercial release.

A further resistance gene, *P*, derived from *R. nigrum* var. *sibiricum* has also been exploited (Anderson, 1971), although the resistance conferred by this gene permits mites to survive for sufficiently long to transmit reversion before necrotic tissues develop in the bud. Other sources of resistance exist in species such as *R. pauciflorum* and *R. cereum*.

The identification of resistant genotypes has traditionally involved the use of field infestation plots, with attendant problems of escapes, uneven pest pressure, cost and duration. A rapid, laboratory-based screening technique based on metabolic profiling was described by Brennan *et al.* (1992), and correctly predicted the resistance status in 88% of the genotypes tested. Work to develop molecular markers linked to the *Ce* and *P* gall mite resistance genes is currently in progress.

Sources of resistance to reversion disease have also been exploited, notably from *Ribes dikuscha* and its derivatives, such as the Russian cultivar 'Golubka'. This resistance has proved to be readily inherited, as confirmed by graft-testing, although the genetic control is unclear. Implications derived from segregation ratios are contradictory, with some suggesting the action of a single dominant gene for resistance and others suggesting a more complex situation. Reversion-resistant genotypes of high agronomic value are presently in trials and should be released in the foreseeable future. A

combination of reversion resistance and mite resistance should give a durable form of protection against this disease complex, although the exploitation of alternative resistance genes remains a breeding priority.

Blackcurrant leaf midge

The blackcurrant leaf midge (*Dasineura tetensi*) has developed into a serious pest in the UK and Europe, going through several life cycles each year. Its effective distribution in the UK appears to have moved north in recent years, and has proved difficult to control, requiring repeated spraying. Several sources of resistance have been identified, based on the single dominant gene *Dt*, although the mechanism of resistance remains unclear (Brennan, 1990). The influence of leaf surface characteristics and volatiles from the leaf surface require further examination. Various levels of resistance have been demonstrated in advanced breeding material and the resistant cultivar 'Ben Connan' is due to be released by SCRI in autumn 1993.

MINOR AND NEW PEST SPECIES

The reduction in use of insecticides on these crops may lead to a minor pest species becoming more prevalent. This is already happening in raspberry production in eastern Scotland, where the clay-coloured weevil (*Otiorhynchus singularis*) is becoming more common since the withdrawal of DDT. Similarly, damage to strawberries by vine weevil (*Otiorhynchus sulcatus*) has increased since the use of aldrin was prohibited. In an experimental raspberry plantation at SCRI, where no insecticides have been used for eight years, the raspberry moth (*Lampronia rubiella*) has become common, but in commercial raspberry plantations this species is still controlled by insecticides used against raspberry beetle.

UNDERSTANDING THE MECHANISMS OF PEST RESISTANCE BY BEHAVIOURAL AND CHEMICAL STUDIES

There are a number of reasons why research emphasis has been placed on understanding the mechanisms of host plant resistance to soft fruit. These include:

1. Providing feedback for developing rapid resistance screens, based on identified chemical factors in plants.
2. Ensuring compatibility with other components of an integrated control strategy.
3. Avoiding problems of selecting for chemical resistance factors which are toxic to the end-user.
4. Helping to develop durable forms of resistance by decreasing selection of virulent biotypes or secondary pests.
5. Ensuring that the resistance is stable to environmental effects and plant growth stage.
6. Selection of types of resistance which reduce virus spread, by studying effects of resistance on insect feeding behaviour.

We have adopted this common strategy for identifying and studying resistance mechanisms in a range of soft fruit crops. Initially field trials are undertaken to identify sources of resistance in existing cultivars,

breeding lines or wild relatives. Field studies are also used to identify the main components of the resistance. For example, it was found that resistance to raspberry aphid was primarily due to antixenosis (plant factors resulting in non-preference by the insect during initial settling) rather than antibiosis (plant factors adversely affecting the growth, survival and reproduction of the insect) or tolerance.

Once the main components of resistance are identified research is taken into the laboratory, for detailed behavioural bioassays. We are particularly interested in the plant volatiles (e.g. from flowers and leaves) which insects such as the raspberry beetle can perceive from a distance and use to recognise a susceptible host plant (Woodford *et al.*, 1992). To study these responses we use a specially designed wind tunnel and a 'linear track' olfactometer. A specialised computer package ('The Observer', Noldus Information Technology) is used to record and analyse insect behaviour on resistant and susceptible plants. In order to identify which particular plant volatile chemicals are the key attractants or repellents out of a complex plant chemical profile, electrophysiological techniques are used. For example, in collaboration with scientists at IACR (Rothamsted) electrophysiological recordings from a raspberry beetle antenna (an antennogram) and from individual olfactory receptors, coupled with simultaneous gas chromatography, were used to identify a number of active components in raspberry flower volatiles. To study the detailed feeding behaviour of aphids, other techniques are used. By attaching a thin gold wire to a feeding aphid electrical signals can be detected using a special amplifier. The electrical signals produced in this 'Electrical Penetration Graph' provide information on aphid behaviour once it has started to penetrate a plant during feeding. This is being used to identify the stage at which individual aphids reject a resistant plant, and whether the type of probing or feeding is likely to result in virus spread by vector aphids.

Sophisticated analytical equipment is now also in use for the identification of plant chemicals involved in resistance and susceptibility mechanisms. For example, plant volatiles can be trapped on to a suitable adsorbent and then thermally desorbed directly into a gas chromatograph-mass spectrometer. This process, known as Automated Thermal Desorption is proving invaluable for identifying individual compounds in a complex mixture of up to 200 individual components and has identified a number of plant compounds from raspberry flowers and leaves for further behavioural studies with raspberry beetles and aphids. Apart from plant volatiles, behavioural studies indicate that plant surface waxes and other compounds are involved in pest resistance mechanisms (Robertson *et al.*, 1991). In this case we have analysed the leaf surface waxes of raspberry plants segregating for the aphid resistance gene, A₁₀. Following gc-ms analysis 13 major compounds were identified and used in a linear discriminant analysis. This technique successfully identified 96% of the progeny plants into resistant and susceptible types, indicating that it should be possible to design rapid chemical screens for pest resistance in the near future.

GENETIC RESISTANCE, BIOLOGICAL CONTROL AND NATURAL ENEMIES

Many natural enemies have been associated with pests of raspberry. Although none have been shown to effectively control pest outbreaks, some suppression of pest populations must occur. Syrphid larvae were the most

common predator associated with raspberry aphids in Scotland (Dickson, 1979) and lacewings, anthocorid bugs, spiders and coccinellid beetles are abundant in an experimental raspberry plantation managed without insecticides. The indiscriminate use of insecticides and fungicides will clearly affect these natural control agents and reduce their influence on the population dynamics of pest species.

Combining resistant and/or partially resistant genotypes with a strategy designed to build up the numbers of natural predators and parasites before pest outbreaks occur should prove to be a valuable tool in future Integrated Control Strategies, but requires further research.

It should be noted that in any breeding programme, it is not practicable to carry out resistance breeding for more than a very few of the important diseases and pests combining with selection for essential agronomic and fruit traits. The more selection objectives that are introduced into a breeding programme, the harder it becomes to produce cultivars that pass through all the selection screens. For minor pests it may be wise to rely on methods of control other than inherent plant resistance and this is where a truly Integrated Control Strategy will be invaluable.

The identification and availability of resistance genes against pests of soft fruit as described above is contributing greatly to the production of resistant cultivars of soft fruit. However using classical breeding techniques it may take c. 30-40 years to incorporate a particular resistance gene from a related plant species into a commercially-acceptable cultivar. New technology offering the prospect of incorporating a single gene for pest resistance into a genotype of known and proven agronomic merit can greatly accelerate progress. Transformation with potentially useful genes is proceeding in *Fragaria*, *Ribes* and *Rubus*, with pest resistances a particular area of development at SCRI (Graham & McNicol, 1989). The cowpea protease trypsin inhibitor gene, coding for a low molecular weight insect antimetabolite effective against a range of Lepidopteran, Coleopteran and Orthopteran pests (Hilder *et al.*, 1987) has already been inserted into these crops. Glasshouse assessments of the level of expression of this gene in transgenic plants is in progress. *Bacillus thuringiensis* toxin gene offers the prospect of further and possibly more specific resistance to insects.

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