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The impact of climatic change on European agriculture

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ABSTRACT

A review is given of the greenhouse-gas-induced changes of climate currently projected for Europe. The implications of these changes are then evaluated with respect to agricultural potential in this region. Although there are many uncertainties, in general the more positive effects may be expected in the north and the more negative in the south. Management and technology can adapt to this south-to-north shift in agricultural resources but there may also need to be changes in Europe-wide agricultural policies.

INTRODUCTION

Over the past 15 years increasing attention has been given to modelling the likely effects on the world's climate of increasing greenhouse-gas emissions. Over the last five years there has developed a significantly enhanced ability to predict, at the large-region level such as Europe, the spatial patterns of change in temperature and rainfall; in parallel with this effort has been one to evaluate the implications of these changes for agricultural potential. In reality, the latter has lagged significantly behind atmospheric modelling, largely because of the complexity of the many non-climate, as well as climate, variables that affect agricultural potential.

THE CAUSES OF CLIMATE CHANGE

The main energy source warming the earth is radiation from the sun. This is short-wave radiation, due to the high temperature of the sun (6,000°C), and includes visible light and ultra-violet radiation. The earth intercepts some of this radiation energy, which warms the surface and is re-emitted to balance the incoming energy. The earth is much cooler than the sun, and it emits terrestrial radiation at longer wavelengths in the infra-red part of the spectrum, invisible to the human eye.

The earth's atmosphere is made up of gases, some of which are able to absorb radiation at particular wavelengths. The gases that make up the bulk of the atmosphere, nitrogen (78%) and oxygen (21%), neither emit nor absorb terrestrial radiation. However, water vapour, carbon dioxide and a number of other trace gases absorb some of the terrestrial radiation leaving the earth while being transparent to the incoming solar radiation. The effect of this is to warm the earth's surface to an average temperature of 15°C, which is highly amenable for life on earth and some 34°C higher than the frigid temperature (-19°C) to be expected in the absence of an atmosphere (IPCC, 1996). This is the *natural greenhouse effect*, so called because the absorbing gases act like the glass in a greenhouse, allowing the sun's rays to penetrate inside, but re-emitting some of the outgoing terrestrial radiation back into the greenhouse, thus helping to keep it warm.

Over the last two centuries, continuous increases in atmospheric concentrations of many of these 'greenhouse gases' have been observed. This period coincides with the industrialisation of human societies, beginning in Europe but spreading to become the global phenomenon it is today. Industrialisation has been associated with massive land clearance for agriculture and the combustion of fossil energy sources such as coal, oil and gas. Both of these activities have resulted in increasing emissions of natural greenhouse gases (such as carbon dioxide, methane and nitrous oxide) into the atmosphere.

Growing emissions of greenhouse gases have resulted in increasing atmospheric concentrations since pre-industrial times (Table 1). The gases are well mixed in the atmosphere and their global average concentrations can be estimated using ice-core evidence and, more recently, by direct measurements. Rising concentrations of greenhouse gases mean that more terrestrial radiation is absorbed and re-emitted back to earth, resulting in a warming of the atmosphere near the surface. This is known as the *enhanced greenhouse effect*. The effectiveness of a greenhouse gas in warming the atmosphere (its 'radiative forcing') depends both on its concentration and on the amount of time it remains in the atmosphere. These are both shown in Table 1. Of the greenhouse gases, carbon dioxide has contributed about 64% of the radiative forcing, methane about 19%, halocarbons 11% and nitrous oxide about 6%.

Table 1. Greenhouse-gas concentrations, increases and lifetimes.

	CO_2	CH_4	N_2O	CFC-11	HCF-22 (a CFC substitute)
Pre-industrial concentration	-280 ppmv	-700 ppbv	-275 ppbv	0	0
Concentration in 1994	358 ppmv	1720 ppbv	312 ppbv	268 pptv	110 pptv
Rate of concentration change	1.5 ppmv/yr 0.4%/yr	10 ppbv/yr 0.6%/yr	0.8 ppbv/yr 0.25%/yr	0 pptv/yr 0%/yr	5 pptv/yr 5%/yr
Atmospheric lifetime (years)	50–200	12	120	50	12

Source: IPCC, 1996

Estimates of future climate

There is little doubt that the increases in greenhouse-gas concentrations observed over the past 100 years will continue well into the 21st century. We can be confident of this for two reasons. First, as human population grows and combustion of fossil fuel continues to rise, the rate of emissions of greenhouse gases into the atmosphere is unlikely to be abated for many decades. Second, even if emissions were reduced immediately, concentrations would continue to rise for some time, because of the long residence times of these gases in the atmosphere and their slow uptake and release in the oceans.

In 1992, the Intergovernmental Panel on Climate Change (IPCC) developed six projections of future global emissions to the year 2100 – the IS92 scenarios (IPCC, 1992). These scenarios attempt to represent six possible paths of future emissions, based on alternative assumptions about world population growth, economic activity and energy use. They include all of the greenhouse gases, as well as sulphate aerosols. Further, they range from a low scenario (IS92c), which assumes low population growth, low economic growth and severe constraints on fossil fuel supplies, to a high scenario (IS92e), which assumes moderate population growth, high economic growth, high fossil fuel availability and a phase-out of nuclear power. Based on these different assumptions it is projected that global mean temperature by the year 2100 could range from about 0.8°C to 4.5°C above 1990 levels.

Projections of global mean annual temperature change can be quite useful for examining policy issues such as the effect on global climate of reducing greenhouse-gas emissions. However, they tell little about the magnitude, rate and pattern of climate change in different regions. Such information is of critical importance for assessing the impacts of climate change on ecosystems, water resources and economic activities such as agriculture and forestry, all of which are highly region-specific.

The main sources of information on possible regional changes in climate are general circulation models (GCMs). Typical results from such simulation models include:

- greater surface warming of the land than the oceans in winter;
- a minimum warming around Antarctica and in the northern Atlantic, associated with deep water formation;
- maximum warming at high northern latitudes in late autumn and early winter, associated with reduced sea ice and snow cover;
- little warming over the Arctic in summer;
- little seasonal variation of warming at low latitudes or over the southern oceans;
- a reduction in diurnal temperature range over land in most seasons and in most regions;
- an increase in anomalously high temperature events and a decrease in anomalously low temperatures;
- an enhanced global mean hydrological cycle;
- increased precipitation at high latitudes in winter;
- decreases in precipitation in some parts of the subtropics, with a possible weakening of the summer monsoon over Asia;
- probable increases in intense precipitation events in many regions.

For Europe, the projections indicate an increase in mean annual temperatures of from 1°C to 2°C (with the greater increases being in the south and east); with increases in summer precipitation in the northern half and decreases in the southern half.

THE DETECTION OF EARLY CLIMATE CHANGE

The most accurate determinations of variations in global climate are based on instrumental measurements with standard equipment at sites around the world (both on land and at sea), supplemented in recent years with monitoring from satellites outside the earth's atmosphere. There are sufficient observations of surface temperature to allow reconstructions of global mean annual temperature changes over the past 130 years. The instrumental record shows a warming of 0.3°C to 0.6°C since the late 19th century, with a warming of 0.2°C to 0.3°C over the 40 years up to 1994 – the period with the most reliable data (IPCC, 1996). The 1980s and 1990s have been amongst the warmest since 1860. The warming has not been uniform, however, but is strongest over the continents between 40°N and 70°N. A few areas, such as the North Atlantic Ocean north of 30°N and nearby land areas, have cooled in recent decades. Over many land areas, there has also been a trend since the 1950s towards a reduced daily temperature range, meaning that where average temperatures have increased, nights have warmed by more than days. This is thought to be due to increased cloudiness and possibly also to increases in atmospheric aerosols owing to the combustion of fossil fuel.

Precipitation averaged over land areas increased from the start of the 20th century up to about the 1960s, but has decreased since about 1980. There are large regional variations in these changes and they are further complicated by El Niño events. Prominent among the regional changes are a long-term increase in winter precipitation at high latitudes in the northern hemisphere and a sharp decrease in precipitation from the 1960s over the subtropics and tropics, from Africa to Indonesia. This includes the Sahelian zone of west Africa, which has recorded only about half the precipitation in recent decades compared with the wet 1950s. However, similar dry periods in this region have also occurred in the historical and recent geological past.

There is increasing confidence among climatologists that the main features of the observed record of global climate temperature change during the past century can be explained, although details remain that are not fully understood. Some short-term variations in the order of several tenths of a degree Celsius can been attributed to natural causes such as the ENSO (El Niño Southern Oscillation) phenomenon (producing surface warming), volcanic eruptions (surface cooling), changes in atmospheric circulation patterns or minor variations in radiation output from the sun. However, in an authoritative statement agreed by scientists in 1995, it is now accepted that natural causes alone are not sufficient to explain the rate and pattern of long-term change during the past century, but that the evidence points towards 'a discernible human influence on global climate' (IPCC, 1996). This refers to the observed build-up of greenhouse gases in the atmosphere since pre-industrial times owing to human activities, especially combustion of fossil fuel and changes in land use.

TYPES OF EFFECT OF CLIMATE CHANGE

There are three ways in which the greenhouse effect may be important for agriculture. Firstly, increased atmospheric CO_2 concentrations can have a direct effect on the growth rate of crop plants and weeds. Secondly, CO_2-induced changes of climate may alter levels of temperature, rainfall and sunshine that can influence plant and animal productivity. Finally, rises in sea level may lead to loss of farmland by inundation and to increasing salinity of groundwater in coastal areas. The first two types of effect will now be considered but not the third, the effects of which are more localised. The methods used in analysing these effects are described in Parry & Carter (1998).

Effects of CO_2 enrichment

Effects on photosynthesis

If increases in atmospheric CO_2 were occurring without the possibility of associated changes in climate then, overall, the consequences for agriculture would probably be beneficial. CO_2 is vital for photosynthesis, and the evidence is that increases in CO_2 concentration would increase the rate of plant growth. More CO_2 enters the leaves of plants, owing to the increased gradient of CO_2 between the external atmosphere and the air space inside the leaves. This leads to an increase in the CO_2 available to the plant for conversion into carbohydrate by respiration.

There are, however, important differences between the photosynthetic mechanisms of different crop plants and hence in their response to increasing CO_2. Plant species with the C3 photosynthetic pathway (the first product in their biochemical sequence of reactions has three carbon atoms) use up some of the solar energy they absorb in a process known as photorespiration; here, a significant fraction of the CO_2 initially fixed into carbohydrates is reoxidized back to CO_2. C3 species (e.g. wheat, rice, soya, barley, sunflower) tend to respond positively to increased CO_2 because this gas tends to suppress rates of photorespiration.

However, in C4 plants (those in which the first product in their biochemical sequence of reactions has four carbon atoms) CO_2 is first trapped inside the leaf and then concentrated in the cells which perform the photosynthesis (Rosenzweig & Hillel, 1998). Although more efficient photosynthetically under current levels of CO_2, these plants (e.g. maize, millet, sorghum) are less responsive to increased CO_2 levels than C3 plants.

The actual amount of increase in usable yield, rather than of total plant matter that might occur as a result of increased photosynthetic rate, is problematic. In controlled-environment studies, where temperature and moisture are optimal, the yield increase can be substantial, averaging 36 per cent for C3 crops under a doubling of ambient CO_2 concentration (Warrick *et al.*, 1986). Few studies have yet been made, however, of the effects of increasing CO_2 in combination with changes in temperature and/or rainfall.

Little is also known about possible changes in yield quality under increased CO_2. The nitrogen content of plants is likely to decrease, whereas the carbon content increases, implying reduced protein levels and reduced nutritional levels for livestock and humans. This, however, may also reduce the nutritional value of plants for pests, so that they need to consume more to obtain their required protein intake.

Effects on water use by plants

Just as important may be the effect that increased CO_2 has on the closure of stomata (the small openings in leaf surfaces through which CO_2 is absorbed and through which water vapour is released by transpiration). This tends to lower the water requirements of plants by reducing transpiration (per unit leaf area), thus improving what is termed water use efficiency (the ratio of crop-biomass accumulation to the water used in evapotranspiration). A doubling of ambient CO_2 concentration causes about a 40% decrease in stomatal aperture, in both C3 and C4 plants, which may reduce transpiration by 23–46% (Cure & Acock, 1986). This might well help plants in environments where moisture currently limits growth (e.g. in semi-arid regions), but there remain many uncertainties, such as how much the greater leaf area of plants owing to increased CO_2 will balance the reduced transpiration per unit leaf area.

In summary, a doubling of atmospheric CO_2 concentrations from 330 to 660 ppmv can be expected to cause a 10–50% increase in growth and yield of C3 crops (such as wheat, soybean and rice) and a 0–10% increase for C4 crops (such as maize and sugarcane) (Warrick *et al.*, 1986). Much depends, however, on the prevailing growing conditions. Present knowledge is based on a few experiments (mainly in glasshouses) and has not yet included extensive study of response in the field. Thus, although there are indications that, overall, the effects of increased CO_2 could be distinctly beneficial, and could partly compensate for some of the negative effects of CO_2-induced changes of climate, we cannot at present be sure that this will be so.

Effects of increased temperatures

Effects on growth-rates

In high mid-latitude regions (above 45°N), at high latitudes (above 50°N) and at high altitudes, temperature is frequently the dominant climatic control on crop and animal growth. It determines the potential length of the growing and grazing seasons, and generally has a strong effect on the timing of developmental processes and on rates of expansion of plant leaves. The latter, in turn, affects the time at which a crop canopy can begin to intercept solar radiation and thus the efficiency with which solar radiation is used to make plant biomass. Plant development does not begin until temperature exceeds a certain threshold; then the rate of development increases broadly linearly with temperature to an optimum, above which it decreases also broadly linearly.

However, the effect of this development on plant biomass depends on whether the growth habit of the plant is determinate (it has a discrete life cycle which ends when the grain is mature, such as in cereals) or whether it is indeterminate (it continues to grow and yield throughout the season, such as in grasses and root crops). Temperature increase shortens the reproductive phase of determinate crops, decreasing the time during which the canopy exists and thus the period during which it intercepts light and produces biomass. The canopy of indeterminate crops, however, continues to intercept light until reduced by other events such as frost or pests, and the duration of the canopy increases when increased temperatures extend the season over which crops can grow (e.g. by delaying the first frosts of autumn). An increase in temperature above the base (but not exceeding optimum temperatures) should, therefore, generally lead to lower yields in cereals and higher yields of root crops and grassland; higher temperatures may also lead to higher rates of evaporation and, therefore, reduced moisture availability that can also be expected to affect yields.

Effects on growing seasons

One of the most important effects of an increase in temperature, particularly in regions where agricultural production is currently limited by temperature, would be to extend the growing season available for plants (e.g. the period between last frost in spring and first frost in autumn) and shorten the growing period required by crops for maturation.

The effects of warming on length of growing season and growing period will vary from region to region and from crop to crop. For wheat in Europe, for example, the growing season is estimated to lengthen by about 10 days per 1°C increase in mean annual temperature (Brouwer, 1988). In general, the conclusion is that increased mean annual temperatures, if limited to two or three degrees, could generally be expected to extend growing seasons in high mid-latitude and high-latitude regions. Increases of more than this could increase evapotranspiration rates to a point where reduced crop-water availability would begin to limit the growing season.

Effects on yield

Whether crops respond to higher temperatures, with an increase or decrease in yield, depends on whether they are determinate or indeterminate, and whether their yield is currently strongly limited by insufficient warmth. In cold regions very near the present-day limit to arable agriculture, any temperature increase can be expected to enhance yields of cereal crops. For example, near the current northern limit of spring-wheat production in the European Russia, yields increase about 3% per °C, assuming no concurrent change in rainfall (Pitovranov *et al.*, 1988). In Finland, the marketable yield of barley increases 3–5% per °C (Kettunen *et al.*, 1988), and in Iceland hay yields increase by about 15% per °C (Bergthorsson *et al.*, 1988).

In regions where temperature maxima are near the optimum under current climatic conditions, such as in central and southern Europe, increases in temperature would probably lead to decreased yields. The patter of such effects in Europe will be considered in a later section of this paper. Prior to this, it is relevant to observe the likely implications world-wide.

EFFECTS ON YIELDS WORLD-WIDE AND ON GLOBAL FOOD SUPPLY

European agriculture is, increasingly, part of a global food system and responds to global trends in demand, supply and prices. Possible world-wide effects of climate change on agriculture, drawn from recent published research (Rosenzweig & Parry, 1994; DETR, 1997), are summarised below.

Validated models of dynamic crop growth have been used to simulate the effects of climate change and increased atmospheric CO_2 on the yield of major crops. Their outputs (estimated changes in yield) have been used as inputs to established models of world food trade, to estimate the changes in world food output, in world food prices and in the number of people at risk from hunger.

Crop yield changes

The general pattern of average crop yields for projected changes of climate for the 2020s, 2050s and 2080s is one of positive changes in the mid- and high latitudes and negative yield changes in the lower latitudes. There are, however, important regional variations. For example, the Indian subcontinent and the Middle East are characterised by simulated yield losses, whereas Canada, Japan, the European Union and New Zealand experience yield gains.

World food output

The world food model incorporates climate responses as changes in average national or regional yield per commodity. Economic adjustments include changes in agricultural investment, allocation of land to different crops, land reclamation and land prices. A 'risk of hunger' index is based upon methods developed by the UN Food and Agricultural Organisation .

Under standard assumptions about the future, and assuming no change in climate, world cereal production is estimated to grow from about 1,800 million t in 1990 to about 3,500 million t in 2050, matching global food requirements throughout the period. Food prices are estimated to rise but the relative risk of hunger will decrease. These projections are consistent with those of FAO. They assume a 50% liberalisation of trade by the year 2020 and an annual increase in cereal yields of just under 1%. Some consider these assumptions to be optimistic, but they are consensus best estimates.

Climate change owing to greenhouse gases alone (without the effects of sulphate aerosols) will cause world cereal production to be progressively reduced: by *c.* 15 million t in the 2020s, by 60 million t in the 2050s and by 105 million t (or 2%) in the 2080s. While these amounts do not appear large, they imply significant effects on global food prices and the risk of hunger. Food prices (above the level otherwise expected) are forecast to increase by 5% in the 2050s and by around 10% in the 2080s. The number of people at risk of hunger (again, above the level otherwise expected) is projected to be *c.* 36 million more by the 2020s.

Regional effects

The global estimates presented above mask important regional differences in impacts. In general, yield increases at high and high mid-latitudes lead to production increases in these regions, a trend that may be enhanced owing to the greater adaptive capacity of countries in such regions. Both Canada and Europe are good examples of this. In contrast, yield decreases at lower latitudes, and in particular in the arid and sub-humid tropics, lead to production decreases and to increases in the risk of hunger, effects that may be exacerbated where adaptive capacity is lower than the global average. For example, in Africa, cereal productivity is estimated to be reduced by about 10% from the reference case by 2080, and the consequent risk of hunger would increase by one fifth.

EFFECTS OF CLIMATE CHANGE ON EUROPEAN AGRICULTURE

The following is a summary of current knowledge concerning possible effects in Europe, which is taken to be the region from the eastern Atlantic seaboard to the Ural Mountains (i.e. including European Russia and the Ukraine) and from northern Scandinavia to the Mediterranean. It is drawn largely from a number of recent reviews (Parry, 1990; Harrison, *et al.*, 1995; IPCC, 1997). Unless otherwise stated the estimated effects are for greenhouse-gas-induced climate change expected by *c.* 2050 under the IPCC IS92a scenario ('business-as-usual').

Changes of location of crop suitability

Increased rates of maturation, and reduced risk of early and late frosts, are likely to lead to a northward shift of crop potential throughout Europe. There is a strong likelihood that zones of suitability for grain maize will extend into southern Sweden, southern Finland and the Baltic states, and for early-maturing sunflower and soya bean into parts of Ireland, the southern UK and as far east as Poland. Broadly similar analyses suggest a northern shift of southern European temperature-limited crops such as citrus, olives and vines (Harrison *et al.*, 1995).

These are, of course, assumptions based on altered climatic potential (indeed, of only thermal potential). Much will also depend on changes in moisture availability; further, the local pattern of real physical potential is much affected by suitable soils and terrain. Also, these are not projections of actual changes in land use, as these will depend on the decisions as to whether such altered potentials will be exploited.

Crop yields

Accounting for the enhancement of growth resulting from increasing CO_2 concentrations, the yield of winter cereals (largely C3 crops) increases across most of Europe. In the case of winter wheat, the rate of increase in yields across Europe could be 0.20–0.13 t/ha/decade (see Tables 2 and 3). The largest increases per country might occur in northern Europe, because of increased possibilities of converting from spring to winter cereals. The southern half of Europe may experience yield increases overall, but the deep south (Mediterranean region) would be characterised by yield decreases if the projected reductions in available moisture were to occur. Much depends on projected changes in moisture and these are, at present, most insecure.

With this caveat in mind, and other things being equal, the potential increases in yield could lead to substantial growth in European production, particularly of cereals. As an example, a crude application of yield projections for winter wheat in the EU to currently suitable areas and to yield levels of 1990 suggest an average increase of 9–11 million t/yr for the years 2013–2036 and 24–26 million t/yr for the years 2042–2100 (Harrison *et al.*, 1995).

Table 2. Mean wheat yields (in t/ha) (and standard deviation) simulated with EURO Wheat model for four predefined regions of Europe for baseline climate (1961–1990) and climate-change scenarios (Harrison *et al.*, 1995).

Emmission scenario (CO_2 ppmv)	GCM scenario	Region[1]			
		Europe	EU	Northern EU	Southern EU
Base (353)	Base	8.07 (2.34)	7.77 (2.86)	9.25 (1.22)	5.94 (3.23)
2 × CO_2 (560)	UKHI	8.43 (2.55)	8.50 (2.55)	9.70 (1.37)	6.79 (3.49)
$IS92_a$ (454)	UKTR3140	8.74 (2.50)	8.61 (2.69)	9.86 (1.33)	6.91 (3.09)
$IS92_a$ (617)	UKTR6675	10.21 (2.22)	10.17 (2.62)	11.13 (1.37)	8.83 (3.28)
$IS92_d$ (545)	UKTR6675	9.28 (2.30)	9.21 (2.69)	10.33 (1.32)	7.64 (3.27)

[1] Regions are defined as follows: Europe = the large region from Scandanavia to North Africa and from Ireland to the Black Sea; EU = the 15 countries of the European Union; Northern EU = all EU regions north of 45°N; and Southern EU = all EU regions south of 45°N.

Table 3. Mean sunflower yields (in t/ha) (and standard deviation) simulated with EURO Sunflower model for four predefined regions of Europe for baseline climate (1961–1990) and climate change scenarios (Harrison *et al.*, 1995).

Emission scenario (CO_2 ppmv)	GCM scenario	Region[1]			
		Europe	EU	Northern EU	Southern EU
Base (353)	Base	1.36 (1.22)	1.36 (1.22)	2.41 (1.09)	0.78 (0.84)
2 × CO_2 (560)	UKHI	0.93 (0.77)	0.98 (0.83)	1.46 (0.77)	0.76 (0.74)
$IS92_a$ (454)	UKTR3140	1.37 (1.11)	1.24 (1.05)	1.94 (1.11)	0.86 (0.78)
$IS92_a$ (617)	UKTR6675	1.59 (1.22)	1.47 (1.16)	2.15 (1.11)	1.10 (1.01)

[1] Regions are defined as in Table 2.

For non-determinate crops, potato yields may increase by as much as 35% under northern conditions as a result of the lengthening of the growing season, regardless of CO_2 fertilisation effects. Similar increases might be expected for forage grass.

Effects of extreme weather

Recent investigations show that probabilities of extreme temperatures are likely to increase and that poorly adapted genotypes would experience consequent losses in grain yield and quality.

Higher temperatures in summer should not be a real challenge to summer crops (except spring cereals, if these are subjected to elevated temperatures during the grain-filling period). Drought could be a major concern in the future, however, particularly in the Mediterranean zone and in central Europe. This is a genuinely complex problem: GCM-based scenarios do not agree on the magnitude of changes in space of at least one component of the water budget (precipitation), and changes in another component (potential evapotranspiration, PET) are extremely dependent on calculation methods. A 1°C increase in air temperature will lead to 37 mm more PET south of 40° N (equivalent to a 60% increase in PET in southern European countries). If the projected changes of -10% to -20% in summer precipitation in southern and central Europe are correct, fully irrigated crops may become even greater competitors with domestic and industrial users for available water resources (IPCC, 1997).

Weeds, pests and diseases

Weeds are expected to benefit from higher CO_2 concentrations because in Europe most are C3 plants. Increasing precipitation and temperature in the northern half of Europe probably will be linked to increasing air humidity and, possibly, duration of leaf wetness – factors that are favourable to early disease outbursts for annual and perennial crops. The same holds for early attacks of insect pests.

Northward shifts in the distribution of certain pests could be of similar magnitudes and rates as those estimated for cereal crops. Additional generations of multivoltine species also can be expected.

Soil erosion

Increasing precipitation probably will induce greater risks of soil erosion, depending on the intensity of rain episode (such information is not currently available from available climate scenarios). This possibility needs to be examined, as does the expected evolution of organic matter in the soil. If the organic matter content decreases with increasing temperature (as a result of a higher mineralisation rate), soils will be more susceptible to drying. Also, increased rainfall could increase fertiliser leaching in already-wet areas (CCIRG, 1996).

In the northern half of Europe opportunities for autumn soil tillage will be improved by drier conditions, as long as the future precipitation increase is no more than 15% (that more than compensates for the higher rates of evaporation owing to increased temperatures) (Parry, 1990). This analysis must be verified for spring conditions and for other areas.

ADAPTING TO CLIMATE CHANGE

The assessment of possible effects has, up to this point, assumed that technology and management in agriculture do not alter significantly in response to climatic change and, thus, do not alter the magnitude and nature of the impacts that may stem from such change. It is certain, however, that agriculture will adjust and, although these adjustments will be constrained by economic and political factors, it is likely that they will have an important bearing on future impacts. Two broad types of adjustment may be expected: changes in land use and changes in management.

Changes in Land Use

Three types of change in land use will probably have the greatest effect: changes in farmed area, crop type and crop location.

Changes in farmed area

Where warming tends to reduce climatic constraints on agriculture, an extension of the farmed area can be expected if other environmental factors and economic incentives permit. Expansion may be most marked in the northern half of Europe, although only where terrain and soils will permit further reclamation.

Warming may also tend to induce an upward extension of the farmed area in upland regions. For example, in the European Alps a 1°C mean annual warming can be expected to raise climatic limits to cultivation by about 150 m (IPCC, 1996). These shifts of the limit of the farmed area imply major impacts on the semi-natural environment and on extensive rangeland economies in mountain regions, such as alpine pastures, which may come under pressure both from the upward advance of more intensive agriculture and from afforestation.

In regions where reduced moisture availability leads to decreased productive potential, particularly where agriculture is at present only marginally productive, there may occur a significant decline in the area under use. This may occur, for example, in parts of Mediterranean Europe if projected decreases in rainfall are correct.

Changes in crop type

Changes to crops with higher thermal requirements

In regions where there are substantial increases in the warmth of the growing season (and where output is currently limited by temperature rather than by rainfall) it is logical that substitution by crops with higher thermal requirements would allow higher yields (for example the introduction of sunflowers and soya beans into the UK) (Parry, 1989). In southern Europe, the range of avocado and other southern Mediterranean crops may be extended.

Changes to more drought-tolerant crops

Where moisture, rather than temperature, is more generally the current climatic constraint on output, or where increases in temperature could well lead to higher rates of evapotranspiration (and, thus, to reduced levels of available moisture), there may occur a switch to crops with lower moisture requirements. There is some evidence that, in northern Europe, a switch from spring to winter cultivars of cereals would be one strategy for avoiding losses resulting from more frequent dry spells in the early summer.

Changes in crop location

The switch of crops considered above implies changes in the allocation of land from one use to another. In general, land uses that show a greater increase in productivity than others are likely to increase their comparative advantage over competing uses; and, given sufficient change in the pattern of comparative advantage, decisions then may follow which involve a change in use. The amount of change in land use is likely to depend on how finely land uses in a given area are currently tuned to economics and climate, and much will depend on the changes in prices commanded by different crops. This is partly determined by changes in yield potential in other areas. The response is likely, therefore, to be complex and extremely difficult to predict. It has been shown that re-allocations of land use related to climate change in the UK may well be driven as much by changes in global food prices (owing to global climate change) as by UK changes in rainfall and temperature (Hossell *et al.*, 1995; Parry *et al.*, 1996).

Changes in management

It is reasonable to expect that a large number of changes in management, adopted over time as the effects of climate change are perceived, will modify the effects outlined above. The most important changes would probably occur in the use of irrigation and fertilisers, in the control of pests and diseases, in soil drainage, in farm infrastructure and in forms of crop and livestock husbandry.

Changes in irrigation

Substantial increases are likely to occur in the need for and the costs of irrigation, particularly in southern Europe, in order to substitute for moisture losses due to increased evapotranspiration.

Changes in fertiliser use

More fertiliser may be needed to maintain soil fertility where increases in leaching result from increased rainfall. In other regions, warming may increase productive potential to the extent that current levels of output can be achieved with substantially lower amounts of fertilisers. In Iceland, for example, fertiliser use could possibly be halved under an annual warming of +4°C, while maintaining present-day output (Bergthorsson *et al.*, 1998).

Much will depend on other factors, for example to what extent higher CO_2 concentrations will make nutrients more limiting (thus requiring more use of fertilisers), and how future changes in energy prices affect the cost of fertilisers.

Control of weeds, pests and diseases

The costs of these are likely to alter substantially, although it is quite impossible to specify them with any degree of detail. Possibly most important for cereal production may be the costs of controlling the spread of subtropical weed species into current major cereal-producing regions in Europe.

Changes in farm infrastructure

Regional shifts of farming types and altered irrigation requirements imply major changes in capital equipment, in farm layout and in agricultural support services (marketing, credit, etc.). Because of the very large costs involved only small, incremental adjustments may occur without changes in government policies.

Changes in crop and livestock husbandry

The adjustments summarised above imply a plethora of small, but important, changes in farm husbandry. In particular, there are likely to occur very many alterations to the timing of various farm operations such as tillage (ploughing, sowing, harvesting, etc.), fertilising and pest and weed control (spraying, etc.), because the timing of these in the present farming calendar (though, of course, different for various parts of the world) is frequently affected by present climate. Particular aspects of husbandry are also likely to be affected, such as the density of planting, the use of fallowing and mulching, and the extent of inter-cropping. These aspects are, today, frequently part of a package of strategies designed to mitigate the adverse effects (and to exploit the beneficial effects) of present-day climate. Thus, a change of climate implies a re-tuning of these strategies to harmonise with the new set of climatic conditions.

MITIGATING CLIMATE CHANGE

Climate change, it may be concluded, holds both potential threats and opportunities for Europe. Overall, however, the evidence is that Europe will fare better than the tropics and subtropics, particularly the semi-arid tropics where the most negative effects are currently expected (and, incidentally, where there exists a much smaller capability to adapt). However, it would be a mistake to believe that Europe will be a 'winner' in a game of winners and losers, because climate change is a global issue requiring a global co-operative response. The global response proposed thus far (in the 1997 Kyoto Protocol which is part of the UN Framework Convention on Climate Change) will lead to minimal reductions in climate change from the IS92a (unmitigated) level, perhaps a globally average warming of 1.33°C by the year 2050 rather than by the IS92a's predicted 1.39°C. Not even this small action to reduce emissions has been ratified globally.

There is, therefore, every reason to plan for climate change and not to trust that we can avoid it. The future is not an apocalyptic one: it is one that offers benefits and disbenefits. We must make the most of one and the least of the other.

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SESSION 2A

NEW COMPOUNDS, FORMULATIONS AND USES FOR PEST CONTROL

Chairman	Dr G le Patourel *Imperial College, Ascot, UK*
Session Organiser	Dr R Bateman *CABI BioScience, Ascot, UK*
Papers	2A-1 to 2A-6

MTI-446: A novel systemic insect control compound

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ABSTRACT

MTI-446 [(RS)-1-methyl-2-nitro-3-[(3-tetrahydrofuryl)methyl]-guanidine] is a highly effective novel insect control compound discovered by Mitsui Chemicals, Inc. MTI-446 has a tetrahydrofuran ring in its structure instead of aromatic heterocycles such as chloropyridine which were considered necessary for chloronicotinyls or neo-nicotinoids previously. Laboratory and field studies demonstrate that MTI-446 controls a broad range of Hemipterous target pests and some other important pests in various crops at rates of 100 - 200 g a.i. / ha via ingestion and contact, and also exhibits root-systemic activity. This compound has a favorable toxicological and environmental profile with a low mammalian, avian and aquatic toxicity. MTI-446 shows no cross resistance to pyrethroids, carbamates, OPs and IGRs, and, therefore, is a promising compound in resistance management and integrated insect control programmes.

INTRODUCTION

Previously aromatic heterocycles such as chloropyridine and chlorothiazole were considered necessary for actuvity within the chloronicotinyl or neo-nicotinoid groups of nitroimino derivatives (Mitsui Chemicals Inc., 1998); these act on postsynaptic nicotinic acethylcholine receptors (Bai *et al.*, 1991). While conducting research in nitroimino derivatives considering acethylcholine skeleton, a certain group of nitroimino compounds with an alkoxyalkyl moiety were discovered showing activity. After intensive exploratory research in the nitroimino compounds as lead skeletons, MTI-446 [(RS)-1-methyl-2-nitro-3-[(3-tetrahydrofuryl)methyl]-guanidine] was selected as the most effective promising compound (Figure 1). MTI-446 is currently under development by Mitsui Chemicals, Inc.

DISCOVERY PROCESS

The discovery process of MTI-446 is shown in Figure 1.

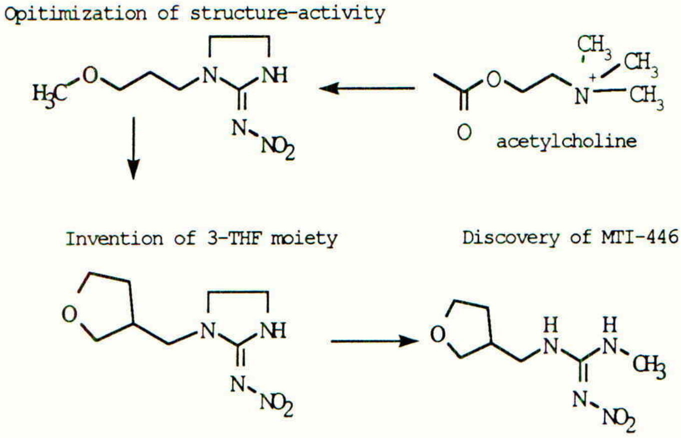
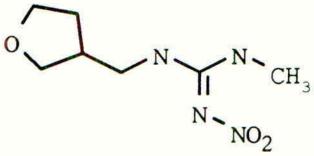


Figure 1. Discovery process of MTI-446.

CHEMICAL AND PHYSICAL PROPERTIES

Code number:	MTI-446
Chemical name(IUPAC):	(RS)-1-methyl-2-nitro-3-[(3-tetrahydrofuryl)methyl]-guanidine

Structural formula:



Molecular formula:	$C_7H_{14}N_4O_3$
CAS Registry No.:	165252-70-0
Molecular weight:	202.21
Melting Point:	94.5-101.5
Relative Density:	1.33
Water Solubility:	54.3 ± 1.3 g/l (purified water,20)
Partition coefficient:	Log_{10} KOW=-0.644 (pH7)
Dissociation constant:	No dissociation between pH value of 1.4-12.3

TOXICOLOGY AND ENVIRONMENTAL PROPERTIES

Molecular Toxicology

Mutagenicity Study	*Status*
Bacterial DNA Repair Study (Rec assay)	Negative
Bacterial Reverse Mutation Study (Ames test)	Negative
In vitro Mammalian Cytogenetics Test (Chromosomal aberration study)	Negative

Mammalian Toxicology

Acute study (LD50, mg/kg)	*Animal*	*Male*	*Female*
Oral:	Mice	2450	2275
	Rats	2804	2000
Dermal:	Rats	>2000	>2000

Dermal Sensitization Study		*Status*
Maximization method:	Guinea Pig	Negative

Environmental Safety

Aquatic Toxicity (LC50, ppm)

Carp	>1000(96hr)
Rainbow trout	>40(48hr)
Crayfish	5-10(48hr)
Daphnia	1000(48hr)

Avian Toxicity (LD50, mg/kg)

Japanese quail	>2000
Mallard duck	1000

BIOLOGICAL PROPERTIES

Laboratory tests

Table 1. Basal activity .

Insect	Activity*	Method
Sogatella furcifera	4	Foliar
Nilaparvata lugens	4	Foliar
Laodelphax striatellus	3	Foliar
Nephotettix cincticeps	4	Foliar
Myzus persicae	3	Foliar
Aphis gossypii	3	Foliar
Trialeurodes vaporariorum	3	Foliar
Bemisia tabaci	3	Foliar
Leptocorisa chinensis	3	Spray on insect
Thrips palmi	3	Foliar
Oulema oryzae	3	Spray on insect
Lissorhoptrus oryzophilus	3	Spray on insect
Chilo suppressalis	2	Spray on insect
Phyllotreta striolata	2	Foliar
Plutella xylostella	2	Leaf dipping
Pieris rapae	2	Leaf dipping
Spodoptera litura	2	Leaf dipping
Liriomyza trifolii	2	Foliar
Musca domestica	2	Spray on glass surface
Blattella germanica	3	Spray on glass surface

* Activity LC$_{50}$ (ppm)

1: > 100 2: 100 - 10 3: 10 - 1 4: 1 - 0.1

Field trials

(1) Eggplant

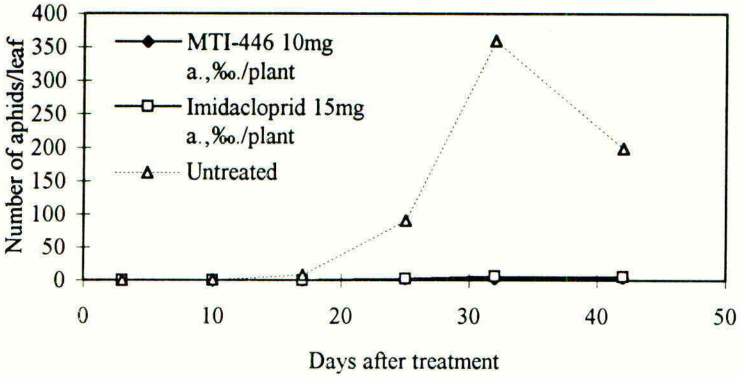


Figure 2. Efficacy of MTI-446 granule formulation applied into a plant hole prior to transplanting at 10 mg a.i/plant against cotton aphid, *Aphis gossypii*, in comparison with imidacloprid (Hiroshima, Japan, 1994).

(2) Cucumber

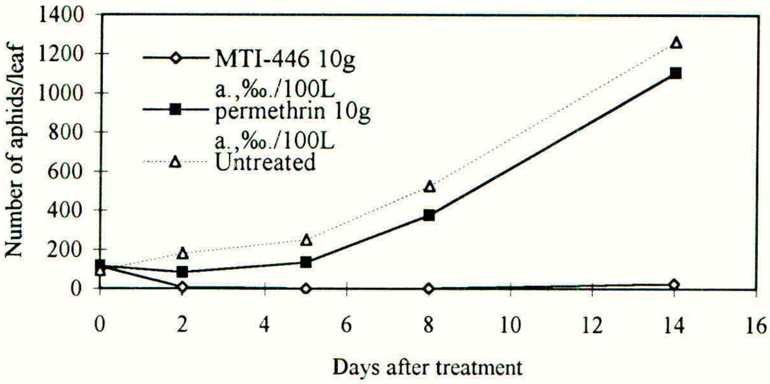


Figure 3. Efficacy of foliar application of MTI-446 soluble powder formulation at 10 g a.i./ 100 litres of water against resistant colony of cotton aphid, *Aphis gossypii*, in comparison with permethrin (Hiroshima, Japan, 1994).

(3) Tomato

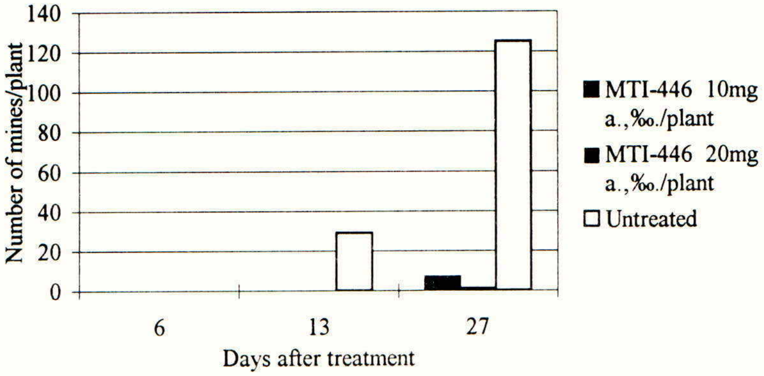


Figure 4. Efficacy of MTI-446 granule formulation applied into a plant hole prior to transplanting at 10, 20 mg a.i./plant against legume leafminer, *Liriomyza trifolii*, (Chiba, Japan, 1997).

(4) Cabbage

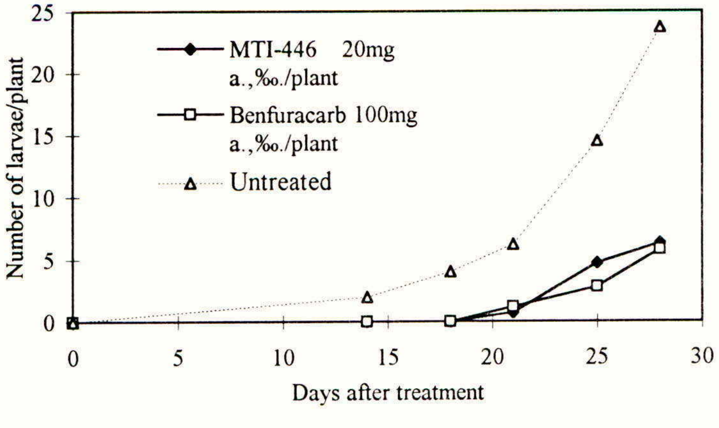


Figure 5. Efficacy of MTI-446 granule formulation applied into a plant hole prior to transplanting at 20 mg a.i./plant against diamond-back moth, *Plutella xylostella*, in comparison with benfuracarb (Chiba, Japan, 1998).

(5) Apple

Table 2. Efficacy of foliar application of MTI-446 soluble powder formulation at 10 g a.i./ 100 litres of water against codling moth, *Cydia pomonella*, in comparison with tebufenozide (Nimes, France, 1998).

Treatment	Dosage (g a.i/100 litres)	% Control at 10 DAT
MTI-446	10	95.1
Tebufenozide	14.4	94.8
Untreated	-	(81.5)

( ) : Number of larvae per 100 fruits

(6) Sugar beet

Table 3. Efficacy of sugar beet seeds treated with MTI-446 wettable powder at 65, 130 g a.i./ unit (ca.100,000 seeds) against flea beetle, *Chaetocnema tibialis* in comparison with imidacloprid (Nimes, France, 1997).

Treatment		Number of stings / 20 plants at 28 days after sowing
MTI-446	65 g a.i./unit	22.3
MTI-446	130 g a.i./unit	8.5
Imidacloprid	130 g a.i./unit	37.5
Untreated	-	147.5

CONCLUSIONS

MTI-446 is a novel insect control compound containing tetrahydrofuryl moiety in its structure. Field trials have shown high efficacy and root-systemic activity of MTI-446 against a relatively broad range of target pests at 100 to 200 g ai/ha. MTI-446 also demonstrates a low toxicity to mammals, birds and fish. MTI-446, therefore, is a promising compound to be used in controlling insect pests in various crops.

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CGA 293'343: a novel broad-spectrum insecticide supporting sustainable agriculture worldwide

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ABSTRACT

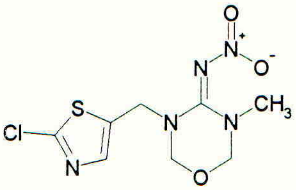
CGA 293'343 (ISO draft common name: thiamethoxam) is a new neonicotinoid insecticide with exceptional activity. Belonging to the subclass thianicotinyl compounds, it represents the first example of the second generation neonicotinoids. It was discovered by Novartis in 1991 and is now being developed worldwide for use in more then 20 crops. CGA 293'343 exhibits rapid plant uptake and is xylem-transported to untreated portions of the plant. Due to its systemic nature, a variety of application methods may be used to apply CGA 293'343. Results from the laboratory and field trials indicate that dose rates between 10 and 200 grams active ingredient per ha applied by foliar/soil or seed treatment, are sufficient for control of all target insect pests such as aphids, whiteflies, thrips, ricehoppers, ricebugs, mealybugs, white grubs, Colorado potato beetle, flea beetles, wireworms, ground beetles, leafminers and some lepidopterous species. CGA 293'343 can virtually be used in all situations - from staple food to highly industrialized crop production. The major crops for foliar and soil treatments are cole crops, leafy and fruity vegetables, potatoes, rice, cotton, deciduous fruit, citrus, tobacco and soya. For seed treatment use, maize, sorghum, cereals, sugarbeet, oil seed rape, cotton, peas, beans, sunflower, rice and potatoes are targeted crops. Market introduction of CGA 293'343 is scheduled for 1998 - 2000 under trademarks ACTARA™ for foliar and soil treatments, and CRUISER® for seed treatment.

INTRODUCTION

Neonicotinoids are a novel and distinct class of insecticides with new mode of action, selective toxicity to insects, and a favourable safety profile (Yamamoto, 1996). Due to these characteristics the neonicotinoids are considered as a suitable substitution of some organophosphate, carbamate, pyrethroid and organochlorines compounds currently used in crop protection, but suffering from high mammalian toxicity, resistance and/or unfavourable environmental properties. CGA 293'343, a thianicotinyl insecticide, is a compound of second generation of neonicotinoids (Maienfisch *et al.*, 1998). This paper describes the technical properties and latest findings on biological performance of CGA 293'343.

CHEMICAL AND PHYSICAL PROPERTIES

Chemical Structure:



Code Number:	CGA 293'343
Chemical Name:	3-(2-Chloro-thiazol-5-ylmethyl)-5-methyl-[1,3,5]oxadiazinan-4ylidene-N-nitroamine
Empirical Formula:	$C_8H_{10}ClN_5O_3S$
Chemical Class:	Neonicotinoid
Subclass:	Thianicotinyl
Common Name:	Thiamethoxam (ISO draft)
Molecular Weight:	291.72
Physical State at 20° C:	Crystalline powder
Melting Point:	139.1° C
Water Solubility 25° C:	4,100 mg/l
Vapor Pressure 25° C:	6.6×10^{-9} Pa
Partition Coefficient 25° C (log P_{ow}):	-0.13
Formulations	WG25, SC240, GR1, WS70, FS350, combinations

MAMMALIAN TOXICOLOGY

Mammalian toxicity is shown in Table 1.

Table 1. Acute toxicity of technical CGA 293'343

Acute Oral LD_{50}, Rat	1,563 mg/kg
Acute dermal LD_{50}, Rat	>2,000 mg/kg
Acute inhalation LC_{50} (4h), Rat	>3,720 mg/m^3
Eye Irritation, Rabbit	Non-irritant
Skin Irritation, Rabbit	Non-irritant
Skin Sensitization, Guinea pig	Non-sensitizing

ECOTOXICOLOGY

CGA 293'343 has favorable ecological toxicology characteristics (Table 2). For birds, CGA 293'343 is slightly toxic by gavage and practically non-toxic when ingested. It is practically non-toxic to fish, *Daphnia*, and molluscs. Algae and earthworms are insensitive to CGA 293'343 and it is moderately toxic to mysid shrimp.

Table 2: Effect of CGA 293'343 on non-target organisms.

Avian Oral LD_{50}	Bobwhite quail	1552 mg/kg
	Mallard duck	576 mg/kg
Avian Dietary LC_{50}	Bobwhite quail	>5200 ppm
	Mallard duck	>5200 ppm
Freshwater Fish LC_{50} (96h)	Rainbow trout	>100 mg/litre
	Bluegill	>114 mg/litre
Marine Fish LC_{50} (96h)	Sheepshead minnow	>111 mg/litre
Freshwater invertebrate EC_{50} (48 h)	*Daphnia magna*	>100 mg/litre
Marine invertebrate EC_{50} (96 h)	Mysid shrimp	6.9 mg/litre
	Eastern oyster	>119 mg/litre
Algae EC_{50} (96h)	Green algae	>100 mg/litre
Earthworm EC_{50} (14d)	*Eisenia foetida*	>1000 mg/kg soil
Beneficial insect LD_{50}	Honey bee	0.024 µg/bee

BIOLOGICAL PROPERTIES UNDER LABORATORY AND GREENHOUSE CONDITIONS

Biological Laboratory Evaluation

In the laboratory, CGA 293'343 has proven to be highly effective against *Lepidopteran, Coleopteran, Thysanopteran* and especially *Homopteran* pests. It exhibits contact, stomach and systemic activity. The long-lasting residual effect is a special benefit of this compound (Maienfisch *et al.*, 1998).

Uptake and distribution

CGA 293'343 has a low molecular weight, low octanol-water partition coefficient and relatively high water solubility, all of which favor rapid and efficient uptake and xylem transport. When applied to the soil or seed, CGA 293'343 is rapidly taken up by the roots, or germinating seedlings respectively, and is translocated to the cotyledons and leaves. CGA 293'343 is transported in the xylem in an acropetal direction. This systemic activity protects plant parts situated acropetally from the application site with efficacious levels of CGA 293'343. Degradation of CGA 293'343 in the plant is slow, resulting in insect control for an extended period of time.

Efficacy against resistant insects

In laboratory and field studies, CGA 293'343 provides excellent control of insects resistant to many chemical classes (Table 3). Laboratory studies indicate no cross-resistance between CGA 293'343 and imidacloprid (Prabhaker & Toscano, personal communication).

Table 3. Resistant factors (RF) of insect strains resistant against various chemical classes, expressed as quotient of LC_{50} values of resistant and susceptible strains. Dose-response assays were performed on punched and foliar treated leaf discs against nymphs N1 (*M. persicae*) or adults (*B. tabaci*).

Compound	Reference strain LC_{50} µg/ml	Reference strain Slope	Resistant strain LC_{50} µg/ml	Resistant strain Slope	RF
Myzus persicae					
CGA 293'343	0.64	4.7	0.61	4.0	1
Pirimicarb	0.55	8.7	50.2	5.0	91
Triazamate	5.1	6.3	302	3.2	59
Bemisia tabaci					
CGA 293'343	0.8	2.1	1.2	1.1	1
Profenofos	3.6	4.5	79.5	4.0	22
Furathiocarb	5.9	3.2	592	1.9	100

BIOLOGICAL PROPERTIES UNDER FIELD CONDITIONS

Foliar and Drench

Vegetables

Field trials were carried out in many leafy and fruity vegetable crops all over the world. CGA 293'343 was proven to be highly active against aphids (*Aphis fabae, A. gossypii, Aulacorthum solani, Myzus persicae, Brevicoryne brassicae, Macrosiphum euphorbiae, Nasanovia ribisnigri*) and, jassids (*Empoasca devastans*, *E. lybica*) in a dose rate of 2.5 g/100 litres. Higher dose rate, 5 g/100 litres, is needed for control of whiteflies (*Bemisia tabaci, B. argentifolii, Trialeurodes vaporariorum*) as well as for the control of flea beetles (*Phyllotreta* spp. and *Chaetocnema* spp.). Regarding the thrips control, CGA 293'343 shows excellent efficacy if applied via soil application.

CGA 293'343 applied as low - medium spray volume (200-400 litres/ha) in furrow application below seed bed is very effective on *Bemisia tabaci and B. argentifolii* in cucumber (Figure 1).

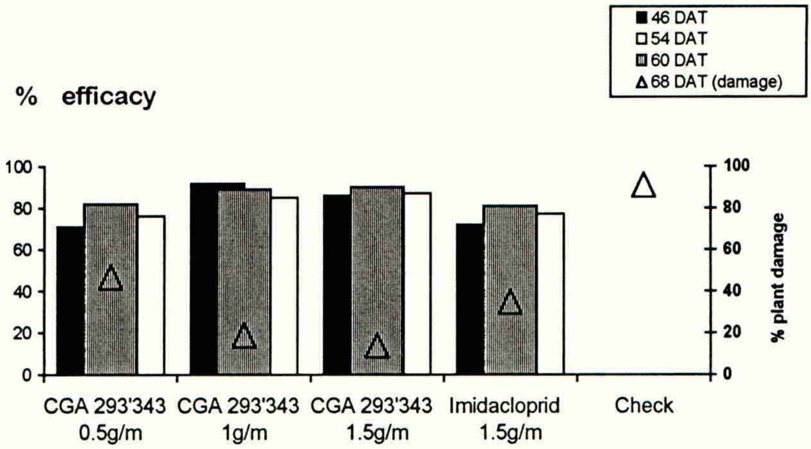


Figure 1. Efficacy of CGA 293'343 applied in furrow against *Bemisia argentifolii* on cucumber, Texas, USA, 1997.

Potatoes

CGA 293’343 was tested in the USA and other countries for the control of the Colorado potato beetle (*Leptinotarsa decemlineata*). The compound showed excellent activity at dose rates of about 25 g a.i./ha. At the same rates aphids (*Myzus persicae* and *Macrosiphum euphorbiae)* and jassids (*Empoasca fabae)* were also controlled. Figure 2 shows efficacy of CGA 293’343 in-furrow application on *Leptinotarsa decemlineata.*

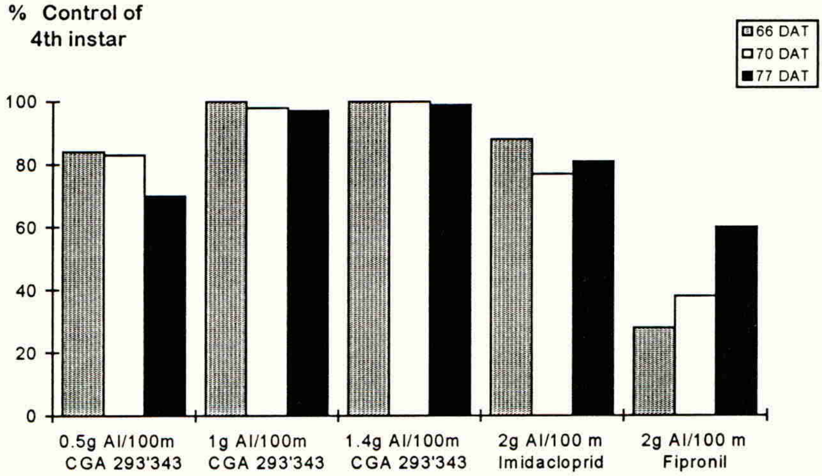


Figure 2. Effect of CGA 293’343 on control of *Leptinotarsa decemlineata* after in-furrow application at planting.

Rice

The performance of CGA 293’343 against the rice water weevil by seedling box application is very promising. Hoppers, which occur relatively early in the rice-growing season, are also controlled by seedling box application at the very low dose rate of 1 g a.i./box. For season-long control of the brown planthopper, the dose rate has to be increased to 1.5 g a.i./box. Foliar application of CGA 293’343 at rates of 6 g a.i./ha provided planthopper control equally to the best standard and better than the other tested neonicotinoid (Figure 3).

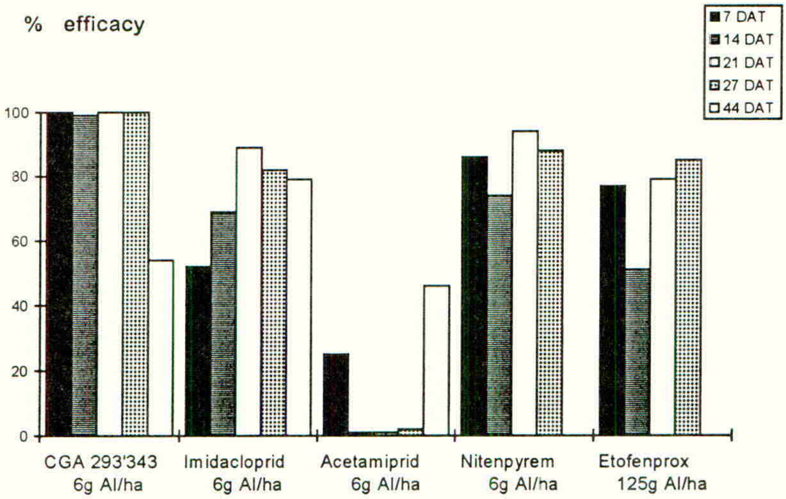


Figure 3. Efficacy of CGA 293'343 against *Nilaparvata lugens* on rice, Indonesia 1997.

Cotton

For control of aphids (*Aphis gossypii*) and jassids (*Empoasca devastans*) , a dose rate of about 30-50 g a.i./ha is recommended which provided control superior to the standard imidacloprid. For the control of plant bugs (*Lygus lineolaris)* on cotton higher rates of 50-100 g a.i./ha are needed.

At 100 g a.i./ha excellent control of whiteflies were reported from Brazil, USA as well as from Turkey (Figure 4).

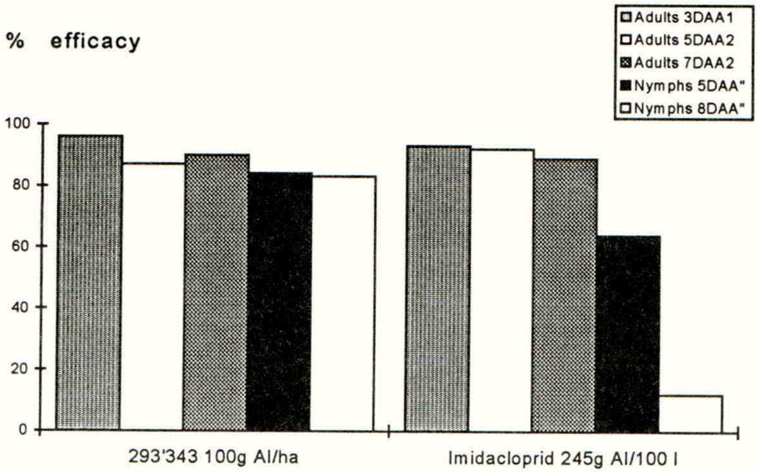


Figure 4. Efficacy of CGA 293'343 against adults and nymphs of *Bemisia tabaci* on cotton after 2 foliar applications, Turkey, 1997.

Seed Treatment

Maize

In maize, CGA 293’343 showed excellent and long-lasting activity against different species of wireworms (*Agriotes sp.*) at tested rates between 50 and 315 g a.i. per 100 kg seed in different climatic conditions around the globe (see Figure 5). At rates between 175 to 315 g a.i. per 100 kg seed, early and mid-season foliar pests including aphids, jassids, frit fly, black maize beetle, false wireworm and leaf bugs (*Rhopalosiphum* spp., *Zyginidia scutellaris, Oscinella frit, Heteronychus arator, Somaticus* spp., *Dichelops* spp. respectively) were also controlled effectively. Compared with the standard imidacloprid, CGA 293’343 had a better overall activity. The tested rates and formulations were well tolerated by the different hybrid and inbred lines used in their tests.

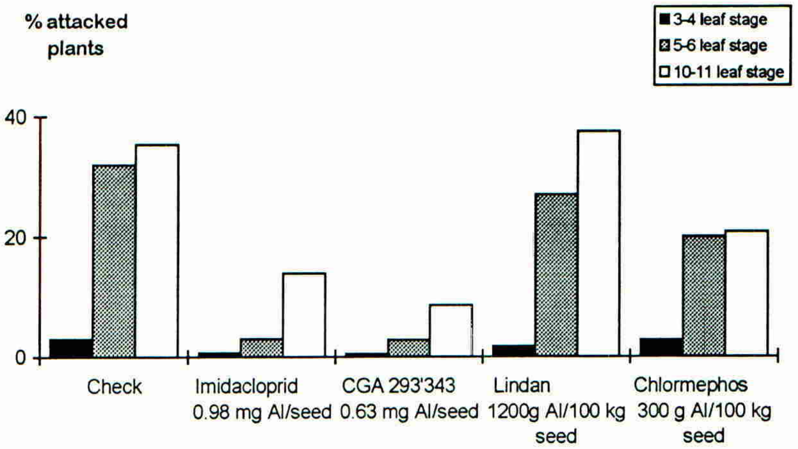


Figure 5. Efficacy of CGA 293'343 against wireworm (*Agriotes* sp.) on maize after seed treatment, France, 1997.

Cereals

The main reason for applying insecticide seed treatments to cereals is to prevent aphid-vectored virus transmission like Barley Yellow Dwarf Virus (BYDV). CGA 293'343 is very active against aphids (*Rhopalosiphum padi*) and a clear effect on virus transmission was observed (figure 7). In high pressure areas like in France, 52 to 70 g a.i./100 kg seeds may be needed whereas in low pressure areas, lower rates are sufficient (35 g a.i.). A rate of 35 g a.i./100 kg is also sufficient to control wireworms (*Agriotes sp.*) and ground beetle (e.g. *Zabrus tenebrioides*) in wheat and barley.

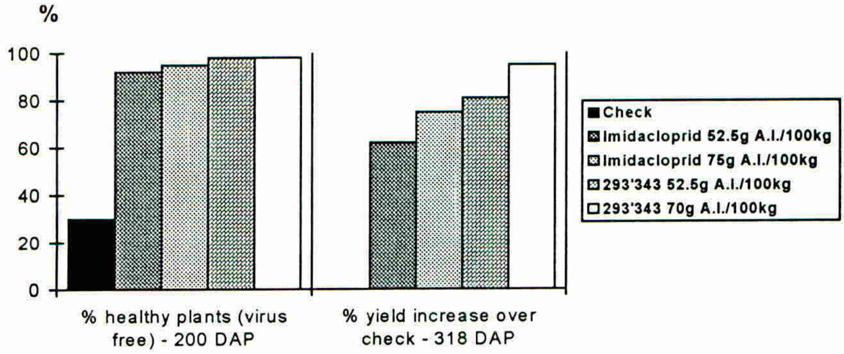


Figure 6. Efficacy of CGA 293'343 against barley yellow dwarf virus (BYDV) on barley after seed treatment, France, 1997. (Efficacy and yield response).

The use recommendation for CGA 293'343 are summarized in Table 4.

Table 4. Use recommendation for CGA 293'343.

Crop	Typical Pest	Foliar / Drench	Seed Treatment
Fruiting vegetables	*Aphis fabae, A. gossypii*	2.5 g a.i./100 litres	
Leafy vegetables	*Aulacorthum solani*		
Cole crops	*Myzus persicae*		
	Brevicoryne brassicae		
	Macrosiphum euphorbiae		
	Empoasca devastans		
	Bemisia tabaci, B. argentif.	5 g a.i./100 litres	
	Trialeurodes vaporiorum		
	Phyllotetra spp.		
	Chaetocnema spp.		
Potato	*Leptinotarsa decemlineata*	25 g a.i./ha	4–7.5 g a.i./100 kg
	Myzus persicae	0.5 - 1 g a.i./100 m	
	Macrosiphum euphorbiae	drench	
	Empoasca fabae		
Deciduous fruit	*Aphis pomi, A. gossypii*	2.5–5 g a.i./100 litres	
	Myzus persicae		
	Schizaphis piricola		
	Dysaphis plantaginea		
Citrus	*Aphis gossypii*	1–3 g a.i./100 litres	
	Toxoptera spp.		
	Phyllocnistis citrella	5–7.5 g a.i./100 litres	
	Planococcus spp.		
Tobacco	*Myzus persicae*	100–150 g a.i./ha	
	Epitrix fasciata	drench	
	Faustinus cubae		
Soybean	*Dichelops furcatus*	12.5–25 g a.i./ha	
	Nezara viridula		
Rice	Water weevil	1–1.5 g a.i./box	
	Planthoppers	6–12 g a.i./ha foliar	
	Deois flavopicta		50–100 g a.i./100 kg
	Elasmopalpus lingnosellus		
Cotton	*Aphis gossypii*	30–50 g a.i./ha	
	Empoasca devastans		
	Lygus lineolaris	50–100 g a.i./ha	
	Whiteflies	100 g a.i./ha	
	Thrips tabaci, Frankiniella		70–210 g a.i./100 kg
	Eutinobothrus spp.		
	Aphis gossypii, Agriotes sp.		
Maize	*Agriotes* sp.		40–315 g a.i./100 kg
	Rhopalosiphum spp.		
	Oscinella frit		
	Heteronychus arator		
	Dichelops spp.		
Cereals	*Rhopalosiphum padi*		35–70 g a.i./100 kg
	Agriotes sp.		
	Zabrus tenebrioides		
Sugarbeet	*Myzus persicae, A. fabae*		60 g a.i. per unit (unit = 100 000 seeds)
	Atomaria spp.		
	Chaetocnema spp.		
	Pegomya betae		

continued

Table 4 continued

Crop	Typical Pest	Foliar / Drench	Seed Treatment
Sorghum	*Rhopalosiphum maidis* *Agriotes sp.* *Schizaphis graminum*		100–200 g a.i./100 kg
Oilseed rapes	*Psylliodes chrysocephala* *Phyllotetra spp.* *Brevicoryne brassicae*		420–400 g a.i./100 kg
Peas/Beans	*Macrosiphum pisum* *Aphis fabae* *Sitona lineata*		52 g a.i./100 kg
	Bemisia tabaci		70–100 g a.i./100 kg
Sunflower	*Anuraphis helichrysi* *Myzus persicae* *Aphis fabae, Agriotes sp.*		350–700 g a.i./100 kg
Peanuts	*Frankliniella sp.*		150–200 g a.i./100 kg

CONCLUSIONS

CGA 293'343 is the first representative of the 2nd generation neonicotinoid compounds and has clear advantages, such as lower use rates and a much broader spectrum of control, than currently marketed products belonging to the neonicotinoid chemical class. It can be used on most agricultural crops and controls a wide range of sucking and chewing insects, including some Lepidoptera pests. CGA 293'343 is suitable for foliar and soil application as well as for seed treatment. Laboratory trials with CGA 293'343 on whiteflies showed no signs of cross-resistance towards the standard neonicotinoids. The safety profile of CGA 293'343 can be classified as favorable.

ACKNOWLEDGMENT

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Metarhizium anisopliae, isolate IMI 330189: A mycoinsecticide for locust and grasshopper control

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ABSTRACT

A cost-effective natural locust control product, trademarked Green Muscle, has been developed by an international research programme called LUBILOSA and will shortly be commercially available in South Africa. It is based on a naturally occurring fungal disease that kills grasshoppers and locusts but is harmless to most other organisms. The pathogen is *Metarhizium anisopliae* var. *acridum* (previously known as *Metarhizium flavoviride*). It is applied using formulations of conidia in a mineral or vegetable oil suspension, allowing the product to be used under dry and arid desert conditions (the application of mycoinsecticides traditionally was thought to require humid conditions). The spores are sprayed at ultra low volume using standard equipment including: motorised mist blowers, hand-held spinning disk or aerial sprayers. *Metarhizium anisopliae* isolate IMI 330189 typically achieves 90% kill in 7 to 21 days. Field trials in West Africa demonstrated that in comparison with a UL formulation of fenitrothion, the advantage of a high initial kill by the OP has been countered by the more sustained killing power of the mycoinsecticide and low impact on natural enemies.

INTRODUCTION

Locusts are considered major pests of agriculture world-wide, particularly in the dry regions, and are often subject to extensive control campaigns involving the use of large volumes of chemical pesticides. During the last Desert Locust (*Schistocerca gregaria*) and grasshopper outbreak between 1986 and 1989 in North-west Africa and the Sahel, the total donor assistance provided for control operations was approximately US$275 million, with the total costs including contributions from the afflicted countries exceeding US$400 million. The locust situation on the African continent remains highly volatile, with Migratory Locust (*Locusta migratoria capito*) spreading in Madagascar, Red Locust (*Nomadacris septemfasciata*) in a threatening position in South-eastern Africa and unusual rainfall patterns increasing the risk of Desert Locust outbreaks in East Africa and the Middle East. In addition, the Desert Locust, the Brown Locust (*Locustana pardalina*) and the Moroccan Locust (*Dociostaurus maroccanus*) continue to require regular intervention with chemical insecticides to prevent outbreaks, while the Sahelian grasshoppers (*Kraussaria angulifera*, *Cataloipus fusciocoedruleipes*, *Hieroglyphus daganensis* and *Zonocerus variegatus*) are regular serious pests of subsistence and cash crops in West Africa.

The extensive use of chemical insecticides, mainly organophosphates and pyrethroids in recent years, for the control of locusts and grasshoppers has prompted support for research into the development of biological alternatives. One of these initiatives, the LUBILOSA Programme (Lutte Biologique contre les Locustes et Sauteriaux - Biological control of locusts and grasshoppers)[1] has developed a mycoinsecticide based on the fungus *Metarhizium anisopliae* for the control of locusts and grasshoppers in Africa. This product is undergoing registration and commercialisation in South Africa.

TECHNICAL SPECIFICATIONS

The technical material of the mycoinsecticide product consists of aerial conidia of *Metarhizium anisopliae* var. *acridum*, isolate IMI 330189, isolated in Niger from the insect *Ornithacris cavroisi* (Finot) (Orthoptera: Acrididae). Before 1996, all scientific papers have referred to IMI 330189 (and similar isolates) as *Metarhizium flavoviride* but recent taxonomic studies using molecular methods have indicated that they are genetically more similar to *M. anisopliae* (Bridge *et al.*, 1997; Driver *et al.*, in press). The technical material (TC) of the product has the following properties:

	Specification
Appearance:	Uniform dark green powder, easily separable from desiccant or other packaging material
Viability:	> 90% at packing
Moisture content:	< 5% at packing (may rise to 6-7% soon after opening)
Contaminants:	<0.001% by number, no human pathogens
Number of conidia:	5±1 x 10^{10}/g dry powder
Particle size:	The technical material (TC): <10 µm: 80% by volume <60 µm: 99.9% by volume <100 µm: 100% by volume
Virulence:	A dose of 5 x 10^4 conidia/ insect kills >50% adult target locusts in 5 days and >90% in 6 days.

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[1] The LUBILOSA programme is an international collaborative research and implementation programme executed by CABI Bioscience (formerly International Institute of Biological Control), the International Institute of Tropical Agriculture (IITA), Comité Permanent Interétat pour la Lutte contre la Secheresse au Sahel (CILSS) and Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ). LUBILOSA is funded by the Canadian International Development Agency (CIDA), the Swiss Development Corporation (SDC), the Directorate General for International Co-operation (DGIS; the Netherlands) and the Department for International Development (DfID; UK).

The minimum standards for storage of the technical concentrate are three years at a temperature not exceeding 20°C (70% + germination after 24hrs incubation at 25°C). A mycoinsecticide product should retain much of its viability for at least one month under field conditions. The spores can tolerate 5 days at 50°C; 14 days at 40°C and 12 months at 30°C.

An oil miscible flowable (OF) formulation has been developed which remains stable for at least 6 months (i.e. one season) without loss of activity.

BIOLOGICAL PERFORMANCE

Metarhizium conidia infect by attaching to the insects' external cuticle, then germinating, penetrating and invading the body tissues with hyphae and blastospores. They are ineffective when ingested. Field observations suggest that spores may persist in the field for up to 10 days, depending on conditions. Unlike chemical insecticides, the mycoinsecticide has the added advantage of "horizontal transmission" (or "secondary cycling") of the pathogen whereby the infected insects produce fungus which sporulates on the cadaver and is released to provide further inoculum.

The ability of the conidia of the mycoinsecticide to persist and germinate on target insects even in arid environments is dependent on a discovery made by Dr. Chris Prior, who demonstrated that when fungal conidia were formulated in oil, their efficacy and speed of kill were improved in comparison with water-based suspensions (Prior *et al.*, 1988). Enhanced efficacy with oils was later confirmed for the desert locust, using formulations of *M. anisopliae* (Bateman *et al.*, 1993) with the difference especially pronounced at low relative humidities (Jenkins *et al.*, 1998). This development enabled *M. anisopliae* to be formulated for use with the normal ULV spraying equipment used for locust control operations in Africa including: motorised mist blowers, hand-held spinning disk or aerial sprayers. For application, the dry spore powder is mixed in suitable (readily available) mineral and/or vegetable oils to prepare ULV suspension (SU) formulations. The standard volume application rate (VAR) for the mycoinsecticide is 1.0 l/ha although rates as low as 0.5 l/ha have been shown to be effective. In South Africa, VARs of about 2.5 l/ha are used for locust control with motorised mist blowers.

IMI 330189 has been extensively field tested in many African countries through collaboration with national plant protection services; these include Benin, Burkina Faso, Chad, Niger, Mali, Mauritania, Senegal, South Africa and Sudan. The mycoinsecticide has been shown to be highly effective in controlling the major six acridid pest species of locusts and grasshoppers (*S. gregaria*, *L. pardalina*, *D. maroccanus*, *N. septemfasciata*, *H. daganensis* and *Z. variegatus*) in addition to a number of grasshopper species that are locally important. In South Africa, first experimental use indicated efficacy of IMI 330189 against the Brown Locust (Bateman *et al.*, 1994). The product has since proved effective in over three seasons of trials in the Karoo (the main Brown Locust outbreak area). Aerial application trials of IMI 330189 have been successfully conducted with the survival of mobile hopper bands estimated with use of enclosures and cages (Figure 1).

Two field trials in Niger have demonstrated that in comparison with fenitrothion, the advantage of an initial high kill by the OP is later countered by the more sustained killing power of the mycoinsecticide (Figure 2); this may partly be due to the effect of preserving natural enemies.

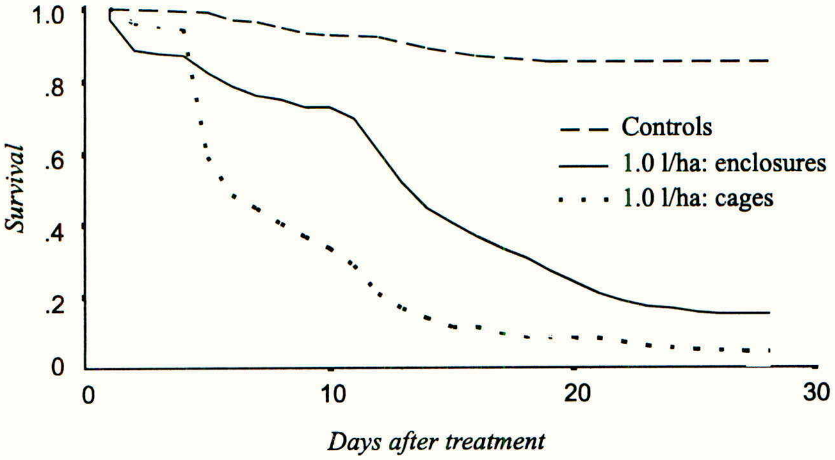

Figure 1. 1995 aerial trial using *Metarhizium anisopliae* IMI 330189 on *Locustana pardalina* in the Karoo, South Africa.

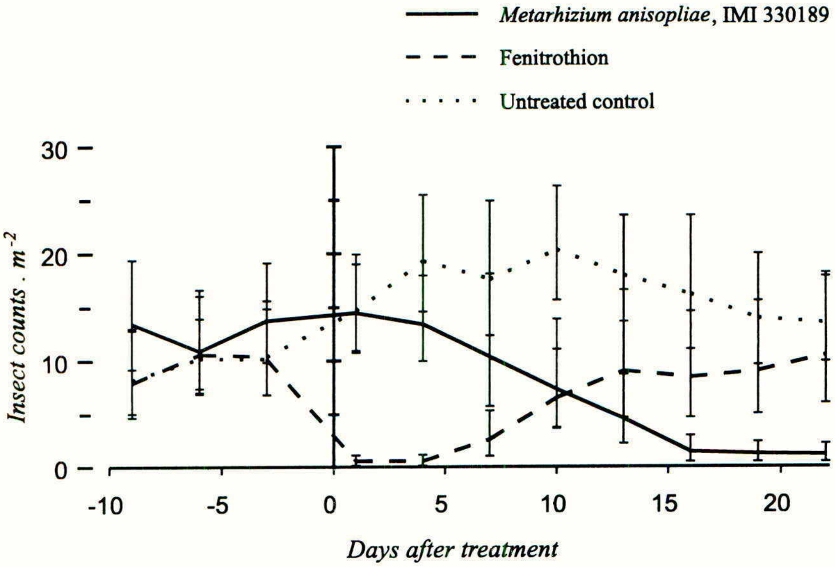

Figure 2. 1997 aerial trial on *Oedaleus senegalensis* using 800 ha plots in Maine Soroa, E. Niger (after Langewald *et al.*, submitted).

TOXICOLOGY

Acute toxicity:	LD_{50}/ oral/ rat (Limit test) >2000 mg/kg.
Eye irritation:	Non-irritant (rabbit).
Skin irritation:	Non-irritant (rabbit).
Acute pulmonary toxicity/infectivity:	LC_{50}/ rat >4850 mg/m^3. Non-infective to mammals.
Acute intra-peritoneal injection:	Non-infective to mammals (rat).

ECOTOXICOLOGY

An extensive range of ecotoxicological tests have been carried out to determine the impact of IMI 330189 on non-target organisms. These studies have shown that IMI 330189 has only low or moderate infectivity to some species of Isoptera, Coleoptera and some Hymenoptera, Hemiptera, Dictyoptera and other Coleoptera and Hymenoptera are not infected (Prior, 1997). The FAO Locust Pesticide Referee Group have added IMI 330189 to their list of recommended products for use in environmentally sensitive areas.

DISCUSSION

There are basic biological constraints which mean that pathogen-induced mortality will always be much slower than that produced by 'knock-down' chemicals. In field trials on locusts and grasshoppers, mortality does not usually occur earlier than 6 days after spraying and may take longer depending on dose and environmental conditions. Thus, biopesticides cannot hope to replace chemicals under all control scenarios. However, there are many situations where speed of kill is not critical; for instance, where locusts and grasshoppers are sprayed in non-crop habitats as part of preventative control measures, rather than crop protection (Prior and Streett, 1997). In these situations the mycoinsecticide has proved its effectiveness even in the harshest of environments. The specificity of the mycoinsecticide and hence its extremely low impact on non-target organisms makes it especially suitable for use against locusts and grasshoppers in environmentally sensitive or conservation areas. Use of IMI 330189 also preserves the action of natural enemies, thereby providing additional levels of control, a characteristic which makes it superior to current chemical locust control agents.

The mycoinsecticide product based on IMI 330189 will be commercially available at the end of 1998 and will provide an effective, environmentally friendly alternative to chemical control for the management of locusts and grasshoppers in Africa.

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Fast release capsules : a new formulation of lambda-cyhalothrin

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ABSTRACT

A suspension of fast release polyurea capsules in water is a unique formulation of lambda-cyhalothrin for agricultural markets, offering clear benefits with respect to worker exposure, product storage, transport costs and convenience. This is achieved without compromising the cost-effective control of a wide range of insect pests or the low environmental risks previously associated with emulsifiable concentrate (EC) and wettable granule (WG) formulations. Significant improvements in the acute toxicological profile of lambda-cyhalothrin products through encapsulation, including reduced paraesthesia (subjective facial sensation), help to meet the demands of society for even greater safety in the use of pesticides. Field data illustrate the equivalent and in some cases enhanced biological performance of capsules compared to EC formulations.

INTRODUCTION

The insecticide lambda-cyhalothrin was launched at the Brighton Conference in 1984 (Jutsum *et al.*, 1984) and since then a range of agricultural and public health formulations, including EC, EW, WG, WP, UL and slow-release CS (capsule suspension), have been developed to meet the needs of customers in various markets around the world. Products based on lambda-cyhalothrin have demonstrated impressive efficacy against a broad spectrum of insect pests (Perrin, 1995) coupled with low environmental and operational risks (Bewick *et al.*, 1984; White *et al.*, 1992). In recent years further development of formulations and packs has been driven by the need to :

a. improve operator safety and convenience
b. minimise the impact of chemicals on the environment
c. improve cost-efficacy through extended residual control, reduced evaporative losses or better delivery to target sites.

Microencapsulation technologies have enabled considerable progress towards these objectives, generally via relatively slow release rates which improve the control of animal and public health pests, but are less suitable for the majority of agricultural markets. In this paper, we describe a water-based microencapsulated formulation of lambda-cyhalothrin which releases the active ingredient very rapidly, thus offering comparable and in certain cases improved control of crop pests to that seen with EC and WG. It is being launched in many parts of the world at various concentrations under the name Zeon Technology®, to distinguish it from other commercial formulations produced by Zeneca.

PHYSICAL PROPERTIES

Fast release capsules consist of a polyurea wall in which monomers (wall building units) reside only in the oil phase and produce a very efficient asymmetric membrane. This encloses the active ingredient (a.i.) dissolved in a small amount of aromatic solvent, the release rate of which is controlled by varying particle size, wall thickness and crosslink density of the wall. Active ingredient remains within the capsules in the container, the spray tank, and even in spray droplets, offering greater protection to users. However, once capsules lose their water barrier on leaf surfaces or insect cuticle, diffusion of lambda-cyhalothrin is very rapid, extending from minutes to hours. It has been noticed that the largest capsules burst upon drying, thus releasing their contents within seconds. A ring of solvent carrier from the capsule core extends the toxic point on a treated surface by up to 40%, and it appears that the transfer of a.i. to insects occurs in a very similar manner to an EC. Capsules were robust during the spraying process, and stable at field dilutions for at least 5 days. Dispersibility and compatibility with other agricultural products was good in all tests, although as a precaution the addition of capsules last in any tank mixing process is recommended.

An ultra-violet absorber is included in the capsule core and some improvement in photostability has been detected in laboratory experiments. Significant rainfastness was achieved within one hour of application. Typical physical properties of a 250 g/l quick release capsule are shown in Table 1.

Table 1. Physical properties of a 250 g/litre capsule formulation of lambda-cyhalothrin.

Weight % a.i	22.8
Density (g/ml)	1.096
pH	5.0
Mean particle size by volume (µm)	2.6
Viscosity (m Pa sec) at 50 sec^{-1} shear rate	140

ENVIRONMENTAL IMPACT

The environmental data for capsule formulations are very similar to that of EC or WG, with a trend towards less toxicity to some non-target organisms in laboratory tests. Capsule size is too small for any risk of confusion with pollen grains by foraging bees. All current formulations of lambda-cyhalothrin represent a low risk to aquatic and terrestrial ecosystems when label recommendations are followed, as proven in over 10 years of commercial use. Registration studies have demonstrated a similar crop residue decay pattern for capsules and EC s.

MAMMALIAN TOXICOLOGY

Significant improvements in the toxicological profile compared to EC result from water-based encapsulation (Table 2). In addition, the paraesthesia (a sensation of prickling or tingling of the skin associated with temporary irritation of sensory nerves, sometimes termed "subjective facial sensation") reported by a small proportion of users of most pyrethroid products, has been shown to be much reduced.

Table 2. Toxicological properties of a 250 g/litre capsule formulation compared with a 120 g/litre EC formulation of lambda-cyhalothrin.

	Capsule	EPA tox*	EC	EPA tox*
Oral LD_{50} (rat) (mg/kg)	245 (m) 180 (f)	II	64 (m) 101 (f)	II
Dermal LD_{50} (rabbit) (mg/kg)	>2000 (m,f)	III	>2000 (m,f)	III
Inhalation LC_{50} (rat) (mg/l)	3.72 (m) 3.12 (f)	III	0.32 (m) 0.18 (f)	II
Eye Irritation (rabbit)	Mild	III	Moderate	II
Skin Irritation (rabbit)	Mild	III	Extreme	I
Skin sensitisation	Mild		Mild	

* EPA toxicity categories: I (most toxic) - IV (least toxic)

FIELD DATA

Capsules of varying a.i. strengths have been evaluated extensively in all major crop outlets for lambda-cyhalothrin around the world. Typical field data comparing capsules with commercial EC formulations are shown in Tables 3 to 8.

Table 3. Control of *Helicoverpa zea* (cotton bollworm) in USA cotton with capsule and EC formulations of lambda-cyhalothrin applied at 33 g a.i./ha.

Formulation	% reduction in square damage		
	3 DAA (12.6)	7 DAA (23.6)	14 DAA (51.0)
EC	79	97	91
Capsules	92	91	96

( ) = % square damage in untreated plots
DAA = days after application

Table 4. Control of *Spodoptera frugiperda* (fall armyworm) in Brazilian maize with capsule and EC formulations of lambda-cyhalothrin applied at 7.5 g a.i./ha.

Formulation	% control of armyworm	
	2 DAA (20)	7 DAA (23)
EC	77	89
Capsules	79	92

( ) = larvae/25 plants in untreated plots

Table 5. Control of *Nephotettix cincticeps* (green leafhopper) in Philippine rice with capsule and EC formulations of lambda-cyhalothrin applied at 1.5 g a.i./ha.

Formulation	% control of GLH	
	3 DAA (13)	7 DAA (22)
EC	60	67
Capsules	77	80

( ) = adults/10 sweeps in untreated plots

Table 6. Control of aphid-transmitted barley yellow dwarf virus in French autumn-sown barley with capsule and EC formulations of lambda-cyhalothrin applied at 7.5 g a.i./ha.

Formulation	% plot area with BYDV symptoms in April (81)
EC	8.8
Capsules	5.0

( ) = % BYDV symptoms in untreated plots

Table 7. Control of *Acyrthosiphon pisum* (pea aphid) in UK peas with capsule and EC formulations of lambda-cyhalothrin applied at 5 g a.i./ha.

Formulation	% control of aphids	
	7 DAA (30)	12 DAA (57)
EC	89	82
Capsules	91	84

( ) = aphids/growing point in untreated plots

Table 8. Control of *Anthonomus grandis* (boll weevil) in Brazilian cotton with capsule and EC formulations of lambda-cyhalothrin applied at 15 g a.i./ha.

Formulation	% reduction in square damage	
	7 DAA 1 (29)	10 DAA 2 (80)
EC	79	64
Capsules	92	72

( ) = % square damage in untreated plots

From a statistical analysis of 146 field trials on 16 crops in North America from 1994 to 1997, it was concluded that the efficacy of the capsule formulations was as good as or in some cases better than EC formulations (K.J. Ward *et al.*, 1998). Assessments made in 22 boll weevil trials indicated a superior performance from the capsules, which is being investigated further in this species and other Coleoptera. In another analysis of 19 trials in South America and Asia in 1996, capsules were equivalent or superior to EC in all cases, with evidence of better residual control from the former. Initial sales of the capsule formulations in North and South America during 1998 have confirmed excellent efficacy and customer acceptance in outlets including vegetables, maize and forestry.

BENEFITS OF FAST RELEASE CAPSULES

End users, distributors and retailers will all benefit from the introduction of fast release, water-based capsule technology as a replacement for solvent-based products. Advantages include :

a. less protective clothing required due to lower toxicity hazards
b. reduced paraesthesia or "subjective facial sensation"
c. safer storage due to reduced flammability and volatility
d. lower packaging and transport costs for higher strength products containing up to 250g ai/l
e. less odour and damage to paint and other surfaces from solvents

The consistently high standards of pest control, compatibility with most application equipment and other agricultural products, and ease of handling experienced with EC and WG formulations of lambda-cyhalothrin have been retained.

CONCLUSIONS

Fast release microencapsulation technology is being launched by Zeneca in agricultural markets worldwide in response to the needs for further improvements in operator safety and convenience, reduced impact of agrochemicals on the environment and increased efficiency and integration with other IPM tools. Benefits for all those who handle lambda-cyhalothrin products have been achieved without compromising cost-effectiveness in pest control and in some cases, which are being investigated further, improving on the levels of control previously seen with conventional formulations.

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The authors would like to thank the many chemists and biologists within Zeneca who have contributed to the current development and understanding of this unique technology.

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Novaluron, optimisation and use for the control of the beet armyworm and the greenhouse whitefly

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ABSTRACT

Novaluron is a new insect growth regulator, acting on a diversity of lepidopteran and whitefly pests. Among the tested formulations, the EC-X was the most efficient for controlling the greenhouse whitefly and the EC for controlling the beet armyworm. In assays with the greenhouse whitefly *Trialeurodes vaporariorum*, novaluron (LC-90 = 3.28 mg a.i./litre) was 2-fold more potent than lufenuron (LC-90 = 6.29 mg a.i./litre) and about 14-fold more potent than teflubenzuron (LC-90 = 47.0 mg a.i./litre). Novaluron is a potent larval growth suppresser of the beet armyworm *Spodoptera exigua*. Feeding on sweet pepper seedlings treated with 0.09 and 0.27 mg a.i./litre, resulted in 46 and 98% larval mortality and 61% and total suppression of larval weight gain. Teflubenzuron at these concentrations was less potent. Novaluron was equally potent on *S. exigua* larvae when assayed with either sweet pepper seedlings or castor bean leaves, indicating that novaluron is equally potent when used on various host plants.

The residual toxicity of novaluron, under greenhouse conditions, was efficient in controlling the greenhouse whitefly and the beet armyworm for about 2 weeks.

Assays are now in progress to optimise the use of novaluron as a component in IPM programs for controlling the above pests.

INTRODUCTION

Novaluron (Rimon), 1-[3-chloro-4-(1,1,2-trifluoro-2-trifluoro-methoxyethoxy)phenyl]3-(2,6-difluorobenzoyl)urea, is a novel benzoylphenyl urea acting by ingestion and contact. It is a powerful suppresser of lepidopteran larvae such as *Spodoptera littoralis* and *Helicoverpa armigera* (by ingestion) and of the cotton whitefly *Bemisia tabaci* (by contact). Recent studies (Ishaaya *et al.*, 1996) indicated that the LC-50 of novaluron on *S. littoralis* is about 0.1 mg a.i./litre. This value resembles that of chlorfluazuron and is over ten-fold that of teflubenzuron. It is a powerful suppresser of the agromyzid leafminer *Liriomyza huidobrensis* (Ishaaya *et al.*, 1996), and of the western flower thrips *Frankliniella occidentalis* (unpublished results).

The beet armyworm *Spodoptera exigua* and the greenhouse whitefly *Trialeurodes vaporariorum* are important pests attacking a variety of vegetables, field crops and ornamentals. Serious outbreaks of the beet armyworm in cotton fields occurred in 1977 in the south eastern part of the US (Mitchell *et al.*, 1977) and since then, it has become a chronic pest of cotton in this area (Akey & Henneberry, 1998). In addition, this pest is important in vegetables and ornamentals in the central and the southern parts of Europe (Van Laecke & Degheele, 1993). The greenhouse whitefly *T. vaporariorum* is a cosmopolitan pest of many crops. A large population of this whitefly affects plant development and decreases crop yield.

In some regions, whiteflies are vectors of viral diseases which are considered a limiting factor for the production of some vegetables and ornamentals. Among the novel insecticides for controlling whiteflies are the chitin synthesis inhibitor buprofezin, the thiourea derivative diafenthiuron, the juvenoid compound pyriproxyfen, and the chloronicotinyl insecticides imidacloprid and acetamiprid (Ishaaya & Horowitz, 1998). However after successive use of pyriproxyfen or buprofezin in greenhouses and cotton fields, a relatively high resistance was recorded, in some locations, to these compounds (Horowitz & Ishaaya, 1994; De Cock *et al.*, 1995). Research is continuously required to evaluate novel insecticides with selective properties to be used, against these pests, as components in IPM programs which are now in a wide practice in most European countries.

During the course of this project, we have optimised the use of novaluron for controlling *S. exigua* and *T. vaporariorum* under both laboratory and greenhouse conditions, along with its suitability to be used as a component in IPM programs.

MATERIALS AND METHODS

T. vaporariorum adults were collected from a standard colony reared on tobacco plants in a greenhouse, at a temperature ranging from 20 to 28°C. *S. exigua* larvae were reared on a modified Poitout artificial diet under standard conditions of 23±1°C, 65% RH and a photoperiod of 16:8 L:D (Smagghe & Degheele, 1994). Both colonies are reared in the Laboratory of Agrozoology of the University of Gent for at least 10 years.

Assays with *Trialeurodes vaporariorum*

Adults (20-30) confined in leaf cages (Ishaaya *et al.*, 1996) were exposed to leaves of bean seedlings for 24 h oviposition. Plants infested with 1st-instars were sprayed until run-off. Assays were kept in controlled conditions of 23±1 °C and 65% RH, and a photoperiod of 16:8 h L:D. Larval mortality, pupation and emergence were then determined. Treatments were done with 5-6 replicates and each mortality curve with at least 4 concentrations.

For determining the residual toxicity under greenhouse conditions, tomato and bean plants were sprayed until run-off. Treated plants were exposed periodically after treatment to whitefly adults (confined in leaf cages) for 24 h oviposition. Larval mortality, expressed in reduced level of pupation, was determined. Determinations were continued for 3 weeks.

Assays with *Spodoptera exigua*

In a first series of tests, sweet pepper plants were sprayed until run-off with the test compound. After air drying at room temperature, each plant was transferred to a plexi-glass cylinder. Ten to fifteen 3rd-instars (0-6 h after ecdysis , 2.0±0.1 mg) were introduced into each cylinder. The cylinders were covered with a gauze and kept under controlled conditions of 23±1 °C, 65% RH, and a photoperiod of 16:8 h L:D . Larval weight gain and mortality were recorded after 6 days. Treatments were done with 4-8 replicates of 12-15 larvae and each mortality curve with at least 4 concentrations. In a second series of tests, castor bean leaves were dipped in the test solution and offered to 3rd-instars for 3-day feeding; untreated leaves were offered for an additional 3 days. Larval weight gain and mortality were then recorded. Treatments were done with 5 replicates of 10 larvae and each mortality curve with at least 4 concentrations.

For determining the residual toxicity under greenhouse conditions, sweet pepper plants were sprayed with the test compounds until run-off. Leaves were collected periodically and offered to 3rd-instars for 4-day feeding; untreated leaves were offered for an additional 2 days and mortality was then determined. Assays were kept under standard conditions as described above. Determinations were continued for about 3 weeks.

For the above assays, 1st-instars were collected from a standard colony and reared on sweet pepper plants or castor bean leaves until early 3rd-instars and then transferred to respective plants or leaves for bioassays as required.

Statistical analysis

All results were subjected to one-way analysis of variance (ANOVA) and means were separated by Scheffé's multiple range test (P=0.05) (Day & Quinn, 1989). Angular transformations for larval weight gain and mortality were done before statistical analysis. POLO-PC (LeOra Software, 1987) was used to calculate slopes and LC values.

RESULTS AND DISCUSSION

Comparative toxicity of two formulations of novaluron (EC-X 0.2%, EC 10%) applied to first-instar *Trialeurodes vaporariorum*

Bean seedlings infested with 1st-instars were treated with various concentrations of the EC-X and EC formulations (Table 1), both of which were potent suppressers of larval growth, resulting in over 90% suppression of pupation and emergence at concentrations of 2 and 8 mg a.i./litre respectively. The higher potency of the EC-X formulation probably resulted from the presence of a special ingredient which facilitates penetration of novaluron into the larval body. A similar potency was also recorded for the cotton whitefly *Bemisia tabaci* (Ishaaya et al., 1996)

Table 1. Effect of two formulations of novaluron applied to first-instar *Trialeurodes vaporariorum* on pupation and emergence.

Formulation and concentration in mg a.i./litre	Total no. of L1	Pupation %±SEM	Emergence %±SEM
- (Control)	351	96±1 a	96±1 a
Novaluron, EC-X			
1	320	29±7 c	24±5 b
2	170	2±2 e	2±2 d
4	232	4±1 e	0 d
8	183	2±1 e	0 d
Novaluron, EC			
1	475	51±5 b	38±6 b
2	440	45±8 bc	28±5 b
4	268	17±4 cd	9±2 c
8	175	8±5 de	7±5 cd

Bean seedlings infested with 1st-instars were sprayed until run-off. Percentages of pupation and emergence were determined. Data are averages of 5 replicates of 20-140 larvae each. Within columns, means followed by the same letter do not differ significantly at P=0.05.

Comparative toxicity of novaluron, lufenuron and teflubenzuron on *T. vaporariorum*

The potency of novaluron on 1-st instar *T. vaporariorum* was compared with lufenuron and teflubenzuron, both of which are among the most potent IGRs for controlling field crop pests.

Table 8. Residual toxicity of novaluron applied to sweet pepper plants on *S. exigua* under greenhouse conditions

Compound and concentration in mg a.i./litre	Larval mortality at various days after treatment			
	1	3	12	18
- (Control)	8±5 a	2±2 a	-	14±10 a
Novaluron, 1	96±4 b	96±4 b	91±4	63±9 b
Novaluron, 5	100 b	98±2 b	97±3	86±4 c

Sweet pepper plants were sprayed, on June 1,1998, until run-off. Leaves were collected periodically after treatment and exposed to 3rd-instar for 4-day feeding.The larvae were fed for additional 2 days on untreated leaves. Larval mortality was then determined. Av. min. temp. = 14.6±0.3 °C and av. max. temp. = 32.5±0.8°C. Data are averages±SEM of 5 replicates of 10 larvae. Within columns, means followed by the same letter do not differ significantly at P=0.05.

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Preliminary investigations on effectiveness of two modern insecticides in controlling codling moth, plum fruit moth and leaf rollers

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ABSTRACT

In a two year study, the modern insecticides methoxyfenozide and indoxacarb were tested in different parts of Poland in the field against codling moths, plum fruit moths and leaf rollers. In the conditions of experiments both insecticides were found to be highly effective in reducing damage due to attacks by pests. The effective control of these pests is determined by three factors: effectiveness of the insecticide, appropriate weather conditions and treatment timing. These factors will differ according to the life-cycle of the pest and the pesticide used. However, more investigations are needed to find a best point of their application.

INTRODUCTION

The codling moth (*Laspeyresia pomonella* (L.)), plum fruit moth (*Laspeyresia funebrana* Tr.) and the complex of leaf rollers (Tortricidae) are orchard pests commonly occuring in Poland as well as in many other countries. In recent years however, especially serious problems have been experienced in some orchards in certain regions of Poland caused by plum fruit moth and tortricids. The larvae of these pests damage fruit directly, so they can be tolerated only at a very low levels.

Effective control of these pests is determined by three factors: appropriate weather conditions for application, an efficient pesticide and an appropriate timing of the treatment, differing according to the pesticide used.

For many years organophosphate insecticides were used against these pests, with a more recent shift by some growers to synthetic pyrethroids. However, it was found that both target pests as well as many secondary pests of apple and pear are able to develop resistance to these chemicals. Moreover, organophosphates and synthetic pyrethroids, although still effective in many places against the pests, are also harmful to most beneficial fauna (predators and parasitoids). According to some authors (Nagy, 1973; Miczulski & Koslinska, 1976; Gall, 1984; Reede *et al.*, 1985; Helsen & Blommers, 1989; Harzer, 1990;) parasitoids can potentially suppress the population of some species of tortricids and even codling moth.

Among insecticides generally used for controlling codling moth, plum fruit moth and tortricids, there are only a few with enough selectivity and effectiveness to be useful for integrated control programs. During the last decade insect growth regulators (IGRs) such as the chitin inhibitors and juvenoids (e.g. fenoxycarb) have been developed for orchard pest control. Results from research trials and grower use have shown that certain chemicals in these groups provide adequate control of both pests mentioned above as well as some others e.g. leaf miners and psyllids. The advantage of IGRs is that they are often more selective than conventional insecticides and have no or a very low detrimental impact on beneficial insects, including natural enemies of pests.

Because the concept of integrated fruit production is increasingly accepted by growers and consumers all over the world, new groups of selective insecticides are still needed. Examples of such compounds are methoxyfenozide (RH-2485), a new ecdysone analogue against and indoxacarb (DPX MP 062), which inhibits Na^+ entry into nerve cells. Both compounds are highly specific, affecting only *Lepidoptera* at recommended application rates. In fruit production areas they are expected to be used mainly against codling moths, plum fruit moths, leaf rollers, other tortricids and possibly against lepidopteran leaf miners.

The overall aims, of which some results are reported here, were to assess the effectiveness of these compounds in commercial apple orchards, growing under different conditions.

MATERIALS AND METHODS

The research was carried out during 1997 and 1998 in commercial apple orchards located in various regions of Poland. Pheromone traps were used for determining the beginning and dynamics of codling and plum fruit moth flights, and timing of treatments was based on trap counts according to the procedure of Koslinska et al. (1987) and Kozlowski (1994). Depending on the orchard area or number of cultivars, 1-2 traps were used. Traps were inspected every 2 or 3 days and specimens counted and removed on each occasion.

In the case of tortricids, the timing of treatment was based on visual evaluation of larval development and species composition. The experimental plot area varied from 0.3 ha to 3 ha, depending on the orchard.
As standard compounds fenoxycarb (Insegar 25 WP), diflubenzuron (Dimilin 25 WP) and fenitrothion (Owadofos EC 50) were used.

In 1997 treatment effectiveness was assessed during harvest time by the inspection of 800 or 1000 fruit (100 items from each of 8 or 10 randomly selected trees) collected within the central part of each section, to record the level of damage.
The effectiveness of the treatments was calculated in two ways.

a) By Abbott's formula (Abbott, 1925)
b) Statistically (ANOVA) on data transformed according to Freeman-Tukey's formula. Mean differences were evaluated with Duncan's multiple range "t" tests at 5% probability level.

In 1998 treatment effectiveness against leaf rollers in orchard 1 and 2 was assessed by number of live larvae found in 200 shoots. In orchard 2 during early spring (April 29, 1998) the shoot infestation on particular plots treated with pesticides tested during 1997 was evaluated.

RESULTS

Codling moth control

In orchards under study the population of codling moth exceeded the economic damage threshold. An especially high level of infestation was observed in orchard 1 (Table 1).

The efficacy of methoxyfenozide and indoxacarb varied from 78.4 up to 93.2% and from 65.9 up to 93.2% respectively, depending on the time of application, number of treatments and dose rate, whereas standard preparation showed an efficacy from 61.9 up to 94.9% (Table 1).

Plum fruit moth control

Against this pest, only methoxyfenozide was tested in two orchards with different infestation levels (Table 2).

The effectiveness of the compound was also influenced by factors mentioned earlier and varied from 79.3% up to 92.3%. The effectiveness of standard preparations at the same time varied from 81.7% up to 92.3%.

Leaf roller control

The effectiveness of methoxyfenozide was tested in 1997 in two apple orchards with high populations of tortricids. Especially in orchard 2, they were very numerous, and the level of fruit damages on the check plot was very high (Table 3). In such situation two trials, both with methoxyfenozide as well as with standard preparations were performed.

Both in orchard 1 and 2, methoxyfenozide provided satisfactory control of pest damage. Its effectiveness was similar to that of fenoxycarb and better (in orchard 1) than that of fenitrothion at the application rates used.

The second compound - indoxacarb - was tested in 1998, also in two apple orchards with different levels of pest population (Table 4). The results evaluated after the first trial showed that indoxacarb significantly reduced the number of tortricid larvae and its effectiveness was better than that of the standard preparation - fenitrothion (Table 4).

DISCUSSION

A field study in two commercial orchards showed that these two new compounds were promising in the control of such important pests as codling moth, plum fruit moth and leaf rollers. Both compounds reduced the number of damaged fruits to an extent comparable with that of standard insecticides at the dose rates used.

Taking into consideration different factors influencing the effectiveness of the compounds one can say that the best control of codling moth with methoxyfenozide was obtained when it was applied twice (at the first and second peak of egg laying: see Table 1) at the dose rate 0.4 l/ha. Indoxacarb applied twice (in term A and B and dose rate 0.17 kg/ha or in term C and D and dose rate 0.2 kg/ha) has also given good results in controlling this pest.

In the case of plum fruit moth only methoxyfenozide (in term C) was tested and the best results were obtained with the dose rate 0.5 l/ha (Table 2).

Both compounds also provided very good control of tortricids complex, among which *Adoxophyes orana* was dominant in orchard 1 and *Archips rosanus, Pandemis heparana,*

Table 1. Effectiveness of insecticides in reducing codling moth damage.

Treatment (active ingredient)	Product dose rate (l or kg/ha)	Time of treatment	Orchard no. 1 1997		Orchard no. 1 1998		Orchard no. 2 1997	
			% wormy fruit	% effectiveness*	% wormy fruit	% effectiveness*	% wormy fruit	% effectiveness*
Check	-	-	12.6 d**	-	11.8 b	-	1.4 b	-
methoxyfenozide	0.4	C	2.0 ab	84.1			0.3 a	78.4
methoxyfenozide	0.4	A, B			0.8 a	93.2		
methoxyfenozide	0.4	C, D			1.6 a	86.4		
indoxacarb	0.17	A, B	1.7 ab	86.5	1.6 a	86.4		
indoxacarb	0.17	B	4.3 c	65.9				
indoxacarb	0.17	A					0.3 a	78.6
indoxacarb	0.2	C, D			0.8 a	93.2		
diflubenzuron	0.6	A, B			0.6 a	94.9		
diflubenzuron	0.9	A	1.2 a	90.5				
diflubenzuron	0.9	B	4.8 c	61.9				
fenitrothion	2.25	C					0.2 a	85.7
fenitrothion	2.25	C, D	2.2 b	82.5	1.0 a	91.5		

* calculated according to Abbott's formula

** means followed by the same letter within a column does not differ significantly (P= 0.05) according to Duncan's multiple range "t" test

A and B: the first and second peak of egg laying in the first generation, respectively

C and D: "black head" developmental stage of eggs laid during peaks A and B, respectively

Table 2. Effectiveness of insecticides in reducing plum fruit moth damage.

Treatment (active ingredient)	Product dose rate	Period of treatment	Orchard no. 1 1997		Orchard no. 2 1997	
	(l or kg /ha.)		% wormy fruit	% effectiveness*	% wormy fruit	% effectiveness*
Check	-	-	8.2 b**	-	1.3 b	-
methoxyfenozide	0.4	C	1.7 a	79.3	0.2 a	84.6
methoxyfenozide	0.5	C	0.8 a	90.2	0.1 a	92.3
diflubenzuron	0.9	A	0.8 a	90.2	0.1 a	92.3
fenitrothion	2.25	C	1.5 a	81.7		

* calculated according to Abbott's formula

** see Table 1.

A - period of egg laying by first generation

C - "black head" developmental stage of eggs laid by first generation

Table 3. Effectiveness of insecticides in control of leaf rollers (Tortricidae).

Treatment (active ingredient)	Product dose rate	Time of treatment	Orchard no. 1 1997		Orchard no. 2 1997	
	(l or kg/ha)		% wormy fruit	% effectiveness*	% wormy fruit	% effectiveness*
Check	-	-	5.6 c**	-	24.2 c	-
methoxyfenozide	0.4	A, C	0.8 a	85.7	7.3 b	70.0
fenoxycarb	0.6	A, B	0.3 a	94.6	6.1 a	75.0
fenitrothion	2.25	A, C	2,6 b	53.6	7.8 b	68.0

* calculated according to Abbott's formula

** see Table 1.

A - before flowering

B - after flowering

C - period of larvae hatching from eggs laid by the first generation of leaf rollers

Table 4. Effectiveness of insecticides applied before flowering in reducing leaf rollers in 1998.

Treatment (active ingredient)	Product dose rate (l or kg/ha)	No. of live larvae in 200 shoots	
		Orchard no.1	Orchard no.2
Check	-	61 c**	25 c
indoxacarb	0.17	8 a	6 a
fenitrothion	2.25	13 b	15 b

** see Table 1.

Spilonota ocellana were most numerous in orchard 2. In this orchard the effect of trials was observed not only in 1997 but also in early Spring 1998. Infestation of shoots by leaf roller larvae was 28%, 4% and 3% in "check", fenoxycarb and methoxyfenozide treated plots, respectively. In the case of indoxacarb applied against leaf rollers, the data presented concern only the first part of growing season 1998 after performing a single treatment, so it is very likely that after the second spraying the results will be even better.

Considering: a) the good results obtained with insecticides tested, b) their novel modes of action and c) their selectivity toward beneficial insects (Harder *et al.*, 1996; Le *et al.*, 1996) we believe that in forthcoming years the application of these insecticides will be recommended for control of pests mentioned in this paper and probably for some other lepidopteran pests. Such compounds will be especially useful in integrated fruit pest management.

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