SESSION 8A

DISEASES AND PESTS OF NON-BRASSICA OILSEED CROPS

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SESSION
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INVITED PAPER   8A-1

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LINSEED DISEASES IN THE UK AND THEIR CONTROL

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ABSTRACT

The principal diseases of linseed in the UK are seedling blights, grey mould and mildew. The main pathogens involved are *Alternaria linicola*, *Botrytis cinerea*, *Oidium lini* and *Fusarium* spp. There are also occasional attacks by *Fusarium oxysporum* f.sp. *lini*, *Verticillium dahliae*, *Phoma* spp., *Sclerotinia sclerotiorum*, *Colletotrichum linicola* and *Mycosphaerella linicola*.

INTRODUCTION

In terms of area, linseed has been the fastest expanding crop in the UK in the last five years and it is estimated that 150,000 ha were grown in 1992. Farmers, attracted by the subsidy and the lack of profitable alternative enterprises, are now growing a crop which few of them have grown before. There is consequently little experience of husbandry and disease control. Most of the recent increase in area of the crop has occurred in a series of unusually dry seasons, when the incidence of seed-borne diseases has been low, while attacks from mildew have been moderately severe, particularly in the SE of England. However, unless the current hot, dry weather is the beginning of long-term climatic change, a return to the more usual, wetter UK summers will alter the disease spectrum, with a higher incidence of seed-borne diseases and a lower incidence of mildew.

This paper reviews current knowledge on the epidemiology and control of the principal diseases of linseed in the UK and also includes a section on the less common diseases.

ALTERNARIA SPP.

At least three species of *Alternaria* are found on linseed - *A. linicola*, *A. alternata* and *A. infectoria* (Fitt *et al.*, 1991a). However, only the former is considered to be pathogenic, the others being generally saprophytic.

Life cycle and symptoms

A. linicola enters the outer layer of the seed coat as the capsules mature, particularly if the weather is wet during this period (Table 1). The apparent discrepancy between the incidence of the pathogen and weather during the maturing period in 1991 is probably connected with variations in daily and regional rainfall. Infection of the seed may be through either

TABLE 1.   Occurrence (% samples affected)[a] and incidence (mean % seed affected)[a] of pathogens on untreated seeds of linseed after harvest in UK in relation to temperature and rainfall during July/August[b].

Pathogen	1987	1988	1989	1990	1991
	% samples affected (% seeds affected when pathogen present)				
A. linicola	98 (58)	97 (51)	59 (2)	4 (1.1)	31 (1.8)
B. cinerea	25 (2)	29 (3)	12 (2)	17 (1.4)	23 (2)
C. linicola	0.1 (4)	0.4 (3)	0 (0)	0.2 (1.0)	0 (0)
Fusarium spp.	87 (15)	46 (5)	7 (0.8)	3 (1.1)	10 (1.3)
P. exigua	4 (2)	5 (3)	1.4 (0.8)	0.5 (0.7)	1 (1.1)
Mean temp.(^{o}C)	15.4	15.0	17.5	17.3	17.1
Rainfall (mm)	122	155	85	71	119
No. of samples	483	503	820	976	1953

[a] values obtained from official and advisory seed tests performed by Department of Agriculture for N. Ireland
[b] readings taken at Rothamsted Experimental Station

the capsule stalk or walls. It is clear from extensive dissection and ultrastructural studies (Mercer & Hardwick, 1991) that the pathogen tends to be confined to the outer layer and rarely enters the embryo. The pathogen appears to survive in the seed coat as thick-walled resting hyphae. There is very little evidence of survival as spores. Although studies over a number of years have shown that the incidence of the pathogen declines with time, the decline is very slow - one sample, originally with all seeds infected with A. linicola, still had over 20% of seeds infected with viable mycelium after 5 years (Mercer et al., 1991a). However, over a shorter time-scale, a study of the incidence of A. linicola on seeds received over the 1991/92 seed-testing period (Fig. 1) showed a rise with time followed by a decrease. The reason for this is not clear, but it may have resulted from a higher incidence of A. linicola on later-harvested crops and changes in the balance between pathogen and antagonistic micro-organism populations on the seed.

When infected (but chemically untreated) seeds are sown and begin to germinate, the pathogen hyphae rapidly become active, and if conditions are cold and wet, growth of the emerging seedling is slow and the hyphae begin to infect the seedling roots and hypocotyls. This results in the formation of brick-red lesions, a thickening of root and stem tissues and, in severe cases, prevention of emergence of the plant. The sowing of severely infected seed can thus substantially reduce crop emergence and cause a subsequent loss in yield (Mercer & Hardwick, 1991).

The next stage of the life-cycle is less clear, but it appears that A. linicola maintains itself at a low level on cotyledons, lower leaves and stem bases for much of the growing season and only infects capsules and upper leaves towards the end of the growing season (mid to end of August). In N. Ireland in 1990 and 1991, spores of A. linicola were first detected in
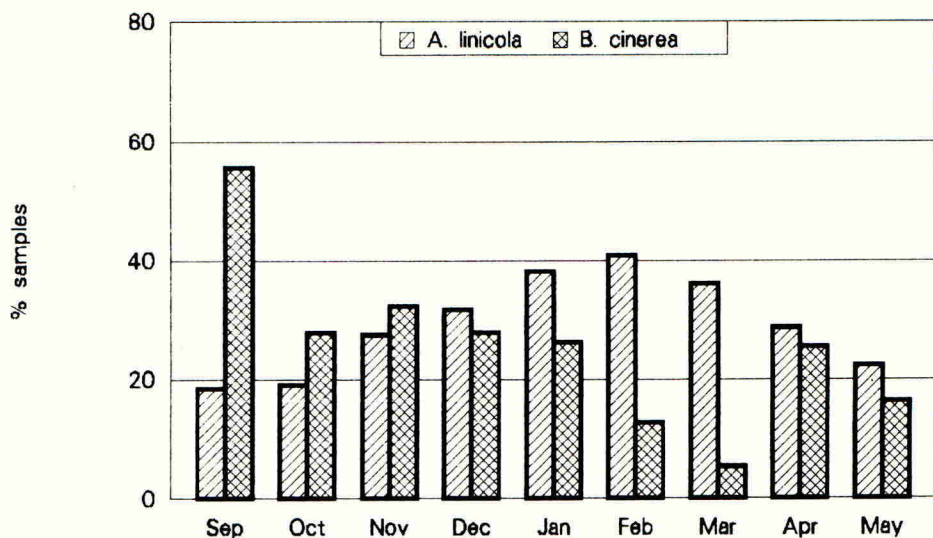
Fig. 1. Percentage of samples of linseed seed, received over the 1991/92 period of testing of UK seed samples, which were infected with either *Alternaria linicola* or *Botrytis cinerea* .

the air around the crop at about this time. Sticky-slide spore traps collected more spores at 20cm above ground level than just above the top of the crop, especially at the beginning of the season (Fig. 2).
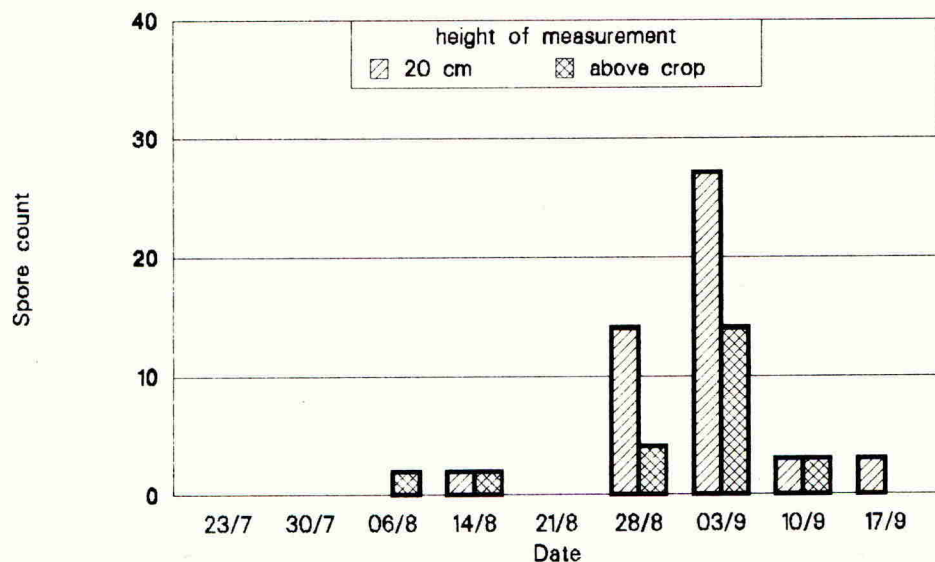

Fig. 2. Numbers of spores of *Alternaria linicola* trapped from the air at two heights in a crop of linseed (cv. Antares) in N. Ireland in 1991.

The level of colonisation of capsules and seeds is higher if conditions are wet. *A. linicola* and other seed pathogens are rare on plants grown in dry seasons or in glasshouses (even from infected seed).

Control strategies

Strategies for control of *A. linicola* have concentrated on two points in the life-cycle - control by seed-treatment of pathogen already present on the seed and prevention of entry of the pathogen to the developing seed.

Fungicidal seed-treatment

This is generally a most effective method of control, the incidence of the pathogen being reduced by up to 100%, even on severely infected seed (Mercer & Hardwick, 1991). Problems have arisen with resistance of *A. linicola* to iprodione seed-treatment (Mercer *et al*, 1991a) and the majority of seed-treatment is now done with prochloraz, which is highly effective at controlling not only *A. linicola*, but also all other major seed-borne pathogens which occur in the UK.

Fungicidal sprays on the growing crop

This method is more problematical. Linseed is a crop with relatively low inputs and under most circumstances no more than one fungicide spray could be justified economically. Mercer & Hardwick (1991); Mercer *et al*. (1991b; 1992a); and Paul *et al*. (1991) have showed reductions, in Britain and N. Ireland, in the incidence of *A. linicola* in developing seed following fungicide sprays, particularly of iprodione, which is surprising considering problems with the chemical as a seed-treatment. However, several sprays were often required, yield increases were either small or difficult to attribute to control of *A. linicola* and the reduction in incidence of *A. linicola* on seed was insufficient to reach the figure required for seed-certification. There were also regional variations. More research is required to identify more accurately the circumstances under which spraying with fungicides would be economically justified.

Control of *A. linicola* by sprays of biological agents has been attempted in N. Ireland (Mercer *et al*., 1991b; 1992a) and isolates of *Trichoderma viride* and *Epicoccum nigrum* have shown some activity. An isolate of *T. viride* gave a level of control approaching that obtained with iprodione, but only when crops were sprayed weekly.

There is evidence that differences occur among cultivars in the incidence of *A. linicola* on their seeds (Mercer *et al*., 1992b). These may be due to inherent genetic differences, but are almost certainly compounded by differences in maturity.

BOTRYTIS CINEREA

Life cycle and symptoms

B. cinerea is commonly isolated from linseed seed particularly when wet weather between flowering and harvest favours the infection of seed, as in 1987 and 1988 (Table 1). Furthermore, the incidence of *B. cinerea* in seed can be as great as 80% (Mercer *et al*., 1991a). However, unlike for *A. linicola*, the decline in incidence of *B. cinerea* on seed is quite rapid (Mercer *et al*., 1991a). In the 1991/92 seed-testing period (Fig. 1), 55% of samples received in September were infected to some extent with the pathogen

compared with 30% or less in the months following. If infected seed is sown and the weather is warm and wet, a reddish brown colouration appears on stems after emergence. The seedlings then collapse and die and the characteristic grey mould (consisting of mycelium, conidiophores and conidia) develops. Large areas of plants and occasionally whole crops, may be killed at this stage (Muskett & Colhoun, 1947). Van der Spek (1965) suggested that infected seed was the principal source of *B. cinerea* infection on crops in the Netherlands. However, many other sources of inoculum are available since *B. cinerea* has a wider host range than any other plant pathogen in the UK and is also a common saprophyte.

B. *cinerea* can attack leaves, stems and capsules of linseed (Muskett & Colhoun, 1947) but generally does not infect crops before flowering unless crop density is very high, or lodging occurs, or excessive rates of nitrogen are used (Mercer *et al.*, 1991a). Initially, infected leaves develop brown lesions, often starting from the tip. In warm, wet weather sporulating grey mould develops on these leaves. Pale lesions develop on stems, which may break at the site of the lesions. Black sclerotia develop on the surface of affected stems, whereas sclerotia of *Sclerotinia sclerotiorum* form within the stem tissue.

Wet weather during flowering is especially favourable for the development of grey mould. Thus, grey mould was commonly observed on crops

TABLE 2. Incidence of leaf browning, capsule browning and grey mould on capsules of linseed (cv. Antares) at GS 10 in relation to yield in plots with or without fungicides at Rothamsted, 1988 - 1992.

	1988	1989	1990	1991	1992
% brown leaf area:					
No sprays	61.1	12.0	-[a]	30.0	53.4
Fungicide	10.8	6.9	-	33.6	34.6
S.E.D.(d.f.)	4.81 (6)	2.02 (15)	-	5.3 (21)	8.1 (27)
% capsules with brown sepals:					
No sprays	6.7	-[a]	-[a]	17.3	43.3[b]
Fungicide	0.3	-	-	8.5	30.4
S.E.D (d.f.)	1.72 (6)	-	-	2.52 (21)	5.09 (27)
% capsules with grey mould:					
No sprays	2.4	0	0	4.1	3.7
Fungicide	0.3	0	0	2.1	0.6
S.E.D. (d.f.)	0.7 (6)			0.99 (21)	1.22 (27)
Grain yield (t/ha):					
No sprays	1.94	1.32	1.86	2.22	-[c]
Fungicide	2.83	1.43	2.03	2.43	-
S.E.D. (d.f)	0.236 (6)	0.238 (5)	0.037 (15)	0.179 (21)	-

[a] not assessed due to rapid senescence
[b] % capsules with brown lesions on sepals or cases
[c] not yet harvested

at Rothamsted in 1987, 1988, 1991 and 1992 when periods of wet weather occurred in July and August but was not observed in 1989 and 1990 when these months were generally dry. *B. cinerea* is dispersed from sources of inoculum by means of wind-borne conidia; maximum concentrations collected above linseed at Rothamsted were $3800/m^3$ in 1991 but only $10/m^3$ in 1990. The pathogen can kill infected flower buds and infection of capsule sepals and capsule cases is probably enhanced by the presence of senescing floral tissues (e.g. petals, styles, anthers). Initially, small brown lesions are observed and these spread over the capsule tissues until the fungus begins to grow up the capsule stalk and produces sporulating grey mould. Frequently, infected capsules drop off and this may contribute to yield losses caused by *B. cinerea*. Furthermore, this loss of infected capsules may explain why the incidence of *B. cinerea* on seed is often not clearly related to the incidence of grey mould on capsules in the crop.

Control strategies

Seed treatments with prochloraz or MBC fungicides have proved effective in decreasing the incidence of *B. cinerea* from 38 to 0% in 1985, from 10 to 2% in 1986 (Paul *et al.*, 1991) and from 16 to 0% (Mercer *et al.*, 1988). Seed for sowing should be cleaned well to avoid inclusion of *B. cinerea* sclerotia. Growers need to avoid high plant populations and the excessive use of nitrogen fertilizers, both of which favour the disease. Crop rotation and breeding for resistance are unlikely to be effective against *B. cinerea* since it is so non-specific and widespread.

As already observed, application of fungicide sprays to control diseases of linseed is often not appropriate economically. However, fungicide sprays during or after flowering have consistently decreased the incidence of grey mould and these decreases have sometimes been associated with substantial yield increases (Table 2). In experiments at Rothamsted, fungicide sprays consistently decreased the incidence of leaf and capsule browning, which was associated with *B. cinerea* and *Alternaria* spp. Treatments decreased the incidence of capsules with grey mould in 1988, 1991 and 1992 but no disease was observed on capsules in 1989 or 1990 when hot weather did not favour the disease. The greatest yield response occurred in 1988, when the most effective disease control was achieved. Similar decreases in leaf browning and in grey mould on capsules have been obtained in response to fungicide sprays in other UK experiments, e.g.Mercer & Hardwick (1991), sometimes, but not invariably, resulting in increased yields. However, fungicide sprays applied to crops have rarely affected the incidence of *B. cinerea* on seeds after harvest.

FUSARIUM SEEDLING DISEASES

Several *Fusarium* spp. are associated with seedling diseases of linseed. Although there is some confusion as to their identity, the main species infecting seedlings in the UK appear to be *F. culmorum* and *F. avenaceum*.

Symptoms and life cycle

Both *Fusarium* spp. can cause damping-off of seedlings under UK conditions (Mercer *et al.*, 1991a), producing symptoms similar to those produced by *Alternaria linicola*. Both *Fusarium* spp. are also capable of being seed-borne and tend to be found more frequently on seed following a

wet period prior to harvest, such as occurred in 1987 and 1988 (Table 1). However, unlike *A. linicola*, which appears to be almost completely seed-borne, the *Fusarium* spp. are also found widely in soil, air and splash droplets.

The effects of *Fusarium* spp., particularly *F. culmorum*, on adult plants affected by other pathogens, such as *Aureobasidium lini* or *Melampsora lini*, have been observed by Muskett & Colhoun (1947). However, neither of the latter pathogens has been recorded recently on linseed crops in the UK.

Control strategies

Seed with a high incidence of seed-borne Fusaria was found on samples in 1987 and 1988. In such situations, seed sown without treatment may well result in reduced crop stands. As with *Alternaria linicola*, control of seed-borne Fusaria is most readily achieved by the use of seed-treatments. Iprodione is ineffective at controlling *Fusarium* spp. and if this seed-treatment is being used for the control of *A. linicola*, an addition of benomyl will be required. However, prochloraz seed-treatment will control both *A. linicola* and *Fusarium* spp. Crop sprays of carbendazim in N. Ireland have been shown to decrease the incidence of *Fusarium* spp. on the subsequent seed, whereas sprays of prochloraz were ineffective and those of iprodione increased pathogen incidence (Mercer *et al.*, 1991b). Because of dry weather in recent years, the incidence of *Fusarium* spp. has been low. The economics of applying a spray for the control of *Fusarium* spp. under wetter conditions, more conducive to disease, is a matter for speculation.

OIDIUM LINI

Symptoms and life cycle

Powdery mildew, caused by *Oidium lini*, occurs on linseed or fibre flax wherever these crops are grown. It can cause serious losses in India, especially if epidemics develop before flowering, and is considered the second most important disease after rust (Saharan, 1990). However, in the UK losses are generally smaller, especially if epidemics occur late in the season. Symptoms of the disease are typical for a powdery mildew, with white mycelium and spores covering the surfaces of leaves, stems and capsules. When infected leaves are observed under the microscope, chains of spores can be seen (Muskett & Colhoun, 1947). Affected leaves become yellow, frequently with black spots associated with groups of dead cells, and senesce prematurely.

O. lini spreads into linseed crops by means of air-borne conidia. Air-borne concentrations as high as 9300 conidia/m^3 have been detected above linseed crops at Rothamsted. The occurrence of high concentrations of spores coincides with the rapid development of the disease in the crop. The development of epidemics is most rapid in lush crops; periods of high humidity favour infection and warm, dry conditions favour dispersal of the spores (Mercer *et al.*, 1991a).

Control strategies

Yield losses from powdery mildew frequently do not justify control measures. In experiments at Rothamsted, fungicide spray treatments have consistently decreased the incidence and severity of powdery mildew but

associated yield responses have never been more than 10% (Fitt & Ferguson, 1990). However, control of mildew, associated with a delay in senescence of leaves, has given yield responses as high as 18% in other UK trials (Beale, 1991).

Cultivar resistance is probably the most effective method for control of mildew. Resistant cultivars have been developed in India, with resistance governed by a single dominant gene (Saharan, 1990). However, European breeding programmes are not generally placing a high priority on selecting for resistance to mildew. In NIAB trials at Cambridge, differences between cultivars in the incidence and severity of mildew were observed (Beale, 1991). However, those cultivars with most disease were early-maturing and those with least disease were late maturing and it is not clear whether the observed differences were true differences in resistance or merely associated with differences in maturity.

MINOR DISEASES

Phoma spp.

Although disease caused by *Phoma* spp. has been noted in linseed and in fibre flax crops in N. Ireland in most seasons and in a crop of linseed in Essex in 1987 (Mercer & Jeffs, 1988), it has rarely been reported elsewhere. *Phoma* is, however, present at a low incidence in some UK seed samples (Table 1). Symptoms on plants consist of elongated brown lesions, typically on the lower stems and about 1cm above ground level, although in severe cases they may extend over the whole stem, causing premature senescence. Because of the position of the disease, it is probable that fungicide sprays would not be very effective at control. There is, however, evidence for differences in varietal susceptibility, at least in seed colonisation (Mercer & Jeffs, 1988).

Fusarium oxysporum f.sp. *lini*

Fusarium oxysporum f.sp. *lini* causes wilt and occurs in most countries where linseed or fibre flax is grown. Severe epidemics occur from time to time in the UK, generally on sites where farmers have grown several successive linseed crops and when there are periods of very hot weather in early summer, as in 1990 (Mercer, *et al.*, 1991a). Occasionally *F.oxysporum* f.sp. *lini* can kill seedlings but usually symptoms of wilt do not develop until after flowering. Affected plants begin to droop from the top down and affected leaves turn yellow and then brown as plants senesce prematurely. Both internal and external necrosis of stem tissue are observed. Sometimes the disease does little damage with only a few isolated plants affected but it can also destroy whole crops. The occurrence of dry weather after infection may increase the severity of the symptoms. The pathogen is also affected by soil pH and is rare in soils with pH greater than 6.8. The main method of control of *Fusarium* wilt is the breeding of resistant cultivars, since the disease cannot be controlled by fungicide sprays and soil-borne inoculum remains viable for many years. Selection for resistance to Fusarium wilt is an important part of breeding programmes throughout Europe, Asia and North America.

Verticillium dahliae

Verticillium dahliae has been reported to cause a wilt on linseed and

fibre flax crops in Europe and North America (Mercer *et al.*, 1991a). Its presence on linseed in the UK has only recently been confirmed (Fitt *et al.*, 1991b). The symptoms first observed are generally grey, chlorotic or dark brown stripes on green stems or dark brown stripes on maturing light brown stems. These symptoms occur along the whole length of stems and branches up to the capsules. Affected stems are brittle and white mycelium of the fungus develops at the base. Numerous black microsclerotia develop in stems with these symptoms and *V. dahliae* is consistently isolated from them (Mercer *et al.*, 1991a). Late in the season *V. dahliae* can also be isolated from capsules and seeds. It is not clear whether the disease decreases yields, although yields in experiments at Rothamsted were lowest in dry, hot years when symptoms of verticilliosis were widespread. It is possible that root damage caused by the disease may aggravate stress caused by dry soil conditions in such years.

Since the disease is essentially soil-borne and seed-borne inoculum is not important, it cannot be controlled by fungicide sprays or seed-treatments. The effect of rotation is also likely to be limited as *V. dahliae* has a wide host range and the inoculum can remain viable in soil for many years (Schnathorst, 1981). Breeding for resistance is possible but is not a current strategy.

Sclerotinia sclerotiorum

S. sclerotiorum can attack crops, such as potatoes, oilseed rape and beans, as well as linseed, and is therefore a potential threat in the UK. However, although one instance of *S. sclerotiorum* was reported from Hertfordshire by Mitchell *et al.* in 1986, only occasional infections have been reported since then. Typically small patches of affected plants are attacked near ground level, where water-soaked lesions are produced. Affected plants senesce prematurely or lodge. White, fluffy mycelium can be seen on surfaces and inside stems, eventually associated with the formation of hard, black sclerotia. Cultivar resistance has been observed and there are indications that it could, if necessary, be controlled by fungicdes (Mercer *et al.*, 1991a).

Mycosphaerella linicola (Pasmo)

Disease caused by this pathogen has been observed in Scotland, N. Yorkshire and N. Ireland (Mercer *et al.*, 1991a) on isolated occasions, generally associated with affected seed. It can cause severe desiccation of stem tissues. Although *M. linicola* is seed-borne, it is generally more deep-seated in the seed than pathogens such as *A. linicola* or *F. avenaceum* and may therefore be more difficult to eradicate by the use of seed-treatment (Mercer *et al.*, 1991a). At present it must be regarded as a potential threat in the UK.

Colletotrichum linicola

Although disease caused by *C. linicola* has been a serious problem in the past in the UK (Muskett & Colhoun, 1947), its present incidence in UK seed samples is extremely low (Table 1). It has only been recorded once on a crop in recent years (Rawlinson & Dover, 1986) when it was associated with imported seed. Although *C. linicola* can attack adult plants, it is primarily a cause of seedling blight. It can be controlled by seed-treatment and by early sowing. There also a wide range of cultivar resistance.

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CONTROL OF SCLEROTINIA SCLEROTIORUM ON SUNFLOWER

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ABSTRACT

This paper describes the main results of studies carried out on different control strategies against *Sclerotinia sclerotiorum*, on leaves, terminal buds, stems and heads of sunflower. Studies on agronomic control led to the development of a technical protocol with reduced risk of *S. sclerotiorum*. Studies on chemical control over the last four years gave some encouraging results in the control of the disease on leaves, buds and stems, and since 1991, it has been possible to have fungicidal control on buds in the field. In the case of the diseases on heads while there is some fungicide efficacy they could not be used for technico-economic reasons. Significant progress has been made, concerning genetic control, especially in the yearly estimation of the sensitivity of registered or pre-registered varieties to *S. sclerotiorum*.

INTRODUCTION

Sclerotinia sclerotiorum is the most important disease of sunflower in France today. This disease has three principal manifestations :
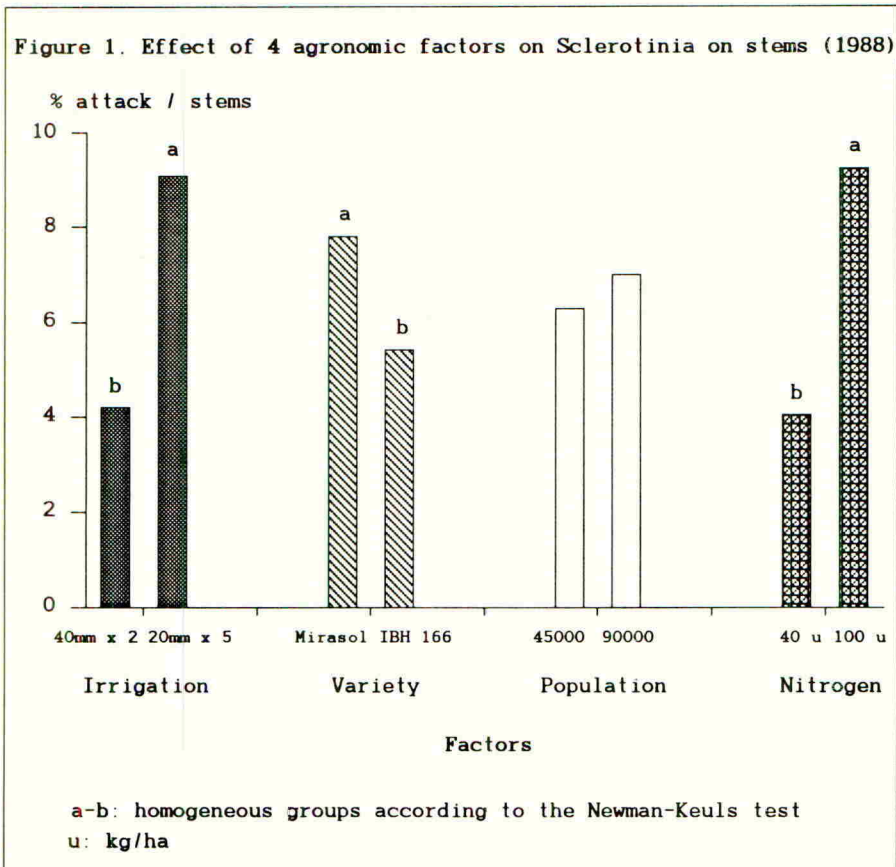
- disease on heads due to aerial contamination by spores on floral parts of the plant at the beginning of flowering (Says-Lesage *et al.*, 1988; Lamarque, 1976)
- disease on leaves due to contamination by spores, in the early vegetative stages, which can cause rot of floral buds or stems (Pérès *et al.*, 1989)
- disease on the collar due to mycelial germination from sclerotia. This form of attack has increased in France for the last two years.

These forms of attack by *S. sclerotiorum* occur on different parts of the plant at different stages. Thus, in order to have a good control, the three forms of attack must be considered as three different diseases.

AGRONOMIC CONTROL

A technical protocol was developed by applying simple agronomic rules to control attack by *S. sclerotiorum*. Studies carried out in 1988, 1989 and 1990 showed significant effects of irrigation, variety, row-spacing and nitrogenous fertilization on the incidence of *S. sclerotiorum* infection of leaves, floral buds, heads and stems (Fig. 1). Dense leaf cover was found to provide conditions conducive to infection and from which further attacks may develop. So, it will be necessary to reduce leaf cover by the following series of measures :

- to reduce the nitrogen fertilization at sowing (40 units maximum)
- to give preference to wide row-spacing
- to choose a variety with a low leaf area index
- to avoid early irrigation in order to not have a too dense leaf canopy
- to reduce the irrigation scheduling during the period of active contamination and of plant sensitivity (6-8 leaf stage and the beginning of flowering).

Figure 1. Effect of 4 agronomic factors on Sclerotinia on stems (1988)

a-b: homogeneous groups according to the Newman-Keuls test
u: kg/ha

CHEMICAL CONTROL

This form of control must be complementary to agronomic and genetic options, which are the priority control strategies. As the attacks on leaves and on heads are independant, they must be considered as two different diseases for the purposes of chemical control:

- *S. sclerotiorum* on leaves can lead to rot on floral buds or stems
- *S. sclerotiorum* on heads can lead to head rot in the month before maturity

. <u>*S. sclerotiorum* from leaves to floral buds</u>

Trials carried out for the last four years in greenhouse (4 trials) and in open field (17 trials) showed that the earlier the treatment, the better the results of the fungicidal control (Table 1). The plant can be infected at the 4-6 leaf stage. Thus, preventive treatments before infection or after infection but before the appearance of symptoms, give a very good level of protection. On the other hand, the efficacy of early curative treatments was more risky, because they are highly dependent on weather conditions and the depth of lesions at the time of the treatments (Table 2). The majority of the results were obtained with vinclozolin + carbendazim, the only product authorized for sale in France today, against *S. sclerotiorum* on sunflower. Since 1991, the control strategy in the field with this product in a case of risk is as follows :

- 1st treatment : at the 6 leaf stage (except in dry weather conditions)
- 2nd treatment : 10-15 days after the first one (according to the weather conditions)

The presence of aphids (*B. helichrysi*) increases the damage due to an attack by *S. sclerotiorum* if the variety is sensitive to aphids. Thus, good control against aphids can reduce the severity of attack by *S. sclerotiorum*. However, the biological rules involved in the relations varieties x aphids x Sclerotinia are not well known yet (work in progress).

TABLE 1. Study in greenhouse of vinclozolin + carbendazim (500g+330g/ha 1990).

Treatments	Sclerotinia: % of destroyed buds	% of efficacy
Untreated	66	
4 days after infection	0	100
5 days after infection and first symptoms (10%)	0	100
8 days after infection (very early symptoms on 38% of plants)	25	62
11 days after contamination (deep lesions on 43% of plants)	58	12

TABLE 2 . Sclerotinia on terminal bud: 1991. (Regrouped results of 4 experiments in the field on variety Vidoc.)

N	Date	Fungicides	% Destroyed buds	% Efficacy	Yield qx/ha	Difference yield /untreated
1		Untreated	26 a		23	
2	D1	Carbendazim	23 ab	12	23	+ 0,3
3	(10/6)	Vinclozolin + Carbendazim	16 b	38	25	+ 1,8
4	D2	Carbendazim	24 ab	10	24	+ 0,7
5	(18/6)	Vinclozolin + Carbendazim	25 ab	7	25	+ 1,8
6	D1+D2	Carbendazim	17 b	34	26	+ 2,6
7		Vinclozolin + Carbendazim	17 b	35	27	+ 3,7
8	D3	Carbendazim	25 ab	6	24	+ 1,2
9	(20/6)	Vinclozolin + Carbendazim	24 ab	11	24	+ 1,5
10	D1+D2	Difenoconazole + Carbendazim	15 b	41	26	+ 3,1
Factor treatment			HS		LS	
Factor place			HS		HS	
Interaction treat x place			NS		NS	
CV			18,6		7,1	

- *S. sclerotiorum* on leaves, leading to stem infection

S. sclerotiorum on stems can have two forms :

- early attack due to early contamination of young apical leaves, maybe more or less latent at the beginning; but disease can develop very rapidly when the weather is warm and wet. The first third or half of the stem breaks early, when the plant is still at the"bud" stage. The strategic control, previously described for floral bud

rot, can have an effective preventive action in the case of stem rot too.

- a later attack due to contamination of adult leaves can lead to dry stems which can break or stop translocation to the head. It is more difficult to control this form of attack because the period of plant sensitivity is very long (from the 10 leaf stage to the end of flowering).

The studies of fungicidal control carried out in four trials with carbendazim (500 g/ha) and vinclozolin + carbendazim (375 + 248 g/ha or 500 +330 g/ha) showed significant efficacies of the treatments when the products were applied at the right time in relation to the infection. A preventive control strategy will be really effective when a warning system is developed (work on "control of risk" in progress).

• *S. sclerotiorum* on heads

Fungicidal control against *S. sclerotiorum* on heads must take into account two difficulties peculiar the sunflowers :

- the non-systemic nature of the fungicides applied to sunflower
- the low penetration and quick degradation of these products when applied to the flowering heads.

To overcome these problems, studies were carried out for four years, into new additives and formulations. As a result fungicidal efficacies rose to above 65% in the best cases (means of 2-6 trials).

With studies carried out on two new active ingredients (FG 268 and FG 311), of equivalent efficacy, Fig. 2 shows that :

- mixtures with additives are more effective than the fungicide used alone
- double applications (at the beginning and at the end of flowering) give better results than single applications (at the beginning of flowering).
- FG 268 is more effective than FG 311 (except in the case of a very severe attack).

The significant progress which has been made, should give us some solutions for the control of the disease in the future. However, considering technical constraints linked to the application of products at the time of flowering (high-clearance tractor, adjustment of pendant lances on the ramps, ...) and the present economic situation, the elaboration of a control strategy has not been possible until now. However, work aiming at developing application techniques is in progress, and at the same time, the study of new active ingredients to widen the range of available products is still under way.

Figure 2 . Efficacy of fungicides (average)
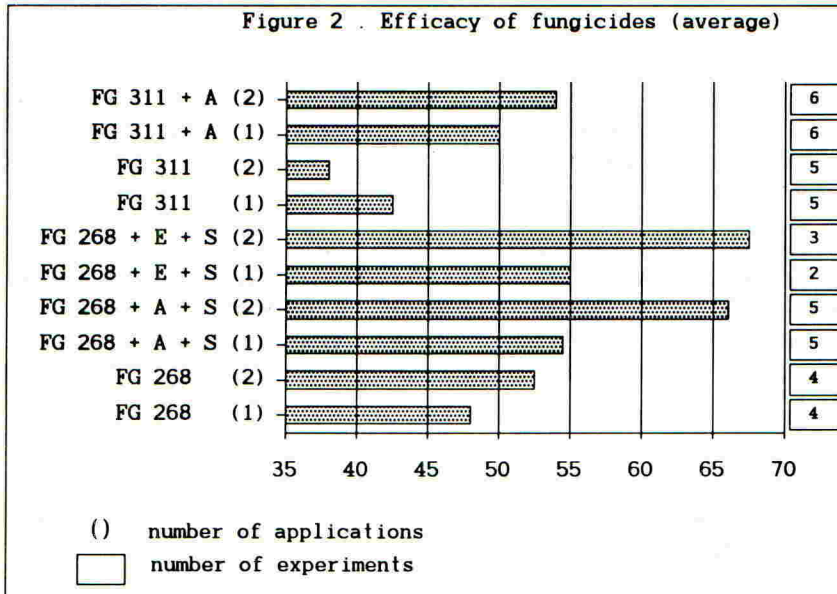
GENETIC CONTROL

With the present economic situation, this form of control is very important and must be considered as a priority point in the choice of the variety, when there is risk of attack by *S. sclerotiorum*. The variety will be choosen to be the most resistant to the form of the disease which is prevalent in the locality.

Trials carried out by the "Comité Technique Permanent de la Sélection" and those carried out by "CETIOM", give us, each year, the level of sensitivity of hybrids to *S. sclerotiorum* on heads and floral buds. For the registered varieties, the results of the estimation of varietal susceptibility are published and brought up to date each year in the "cultural guide" which is edited by "CETIOM" (Table 3). Thus, the "cultural guide" from 1992 shows :

- 7 varieties moderately resistant to *S. sclerotiorum* on floral buds (ex : Frankasol, Albena, Eurosol)
- 18 varieties moderately resistant to *S. sclerotiorum* on heads (ex : Alphasol, Cargisol, Mirasol).

Year by year, the number of qualified varieties increases. However, a variety does not have the same response towards the two different forms of attack. Thus, the choice of the variety must be made according to the form of attack usually present in the area.

In the case of collar rot, the first work on comparison of commercial varieties in the field started in 1991. At the same time, the "Institut National de la Recherche Agronomique" developed a test to estimate the behaviour of the lines (Tourvielle de Labrouhe *et al.*,1990)

TABLE 3. Varieties moderately resistant to *Sclerotinia sclerotiorum* (Cultural guide 1992)

Varieties	Varieties moderately resistant to *S. sclerotiorum*	
	on floral buds	on heads
Coril	X	
Frankasol	X	
Alphasol		X
Eurosol	X	
IBH 166		X
Albena	X	
Video		X
Oscar		X
Cargisol	X	X
Hoggar	X	
Mirasol		X
Upsol-Veraflor		X
Emil		X
Briosol	X	
Vital		X
Iseo		X
Dollar		X
Istria		X
Odil		X
Phoebus		X
Flambo		X
Lipo		X
Matador		X
Amilcar		X

CONCLUSION

Studies carried out in the framework of agronomic, chemical and genetic controls against the three principal forms of attack by *S. sclerotiorum* gave some significant and encouraging results.

In the present economic situation, when there is a risk of attack by *S. sclerotiorum*, the choice of resistant varieties is a priority decision factor which has to be taken into account according to the different forms of attack. Then, the sunflower growers will apply the agronomic rules to reduce the development of the attack. Chemical control is advisable only against early attacks on leaves, which can end at the destruction of the floral bud or at the early breaking of the stems. Vinclozolin + carbendazim is the only product authorized for

sale in France today. This chemical control is recommended when the variety used is sensitive to the form of attack previously described; it complements the low risk technical protocol.

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CONTROL OF SOILBORNE AND FOLIAR DISEASES OF PEANUT

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ABSTRACT

Peanut, *Arachis hypogaea*, an important economic crop grown in the southern U.S.A., has suffered a decline in yields in recent years. The decline is attributed in part to increased disease pressure induced by poor crop rotation practices. In particular, the soilborne diseases caused by the fungi *Sclerotium rolfsii*, *Rhizoctonia solani* and *Sclerotinia minor* have become increasingly important in crop loss estimates. The experimental fungicide, tebuconazole, provided good control of *S. rolfsii* and *R. solani*, and it increased peanut yields over those obtained in a typical grower's fungicide program.

INTRODUCTION

Peanut has long been an important agronomic crop in the southern U.S.A. The states of Georgia, Texas, Alabama and North Carolina represent over 80% of the 674,000 hectares of peanut grown in the U.S.A. The nuts are utilized in processed food (peanut butter), salted nuts, candies, oil stock and seed.

Peanut plants are susceptible to many foliar and soilborne pathogenic fungi. Infection by one or more of these pathogens during a growing season can cause yield losses of 50% or more. Some foliar and soilborne diseases would be limiting factors in commercial peanut production in some parts of the U.S.A. without chemical control and cultural practices to mitigate the damage caused by these pathogens.

Late leaf spot (*Cercosporidium personatum*) and early leaf spot (*Cercospora arachidicola*) are estimated to cause yield losses of up to 5% annually in the U.S.A. (Young, 1988). *C. personatum* is the more serious pathogen, and therefore of greater economic importance. Six or more fungicide applications are necessary in some years for economic control of *C. personatum*. Four or less applications may provide acceptable control of *C. arachidicola*, particularly where university advisory programmes are available which inform growers when to spray. Advisory programmes have not been as successful for control of *C. personatum* because of its high inoculum potential and severity.

Rust (*Puccinia arachidis*) is generally of little economic importance because it tends to occur late in the crop season. Areas of the U.S.A. can experience severe rust infections in some years which can cause growers to harvest prematurely resulting in yield losses and poor nut quality.

The soilborne diseases, white mould (*Sclerotium rolfsii*), limb rot (*Rhizoctonia solani*) and sclerotinia blight (*Sclerotinia minor*) cause conomic losses on over 20% of the peanut hectares grown in the U.S.A. and usually occur simultaneously with the leaf spot diseases. The soilborne diseases often cause greater crop damage on a localized basis than the leaf spot diseases.

S. rolfsii is the leading cause of yield loss in peanuts in the U.S.A. (Porter *et al.*, 1984). The pathogen may kill several lateral branches on a plant, an entire plant, or several plants in a row. Distribution of infected plants or "hits" within a field tends to be erratic or random. Pentachloronitrobenzene (PCNB), the only fungicide registered for control of *S. rolfsii* in peanut, is not widely used by growers because it is expensive, requires special handling, and provides only moderate control of the disease (Csinos, 1985). The Georgia Extension Service estimated yield losses to *S. rolfsii* of 30.5, 37.5, 42.8, and 11.6 million dollars in the years 1987 - 1990, respectively (Thompson, 1987, 1988, 1989, 1990). The lower yield loss in 1990 was due to a severe drought, emphasizing the importance of environmental conditions in disease development on peanut. Similar losses have been reported from other states.

R. solani became a serious problem in peanut in the U.S.A. in the early 1980s. It attacks lateral stems, foliage, roots and pods, and weakens pegs so that the nuts remain in the soil at harvest. The disease is associated with a dense canopy of foliage which creates a microenvironment favourable for infection, and with mechanical damage to peanut vines caused by tractor tyres during spraying and other cultural operations (Brenneman & Sumner, 1989). Yield losses due to *R. solani* in Georgia were estimated at 17.2, 44.0, 17.6, and 7.0 million dollars in the years 1987 to 1990, respectively (Thompson, 1987, 1988, 1989, 1990). The Alabama Extension Service estimated yield losses of 4.1 to 12.1 million dollars annually (personal communication, A. Hagan). There is no commercial fungicide available for control of *R. solani* limb rot at present and cultural methods have had only limited success in controlling the pathogen in peanut.

S. minor is the most important disease of peanut in Virginia and Oklahoma (Porter *et al.*, 1984). Although not common throughout the peanut producing states, *S. minor* can be devastating where it occurs.

A gradual decline in peanut yields in the U.S.A. has been noted in recent years. During the period 1984 - 1989, the average peanut yield in the U.S.A. declined 15.7% or 507 kg/ha. A 20% yield decline (758 kg/ha) occurred during the same period in Georgia, the leading peanut producing state (Coley, 1991). Although droughts occasionally contributed to yield decline, it is thought that other factors also affected yields adversely. Federal legislation enacted in 1978 allowed growers to plant unlimited hectares of peanuts. This led to poor crop rotation practices; as more land went into peanut production, less land was available for rotation purposes. Researchers have established that a three-year crop rotation schedule is optimum for peanuts, with crops such as cotton, corn, and grasses being beneficial in reducing disease and nematode problems. Proper crop rotation practices are particularly important in controlling *S. rolfsii* and *R. solani*.

Other cultural methods for disease management include deep ploughing to bury plant debris, proper irrigation timing, and avoiding movement of soil against plants during cultivation.

Miles Inc. began researching the biological properties of tebuconazole, a systemic triazole fungicide, in the U.S.A. in 1982. Early data indicated that the fungicide was highly active against *S. rolfsii*, *R. solani*, *C. personatum*, *C. arachidicola* and *P. arachidis*. It did not control or enhance development of *S. minor*. Subsequent field trials by state, federal and Miles researchers further defined the usefulness of tebuconazole in various foliar spray schedules for control of the major foliar and soilborne diseases of peanut and in enhancing yield production.

A grower fungicide schedule usually consists of 5 - 7 or more foliar spray applications of chlorothalonil for leaf spot control. One or two applications of PCNB granules may be applied on fields with a severe infestation of *S. rolfsii*. Experience with tebuconazole indicated that it could be applied in lieu of chlorothalonil and PCNB in a mid-season, 4-application block spray schedule and effect economic control of *S. rolfsii*, *R. solani*, *C. personatum* and *C. arachidicola*. Chlorothalonil was applied before and after the tebuconazole spray block to provide continuous control of leaf spot.

MATERIALS AND METHODS

In 1991, 9 small-plot field trials were conducted in commercial peanut fields in Georgia and Alabama. The purpose of the trials was to confirm the use pattern for tebuconazole under grower conditions. All trials were conducted on the peanut variety Florunner in grower fields so that the research plots received the same cultural practices as the grower fields. Plot size was 4 rows (0.91m spacing) by 15.2m long. Experimental design was a randomized complete block with 4 replications. Tebuconazole was applied as a liquid flowable (SC) formulation at a dosage of 0.25 kg ai/ha at 14-day intervals in applications 3, 4, 5, and 6 in a 7-application schedule with chlorothalonil 720 SC applied at 1.26 kg ai/ha in applications 1, 2, and 7. Chlorothalonil, the commercial standard, was applied at a dosage of 1.26 kg ai/ha at 14-day intervals in applications 1-7 for comparison to tebuconazole. The chemicals were applied as broadcast foliar sprays in 140 l/ha using a CO_2 powered backpack sprayer with 3 8004 nozzles per row at 2.3 bars. All trials included an untreated control.

Disease ratings were made approximately 13 (range 8-21) days after the last fungicide application. Control of *C. personatum* was determined by counting the number of lesions per 50 leaves per plot prior to harvest. For *S. rolfsii*, control was determined by counting the number of hits per 30.4 m row. *R. solani* control was determined by assessing the percentage of peanut plants infected per plot.

Normal grower harvest and drying procedures were followed for all treatments. Yields were determined by weighing all pods harvested from the treated plots and converting to a hectare basis. In addition, 6 of the 9

locations obtained pod quality evaluations from federal buying points which were determined by assessing the percentage of sound mature or fully developed intact kernels and sound splits or fully developed split kernels (% SMK + SS).

RESULTS

Disease pressure was moderate to severe due to frequent rains which occurred from April to early August. The tebuconazole block spray schedule, preceded and followed by chlorothalonil, provided greater control of *S. rolfsii, R. solani* and *C. personatum* than chlorothalonil alone.

TABLE 1. Effect of tebuconazole on *Sclerotium rolfsii, Rhizoctonia solani* and *Cercosporidium personatum* on peanut.

Treatment kg ai/ha		Applications	% Control		
			S.rolfsii	*R.solani*	*C.personatum*
Untreated Control			(13.5)a/	(61.6)b/	(443)c/
Chlorothalonil/ Tebuconazole	1.26 0.25	1,2,7 3-6	70	65	86
Chlorothalonil	1.26	1-7	18	27	62

a/ Hits/30.4 m row.   b/ % infected plants.   c/ Lesions/50 leaves.

Pod yields were also greater from tebuconazole plots than from either the untreated control plots or plots treated with chlorothalonil alone (TABLE 2). Pods from tebuconazole plots were equal to pods from control plots in percentage of sound mature kernels plus sound splits (% SMK + SS), whereas chlorothalonil treated pods achieved a lower % SMK + SS rating.

TABLE 2. Effect of tebuconazole on peanut yield, grade and value.

Treatment kg ai/ha		Applications	% SMK + SS	$/t over Chloro- thalonil	Yield t/ha
Untreated Control			75		2.7
Chlorothalonil/ Tebuconazole	1.26 0.25	1,2,7 3-6	75	21.82	5.2
Chlorothalonil	1.26	1-7	73		3.8

DISCUSSION

Based on federal peanut loan schedule values, pods from tebuconazole treated plots were worth an additional $21.82/t over pods from chlorothalonil treated plots. This is in addition to the 1.4 t/ha yield increase provided by tebuconazole. Assuming a value of $0.66/kg of pods, the yield increase represents a return to the grower of $924/ha above the chlorothalonil yield.

When registered for commercial use in the U.S.A., tebuconazole will offer peanut growers the following benefits:

- A single product to provide acceptable control of *S. rolfsii*, *R. solani*, *C. personatum*, *C. arachidicola* and *P. arachidis*.
- Higher yield and pod quality than with current commercial products.
- Allow growers to achieve federal production quotas on fewer hectares. Planting fewer hectares will be conducive to better crop rotation practices which will enhance soil conservation and disease management. Achieving yield quotas on fewer hectares will also reduce growers' production costs (seed, fertilizer, pesticides, labour, fuel, harvest, etc.)
- Reduce environmental pesticide load. Tebuconazole will be applied at a dosage of 1.0 kg ai/ha/season (4-application schedule). This will replace 5.0 kg ai/ha/season of chlorothalonil plus an additional 2.2 to 14.5 kg ai/ha of insecticides or insecticides plus PCNB which are currently applied for suppression of *S. rolfsii*. These amounts multiplied by the thousands of affected peanut hectares, represent a substantial reduction in pesticide load in the environment.

Tebuconazole is currently registered for use on peanuts in Argentina, Australia, South Korea, South Africa, Thailand and Zimbabwe. Registration is pending in Indonesia.

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EFFECTS OF PESTS AND AGROCHEMICAL MEASURES ON OLIVE OIL QUALITY

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ABSTRACT

Olive oil is a very important agricultural product in the Mediterranean Region. The quality of the olive oil itself is controlled by the pattern of fatty acids produced by the fruit and the relative activity of the different acyltransferases. The importance of fruit photosynthesis versus leaf photosynthesis in altering quality and the possible changes invoked by pest attack (and control) on these parameters is discussed. Insecticides, such as dimethoate, may themselves also produce alterations. Insect attack may be influenced by lipids in the cuticular layer which will also regulate pesticide entry and efficacy. Finally, the olive oil can be hydrolysed by microbial lipases during maturation or post-harvest or by endogenous lipases during processing. The action of these lipases increases acidity and reduces olive oil quality significantly.

INTRODUCTION

Olive oil is the major edible oil of countries in the Mediterranean basin. World production in 1983 amounted to some 2.16 million tonnes (Gunstone et al., 1980), two-thirds of which was produced in Southern Europe. The value of a vegetable oil is determined largely by the quality of its triacylglycerol component, which in almost all edible oils is the main substituent. The quality of this triacylglycerol is controlled by the acyl components and which combinations are used to produce the various molecular species. The balance of molecular species controls the physical properties of triacylglycerol while the overall acyl composition is also of relevance to nutritional considerations. In the case of olive oil, the major fatty acids are palmitate (10-15%) and oleate (70-75%). Small amounts of linoleic acid provide dietary essential fatty acids while the exceptionally high oleate proportion gives good nutritional and stability characteristics. As would be expected from such a relatively simple acyl composition, olive oil contains a limited number of molecular species. For olive oil to be considered of good

quality it has to have an exceptionally high triacylglycerol content. As soon as the unesterified fatty acid proportion rises significantly then the quality and flavour are immediately down-rated. Thus 1% of acids is the maximum level for extra virgin olive oil, 1.5% for fine and 3% for ordinary grades (see Gunstone et al., 1986).

The pathways by which storage lipids are synthesised in plants have been basically described. De novo synthesis of fatty acids is followed by acylation of these fatty acids to the glycerol backbone by the Kennedy pathway (see Gurr and Harwood, 1991). Possible points at which the quantity and quality of the accumulating oil can be affected are discussed below. The ultimate source of the carbon for olive oil formation is photosynthesis. In olive, photosynthesis can take place in the fruit and this can provide an alternative source of photosynthate to the transported carbohydrate originating from the leaves. Fruit photosynthesis has its own special characteristics (Blanke and Lenz, 1989). In addition, in olives the outer epicarp is the active photosynthetic layer and has a higher capacity (per gram) for fatty acid synthesis than the mesocarp. Moreover, the epicarp will produce a different pattern of lipid products than mesocarp tissue when measured in vitro (Sanchez et al., 1992). Thus, factors, such as pests, causing changes in the capacity of leaves versus fruit for photosynthesis might be expected to affect storage lipid quality. This aspect has not been addressed but, clearly the relative balance of fruit versus leaf photosynthate in triacylglycerol synthesis would repay careful investigation. Only then could the influence of pest attack on either source of storage carbon be assessed.

LIPID BIOSYNTHESIS AND REGULATION OF ACYL QUALITY

A complete discussion of triacylglycerol formation is impossible here. The main features of the process are illustrated in Fig. 1. For further information on de novo synthesis of fatty acids, desaturation and triacylglycerol formation see chapters in Stumpf and Conn (1987).

Activity of fatty acid synthetase (FAS) results in the formation of long chain fatty acyl-acyl carrier protein (-ACP) products. In most tissues, as with olive, these will be palmitoyl- and stearoyl-ACP. The balance of the C_{16} to C_{18} end products, which is low (up to 90% C_{18}) in the case of olives, is determined by the relative activities of two condensing enzymes β-ketoacyl-ACP synthetase 1 (responsible for forming acids up to sixteen carbons) and β-ketoacyl-ACP synthetase 2 (which condenses palmitate with a two-carbon unit to form stearate). It is well known that the pattern of fatty acid products formed by FAS can be changed under physiological conditions (see Harwood, 1988) and, moreover, in vitro experiments on FAS from epicarp and mesocarp olive cells (Sanchez et al., 1992) have shown different products for these tissues. Thus, as discussed above the relative supply of
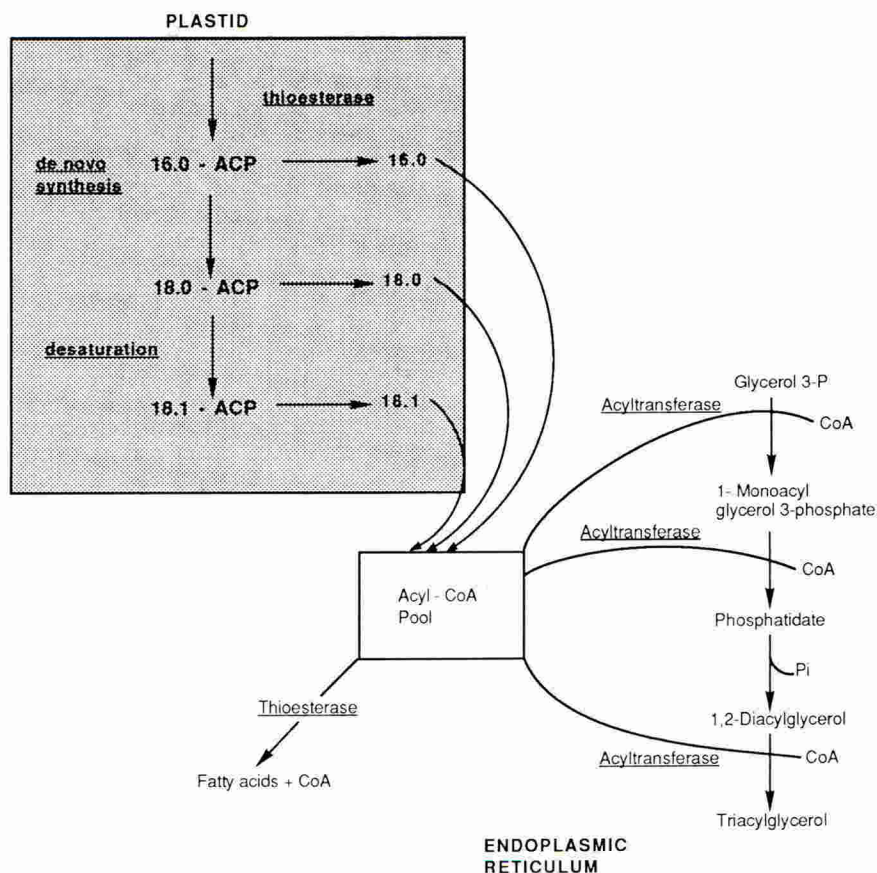
FIGURE 1. Major pathways for triacylglycerol synthesis in plants. The plastid is the main site of fatty acid formation de novo as a result of the combined activities of acetyl-CoA carboxylase and fatty acid synthetase. The main products of this synthesis are palmitoyl- and stearoyl-ACP. The latter is then desaturated by a stromal 9-desaturase to form oleoyl-ACP. Thioesterases in the plastid cleave acyl-ACPs to release unesterified fatty acids for export whereas fatty acids destined for plastid lipid formation are transferred directly from ACP to glycerol 3-phosphate. The unesterified fatty acids are converted to acyl-CoAs on the plastid envelope. They can then become part of the extra-plastidic acyl-CoA pool. The quality of the final triacylglycerol accumulated will depend on the composition of the acyl-CoA pool (i.e. available fatty acids) and the substrate specificities of the three acyltransferases. Further metabolism of fatty acids from the acyl-CoA pool (e.g. desaturation, hydroxylation, elongation) can also take place but is not shown in the Figure.

carbon from these two sources could influence the quality of olive oil. Further modification of the fatty acid supply can take place through the activity of desaturases and the release of fatty acids from their acyl-ACP esters by plastid thioesterases. For any fatty acid to be used by the acyltransferases of the endoplasmic reticulum it has to be available as an acyl-CoA ester. This depends on enzymes involved in the release and export of fatty acids from the plastid as well as the activity of acyl-CoA synthase.

From the acyl-CoA pool (Fig. 1) the acyl groups are esterified to the sn-1 and, then, the sn-2 position of glycerol 3-phosphate. After phosphate hydrolysis, the diacylglycerol product is finally esterified at the sn-3 position to yield triacylglycerol (Fig. 1). It is well known that the substrate specificity of the three acyltransferases, together with the nature of the acyl-CoA pool, determines the final quality of the triacylglycerol accumulating (see Stymne and Stobart, 1987).

Pest attack can, therefore, be anticipated to alter olive oil quality through a change in the relative balance of photosynthate used from either olive fruits or leaves - given that it has been shown that the photosynthetic fruit epicarp produces a different balance of products to the mesocarp which relies on substrates imported from the leaves (Sanchez et al., 1992). Moreover, any pesticide treatment which altered lipid metabolism could affect olive oil quality by a similar mechanism and/or because of a direct action on any of the individual enzymes involved in controlling lipid quality. A number of pesticide classes are known to have potent actions on different lipid-metabolising enzymes (Harwood, 1991) so it is clearly important to assess particular treatments used in olive agriculture.

SPECIFIC EFFECTS OF DIMETHOATE

Dimethoate (phosphorodithioic acid 0,0-dimethyl S-[2-(methylamino)-2-oxoethyl]ester) is an effective pesticide commonly used to control olive fly. The compound was tested in vitro for possible effects on lipid metabolism in olive (Olea europaea cv. Picual) at two levels - fatty acid synthesis and triacylglycerol formation (De la Vega et al., 1992).

TABLE 1. Dimethoate affects fatty acid synthetase activity in soluble fractions from olive fruits (De la Vega et al., 1992).

Dimethoate (μM)	Total activity (nmol/h/mg protein)	Pattern of products (%) $<C_{16}$	16:0	18:0
–	4.7	18	29	53
1	4.5	19	24	57
10	2.6	26	48	26

Fatty acid synthetase was assayed with [2-^{14}C]malonyl-CoA using soluble preparations from fruits (De la Vega et al., 1992) and the products analysed by radio-GLC. In Table 1 it will be seen that dimethoate produced two effects. First, at 10μM the insecticide inhibited total fatty acid synthesis significantly. Second, the pattern of products was changed in that only the formation of stearate was reduced. The simplest explanation of these data is that dimethoate specifically inhibits β-ketoacyl-ACP synthetase 2 (see Harwood, 1988).

TABLE 2. Effect of dimethoate on glycerolipid labelling from [^{14}C]acyl-CoAs by olive microsomal fractions (De la Vega et al., 1992).

^{14}C-Substrate	Dimethoate μM	Total incorp. (nmol/h/mg)	Distribution of label (%)*			
			PtdCho	DAG	TAG	NEFA
16:0-CoA	–	1.3	14	4	7	61
	0.5	1.3	14	5	5	61
	5.0	1.3	10	4	2	68
18:1-CoA	–	0.9	40	5	14	18
	0.5	0.9	34	6	12	30
	5.0	0.9	33	7	8	34

Abbreviations: PtdCho = phosphatidylcholine; DAG = diacylglycerol; TAG = triacylglycerol; NEFA = non-esterified fatty acids.
* Only the major labelled lipid classes are shown.

When the incorporation of [^{14}C]acyl-CoAs into triacylglycerols was examined using microsomal fractions (De la Vega et al., 1992; Table 2), dimethoate was found to cause a significant decrease in triacylglycerol labelling. In the case of [^{14}C]oleoyl-CoA, which is a good acylating substrate for phosphatidylcholine, a significant reduction of the radioactivity in that lipid was also seen. Commensurate rises in non-esterified fatty acids were seen due, presumably, to thioesterase activity. If such a result was obtained in vivo

then it would mean that the total amount of triacylglycerol synthesis would be reduced as well as its quality being changed (Table 1). However, when we challenged tissue slices with dimethoate (up to 0.5mM) the incorporation of radioactivity from [1-^{14}C]acetate into lipid classes was unchanged (De la Vega et al., 1992). These experiments clearly need to be extended to intact tissues, such as tissue cultures, in order to evaluate further the possible effects of dimethoate. In addition, the possible effects of other commonly used pesticides need to be assessed against lipid metabolism.

SURFACE WAXES MAY INFLUENCE PEST ATTACK AND PESTICIDE PENETRATION

The surface layer of plant tissues is provided by protective extracellular envelopes in which lipids provide not only the waterproofing layer of soluble wax but also the insoluble, polymeric structural matrices, cutin and suberin (Walton, 1990). These surface layers not only restrict water loss and control gas exchange but provide physical protection from pathogen or insect invasion and also limit uptake of pesticides and reactive environmental pollutants. Clearly the molecular composition and structure of wax, cutin and suberin will have an influence on their properties. For instance, it is well known that cuticular structure and, in particular, the wax composition largely determines pesticide penetration (Kirkwood, 1991) and surfactants have to be added to aid this process. The molecular properties of the cuticle which determine pesticide absorption have been reviewed (see Kirkwood, 1991).

Any factors, such as natural environmental ones, which regulate the synthesis of surface layers will lead to changes in the final structure and, hence, the detailed properties of the layer. The influence of the latter on pest attack and pesticide penetration will then possibly affect both quantitative and qualitative aspects of oil accumulation, as discussed in the previous section. Although little is known about how wax or cutin synthesis is controlled, some work has been done on suberin formation which is under abscisic acid control (Kolattukudy, 1987).

Recently, Montiel and co-workers (1991) have observed that infestation of olive fruits by the olive fly, Bactrocera oleae, is highly dependent on their surface appearance which, in turn, is known to be due to the wax layer (Von Wettstein-Knowles, 1979). This is a direct demonstration of the importance of the surface layer in insect attack as well as its other properties in regulating microbial penetration (Kolattukudy, 1987).

OLIVE OIL ACIDITY AS REGULATED BY LIPASES

As mentioned in the INTRODUCTION good quality olive oil contains very low levels of fatty acids. These non-esterified fatty acids are mainly accumulated in tissues as a result of lipases which degrade the storage triacylglcyerols (see Huang, 1987). The lipases responsible come from two sources. First, they can be extracellular lipases produced by infecting microbes (Borbolla et al., 1958) such as Gloeosporium olivarum which attacks ripening fruits or by Penicillium notatum, Aspergillus flavus and Trichosporon sericeum which can contaminate olives post-harvest (Table 3). Obviously, pesticides applied during the olive maturation period may be beneficial in preventing microbial infestation (and hence keeping acidity of the final olive oil product low) but could also have effects per se on lipid metabolism (see above). Antimicrobes applied post-harvest are unlikely to have any harmful effects on triacylglycerol quality but, on the other hand, any appreciable accumulation of these (hydrophobic) chemicals in the edible oil product would render it unsaleable for human consumption.

TABLE 3. Effect of microbial contamination of olives post-harvest on acidity and quality of the oil (Borbolla et al., 1958).

	Expt. 1		Expt. 2	
	Acidity	Effect on quality	Acidity	Effect on quality
Control (no infection)	1.4		0.6	
Aspergillus flavus	6.2	+++	14.5	+++
Aspergillus niger	2.3	+	1.6	+
Penicillium notatum	3.4	+++	2.2	+++
Trichosporon sericeum	6.3	+++	11.0	+++

A second source of lipase is the olive itself. There is good evidence that the stone (seed) contains significant lipase activity (Cantarelli, 1960). Any damage of the seed during processing or contamination with the 'orujo' will lead to a rapid rise in unesterified fatty acid content. Again, the use of chemicals to prevent this are essentially precluded for safety reasons.

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SESSION 8B

MODELS IN THE CONTROL OF INVERTEBRATE PESTS

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SESSION
ORGANISER   DR N. CARTER

THE ECOLOGICAL BASIS FOR CROP PROTECTION: THEORY AND PRACTICE

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ABSTRACT

Crop production and protection are applied aspects of ecology, and hence must be based on the existing body of ecological theory. The development of crop / pest models based on demographic theory and driven by the interaction of energy (biomass) supply / demand are reviewed. The development of simple rules for the economic threshold based on insights gained from modeling are examined.

INTRODUCTION

Applied ecologists are asked to find real world solutions (Strong, 1983), but they are criticized because their work supposedly lacks a theoretical basis (Levins & Wilson, 1980). In the past, applied ecologists became lost in the minutia of the biology, satisfying themselves with empirical studies and hiding behind the assumption that nature is too complicated to model. Field ecologists tended to stress natural history, sampling, field and laboratory life tables, and only marginally modeling and theory. In crop protection we must manage populations of plants for yield and populations of pests that may reduce it to unacceptable levels. Because we are dealing with populations, the research methods we must use are of necessity based on population dynamics theory. To describe the system dynamics, we must develop mathematical models to describe it. Such models are most useful when they help us test hypotheses that improve our understanding of agroecosystems sufficiently to manage them in environmentally sound ways.

When applied ecologists develop models, they may not examine their mathematical structure. On the other hand, theorists propose ecological theory but seldom test it except in *ad hoc* ways. This problem led to an impasse between the extremes of population ecology, but this is not an unreasonable state of affairs as such schisms have existed in all fields of science until a convincing theory develops to unify it. Progress in population ecology has by and large been modest, limited mostly to simplified representations of two species interactions. Many of the common techniques that have been used to analyze the impact of natural enemies in the field are reviewed in Southwood, (1975) which remains an important source book for field techniques, and May (1973, 1976) who pioneered theoretical approaches.

THE MODEL

The modelling approach emphasised here is an evolution of work on *time-varying life tables* since the publication of *Ecological Relationships* (Gilbert *et al,*. 1976; see Lawton, 1977 for criticisms). These life tables are not static, rather the parameters are changing over time and with age in response to various biotic and abiotic factors (i.e., they are population dynamics models). These notions are used to develop realistic models of plant / herbivore /

natural enemy interactions (*tri-trophic interactions*) that can be tested against theory and field data. These models are based on well know demographic models that may include age, stage and morph structure of each population (Leslie, 1945; von Foerster, 1959; Manetsch, 1976; Vansickle, 1977). The number dynamics of a species as well as age structured mass and other attributes may also be included (Sinko & Striefer 1967), and distributed maturation times are handled with ease (Gutierrez *et al.*, 1984). Interested readers are referred to Wang *et al.* (1977) and Severini et al. (1990) for a theoretical justification of the mathematics of our applications as this is well beyond the scope of this paper.
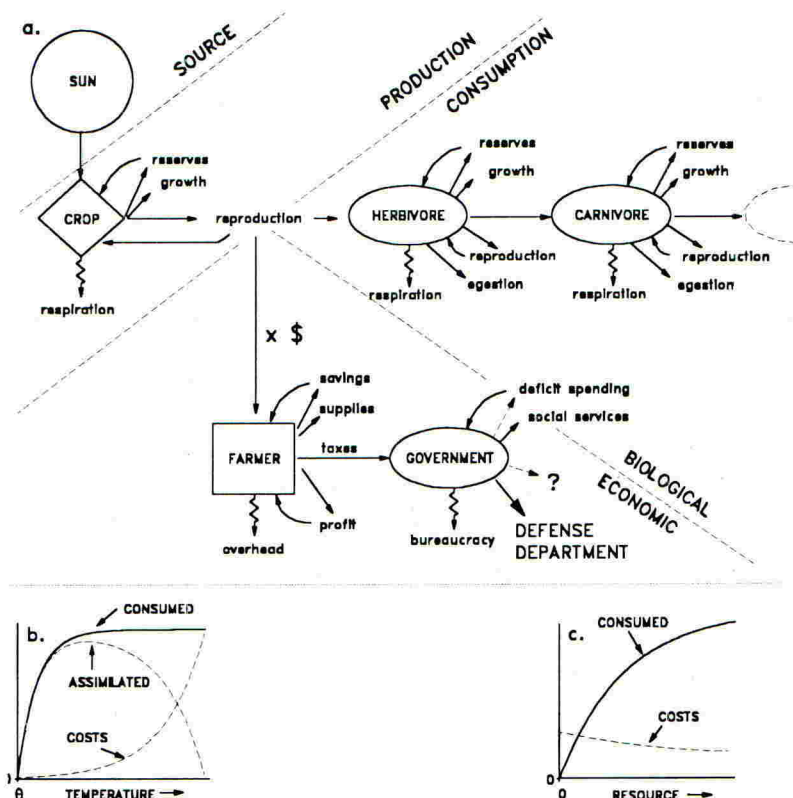

Figure 1. The energy flow dynamics in a multitrophic system (a.), and the hypothetical shape of the acquisition and cost rate functions and the net on temperature (b.) and resource level (c.) (modified from Gutierrez & Curry, 1991).

All organisms (including resource managers) prey on lower trophic levels, and are faced with the problems of resource acquisition and allocation. The concept of predator encompasses this, and here it is used in its *broadest* sense to include plants (because they seek light, nutrients and water), herbivores (i.e., plant predators), true predators, parasitoids and parasites (which are special kinds of predators). Humankind is the ultimate predator harvesting all lower trophic levels. The term 'prey' is applied to the victims of predation. The distinctions between predator and parasitoid are important in formulating an appropriate acquisition model (i.e., the functional response model, Royama, 1971), although a parasitoid is in reality a specialized predator. The shapes of functions describing the different

components of the predation process are similar across trophic levels including the economic one. The currency of interactions may be energy or biomass, but other resources (H_2O, nutrients, etc.) may also affect the dynamics and may be modelled in the same way. At the economic level, the energy fixed by lower trophic levels is multiplied by price. The interactions of several trophic levels are depicted in **Figure 1a** with the shapes of the benefit and cost functions on temperature and resource depicted in **1b,c** (c.f., Gutierrez & Curry, 1989).
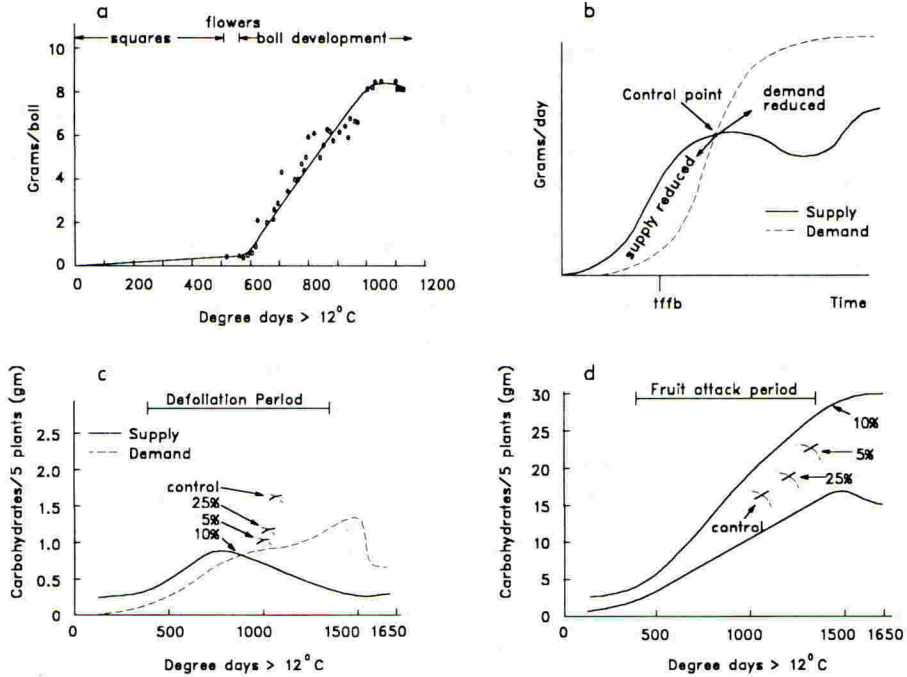

Figure 2. Carbohydrate stress in indeterminate cotton: (a) the phenology of fruit growth, (b) the stylized interplay of resource demand and supply indicating the normal time of carbohydrate stress under pest-free conditions (i.e., the control point), (c) effects of different percentages of defoliation on the supply side and its effects on the time of stress, and (d) the effects of different percentage of fruit loss on reducing demand and on the time of stress. (after Wang *et al.*, 1977). The control point is that expected under pest free conditions.

We use a demand driven functional response model to estimate the supply of resource obtained. The demand is defined as the maximum per capita quantity that can be processed per unit of time t at age *a* in a population of size N(a,t) and mass M(a,t). For parasitoids, the per capita demand rate is the number of hosts that may be attacked per unit time, and in some cases, a host may be attacked several times by the same or different parasitoids. Except in economics, the amount an organism can acquire has a theoretical maximum because the demand may increase due to technological innovations or greed, but at any point in time there is an economy of scale. Particularly useful demand driven acquisition models are the Frazer & Gilbert (1976) and Gutierrez & Baumgaertner (Gutierrez *et al.*, 1981) models. The basic concept is an economic one based on supply - demand considerations.

The effects of supply or demand

The ratio of resource acquired to that demanded (i.e., $0 \leq s/d < 1$) regulates all birth, death, net immigration, aging and net growth processes in models. DeWit & Goudriaan (1978), their colleagues and other plant physiologists pioneered the use of such resource allocation schemes in plant model, and indirectly influenced our work (Gutierrez *et al.*, 1975, 1981; Wang *et al.*, 1977). The use of this paradigm in a demographic sense was developed for plants (Gutierrez *et al.*, 1975; Wang *et al.*, 1977), and applied to animals by Gutierrez and Baumgaertner (1984) and Gutierrez et al. (1988b). Biotic and abiotic factors may affect either the supply or demand side of the ratio. On the supply side, prey may be low relative to demand, of poor nutritional quality or of the wrong size or stage and this may greatly affect the biology of the predator. Such supply side considerations are commonly accepted in fertilizer experiments and in animal husbandry where quality and quantity of food are known to alter production.

Factors that reduce the demand side are more difficult to estimate because we see the realized rate and rarely the maximum rate. In some plants with large assimilation rates to fruits (e.g., apple, common bean, and cotton), it is accepted that excess fruit are shed and/or if too many are retained the survivors are greatly reduced in size. In the s/d paradigm, this could be explained as a short fall in the supply relative to the *genetic demand* for growth. In others the fruit demands may be small relative to the overall vegetative demand such that stress due to reproductive demands may not occur (e.g., cassava). The shortfall may also occur because of weather (low solar radiation, drought stress, high and low temperatures, etc.) or edaphic factors such as low levels of essential nutrients all of which may affect photosynthesis. Some variables may affect both the supply and demand side (e.g., temperature via respiration and growth rates in poikilotherms).

The per capita growth rate of fruit as a function of age, the interplay between the supply and demand and the effects of factors that affect the supply or demand sides of the system are shown in Figure 2. The control point in plants growing under ideal conditions occurs where the supply equals the demand (2b). Factors that affect the supply (2c) cause the point to be moved earlier in time (e.g., loss of leaves) resulting in smaller plants, while factors that affect the demand (2d, e.g., loss of fruit) cause the control point to be moved later in time resultng in plant with excessive vegetative growth, and in the extreme, the control point may fail to materialize except when the plant becomes so large that respiration rate exceed the rate of supply causing death. Crops have been bred away from wild ancestors, and the genetic legacy serves as a basis for modeling the s/d effects. Examples of the application of this paradigm are that of Gutierrez *et al.* (1988a; cassava), Graf *et al.* (1990; rice), Wermelinger *et al.* (1990; grape) and Gutierrez *et al.* (1991; cotton).

The effects of demand are not as obvious in animals, but reproductive stress may occur in organisms such as aphids which have distinct patterns of reproduction under optimal conditions and resorption of embryos occurs when the parent is stressed. Coccinellids, on the other hand, produce eggs at an undiminished rate as long as food is abundant or until they senesce. By analogy with plants, abiotic and biotic factors affect both sides of the s/d equation, and the same models are used to describe the effects (Gutierrez *et al.*, 1987).

Despite our ability to simulate the dynamics of various crops and animals, there are still too many uncontrolled variables (e.g. weather, migration rates) that make predictions of yields an unrealistic goal. Hence, the common misconception that prediction is a realistic objective has hindered the effective use of models in crop protection. General understanding of agro- ecosystem interactions and the development of management strategies are more reasonable goals.

The insights gained through modelling are easily demonstrated using a combination of field data from Brazil and Nicaragua on cotton / boll weevil / bollworm (*Gossypium hirsutum* L / *Anthonomus grandis* Boh./ *Heliothis zea* Hubner) interactions .
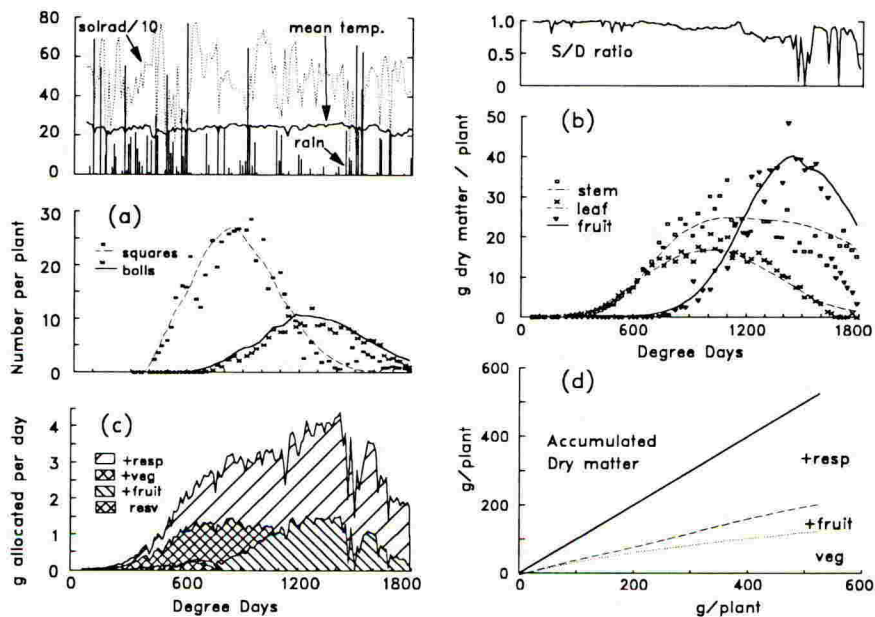
Figure 3. Simulated and observed pest free IAC-17 cotton at Londrina, PR, Brazil during 1982: the dynamics of (a.) buds and bolls (large fruit), (b.) of dry matter allocation to plant subunits, (c.) the pattern of daily allocation to vegetative and fruit growth and to respiration, and (d.) the cumulative allocation. The observed weather is depicted above (a.) (after Gutierrez *et al.*, 1991).

THE COTTON SYSTEM

Cotton crops from various areas of the world have been modeled (Gutierrez *et al.*, 1991) using real time weather, and multiple criteria have used to determine whether the essential biology has been captured. Simulated and observed data from pest-free and bollweevil infested cotton in Brazil are shown in **Figures 3** and **4** respectively using the same variety. In a pest free crop (Figure 3), the plants reach a carrying capacity for fruits at the control point, the excess buds and small bolls are shed, and photosynthate is allocated to

fruits at the expense of vegetative growth. In an infested crop (Figure 4), the cotton bollweevil prunes young buds decreasing present and future demands causing the unaltered production of photosynthate to be allocated to vegetative growth. This results in plants with stem mass four times that of pest-free plants (**3b vs. 4b**). These general results are predicted by the general model in **Figure 2**. Note also that the model predictions are largely independent of the field data.
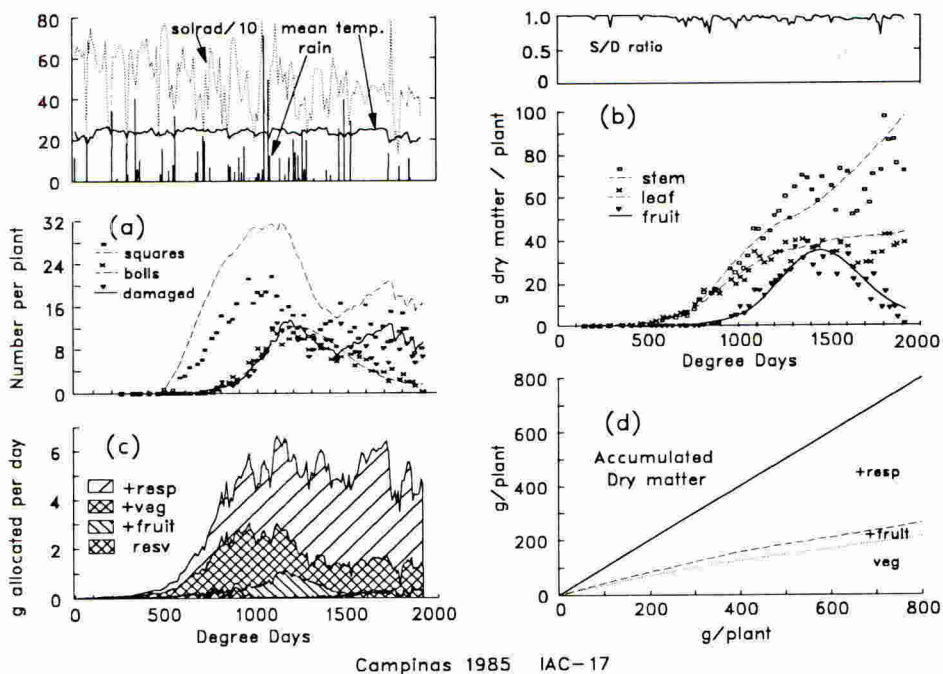

Figure 4. Simulated and observed bollweevil infested IAC-17 cotton at Campinas, SP, Brazil during 1985: the dynamics of (a.) buds and damaged and undamaged bolls (large fruit), (b.) of dry matter allocation to plant subunits, (c.) the pattern of daily allocation to vegetative and fruit growth and to respiration, and (d.) the cumulative allocation (after Gutierrez *et al.*, 1991). The observed weather is depicted above (a.) .

PLANT COMPENSATION AND THE ECONOMIC THRESHOLD

Data collected by Rainer Daxl and his associates in Nicaragua provide the basis for formulating a simple economic threshold for the interactions of cotton and two fruit feeding herbivores (Gutierrez, Daxl *et al.*, 1982). Bollworm and cotton bollweevil damage cause premature abscission of buds, but they also attack large fruits. The analysis assumes that it matters little to the plant which pest cause the damage; but rather the rate and the amount of time and energy lost in abscised fruits. Per plant and per unit area fruit point production rates are mostly linear functions of temperature and plant density until carbohydrate stress and the rates slow (e.g., Figure 3). Different rates of fruit depletion affect the times of carbohydrate stress and cessation of fruit bud production. The field data confirm the

predictions of the s/d model that plants with high damage levels continue producing buds when the demand side is reduced (i.e., Figure 5a),.and those with low rates of damage cease producing buds (5b) earlier due to fruit-demand induced stress (i.e., vegetative growth, Figure 4b,5b).
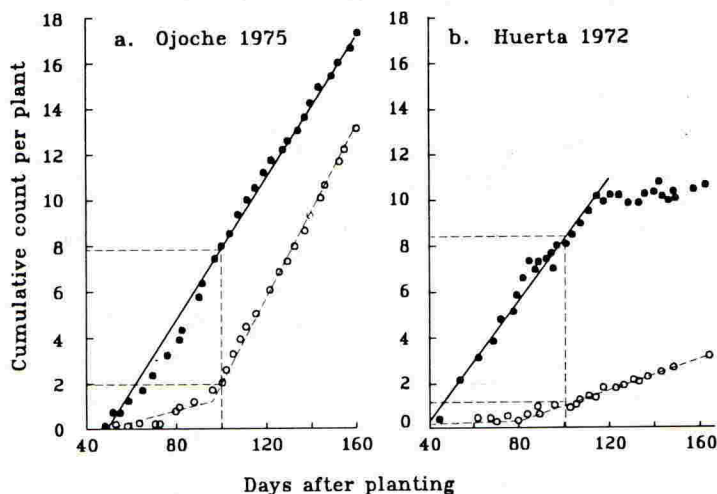

Figure 5. Observed cumulative cotton fruit bud production (_____, β_T) and cumulative buds damaged by bollweevil and bollworm (- - - -) at two sites in Nicaragua. The early (β_1) and late season (β_2) damage rates are indicated.

Production (β_T) and depletion (β_2) rates of fruits were estimated in the field during different years and the yields from all trials in the same field were plotted on their respective β_T/β_2 indices. All of the data fall on a common concave line which has an asymptote near an index value of 3.5 (**Figure 6a**). This suggests that plants compensate for ca. 30% of fruit loss before serious reductions in yields occur - i.e., *the compensation point*. Yield declines rapidly after the compensation point, suggesting that the pest is causing irreplaceable damage to the crop. An hypothetical economic threshold is superimposed upon the figure indicating when yield loss equals the cost of a control measures (i.e., *the economic threshold*). The model explains why the damage due to *Lygus* bugs in California cotton does not normally cause economic damage, as their per capita rate of depletion of fruits is low, and the losses caused by its populations rarely exceeds 30%.

Cotton plant that produce small fruits may not be stressed until very late in the season and the function of yield on β_T/β_2 would be displaced to the right (i.e., Egyptian cotton, *Gossypium barbadense* L., Gutierrez *et al.*, 1991). Varieties with more and smaller fruits having short maturation times (progeny) have greater compensation abilities, but then elementary life table statistics tell you this. These relationships are predicted by the dynamics model, and the time varying index β_T/β_2 may be used in this model as an economic threshold criterion (Gutierrez *et al.*, 1991). This relationship is not unique to cotton, as it has been found in many other crops (e.g., bean, rice).

Defoliation affects the supply side and decreases the ability of the plant to compensate causing the curve inFigure 6a to be shifted to the left and lower. In crops like alfalfa (*Medicago sativa* L.), increasing the rate of defoliation (i.e., lowering the supply) causes increasing yield losses not only in the cutting affected but also in later cuttings because of the depletion of reserves (**Figure 6b**). The economic threshold for such crops must include losses across all cuttings. Similar effects of defoliation were found in cassava when nutrient and water were reduced.
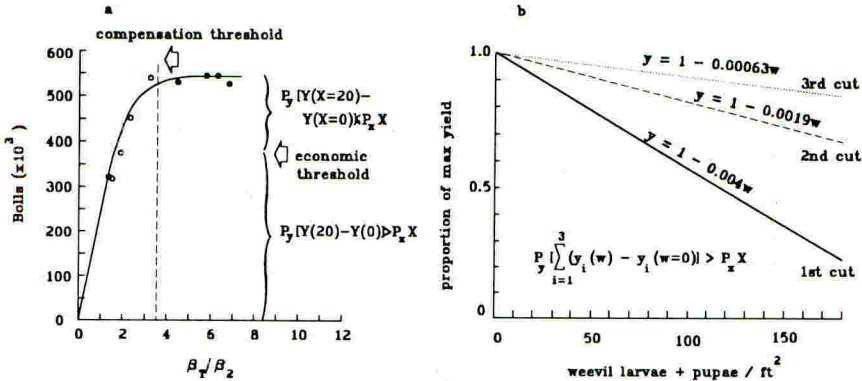

Figure 6. A simplified model of the economic threshold, (a.) *demand side effects* - the relationship of the final number of mature bolls and the ratio of cumulative fruit bud produced (β_T) and cumulative fruit buds damaged (β_2). Indicated are the plants compensation and economic thresholds. The closed and open circles are data from sprayed and non-sprayed fields respectively. P_x is the price of the control measure X and P_y is the price of yield Y (after Gutierrez & Daxl, 1984), and (b.) *supply side effects* - the effect of alfalfa weevil feeding damage on three cutting of alfalfa (C.G. Summers unpublished data; after Gutierrez & Wang, 1984).

This simple supply/demand model draws together modeling and field data to show how field counts may be interpreted in a dynamic way to determine the economic threshold. It tells us to read the plant to assess what pests and abiotic factors are doing, but then my colleague LA. Falcon knew this intuitively for quite some time (Falcon *et al.*, 1971)

Lastly, the argument concerning compensation in plants is the same as that for dispensable and indispensable mortality in animal predator - prey systems. *The dispensable mortality is that which would occur due to carbohydrate stress alone, and the indispensable mortality is that additional amount due to other factor for which the plant cannot compensate.*

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THE VALUE OF STATISTICAL MODELS IN APHID FORECASTING

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ABSTRACT

Simple statistical models are used to demonstrate that winter temperature is strongly correlated with the date of first appearance of the aphid, *Myzus persicae*, in suction traps. This date is strongly correlated with the number of aphids trapped until mid July. Models based on data from 1966 to 1988 are used to forecast the date of first record and numbers trapped for each year from 1989 to 1992. The forecasts are sufficiently accurate to warn growers by the end of February of the likelihood of an early, normal or late migration. The performance over four years of a statistical model to forecast the incidence of sugar beet yellows viruses is assessed. The implications of a changing climate are discussed in the light of these models.

INTRODUCTION

Statistical models depend on the availability of at least two comparable long term data sets. Cause and effect are implied but not proven without supporting experimental work. They can often provide long range forecasts. Simulation models are based entirely on cause and effect and are assembled as a result of experimental work without the need for long term survey data. The range of forecasts derived from simulation models is only as long as the range over which the driving variables (e.g. weather aspects) can be forecast, but early warning is not normally their purpose. Here we describe simple, regionally based statistical models for long range forecasting of the need for early season aphid control.

Aphid-borne viruses generally cause more damage if transmitted to plants at an early stage of development (Smith & Hallsworth, 1990; Beemster, 1972). An aphid population of a given size is also likely to cause more direct damage by feeding on young plants than on older plants (Dixon *et al.*, 1988). In spring-sown crops, early and large aphid populations may therefore require control, for example, by the use of insecticidal granules at planting. If few aphids are expected to be present during the early stages of crop growth, such

treatments may be of no value as their efficacy will have ceased and plants are less damaged by the time aphid populations build up. A forecast of likely early-season aphid population levels can thus be useful in assessing the need for control.

Newly-sown crops are colonised by alate aphids and their migrations are monitored by the Rothamsted Insect Survey using a network of suction traps (Macaulay *et al.*, 1988, Tatchell, 1991). The time span (27 years) of data available from this system facilitates the use of statistical models in forecasting early-season activity of alatae. For aphids that are largely anholocyclic in a given region, there is often a good relationship between the date of the first record in the suction trap and winter temperature (Turl, 1980; A'Brook, 1983; Walters & Dewar, 1986; Harrington *et al.*, 1990, 1991).

In this paper we concentrate on one aphid species, *Myzus persicae* (Sulzer) at one site (Rothamsted) and on the influence of temperature in one time period, January to February, which has been shown to be the most closely related to early season activity (unpublished data). This aphid is the most important vector of viruses of potato and sugar beet, and insecticidal granules are often used at planting to control it (Cooke *et al.*, 1989). The same principles are likely to apply to other species in areas where they are largely anholocyclic. The objectives of this work were i) to investigate the relationship between mean temperature and the time of the first, second, third, fourth and fifth aphid recorded in the trap, to justify the general use of the first record; ii) to investigate the relationship between the time of the first record of *M. persicae* in the trap and the number of alatae recorded subsequently, to clarify the value of the time of the first record as an indication of the size of the spring migration; iii) to evaluate the performance of these simple linear regression models over the past four years and iv) to use the relationships to consider the potential consequences of long term change in winter temperature on problems caused by the aphid.

METHODS

Date of first five aphids trapped

The Julian dates of the first to fifth records of *M. persicae* in the suction trap at Rothamsted were each regressed on the mean screen temperature for January to February recorded at the meteorological station adjacent to the trap in the years 1966 to 1988. Predicted dates for 1989 to 1992 were compared to actual dates.

Numbers trapped

The numbers of *M. persicae* trapped (log (N+1)) until the ends of Rothamsted Insect Survey standard weeks on June 10th, 17th, 24th, July 1st, 8th, 15th, 22nd and 29th (Taylor *et al.*, 1981) were regressed individually on the date of the first record and on January to February mean temperature in the years 1966 to 1988. Predictions for 1989 to 1992 were compared to actual numbers.

Climate change

The mean UK temperature in January and February is expected to rise by 2.9°C by the year 2050 (Anon., 1991). Using the regression relationships above, the mean date of the first record of *M. persicae* at Rothamsted from

1966 to 1992 was compared with this increase. The numbers trapped until July 15th were compared with the number likely to be trapped under these conditions.

RESULTS

Date of first five aphids trapped

The relationships between the mean temperature in January and February and the date of the first to fifth record of *M. persicae* in the Rothamsted suction trap become weaker with later records (Table 1) but in all cases there was a significant (P<0.001) relationship between the two factors.

TABLE 1   Relationship between mean screen temperature at Rothamsted for January to February (x) and date of the first to fifth record of *Myzus persicae* in the suction trap (y).

APHID RECORD	REGRESSION EQUATION	VARIANCE ACCOUNTED FOR
First	y = -14.0x + 190.0	77.5%
Second	y = -13.5x + 195.7	60.4%
Third	y = -13.6x + 201.6	58.5%
Fourth	y = -14.0x + 204.3	60.5%
Fifth	y = -12.8x + 204.2	52.7%

Predicted and actual dates for 1989 to 1992 are shown in Table 2 together with the range of dates found in 1966-1988. The error in predicting the first record ranged from 12 days early to 32 days late; the second record from 10 days early to 5 days late; the third and fourth records from 8 days early to eight days late and the fifth record from 7 days early to 13 days late.

Numbers trapped

The relationships between the date of the first record and the numbers trapped until June 10th, 17th, 24th, July 1st, 8th, 15th, 22nd and 29th become weaker with the later dates (Table 3) but are all significant except for the period until July 29th (P<0.001 for all dates until July 15th, P<0.01 until July 22nd). The date of first record showed a marginally closer correlation with numbers caught than did mean January to February temperature, for all dates up to July 8th.

Predicted and actual numbers trapped in 1989 to 1992 are shown in Table 4 together with the ranges of numbers trapped from 1966 to 1988. Both the predicted and actual values were smallest in all weeks in 1991. Predicted numbers were greatest in 1989 except for the period to July 29th. Actual numbers trapped in 1989 were the greatest except for the period to June 10th.

Climate change

The mean screen temperature for January to February from 1966 to 1992 was 3.3°C. The mean temperature for the same period is expected to be 6.2°C by 2050. Using the relationships described above, it is expected that the current mean of May 23rd for the date of first record of *M. persicae* will be

advanced by 6 weeks to April 10th. The number of *M. persicae* trapped by July 15th is expected to rise from a mean of 49 to 385.

TABLE 2. Predicted (PRED) (+/- 95% confidence limits) and observed (OBS) dates of first five *Myzus persicae* in the Rothamsted suction trap from 1989 to 1992.

APHID RECORD		YEAR				RANGE 1966-1988
		1989	1990	1991	1992	
First	PRED	Apr 26	Apr 10	Jun 11	May 13	
	+/-	24	25	23	23	
	OBS	Apr 2	Apr 22	Jun 23	Apr 11	Apr 12 - Jul 24
Second	PRED	May 4	Apr 19	Jun 18	May 20	
	+/-	32	36	33	33	
	OBS	May 3	Apr 28	Jun 28	May 15	May 5 - Jul 24
Third	PRED	May 10	Apr 25	Jun 24	May 26	
	+/-	36	38	34	34	
	OBS	May 5	Apr 29	Jul 2	May 18	May 5 - Jul 24
Fourth	PRED	May 10	Apr 25	Jun 25	May 27	
	+/-	35	38	34	34	
	OBS	May 7	Apr 30	Jul 3	May 19	May 5 - Jul 24
Fifth	PRED	May 17	May 2	Jun 28	Jun 1	
	+/-	38	40	36	36	
	OBS	May 8	May 2	Jul 5	May 19	May 5 - Jul 24

TABLE 3. Relationships between Julian date of first record (x) of *Myzus persicae* in the Rothamsted suction trap and numbers trapped (log n+1) (y) until June 10th and each week to July 29th.

NUMBERS TRAPPED UP TO:	REGRESSION EQUATION	VARIANCE ACCOUNTED FOR
June 10	$y = -0.020x + 3.73$	64.7%
June 17	$y = -0.020x + 3.96$	63.4%
June 24	$y = -0.023x + 4.48$	58.1%
July 1	$y = -0.025x + 4.87$	56.4%
July 8	$y = -0.026x + 5.15$	54.4%
July 15	$y = -0.021x + 4.71$	43.4%
July 22	$y = -0.019x + 4.43$	35.5%
July 29	$y = -0.006x + 2.82$	4.4%

DISCUSSION

The variance accounted for in the relationship between mean January to February temperature and date of the first suction trap record of *M. persicae* was greater than with second, third, fourth and fifth records, although in 1989 to 1992, the date of the later records was predicted more accurately than

TABLE 4. Predicted (PRED) and observed (OBS) numbers of *Myzus persicae* in the Rothamsted suction trap until June 10th and accumulated every week until July 29th from 1989 to 1992.

NUMBERS TRAPPED UP TO:		YEAR				RANGE 1966-1988
		1989	1990	1991	1992	
June 10	PRED	78	31	1	51	
	OBS	89	139	0	23	0-118
June 17	PRED	117	45	1	76	
	OBS	281	229	0	28	0-162
June 24	PRED	217	74	2	134	
	OBS	430	248	1	52	0-372
July 1	PRED	359	112	2	213	
	OBS	480	283	2	129	0-820
July 8	PRED	570	171	3	332	
	OBS	503	295	7	176	0-888
July 15	PRED	556	207	9	356	
	OBS	503	300	10	240	0-896
July 22	PRED	522	221	15	354	
	OBS	506	300	13	248	0-896
July 29	PRED	171	127	51	150	
	OBS	506	300	25	248	0-896

the date of the first. The date of the first record is significantly correlated with numbers trapped until mid July. It therefore seems reasonable to pursue the potential of using the relationship between winter temperature and first record as a warning of the likely timing and scale of early season alate aphid activity.

The 95% confidence limits for the predictions of dates of first record are in the order of three to four weeks on either side of the predicted date. These span half the range of dates experienced and it is clearly desirable to improve the predictive value of such relationships. The use of further weather variables in a multiple regression is being assessed as a method for achieving this, but in analyses completed to date (Harrington *et al*., 1991), the confidence limits for predictions are very similar to those for simple linear regression with mean temperature. In all cases, the confidence limits increase the further the predicted value is from the mean of values used to formulate the prediction. This combined with the inherent danger in extrapolating from regression models (Weisberg, 1985) signals caution is necessary when new conditions are near or beyond the extremes of previous experience as in the very mild winters prior to the springs of 1989 and 1990. The predictions for aphid activity in a warmer climate also fall into this category, and it is clear that other factors such as changed cropping practices could influence aphid phenology by the year 2050. At present it would at least seem reasonable to predict an 'early', 'normal' or 'late' migration from the relationships described.

Although cause and effect are implied in these relationships, the significance of the relationships themselves does not prove this. It is essential to do experimental work to justify these implications and this is being done. Low temperature affects aphid winter survival in a variety of ways. Firstly, low temperatures kill *M. persicae* directly. The temperature that kills 50% of acclimated *M. persicae* in laboratory trials (LT_{50}) is approximately -16°C for first instar nymphs and -12°C for adults when held at the minimum temperature for one minute (Bale *et al.*, 1988). As the length of time the aphids are kept at low temperature increases, mortality rises. For example, 50% of acclimated first instar *M. persicae* are killed when kept at 5°C for 54 h (95% fiducial limits 29-66 h) (unpublished data). Secondly, recent studies have shown that temperatures above the LT_{50} can have sub-lethal effects on survivors, reducing reproductive output and longevity. Thirdly, these and still higher temperatures can prevent essential movement to new feeding sites as old ones become unsuitable (Harrington & Taylor, 1990). Furthermore temperature affects aphids indirectly through effects on the host plant, and it will also affect any influence that natural enemies may have through the winter months. The development of a simulation model that takes account of all these influences would be difficult given the wide range of overwintering situations from which *M. persicae* emerges and becomes available to infest a spring crop. Provided that supporting studies indicate a reasonable likelihood of cause and effect in statistical models of winter survival, such models provide the best hope for forecasting early season alate activity far enough in advance to assist growers with decisions on control when planting spring crops. Comparisons of the performance of such models for different aphid species and different locations are likely to give further clues as to the characteristics of aphids and weather which influence survival.

No attempt has been made here to predict the build up of populations of *M. persicae* on crop plants. The relationships only describe the initial movements of alatae, which although particularly important in virus spread, are not necessarily related to total direct feeding damage. Later in the season, as the growth and development rates of aphids, their natural enemies and their host plants increase, it becomes increasingly difficult to predict changes far ahead. Dixon *et al.* (1988) found a very weak association between spring suction trap catches of the largely anholocyclic grain aphid, *Sitobion avenae*, and peak population density on the crop. Dewar & Carter (1984) found that small spring migrations of *S. avenae* were never followed by an outbreak, whereas larger spring migrations occasionally did lead to outbreaks although the actions of natural enemies frequently prevented them.

Little long-term data are available for damage to potato crops against which to assess the economic importance of early season alate activity. However, for the sugar beet crop, data on the incidence of yellows viruses in the UK are available throughout the operation period of the suction trap system, and the time of the first record of *M. persicae* in the suction traps is an important factor in an early warning of virus incidence (Harrington *et al.*, 1989).

Early forecasts, based on winter temperatures and previous virus incidence, give a broad indication of virus levels in sugar beet in any one year, but these are updated when the first *M. persicae* is caught in the suction trap at Broom's Barn.

In 1988 and 1991, the early forecasts for all regions were reasonably accurate, with virus levels within 5% of predicted values. However in 1989,

early predictions considerably underestimated eventual virus incidence, and in 1990 these predictions overestimated virus infection in the Eastern region and underestimated it in the north (Table 5). Inclusion of trap data in the later forecasts gave better predictions in Eastern and Western, but not in Northern regions, in 1989; however, in 1990, only the later forecast in the Northern region accurately predicted the eventual infection in August.

These discrepancies mostly err on the side of caution i.e. they overestimated infection. The one exception to this, in the Northern region in 1989, was due to exceptionally large numbers of aphids coming from overwintering oilseed rape and brassicas (Dewar & Smith, 1990). The relatively poor accuracy of recent forecasts for that region may be explained by widespread changes in cropping practices over the last 10 years, especially the area of oilseed rape grown. This crop, which is an overwintering host of *M. persicae*, was relatively uncommon during the period over which the prediction equations were formulated, and it may now be necessary to revise the forecasting scheme to take account of changing crop rotations.

TABLE 5. Comparison of predicted and actual incidence (% plants infected) of virus yellows in sugar beet in England at the end of August 1988-1991.

YEAR	REGION	FORECAST		ACTUAL INCIDENCE
		IN MARCH	AFTER 1ST APHID CAUGHT	
1988	Eastern	5.8	5	9
	Western	1.8	2	5
	Northern	1.8	2	6
1989	Eastern	5.8	25	17.5
	Western	1.9	9	9
	Northern	1.9	7	27.5
1990	Eastern	34	83	13
	Western	13	40	10
	Northern	9	26	24
1991	Eastern	0.7	1.5	2.5
	Western	0.2	0.4	6.7
	Northern	0.4	0.7	2.2

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A PROTOTYPE SIMULATION MODEL TO EXPLORE OPTIONS FOR THE MANAGEMENT OF RICE TUNGRO VIRUS DISEASE

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ABSTRACT

Rice tungro virus disease (RTVD) is a major problem for growers of irrigated rice in S. E. Asia. A simulation model is being developed to help improve RTVD risk assessment, evaluate management tactics and identify targets for field research. The model simulates the position and infectivity status of the green leafhopper vectors and the corresponding RTVD infection pattern in a square grid of 2500 rice hills during the first 60 days of crop development. Based on published information, assumptions are made about virus transmission, vector population dynamics and vector dispersal. Results from a programme of field experiments in the Philippines provide a basis for model validation. In the usual pattern of disease development, low numbers of infective vectors enter the crop and the disease is subsequently spread by other, initially non-infective, insects. A preliminary analysis using the model suggests that in the dry season, vector numbers may be sufficiently low to impose some constraint on disease spread. In the wet season, however, disease progress is likely to be constrained more by the source of inoculum than by the numbers of vectors. For purposes of assessing tungro risk by monitoring early-season vector immigration, an infective immigrant is likely to contribute about two orders of magnitude more than a non-infective immigrant to the level of tungro infection in the wet season crop.

INTRODUCTION

Rice tungro virus disease (RTVD) is a major problem in S. E. Asia, particularly in regions with multiple cropping and asynchronous planting dates (Thresh, 1989). The rice tungro viruses are transmitted by several leafhopper species, of which, the green leafhopper, *Nephotettix virescens* (Distant), is often the most abundant. Symptoms, leaf yellowing and stunted growth, start to appear about 1 - 2 weeks after infection. Total crop loss can result, particularly from infections initiated in the first weeks of crop development.

Two viruses are associated with RTVD and both are semi-persistent in the vector. The spherical virus is retained for about 2 days and the bacilliform virus for 4 days (Chowdhury *et al*., 1990a). New infections

are initiated in a crop by the immigration of viruliferous vectors, or by the transplanting of seedlings which were infected by vectors in the seedbed. About 1 week after infection, rice plants become fully effective sources for further infection (Narayanasamy 1972), but can be infective to some degree within a 2 - 3 days of inoculation (Chowdhury *et al.*, 1990b). The spherical virus can be acquired by the vector and transmitted independently to new plants, but acquisition and transmission of the bacilliform virus requires the presence of the spherical virus (Chowdury *et al.*, 1990b).

Rice varieties with resistance to the vectors are widely used in tungro management but resistance breakdown occurs (Anon, 1990). Control at the field level is difficult because of (a) the delay in symptom expression, (b) the low density of vectors necessary for rapid spread, (c) the delay and labour associated with the bioassay required to detect the virus in the vector, and (d) the long period over which viruliferous vectors may enter the crop and initiate a serious infection. Nevertheless, suggested field-level control tactics have included: use of systemic insecticides in the seedbed and newly planted crop, covering of seedbeds with netting, early season spraying with contact insecticides, application of insect growth regulators and removal of diseased plants (e.g. Satapathy & Anjaneyulu, 1989; Estano & Shepard, 1989; Mas'ud & Moeh, 1987; Mochida *et al.*, 1986). Because of the difficulties of timely disease detection, prophylactic insecticide application may be the only option in some cases, entailing considerable risk of induced resurgence of other pests. However, an indication of early season vector abundance and infectivity may be possible from pest surveillance schemes, e.g the use of mobile nurseries - trays of seedlings set out in fields prior to planting (Chang *et al.*, 1985).
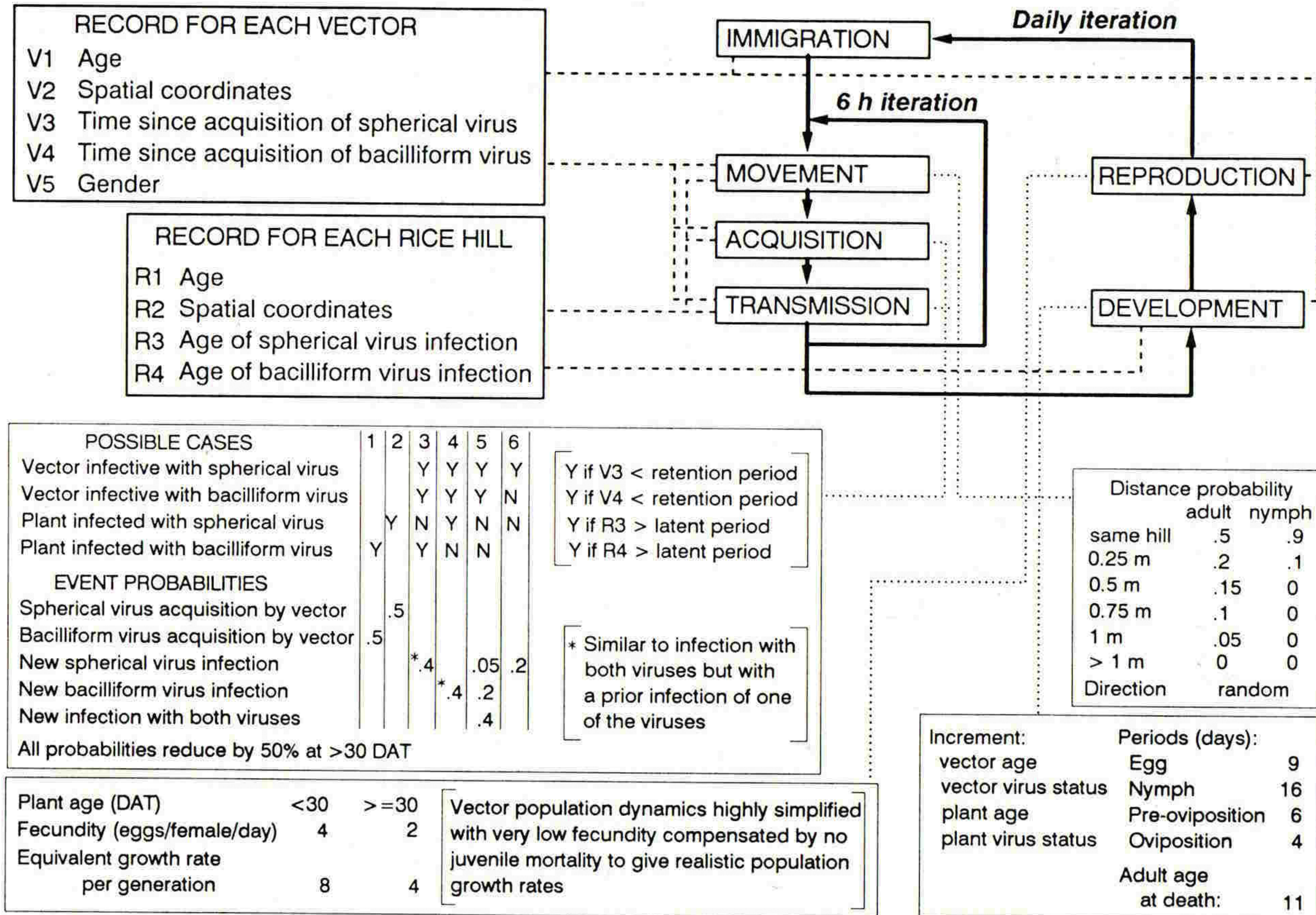
This paper describes initial steps in the simulation modelling of RTVD spread in a rice crop. The objective is to help evaluate the various RTVD control options and surveillance methods which have been advocated. A preliminary analysis is described of the relative importance of primary spread into plantings and secondary spread within plantings in the dynamics of the disease. This question is central to the interpretation of vector surveillance data for tungro risk assessment.

DEVELOPMENT OF THE MODEL

The model is a simulation of the spread of RTVD within a square grid of 2500 rice hills of a tungro/vector susceptible variety. A record for each hill contains plant age, position and infection status with respect to both tungro viruses. The development, reproduction, movement, and virus-vector-plant interactions of up to 10000 individuals of *Nephotettix virescens* can be tracked. A record for each vector includes its age, position, gender and virus infectivity status for both tungro viruses.

The simulation has a daily iteration for development, reproduction and immigration, and within this, a six-hourly iteration for vector movement, virus acquisition and virus transmission. Vector and rice hill records are updated at each iteration according to the assumptions associated with each process. These assumptions are summarised in the lower part of Fig. 1., and for most parameters, simple, multinomial probability distributions are used.

Fig. 1. Summary of the structure and assumptions of the simulation model. Solid lines indicate the sequence of processes, dashed lines, information transfer to and from vector and rice hill records, and dotted lines, links to details of assumptions governing each process.

RECORD FOR EACH VECTOR
V1 Age
V2 Spatial coordinates
V3 Time since acquisition of spherical virus
V4 Time since acquisition of bacilliform virus
V5 Gender

RECORD FOR EACH RICE HILL
R1 Age
R2 Spatial coordinates
R3 Age of spherical virus infection
R4 Age of bacilliform virus infection

IMMIGRATION

Daily iteration

6 h iteration

MOVEMENT

REPRODUCTION

ACQUISITION

TRANSMISSION

DEVELOPMENT

POSSIBLE CASES	1	2	3	4	5	6
Vector infective with spherical virus			Y	Y	Y	Y
Vector infective with bacilliform virus			Y	Y	Y	N
Plant infected with spherical virus	Y	N	Y	N	N	
Plant infected with bacilliform virus	Y		Y	N	N	

Y if V3 < retention period
Y if V4 < retention period
Y if R3 > latent period
Y if R4 > latent period

EVENT PROBABILITIES						
Spherical virus acquisition by vector		.5				
Bacilliform virus acquisition by vector	.5					
New spherical virus infection			*.4		.05	.2
New bacilliform virus infection				*.4	.2	
New infection with both viruses					.4	

All probabilities reduce by 50% at >30 DAT

* Similar to infection with both viruses but with a prior infection of one of the viruses

Distance probability	adult	nymph
same hill	.5	.9
0.25 m	.2	.1
0.5 m	.15	0
0.75 m	.1	0
1 m	.05	0
> 1 m	0	0
Direction	random	

Increment:	Periods (days):	
vector age	Egg	9
vector virus status	Nymph	16
plant age	Pre-oviposition	6
plant virus status	Oviposition	4
	Adult age at death:	11

Plant age (DAT)	<30	>=30
Fecundity (eggs/female/day)	4	2
Equivalent growth rate per generation	8	4

Vector population dynamics highly simplified with very low fecundity compensated by no juvenile mortality to give realistic population growth rates

In virus acquisition for example, the probability of spherical virus being acquired by a vector, at a particular infected hill in a 6-hour contact period has the value 0.5 (before 30 days after transplanting, DAT), 0.25 (after 30 DAT) or 0 (when the source rice hill is not infected with the spherical virus). Similarly for transmission, when a vector is infective with both viruses and the rice hill is infected with neither, the probabilities of new infections of spherical, bacilliform and both viruses are 0.05, 0.2 and 0.4, respectively (before 30 DAT), and 0.025, 0.1 and 0.2 (after 30 DAT). When the vector is infective with the spherical virus only, the transmission probability of this virus appears to be higher (Chowdhury et al., 1990a) (set at 0.2 in the model). A vector ceases to be infective when the time elapsed since virus acquisition exceeds the retention period. Retention periods were set at 2 days for the spherical virus and 3 and 4 days, respectively, for nymph and adult vectors carrying the bacilliform virus. For both viruses, it was assumed that a plant could act as a virus source 7 days after inoculation.

Some indications of probabilities of insect movement were taken from Bottenberg & Litsinger (1989), Ling & Carbonell (1975) and Ito & Miyashita (1961). An equal probability of movement in all directions is assumed, with adults moving a maximum of 1 m (equivalent to 4 hill spaces at .25 X .25 m hill spacing) in any 6 h period. It is assumed that a vector is in contact with only one hill during each 6 h period, giving a maximum of four source contacts per day and movement over a maximum distance of 4 m (16 hill spaces) in a day. It is assumed that most nymphs stay on the hill where they hatch, and consequently contribute very little to virus spread.
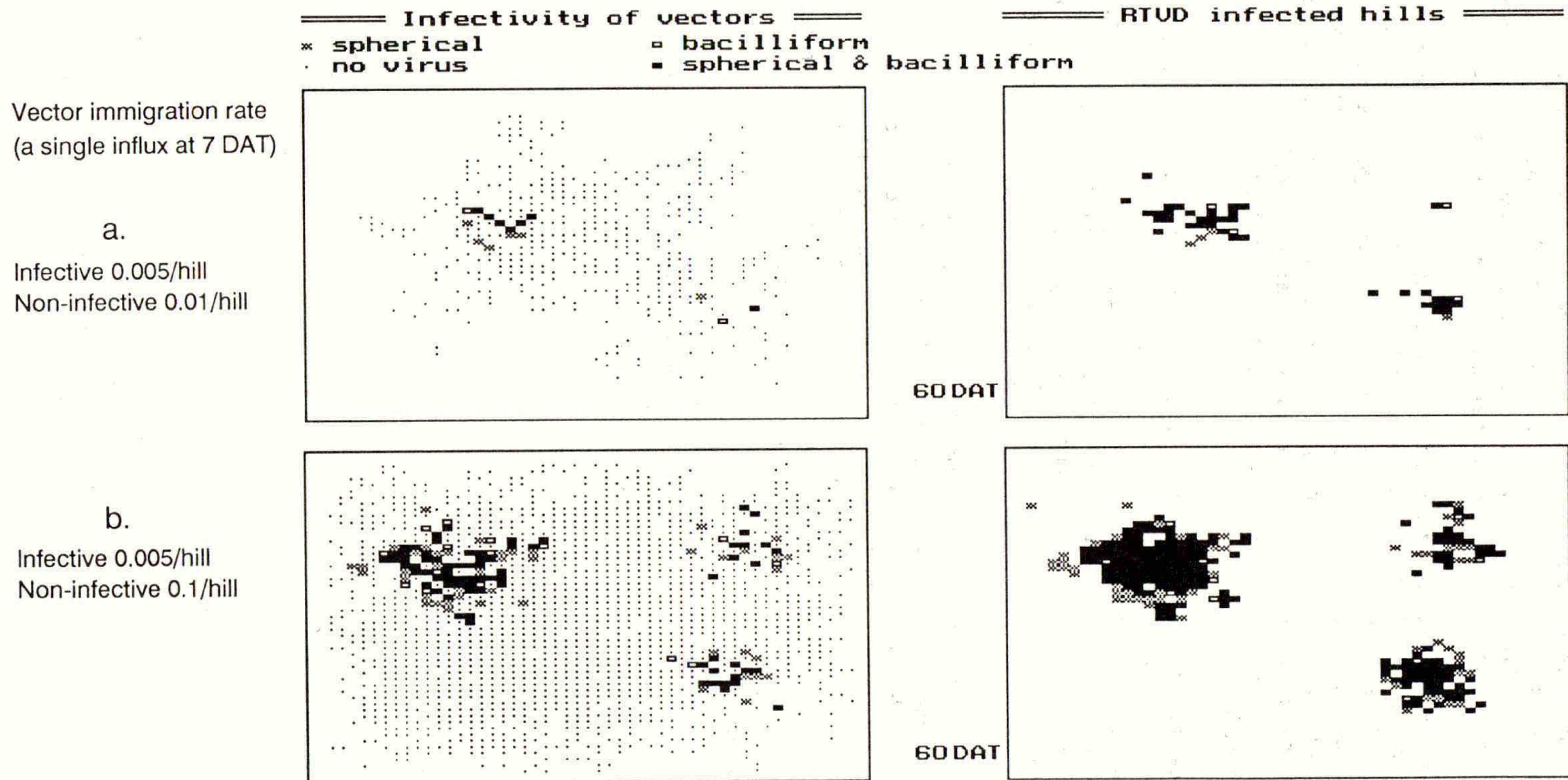
The assumption about limited nymph movement partly justifies the simplified treatment of reproduction and survival, which leads to an unrealistic age structure with too few early instar nymphs (Fig. 1). Development times are fixed and adult survival has a binomial distribution with survival decreasing from 1 to 0 at an adult age of 11 days.

A series of model validation exercises is in progress to compare model output with vector density, and tungro disease incidence data from field trials in the Philippines. Meanwhile, some preliminary analyses raise questions concerning the principles of tungro spread within a rice crop. Fig. 2 shows some example output for two simplified immigration situations, where a mixture of non-infective immigrants and immigrants infective with both spherical and bacilliform viruses, enter the crop at 7 DAT. In both cases the density of infective immigrants is relatively low (0.005/hill), but the density of non-infective immigrants is 10 times greater in Fig. 2b (0.01/hill) than in Fig. 2a (0.1/hill). This gives a difference in the potential for subsequent secondary spread of the disease within the planting, following the introduction of the same amount of primary inoculum into the planting.

ANALYSIS OF THE RELATIVE IMPORTANCE OF PRIMARY AND SECONDARY DISEASE SPREAD

Secondary spread within plantings, by vectors non-infective prior to their arrival in the crop, is clearly of some importance (Fig. 2). A series of simulations were performed in which the numbers of non-infective

Fig. 2. Simulated position and infectivity status of RTVD vectors and the
corresponding RTVD infection pattern in a grid of 2500 rice hills at 60 DAT,
a, with low, and b, with high potential for secondary disease spread

===== Infectivity of vectors =====   ======= RTVD infected hills =======

× spherical   □ bacilliform
· no virus   ■ spherical & bacilliform

Vector immigration rate
(a single influx at 7 DAT)

a.

Infective 0.005/hill
Non-infective 0.01/hill

60 DAT

b.

Infective 0.005/hill
Non-infective 0.1/hill

60 DAT

immigrants and immigrants infective with both viruses were varied over ranges similar to those observed in the field (0.12/hill to 0.002/hill). The number of hills infected with both spherical and bacilliform virus at 60 DAT was recorded for each combination of immigrants tested.

Because probability distributions were used to simulate vector movement, virus acquisition and virus transmission, repeated simulations were required to obtain an average result. Three repeat simulations were performed for each of 50 combinations of non-infective vector density and infective vector density. A polynomial regression was then used as a smoothing technique to show the underlying pattern whilst removing 'noise' (Fig. 3). The regression explained 96% of the variation in the number of hills infected.

For densities of non-infective immigrants in excess of 0.05 / hill, the infection contours shown in Fig. 3 are nearly perpendicular to the y-axis (density of infective immigrants). This suggests that primary spread into plantings is of over-riding importance. Secondary spread is more important, however, when the number of immigrant vectors is low but their rate of infectivity is high. With reference to Fig. 3, we consider four particular immigration cases in more detail:

Case 1: At low densities (0.015/hill) but moderate infectivities (67%), the spread of the disease appears to be limited both by lack of inoculum and by the lack of vectors to spread disease in the crop.
Case 2: At slightly higher densities (0.045/hill) and high infectivities (88%), disease progress is extremely rapid, being limited only by lack of insects to spread the virus - further progress of the disease is promulgated almost equally by adding either infective or non-infective immigrants.
Case 3: In contrast, at higher densities (0.125/hill) but with lower infectivities (2%), disease progress is constrained by lack of inoculum. Small changes in the numbers of infective immigrants have a very large effect on incidence of tungro, with an infective immigrant vector contributing one to two orders of magnitude more to disease progress than a non-infective insect.
Case 4: With similar density to Case 3 (0.13/hill) and slightly higher infectivity (7.6 %), tungro incidence reaches a level similar to that in Case 2.

CONCLUSIONS

Field sampling during the 1991 wet season in the Philippines indicated that the infectivity rates of immigrant tungro vectors were very low, even in situations where a high incidence of tungro disease developed subsequently. During the first 30 days of crop development, the mean density of the major vector, *N. virescens*, was 0.27 / hill. This situation is similar to Case 3 in which vectors are effectively in excess and it is lack of inoculum alone which constrains disease progress.

The situation was different in the 1992 dry season; both vector numbers and rate of infectivity were very low. With a mean density of vectors of 0.02 / hill, this was similar to Case 1 in which lack of inoculum and low vector numbers are both important constraints to disease progress. In the 1991 dry season, the infectivity rate of the vectors was

Fig. 3. Proportion of rice hills infected (with both viruses) at 60 DAT
following an influx of a mixture of infective and non-infective vectors
at 7 DAT. The .75,.5,.25,.1 & .05 infection proportion contours are shown.
Four particular immigration cases, 1 - 4, are discussed in the text.
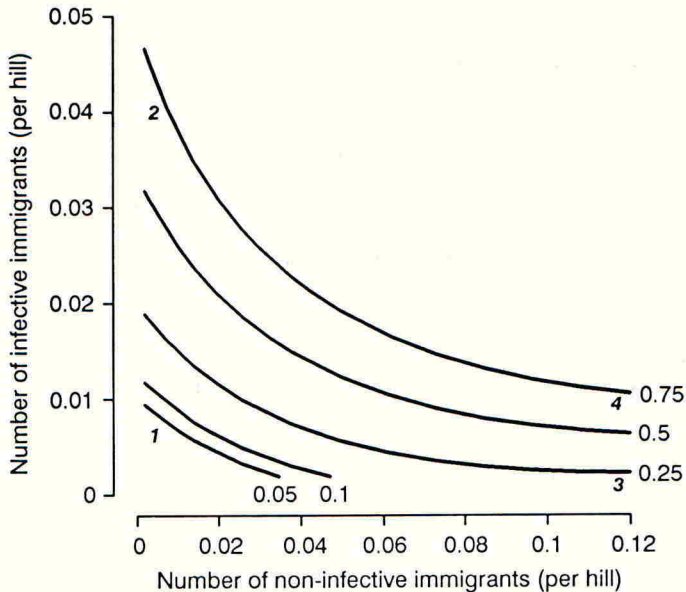
higher than in both the other seasons but this may have been due to the
late planting of the experimental crop two months after the surrounding
rice.

If these observations represent the general picture, then this
analysis suggests that in the wet season, it is necessary only to consider
the density of infective immigrants when assessing tungro risk. In the
dry season, availability of vectors to spread the virus may limit disease
spread in some cases.

The relative trends described are likely to be more dependable than
the absolute values. Clearly, confidence in the results presented here
may be improved by the validation work mentioned earlier, as well as a
systematic sensitivity analysis. Topics for particular scrutiny are the
effect of singly infective immigrant vectors (i.e. infective with only the
spherical or bacilliform virus, rather than all immigrants infective with
both viruses as examined here), the entry into the crop of infective
vectors at different times, the effect of rice variety, and the
assumptions about vector movement and frequency of virus transmission.

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RULE BASED MODELS IN CROP PROTECTION

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ABSTRACT

Models are used to help answer many questions in crop protection. The type of model used will depend on the nature of the question and the level of resolution required. Rule based models have been defined as the qualitative equivalent of conventional quantitative models. When information is sparse it may not be possible to construct a quantitative model but it may still be possible to build a rule based model. Rule based models can be used for diagnosis, for modelling decision making and also for simulation modelling. The nature of rule based models makes them easy to construct, use and interpret, making them highly desirable for use in interdisciplinary projects.

INTRODUCTION

The use of models in crop protection is both widespread and varied. The reason for building a model is to help to answer questions about the management of a particular pest system. The questions that have to be answered may be biological or may concern the decision processes of the farmer. The type of model that is adopted will vary with the type of question to be answered but it would be an over simplification to say that one type of model should be used for answering one type of question and another for a different type of question. A further important consideration in choosing the type of model to use is the level of detail or resolution that is required of the model to answer the question asked of it. In a problem where the decision is whether to spray or not a simple yes or no may be all that is required as output. If an outbreak of a pest, such as locusts, is forecast then the farmer can prepare; if they are not going to appear the farmer need do nothing. The farmer does not require any information on the magnitude of the pest outbreak and to give any information would be a waste of resources and may prove to be confusing. If on the other hand the level of crop loss is proportional to the number of pests on the crop it is necessary to know more precisely the size of an infestation in order to make a decision on the economic benefits of spraying. These two situations illustrate the need to build an appropriate type of model or to model at an appropriate level of detail.

A number of different types of model have been used successfully in crop protection; statistical models are used for forecasting levels of virus (Harrington et al., 1989), simulation models for determining the timing of pesticide application (Cheng & Holt, 1990; Gutierrez & Wilson, 1989), and analytical models for studying the interactions between pests and natural enemies (Godfray & Waage, 1991). All of these

conventional modelling approaches require quantitative data about the system before they can be built.

In many situations our knowledge of a system is very sparse and we do not have quantitative data about all parts of the system in which we are interested. In this situation we could, at best, construct only an incomplete model of the pest system. For example we may have data about the relationship between the development rate of a pest and temperature but know very little about the effects of natural enemies on the mortality of the population. Therefore, we would be unable to model that part of the system. In such a situation we are faced with a number of choices. Firstly we could construct the model with the information that we have on the effects of temperature and ignore the effects of the natural enemies. However, if we suspect the natural enemies are important in the control of pest numbers then this is not acceptable. Secondly we could build a model that included the natural enemies using approximations or best guesses for the values in the model. This could lead to errors and an unbalanced model. Thirdly we could discard information about the relationship between the pest and temperature and model it at the same resolution as the natural enemy component. Finally we could collect the data about the natural enemies and construct a model when the data became available. The overall result is that we have to make trade-offs either in the resolution or balance of the model or in the time spent to build it.

Rule based models have been defined as the qualitative equivalent of conventional quantitative models. A rule based approach provides a means of using knowledge to build a model without the need to represent relationships between components with mathematical equations (Holt & Day, 1992).

Both conventional models and rule based models can simulate how system components respond over time in relation to other components. Conventional models represent the components by numerical variables and changes in variables by equations. In rule based models, components are represented by a small set of discrete states and changes are effected by 'if-then' type rules.

It is important to emphasise that rule based models are not seen as an alternative to simulation or regression models but as being complementary, indeed many situations will require the combination of more than one type of model to provide an answer to the question being asked. For example even when efficient numerical models exist the output often has to be interpreted in a qualitative form before being used for decision making (Guerrin, 1991).

Often there is considerable information about a system but it is qualitative rather than quantitative, much of it being in the form of expertise and experience of individuals. In such cases it may be possible to use a rule based approach for the construction of a model. The resolution of a rule based model is likely to be less than a simulation or statistical model but it has the advantage that it can be constructed immediately. The process of constructing a rule based model often helps to identify areas in the system where information is missing and therefore helps to target the research effort. The highlighting

of these information gaps ensures that the correct data are collected for any subsequent modelling exercise (Norton *et al.*, 1992).

An example of the relationship between pest density and yield illustrates the differences between a simulation and a rule based model.

Quantitative expression:

$$Yield = \frac{100}{(1 + Pest\ density * 0.1)}$$

Rule based:

Defining four states of pest density (low < 5; medium 5-10; high 11-200; very high > 200) and four states of yield (very poor < 5%; poor 5-50%; fair 51-70%; good >70%)

IF pest density is low   THEN yield is good
IF pest density is medium   THEN yield is fair
IF pest density is high   THEN yield is poor
IF pest density is very high   THEN yield is very poor

The absolute numerical values of "good", "fair" and "poor" may not be known but by formalising our thoughts on the relationship we now have a consistent meaning for each. The rule based approach has a lower level of resolution than the simulation approach (Figure 1.) but it is often sufficient to make a control decision. In the quantitative model both the pests (X) and the yield (Y) can be measured and it is possible to derive a mathematical function for the relationship between the two shown by the line on the graph. In the rule based model the pest density, or the yield, either cannot be, or has not been, quantified which means no mathematical relationship can be described. However, it is possible to describe the relationship in qualitative terms which may be sufficient for our purposes.

In the rest of the paper, we will discuss the ways in which rule based models can be used in a number of areas of crop protection.

USES OF RULE BASED MODELS

Simulation/Prediction

A rule based model can be used to produce a simulation model, with outputs in discrete classes rather than continuous values. Figure 2 shows an example of a simple, two rule model in which populations increment by one age class (in classes 0-5), but decrement with rainfall (classes 0-2). Such a situation may apply to pests such as cutworms, for example. Figure 2 shows the rainfall classes over a number of time

Figure 1. An example of quantitative and rule based models to describe pest-yield relationships (the rule based model consists of categories bounded by the filled-rectangular boxes).

Pest-yield models
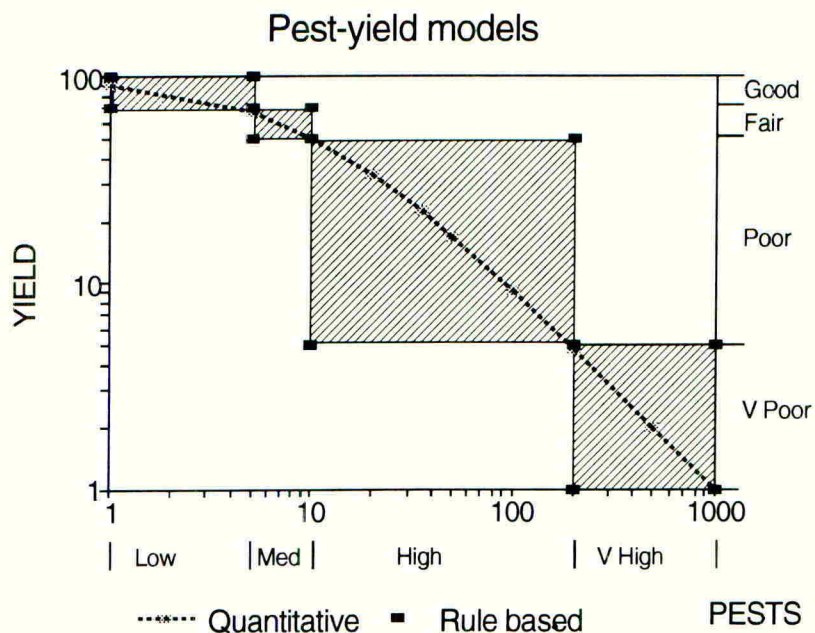
intervals, and the resulting simulation output using rules 1 and 2. The output in this case was produced using a spreadsheet program.

Another use of rule based models is in the prediction of pest problems. An example of this is in the expert system BULBFLY (Jones *et al*, 1990) where a series of rules determine if there is likely to be a problem with wheat bulb fly (*Delia coarctata*) in a particular field. Initially the system assesses if conditions are suitable for egg laying based on the weather conditions in the months of July and August and the area of ground visible to the fly for egg laying, i.e. the density of the crop canopy.

```
IF          The assessment of risk is high
    AND         Soil type is organic
    AND         Present month is December
    AND         Crop was sown in October
THEN        Economic damage is likely in the spring
```

After the system has assessed the probability of damage it recommends that one, or possibly two, deadheart sprays should be applied to control the wheat bulb fly.

Figure 2.   A simple two rule model with examples of input and output.

Rule 1   IF Population(t) < Maximum Population

THEN Population(t+1) = Population (t) + 1 - Rain(t)

ELSE Population(t+1) = Population (t) - Rain(t)

Rule 2   IF Population(t+1) < 0

THEN Population(t+1) = 0

Rain pattern

Rule-based population simulation
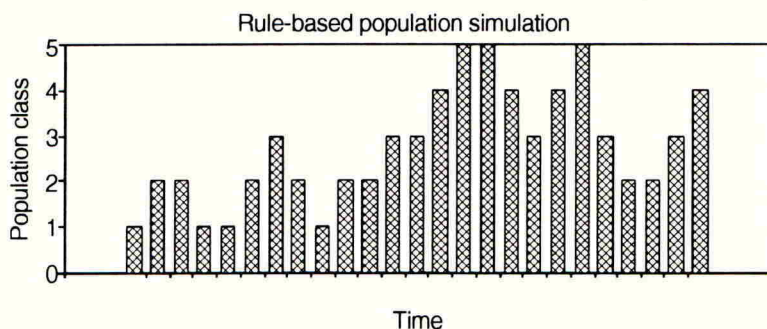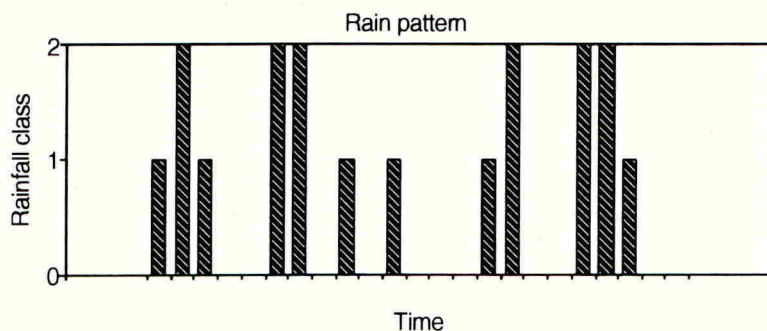
Diagnosis and Decision making

Rule based models are particularly useful in situations where a diagnosis or decision has to be made. Traditional methods of insect identification using dichotomous keys can be difficult and time consuming and an inexperienced person can have a problem when a feature is indistinct or missing. This problem can often be overcome by using rules to model the way in which taxonomists would handle the situation, perhaps by reference to information on the habitat or some other feature, thereby making it possible to provide a positive identification or a short list of possible alternatives. The processes used by experts when decision making can also be modelled successfully using a series

of rules to represent the questions that an expert will ask in order to build a picture of the problem and then come up with a solution.

The form of a rule based model for these types of applications will commonly be a decision tree where the answer to one question will lead onto another question until the final conclusion is reached.

The area where rule based models are used most commonly is in the area of modelling the processes of decision makers. Rules of thumb that are used by experts to make recommendations on crop protection decisions can be incorporated into a model allowing less experienced users to benefit from the expertise of others. This approach has been used widely in advisory systems for the control of pests and pathogens.
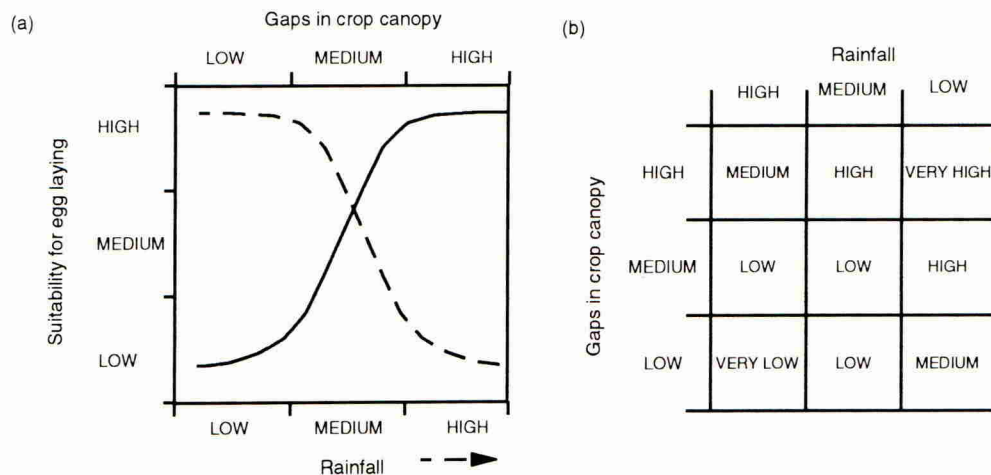
A useful way of representing knowledge about a system is by the use of transition matrices. The example shown here (Figure 3) is based on the knowledge of the biology of the wheat bulb fly (Jones et al., 1990). The risk of an attack is related to the history of previous attack, i.e. whether you are in a high risk area, and the suitability of the soil for egg laying in the summer. The best conditions for egg laying occur when July and August are warm and dry; high levels of rainfall reduce the suitability for egg laying. Sparse crops such as onions provide better egg laying conditions than dense crops such as cereals because more soil is visible to the fly for egg laying. Figure 3a. shows how the suitability for egg laying may decrease with increasing rainfall and also as the crop becomes more dense. The matrix (Figure 3b) shows how the relationship in Figure 3a. can be represented in terms of classes. Thus low rainfall combined with a 'gappy' crop results in very highly suitable conditions for egg laying; few gaps and high rainfall results in very low suitability.

The use of rule based models is complementary to the use of other models. Holt et al. (1990) used the results from a simulation model to produce rules for a rule based model for the control of brown planthopper (Nilaparvata lugens) in rice. In other cases the output from a simulation model can be used as the input for a rule based model or a rule based model can be used to control the values that are used in a simulation model. Statistical or analytical models can also be used alongside rule based models (Knight et al, 1992).

Methods of constructing rule based models

One advantage of rule based models is that they can easily be presented on paper, either as a series of rules or in the form of matrices, or they can just as easily be in a computerised form. Computer based decision models can be developed in any software where it is possible to construct IF-THEN type commands; for example, expert system shells, procedural languages or spreadsheets. Expert system shells and spreadsheets are easy to use and may be the first choice for people who do not have much programming experience. However, if the rule based model is to interact with other models it may be necessary to use a programming language to get all the parts working together.

Figure 3. a. Relationships between suitability for egg laying and rainfall and gaps in the crop canopy. b. Transition matrix for the relationship shown in 3a.

(a) Gaps in crop canopy — Suitability for egg laying vs Rainfall

(b) Transition matrix

	Rainfall		
	HIGH	MEDIUM	LOW
HIGH	MEDIUM	HIGH	VERY HIGH
MEDIUM	LOW	LOW	HIGH
LOW	VERY LOW	LOW	MEDIUM

Gaps in crop canopy (vertical axis for b)

CONCLUSIONS

Rule based models provide a useful addition to the techniques available for the study and solution of crop protection problems. They can be used alone or in combination with the other modelling techniques such as simulation models. The way in which they are constructed ensures that they can be easily understood by people with little or no experience of modelling which makes them potentially very useful in an interdisciplinary environment where each party must be able to understand the thinking of the others. This approach allows managers and biologists to structure the model themselves since the model is often a representation of a managers knowledge of a system. The rule based approach also means that these models can often be built and used without the need for computers which makes them particularly suitable for employment in areas where access to computers is limited or unreliable.

When building any model, where the information is scarce, assumptions have to be made about the unknown parts of the system. Whilst this is true of the rule based model the assumptions do not involve quantitative estimates and the qualitative estimates can be made from expert opinion or 'rules of thumb'.

The construction of rule based models can also present some problems to the modeller. For example, it can be difficult to know how many classes to define or where to make the boundaries between the classes. The modeller has to consider the level of resolution required of the model when making these decisions. One thing that needs to be

considered in this respect is that with a continuous, quantitative model change will be along a continuum; with classes the value assigned to a variable in the middle of the class will be the same as that assigned to a value that falls at the very edge of the class. In these situations a false sense of certainty may be ascribed to the model. This problem can be reduced by increasing the number of classes, however, this then increases the complexity of the model which detracts from the overall simplicity of this approach. Guerrin (1991) describes models with 3,5 and 7 classes.

The construction of a rule based model at an early stage in any project is useful in that it can serve to highlight any gaps in the information about the system and can indicate where information needs to be collected for building more complex simulation models.

In conclusion, the ease of use, construction and interpretation all contribute to making rule based models a practical choice for the investigation and solving of many crop protection problems.

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