FORECASTING ATTACKS BY INSECT PESTS OF HORTICULTURAL FIELD CROPS

R.H. COLLIER

Horticulture Research International, Kirton, Boston, Lincs PE20 1NN

S. FINCH, K. PHELPS

Horticulture Research International, Wellesbourne, Warwicks CV35 9EF

ABSTRACT

The timing of attack by pest insects can vary greatly both from region to region and from year to year. A simulation method, based on rates of insect development, has been developed for forecasting the timing of insect attacks. The method is based on using a fixed number of individuals from one generation to the next; and simulates the timing of events in the life-cycle of the pests rather than the population dynamics of the insects. Forecasts produced for the cabbage root fly, the carrot fly, the bronzed-blossom beetle and the large narcissus fly have been validated using pest monitoring data. Forecasts can be generated on a regional basis from standard meteorological data, or on a local basis from air and soil temperatures collected by participating growers.

INTRODUCTION

Insect pests of horticultural crops are often controlled by spraying insecticide onto established crops. Such sprays are used against root-feeding insects because the activity of insecticides applied at drilling or planting has diminished by the time later generations of the pest are active. Such sprays are also the most feasible way of controlling foliar pests such as aphids and caterpillars. Since the majority of currently-recommended insecticides are of relatively short persistence, treatments are most effective if they are targeted to coincide with periods of peak pest activity. Unfortunately, the timing of such peaks can vary considerably from region to region and from year to year. Although it is possible to monitor the activity of many pest species using insect traps, routine monitoring is laborious and often requires specialist knowledge. For a few pests, such as the large narcissus fly (*Merodon equestris*), an effective monitoring technique has not yet been developed.

An alternative is to use weather data to forecast the timing of pest attacks. Forecasting systems have been developed for many insects. For example, Finch (1989) cites references to ten separate models for forecasting the timing of attack by four pest species of *Delia* (Diptera, Anthomyiidae). Many of these forecasts have been based on day-degrees (e.g. Eckenrode & Chapman, 1972). However, day-degree forecasts have severe limitations, as their accuracy is based on the assumption that the relationship between the rate of insect development and temperature is strictly linear (Baker, 1980). In addition, day-degree forecasts can be used only to predict the start and/or the peak of activity of the population. They cannot readily predict the spread of activity nor can they cope easily with insect populations which have polymodal patterns of activity. For example, the cabbage root fly (*Delia radicum*) can occur as one of two developmental biotypes, that emerge either ‘early’ (in April-May) or ‘late’ (in June-July) in the season (Finch & Collier, 1983; Finch *et al.*, 1988). Within a particular locality, the population of cabbage root flies may consist primarily of one biotype or be a mixture of both. Finally, further problems in the use of day-degree models occur when attempting to interpret the overall effects of periods of insect dormancy, either diapause or aestivation, induced by changes in temperature or photoperiod. Since there is considerable variation between individuals in their rates of development, it is usual for only a proportion of the population to respond at any one time to a particular environmental cue. This is true of cabbage root fly populations during both aestivation and diapause (Collier & Finch, 1983; Finch & Collier, 1985).

At Horticulture Research International, a simulation method, based on rates of insect development, has been produced for forecasting the timing of attack by a number of pest insects (Phelps *et al.*, 1993). Variability between insects in their rate of development is also incorporated. The simulation method has been used to develop forecasts for the cabbage root fly, carrot fly (*Psila rosae*), bronzed-blossom beetle (*Meligethes* spp.) and large narcissus fly. The forecasts produced are now being validated with growers. Similar forecasts for certain pest aphids and caterpillars are under development. The biological basis, validation and practical uses of such forecasts are discussed in this paper.

THE MODEL

The forecasts for cabbage root fly, carrot fly, bronzed-blossom beetle and large narcissus fly were developed using a Monte Carlo simulation method (Phelps *et al.*, 1993). The method uses a fixed number of individuals (usually 500, to obtain repeatable simulations) from one generation to the next and simulates the timing of events rather than the population dynamics of the insects. To develop each model, individuals at each stage of development (egg, larva, pupa, adult) were reared in cooling incubators at a range of constant temperatures between 6 and 30°C to determine the relationship between rate of insect development and temperature. Linear or non-linear (Gompertz) curves were fitted to these data to provide equations which could be incorporated into the model. In addition, variability was incorporated using the 'same-shape property' (Sharpe *et al.*, 1977; Shaffer, 1983). This implies that the coefficient of variation of the rate of insect development is constant at all temperatures. Account was also taken of periods of dormancy (aestivation and diapause) and of activity thresholds which might affect the outcome of the forecasts.

Ideally the forecasts should be run using daily maximum and minimum air temperatures and maximum and minimum soil temperatures at a depth of 6-10 cm. However, maximum and minimum soil temperatures are not available from standard agro meteorological stations in the UK. Therefore, the program uses several equations to estimate soil maximum and minimum temperatures from the air maximum, air minimum and 10 cm soil temperatures recorded daily at 09.00 h GMT. If soil maximum and minimum data are available then the forecasts could be run equally-well using these.

The forecasts are validated using appropriate insect monitoring data. Cabbage root flies are monitored using yellow water traps (Finch & Skinner, 1974) or by sampling eggs (Finch *et al.*, 1975), carrot flies using orange sticky traps (Collier *et al.*, 1990a), bronzed-blossom beetles using yellow sticky traps (Finch *et al.*, 1990a) and large narcissus fly by the emergence and subsequent egg-laying activity of insects maintained in field cages (Finch *et al.* 1990b).

At present, pest forecasts are based on Meteorological Office data collected from the network of weather stations, some of which are not particularly close to areas of commercial vegetable/flower production. The actual forecasts are projected forwards using weather data from a previous, warm, year. In a few instances forecasts have also been generated using growers' own weather data. During the last four years, and as part of the validation process, forecasts of pest activity, based on weather data from 38 weather stations throughout the UK, have been made available to Horticultural Development Council levy payers. Forecasts have been sent to growers each week for several weeks before and during the period of pest activity.

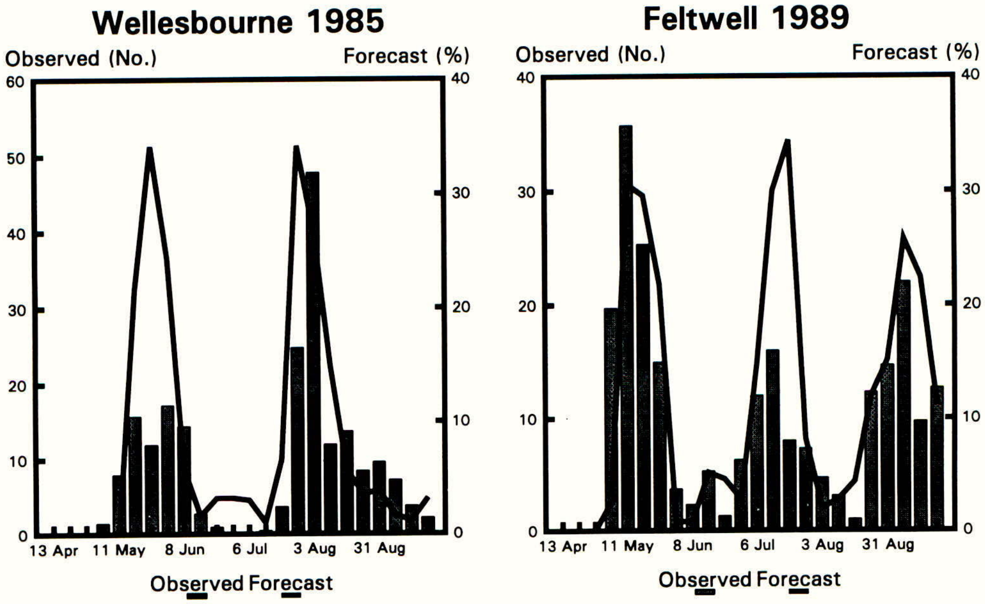
Cabbage root fly

The cabbage root fly forecast (Collier *et al.*, 1991) was developed originally for timing the application of mid-season insecticide treatments to long-season brassica crops such as swedes. Other uses of the forecast include warnings of the likely onset of third generation attack to Brussels sprout buttons and to autumn-sown crops of oilseed rape. At present, most insecticide treatments to leafy brassicas are applied prophylactically, before or soon after transplanting, and treatment against subsequent generations of this fly is usually unecessary. However, the forecast could be used to indicate 'windows' where treatments would not be required. Figure 1 shows comparisons of observed and forecast cabbage root fly activity at Wellesbourne, Warwicks in 1985 and Feltwell, Norfolk in 1989.

Local variations in cabbage root fly activity include the co-existence in certain regions of the two developmental biotypes, with diapause of different durations (Finch & Collier, 1983; Collier *et al.*, 1989). Late-emerging flies emerge several weeks later than early-emerging flies so that their generations alternate. Similar damage to brassicas is caused by the closely-related turnip fly (*Delia floralis*) in Scotland and in some areas of south-west Lancashire (Finch *et al.*, 1986). The presence of the two cabbage root fly biotypes and turnip fly in areas of south-west Lancashire means that there is continuous root fly pressure to brassica crops throughout the summer. The cabbage root fly model produces forecasts for populations containing specified proportions of the two biotypes. A turnip fly forecast has not yet been developed.

The cabbage root fly model has also been used to indicate what might happen as a result of global warming (Collier *et al.*, 1990b) and to predict cabbage root fly phenology in Spain, where calabrese production for the UK market has been affected severely by larval damage to the florets.

Figure 1. Comparisons of observed and forecast cabbage root fly activity. Forecasts of egg-laying are compared with the numbers of females captured in water traps.



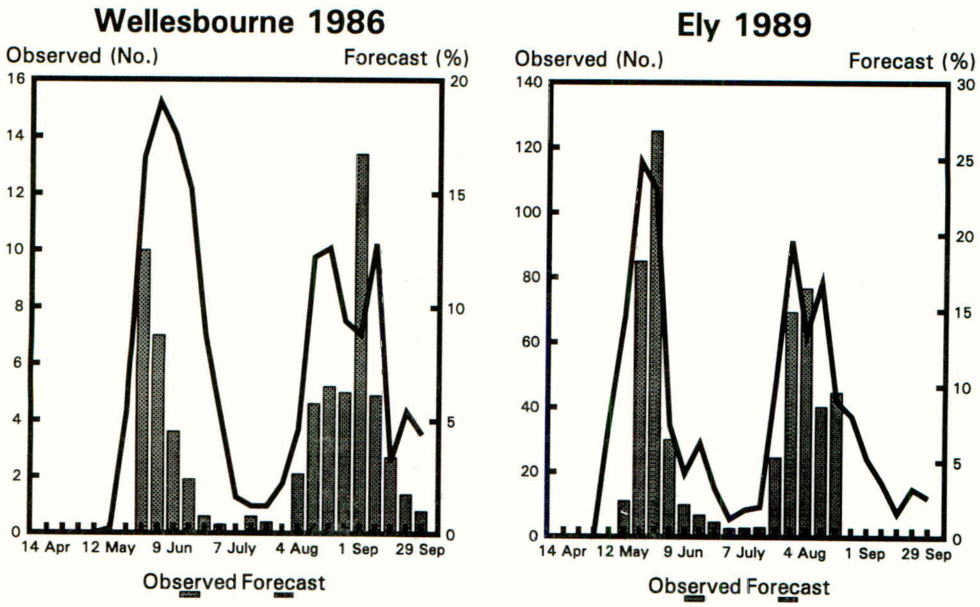
Carrot fly

The carrot fly forecast (Collier *et al.*, 1992) was developed to target mid-season insecticide treatments against attacks by second and third generation carrot fly. The carrot fly overwinters either as a pupa in diapause or remains in the larval stage, forming a non-diapause pupa in the spring. In the spring, adults emerge earlier and over a shorter period from insects that overwinter as larvae than from those that overwinter as pupae. The model can produce forecasts for populations containing specified proportions of diapausing pupae provided such information is known. If not, it is usually assumed that 50% of the population have overwintered in diapause. Figure 2 shows comparisons of observed and forecast carrot fly activity at Wellesbourne in 1986 and Ely, Cambridgeshire in 1989.

Carrot fly is a relatively non-mobile pest and the timing of activity in a particular crop can also be influenced by factors such as drilling date and the proximity of previous infestations. The program will produce forecasts for crops drilled on specific dates. Some mid-season insecticide treatments probably work mainly as larvicides whilst others, such as the pyrethroids, cypermethrin and the newer product lambda-cyhalothrin, mainly kill adults (Dufault, 1994). Therefore, the various insecticides may need to be applied at different times in the life-cycle of the pest.

The carrot fly forecast could also be used to predict the onset of damage in carrots so that they can be lifted and put into cold storage (Jonsson, 1992). This is a technique used widely in Northern Europe and North America.

Figure 2. Comparisons of observed and forecast carrot fly activity. Forecasts of carrot fly egg-laying are compared with the numbers of flies captured on sticky traps.



Bronzed-blossom beetle

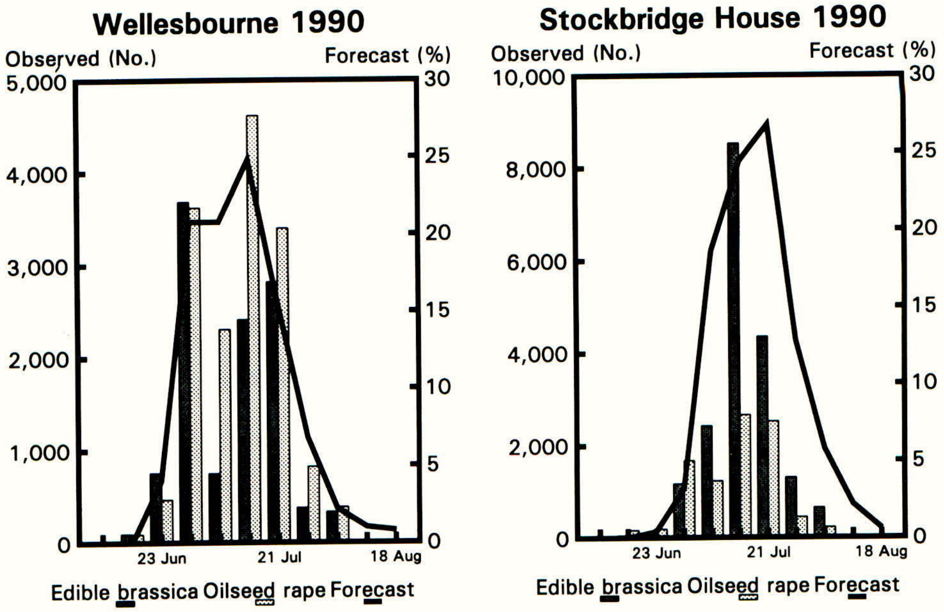
Feeding by adult bronzed-blossom beetles in mid-summer, prior to hibernation, damages the curds or florets of cauliflower and calabrese (Finch *et al.*, 1990a) so that spray treatments are sometimes necessary. The forecast is used to predict the emergence of adult beetles from pupae within the previous host crop; usually oilseed rape. However, beetle infestations are not inevitable and seem to depend both on the proximity of oilseed rape crops and on the occurrence of warm, humid conditions during the main period of beetle migration. Figure 3 shows comparisons of observed and forecast bronzed-blossom beetle activity at Wellesbourne and at Stockbridge House, Cawood, Yorkshire in 1990.

Large narcissus fly

An effective monitoring technique has not yet been developed for the large narcissus fly. Apart from general field observations, growers have no other way of determining when the fly is active. Following the withdrawal of aldrin in 1989, alternative control measures based on less-persistent insecticides and cultural techniques, are now being developed.

One possibility is that insecticides could be used to kill adult flies prior to egg-laying, which would require an accurate forecast of adult emergence. Alternatively, cultural techniques could be aimed at the prevention of egg-laying by, for example, charring or flailing narcissus foliage (S.Tones, personal communication), or lifting the crop early to avoid invasion of narcissus bulbs by newly-hatched larvae. Premature destruction of foliage, or the lifting of bulbs early, may reduce subsequently both bulb and flower yields. Forecasts would be required to indicate the latest date by which cultural operations could achieve adequate pest control without reducing yield.

Figure 3. Comparisons of observed and forecast bronzed-blossom beetle activity. Forecasts of the summer migration of bronzed-blossom beetles are compared with the numbers of beetles captured on sticky traps, both in edible brassicas and oil seed rape.



Adult large narcissus flies have a critical activity threshold, close to 20°C. Flight activity, and mating, is prevented at lower temperatures. Therefore, even if females have completed their 2-3 day pre-oviposition period, they remain hidden in crevices in the soil and are unable to lay until temperatures are high enough for mating. Once a female has mated, egg-laying can occur at lower temperatures (Collier & Finch, 1992). This threshold for mating has been incorporated into the forecast, since it determines the timing of egg-laying. In addition, reduced fly activity during periods of cold weather appears to reduce considerably the efficacy of insecticides applied against adult flies (S.Tones, personal communication). Figure 4 shows comparisons of observed and forecast large narcissus fly activity at Wellesbourne and Starcross, Devon in 1990.

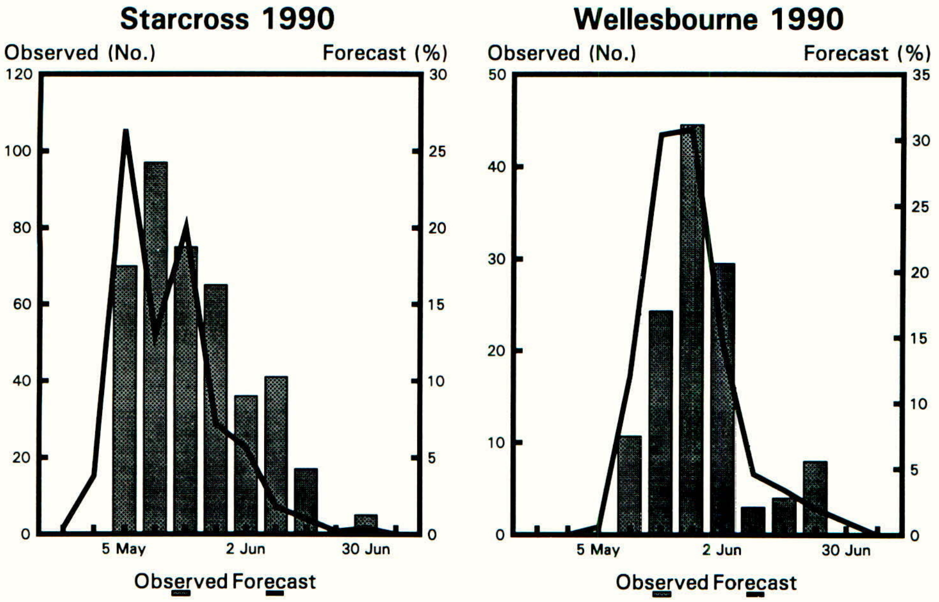
FORECAST VALIDATION

Forecasts have been validated against as many sets of insect monitoring data as possible. The timing of pest activity may vary by 3-5 weeks between years and both the cabbage root fly and carrot fly may have 'partial' third generations in very warm years. The activity of cabbage root fly and carrot fly have been monitored at Wellesbourne for over 10 years. Earliest second generation cabbage root fly activity at Wellesbourne was recorded on 12 July in 1989 and latest activity on 5 August in 1986. Similarly, earliest second generation carrot fly activity was recorded on 21 July in both 1989 and 1990 and the latest on 26 August in 1986. Extensive monitoring data, to validate the pest forecasts, have also been collected over a number of years from the major areas of intensive vegetable production.

Use of the models has indicated that monitoring data must consist of >100 insects per generation if estimates of the timing of pest attacks are to be accurate to within one week (Collier & Phelps, 1994). As the forecasts provide an indication only of the timing of pest activity and not of the severity of attack, forecast data are generally expressed as percentages. When the times to 10% and 50% activity have been predicted and compared with the monitoring data, the majority of the pest forecasts have been accurate to within one week.

Forecasts have been produced using a network of rather widely-dispersed weather stations. However, there are obviously local differences in climate and in the degree of shelter which might affect the timing of pest activity in a particular field. With very mobile insects such as the cabbage root fly, there may be little point in recording temperatures in individual fields since the infesting population will have experienced the climate of the previous weeks, or months, in a different, unknown location. An intensive study in the Vale of Evesham (Finch & Skinner, unpublished data) indicated that there was very little difference in the timing of cabbage root fly activity from crop to crop (Figure 5). Although timing of activity may vary little within a region, intensive sampling in south-west Lancashire showed that the relative proportions of the two cabbage root fly biotypes varied considerably over relatively short distances (Finch *et al.*, 1986).

Figure 4. Comparisons of observed and forecast large narcissus fly activity. Forecasts of large narcissus fly emergence are compared with the emergence of flies into large field cages.



There are indications that the timing of carrot fly activity within a region may be more variable than that of the cabbage root fly but this variation may be attributable to differences in drilling date and to distance from sources of previous infestation. Both factors are now being investigated. With both species of fly, adults can be trapped close to their emergence sites during the pre-oviposition period, which during cold springs may last for several weeks (Collier & Finch, 1985). Therefore, in certain situations, data collected at emergence sites should not be used to discredit the accuracy of the egg-laying forecasts, as the two sets of information relate to different, not comparable, phases in the life-cycle of the pest.

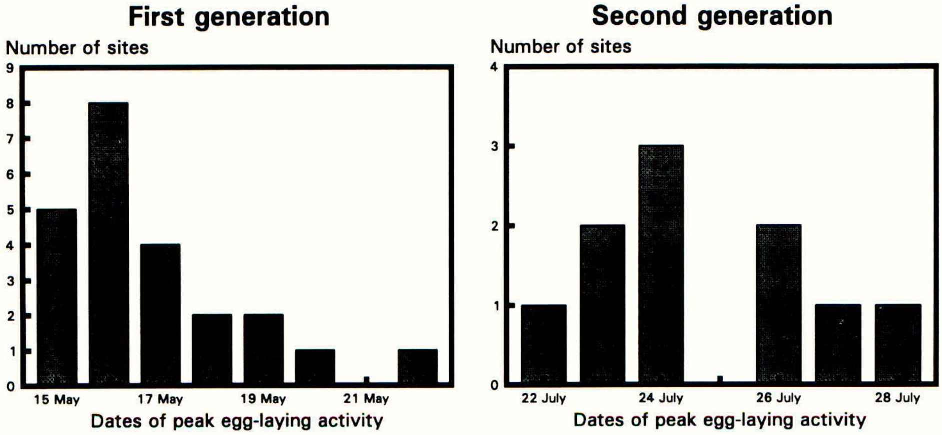
The 20°C activity threshold of the large narcissus fly presents practical problems for validating forecasts of emergence since, on cool days, inactive insects are very difficult to find even in heavily-infested plots of narcissus grown within field cages.

FUTURE DEVELOPMENTS

The use of less-persistent insecticides, and pressure from consumers and retailers to reduce the number of insecticide treatments applied to crops means that growers need to target insecticide treatments more accurately. During a recent survey (Parker & Phelps, 1994), 78% of brassica growers indicated that they would find systems for forecasting pest attacks useful. In future, such forecasts could be produced by continuing to use Meteorological Office data to which could be added refinements to allow corrections for altitude and coastal effects. Alternatively, if growers were to obtain weather stations they could easily run the pest forecast models on their own computers. The brassica growers' survey (Parker & Phelps, 1994) showed that two thirds of growers already own a computer and a similar number make use of weather data collected either by themselves or by the Meteorological Office. Therefore, the option to run their own forecasts may already be feasible for many growers.

The next logical step, after determining the timing of pest activity, is to develop treatment thresholds to determine which of the various treatments are actually necessary. However, this will require a considerable amount of basic research, to produce robust systems that will enable final crop damage to be forecast accurately from the numbers of insects monitored during the early stages of crop infestation.

Figure 5. The times of 50% first and second generation cabbage root fly egg-laying activity in the Vale of Evesham in 1980.



ACKNOWLEDGEMENTS

We thank MAFF for supporting this work as part of Project HH0103JFV and the HDC as part of Projects FV13, FV44, FV127 and BOF1. We thank also participating growers, Miss M. Elliott and Mrs W. Riggall of HRI, and Dr J. Blood Smyth, Mr B. Emmett, Mr S. Tones and Dr W. Parker of ADAS for their help in collecting the monitoring data; and the Meteorological Office for providing the weather data.

REFERENCES

Baker, C.R.B. (1980). Some problems in using meteorological data to forecast the timing of insect life cycles. *EPPO Bulletin* **10**, 83-91.

Collier, R.H. & Finch, S. (1983). Effects of intensity and duration of low temperatures in regulating diapause development of the cabbage root fly (*Delia radicum*). *Entomologia experimentalis et applicata* **34**, 193-200.

Collier, R. H. & Finch, S. (1985). Accumulated temperatures for predicting the time of emergence in the spring of the cabbage root fly, *Delia Radicum* (L.) (Diptera: Anthomyiidae). *Bulletin of Entomological Research* **75**, 395-404.

Collier, R.H., Finch, S. & Anderson, M. (1989). Laboratory studies on late-emergence in the cabbage root fly (*Delia radicum*). *Entomologia experimentalis et applicata* **50**, 233-240.

Collier, R.H., Finch, S., Emmett, B.J. & Blood-Smyth, J. (1990a). Monitoring populations of the carrot fly, *Psila rosae*, with sticky and water traps. *Annals of Applied Biology*, **116**, 441-446.

Collier, R.H., Finch, S., Phelps, K. & Thompson, A.R. (1990b). Possible impact of global warming on cabbage root fly (*Delia radicum*) activity in the UK. *Annals of Applied Biology*, **118**, 261-271.

Collier, R.H.,. Finch, S. & Phelps, K. (1991). A simulation model for forecasting the timing of attacks of *Delia radicum* on cruciferous crops. *EPPO Bulletin* **21**, 419-424.

Collier, R.H. & Finch, S. (1992). The effects of temperature on development of the large narcissus fly (*Merodon equestris*). *Annals of Applied Biology*, **120**, 383-390.

Collier, R.H., Finch, S. & Phelps, K. (1992). The feasibility of using models to forecast carrot fly attacks in commercial carrot crops. *Integrated Control in Field Vegetable Crops. IOBC/WPRS Bulletin XV/4*, 69-76.

Collier, R.H. & Phelps, K. (1994). Carrot fly monitoring as an effective tool for pest management: how many flies have to be trapped? *Aspects of Applied Biology* **37**, 259-263.

Dufault, C.P. (1994). The influence of spray placement, rate of application and rainfall after treatment on the effectiveness of four insecticides for the control of *Psila rosae* (F.) on carrots. *Proceedings of the Entomological Society of Ontario* **125**, 67-79.

Eckenrode, C.K. & Chapman, R.K. (1972). Seasonal adult cabbage maggot populations in the field in relation to thermal unit accumulations. *Annals of the Entomological Society of America* **65**, 151-156.

Finch, S. & Skinner, G. (1974). Some factors affecting the efficiency of water traps for capturing cabbage root flies. *Annals of Applied Biology* **77**, 213-226.

Finch, S., Skinner, G. & Freeman, G. H. (1975). The distribution and analysis of cabbage root fly egg populations. *Annals of Applied Biology* **79**, 1-18.

Finch, S. & Collier, R. H. (1983). Emergence of flies from populations of overwintering cabbage root fly pupae. *Ecological Entomology* **8**, 29-36.

Finch, S. & Collier, R.H. (1985). Laboratory studies on aestivation in the cabbage root fly (*Delia radicum*). *Entomologia experimentalis et applicata* **38**, 137-14.

Finch, S., Collier, R. H. & Skinner, G. (1986). Local population differences in emergence of cabbage root flies from south-west Lancashire: implicatons for pest forecasting and population divergence. *Ecological Entomology* **11**, 139-145.

Finch, S., Bromand, B., Brunel, E., Bues, M., Collier, R.H., Dunne, R., Foster, G., Freuler, J., Hommes, M., Van Keymeulen, M., Mowat, D.J., Pelerents, C., Skinner, G., Stadler, E. & Theunissen, J. (1988). Emergence of cabbage root flies from puparia collected throughout northern Europe. In: *Progress on Pest Management in Field Vegetables*. Eds. R. Cavalloro and C. Pelerents, P.P. Rotondo - D.G. XIII - Luxembourg No. EUR 10514. Balkema, Rotterdam, pp. 33-36.

Finch, S. (1989). Ecological considerations in the management of *Delia* pest species in vegetable crops. *Annual Review of Entomology* **34**, 117-137.

Finch, S., Collier, R.H. & Elliott, M.S. (1990a). Seasonal variations in the timing of attacks of bronzed-blossom beetles (*Meligethes aeneus/Meligethes viridescens*) on horticultural brassicas. *Proceedings 1990 Brighton Crop Protection Conference - Pests and Diseases*, 349-354.

Finch, S., Collier, R.H. & Elliott, M.S. (1990b). Biological studies associated with forecasting the timing of attacks by the large narcissus fly, *Merodon equestris*. *Proceedings 1990 Brighton Crop Protection Conference - Pests and Diseases*, 111-116.

Jonsson, B. (1992). Forecasting the timing of damage by the carrot fly. *Integrated Control in Field Vegetable Crops IOBC/WPRS Bulletin XV/4*, 43-48.

Phelps, K., Collier, R.H., Reader, R.J. & Finch, S. (1993). Monte Carlo simulation method for forecasting the timing of pest insect attacks. *Crop Protection* **12**, 335-342.

Parker, C. & Phelps, K. (1994). Putting the byte into brassicas. *Grower*, October 13 1994.

Shaffer, P.L. (1983). Prediction of variation in development period of insects and mites reared at constant temperatures. *Environmental Entomology* **12**, 1012-1019.

Sharpe, P.J.H., Curry, G.L., DeMichele, D.W. & Cole, C.L. (1977). Distribution model of organisms development times. *Journal of Theoretical Biology* **66**, 21-38.

GROWING MALTING BARLEY WITHOUT THE USE OF PESTICIDES

I.A. RASMUSSEN

Danish Institute of Plant and Soil Science, Dept. of Weed Control and Pesticide Ecology,
Flakkebjerg, DK-4200 Slagelse, Denmark

K. KRISTENSEN

DIPS, Dept. of Biometry and Informatics, Thorvaldsensvej 40, DK-1871 Frederiksberg

S. STETTER

DIPS, Dept. of Plant Pathology and Pest Management, Lottenborgvej 2, DK-2800 Lyngby

ABSTRACT

A decision support system for growing malting barley without the use of pesticides is being developed. The system, which is based on a Bayesian network, estimates the probability distribution of yield and quality. To counter the disadvantages of not being able to use pesticides, varieties chosen are not only suitable for malting but also possess resistance against fungal diseases. Weeds are recommended controlled by harrowing. A submodel for fungal diseases estimates yield with or without use of pesticides, based on the area of a triangle similar to the area under the disease progress curve (AUDPC). Other submodels are being developed. Economic return at different prices is calculated from experimental results. The results indicate that growing malting barley without the use of pesticides can result in satisfactory quality and a yield loss that may be countered by less expenses or better prices.

INTRODUCTION

Research concerning mechanical weed control and disease resistant crop varieties has given the potential for developing a growing strategy entirely without the use of pesticides, and to find out whether this causes loss of quality or economic return. Malting barley for beer production was chosen for the work for several reasons. First, mechanical weed control can be undertaken succesfully in spring barley. Second, several spring barley varieties which possess resistance against the most important fungal pathogens are available. Third, there was at the time the project was initiated a potential market for malting barley grown without the use of pesticides. Fourth, a better price is paid for malting barley than for fodder barley - on the condition that certain quality demands are met. The present project concerning "Production of beer from Danish malting barley grown without the use of pesti-cides" was initiated in collaboration between the Danish Institute of Plant and Soil Science (DIPS) and the Carlsberg Breweries.

For the farmer to grow malting barley without the use of pesticides, it is an advantage if a decision support system is available. The farmer must know which important questions to take into consideration before choosing whether or not to attempt using the pesticide-free strategy. He has to know something about the potential risks and gains. The growing strategy must be planned before the growing season and carried through. And finally, during the growing season, there must be some way to assess the development of the yield and quality of the crop - is the crop being quenched by weeds, will an attack by pests or diseases result in an unacceptable reduction in yield or quality?

The work of the project aims at
a) determining the influence of single factors (weed control, fungal diseases etc.) on yield and quality,
b) setting up growing strategies that optimize these factors and evaluate the interaction,
c) developing a computer-based decision support system,
d) assessing the quality of the malting barley, the malt and the beer produced in the pesticide-free growing strategies,
e) developing methods for analyzing pesticide residues in malting barley and malt,
f) determining the level of contamination by microorganisms in malting barley produced with or without the use of pesticides,
g) calculating the economic consequences, risks and gains, for the farmer and the industry.
In this paper the focus is on the decision support system.

THE DECISION SUPPORT SYSTEM

The decision support system is based on a Bayesian network. A Bayesian network is useful in situations where causal relationships are a natural way of relating concepts, particularly when uncertainty is part of the relations (Jensen et al., 1990). The network can be presented as a set of nodes connected by directed links. The nodes represent the concepts, the links represent the causal relationships. The latter are given as conditional probabilities of the states of the influenced nodes, given the combination of the causal nodes. For further details see Rasmussen et al. (1990) and Kristensen & Rasmussen (1993).

The decision support system for growing malting barley without the use of pesticides consists of a main model and four submodels. The main model relates the basic input factors such as soil type, nitrogen fertilizer, variety, seed rate, sowing time etc. and estimates the distribution of expected yield and quality, assuming average weather and no attacks of pests or pathogens, no weeds, and optimal harvest and post-harvest treatments. The main model is represented in Figure 1. Although the model is rather simple it should be able to take into account the most important factors affecting the yield and quality.

In order to easily adapt new varieties into the model, the effect of varieties is described through different characteristics of the variety. In the main model 5 characteristics are used: germination speed, tillering, kernels per ear, size of kernels and protein content. Each of those characteristics is described by a distribution, e.g. the level of the potential protein content of varieties A, B and C may be described by the figures in Table 1. Other parts of the model estimate the available nitrogen in the soil. The final probability distribution of the protein content is estimated from the combination of the nitrogen potential, the variety specific modification and their interaction.

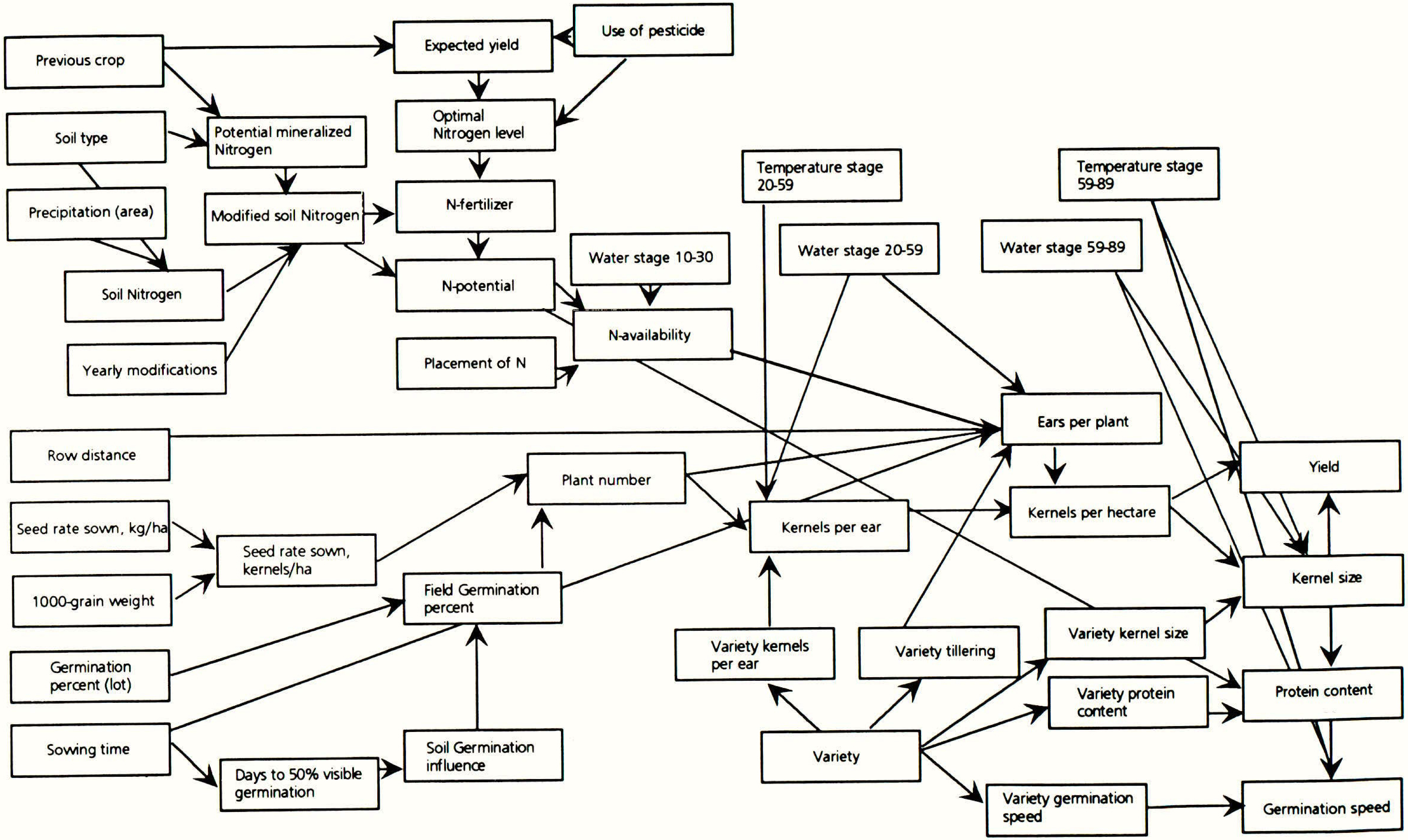


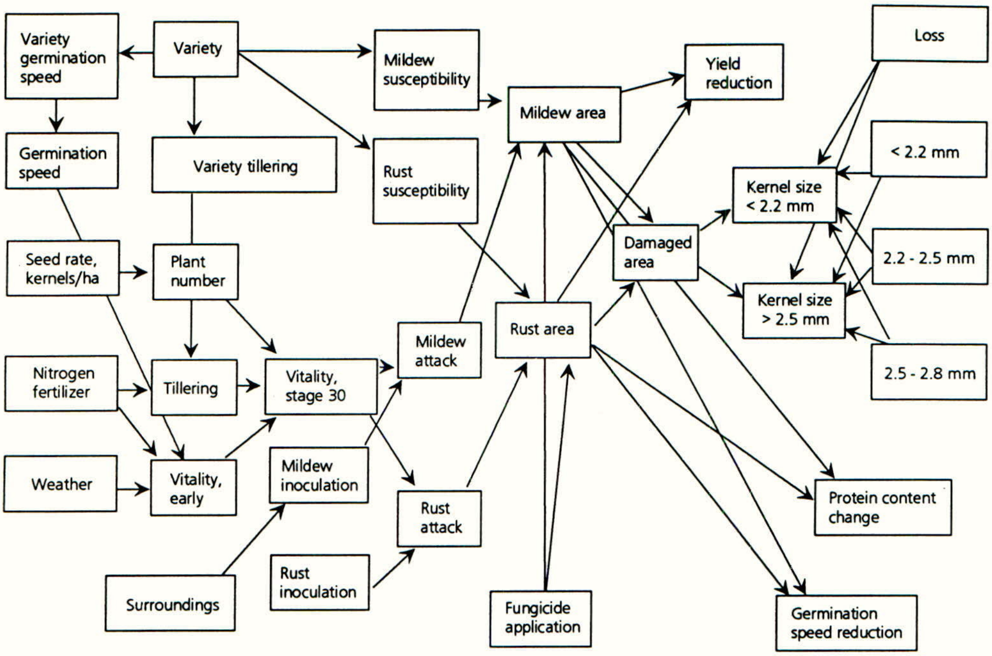
FIGURE 1. Main model of the decision support system for malting barley grown without the use of pesticides. Boxes represent nodes, arrows represent causal relationships, see text.

TABLE 1. An example of a probability distribution of potential protein content level for varieties A, B and C.

Variety	Potential protein content level		
	Low	Medium	High
A	50	30	20
B	25	50	25
C	10	30	60

The four submodels each predict the change in yield and quality caused by one of the following: fungal disease, aphid attacks, weeds/weed control and harvest/post-harvest treatments.

FIGURE 2. Submodel for fungal diseases. Legend as Figure 1.



Submodel for fungal diseases

The model which estimates the effect of attacks of fungal diseases on yield and quality is shown in Figure 2. At the present time, only the effect on yield and kernel size is incorporated into the model. One part of the model is planned to estimate the time when attack by fungal pathogens, mildew (*Erysiphe graminis*) or rust (*Puccinia spp.*), may be expected to occur. The other part of the model estimates the reduction of yield and kernel size given the specified variety and a known, or estimated, time of attack by a fungal pathogen. The latter part of the model will be described in detail as an example.

This model is based on results from one year of experiments. When the effect of a single fungal attack was considered, the estimate of the factor the yield is reduced by was approximated as

$$f = e^{\Theta A}$$

where

$0 \leq f \leq 1$, when $f = 1$ there is no yield reduction, as f decreases the yield reduction grows,

$\Theta < 0$ is a constant specific to each fungal disease (mildew, rust)

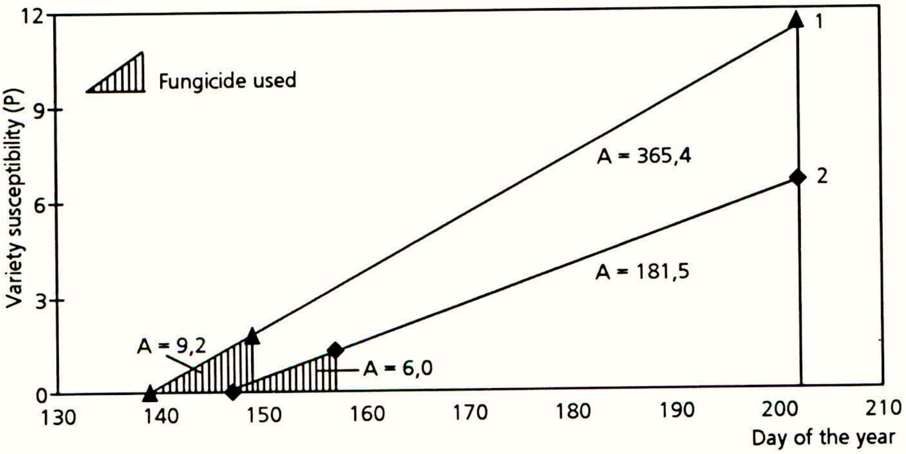
$A = 0.5 * D * p$ is the area of a triangle assumed to be proportional to the severity of the attack,

D is the number of days the fungal attack affects the crop and

p is the susceptibility of the variety measured as pecentage leaf coverage by the fungal attack.

The variety susceptibility measured as percentage leaf coverage (p) was taken from the most recent Danish annual publication of cereal varieties (Rasmussen et al., 1994) where susceptibility to fungal diseases, measured as percentage leaf coverage, are observed for the varieties every year at a number of different locations.

FIGURE 3. Area (A) of the triangles described in the text for mildew attack of two barley varieties (1 & 2) with different susceptibilities (p) and different times of visible attack (d_b) with and without fungicide use.



The triangle, A, was defined by the variety susceptibility, p, the day of visible attack, d_b (> 0.01 % coverage) and the day the crop reaches stage 89, d_{89}, so that the number of

days the fungal attack affects the crop, $D = d_{89} - d_b$. If the crop was sprayed with fungicide, the fungal attack was expected to affect the crop only for 10 days, and the triangle was then defined as the left part of the original triangle that was cut off by a vertical line after 10 days, see figure 3.

To be able to estimate the yield loss at the time of attack, the day stage 89 would be reached must be estimated. For the experiments this could be done by

$$S = -93.70 + 0.90336 * d$$

where d is the day of the year and S is the growth stage the crop is expected to be in at that time.

When both mildew and rust attacks were observed the combined effect was calculated by multiplying the reduction factors:

$$f = f_{mildew} * f_{rust}$$

where f_{mildew} and f_{rust} each are estimated as shown above.

In the model, the uncertainties for each of the factors: 1) the variety susceptibility, which varies between locations, 2) the area of the triangle, and 3) the effect of the fungus on yield (Θ) are taken into account. The values are categorized at each step and the probability distributions are propagated through the system. When a fungal pathogen attack becomes visible in the crop, expected yield and quality can be estimated in the two situations: fungicide use or no fungicide use.

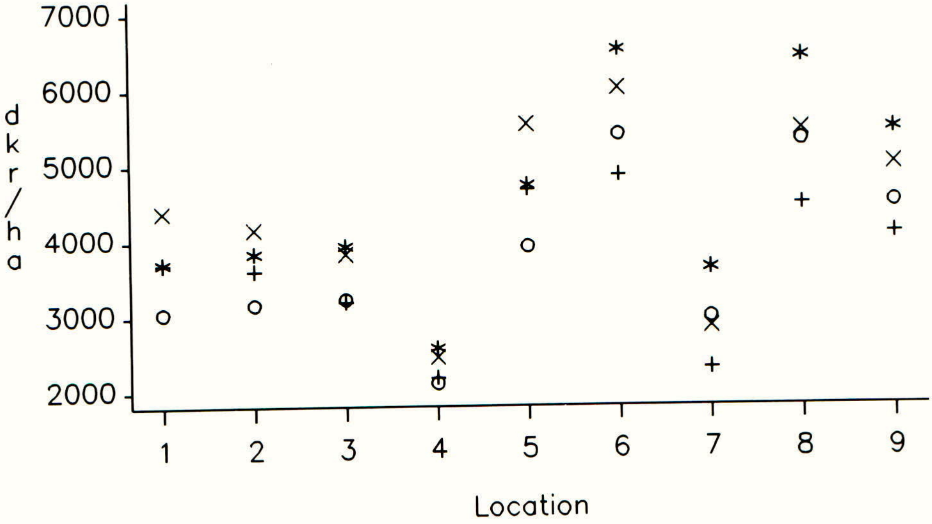
ECONOMIC CALCULATIONS

An experiment with growing systems for malting barley without the use of pesticides was carried out at six different locations in 1993 and 1994 (Rasmussen 1995). Results from 9 of these experiments were used for economic calculations. The two treatments considered were treated the same for variety (Alexis), number of viable seed sown per square meter (300), nitrogen fertilizer (80 kg N per hectare); but differed in pesticide treatment: A (not treated with any pesticides, weed-harrowed), E (treated with pesticides against weeds, fungal diseases and insect pests according to need as adviced by PC-Plant Protection). Expenses for plant protection were calculated from the actual pesticides used, the number of times spraying was carried out and the number of times weed harrowing was conducted. The price received for the malting barley was calculated for the proportion of the yield that did not pass the 2.2 mm sieve, for the fodder yield all the harvest was included. Economic return was calculated at 3 prices: fodder barley, malt barley, and malt barley grown without the use of pesticides at ordinary price and at a price 20 percent above the ordinary price. Net economic return is seen in Figure 4. In four cases, the economic return of malting barley grown without the use of pesticides, given a price 20% greater than ordinary malting barley, exceeds that of malting barley grown with the use of pesticides, in three cases the economic return is almost the same, and in two cases the economic return of ordinary malting barley exceeds that grown without pesticides.

FIGURE 4. Net economic return, Danish kroner per hectare (dkr/ha) from 2 growing systems, with or without pesticide use. For each system and location, actual expenses for plant protection are subtracted. Fodder yield is everything harvested, malt barley yield is the proportion that did not pass the 2.2 mm sieve.

With pesticide use
+ fodder yield, 95 dkr/hkg
x malt barley yield, 115 dkr/hkg

Without pesticide use
o malt barley yield, 115 dkr/hkg
* malt barley yield, 138 dkr/hkg



DISCUSSION

The decision support system is based on a Bayesian network. Other bases for decision support systems may be regression analyses, systems of partial differential equations (Hansen et al., 1990) or knowledge based expert systems (Dindorp, 1992; King et al., 1991). The main advantage of Bayesian networks over those systems is that a Bayesian network can supply the user with information on the uncertainty of the predicted outcome. The network propagates this uncertainty through the network in a logical way and as further information or assumptions are given, the final uncertainty is decreased. The main drawback of a Bayesian network is that all information has to be categorized into a limited number of states. In order to let the network be managable it might be necessary either to simplify the models (or parts of the models) or to restrict the number of states for certain variables to rather few states. We think that the benefits of the information on uncertainty is very important and counter the disadvantages.

The triangle used to predict yield loss at fungal attack is calculated somewhat similarly to the area under the disease progress curve (AUDPC) (Steffenson & Webster, 1992), which has sometimes been mentioned as a means of estimating yield loss (Wright & Gaunt, 1992). The area of the triangle was preferred to the AUDPC for two reasons: it permits an early estimate of the effect of fungal attack and requires only one direct measurement (time of attack) combined with published data, as opposed to AUDPC which requires repeated measurements during the season. Whether the estimates of yield loss are accurate remains to be validated.

It is still too early to conclude whether the decision support system for growing malting barley without the use of pesticides will be succesful, as the system is not finished and has not been validated by experimental work. However, the results from the experiments indicate that growing malting barley without the use of pesticides can be carried out. The yield can be of the required quality, and the expected yield reduction may be countered by less expenses and/or a greater price.

ACKNOWLEDGEMENTS

The project was funded partly by the Directorate for Agricultural Development.

REFERENCES

Dindorp, U. (1992) Agricultural applications of knowledge based systems concepts. *Tidsskrift for Planteavls Specialserie*, **S 2201**, 97 pp.

Hansen, S.; Jensen, H.E.; Nielsen, N.E.; Svendsen, H. (1990) DAISY - Soil Plant Atmosphere System Model. *NPO-forskning fra Miljøstyrelsen*, **A10**, 272 pp.

Jensen, F.V.; Olesen, K.G.; Andersen, S.T. (1990) An algebra of bayesian belief universes for knowledge-based systems. *Networks*, **20**, 637-659.

King, J.P.; Broner, I.; Croissant, R.L.; Basham, C.W. (1991) Malting barley water and nutrient management knowledge-based system. *Transactions of the ASAE*, **34**, 2622-2630.

Kristensen, K.; Rasmussen, I.A. (1993) Models to assist the choice of strategies for growing malting barley without the use of pesticides. *Workshop on Computer-based DSS on Crop Protection, SP-report*, **1993** (7), 39-46.

Lancashire, P.D.; Bleiholder, H.; van den Boom, T.; Langelüddeke, P.; Stauss, R.; Weber, E.; Witzenberger, A. (1991) A uniform decimal code for growth stages of crops and weeds. *Annals of Applied Biology*, **119**, 561-601.

Rasmussen, L.K.; Thysen, I.; Pedersen, K.M. (1990) An application of causal probabilistic networks to examine reproduction of dairy cows. *Fællesberetning*, **SF1**, 59-68.

Rasmussen, J.; Nielsen, B.S.; Pedersen, J.B.; Olsen, C.C.; Welling, B. (1994) *Kornsorter*. Statens Planteavlsforsøg & Landsudvalget for Planteavl. 32 pp.

Rasmussen, I.A. (1995) Integrated production - an example concerning malting barley grown without the use of pesticides. *SP-rapport*, **1995** (3), 255-268.

Steffenson, B.J.; Webster, R.K. (1992) Quantitative resistance to *Pyrenophora teres f. teres* in barley. *Phytopathology*, **82**, 407-411.

Wright, A.C.; Gaunt, R.E. (1992) Disease-yield relationship in barley. I. Yield, dry matter accumulation and yield-loss models. *Plant Pathology*, **41**, 676-687.