Economic decision models for agricultural pest control, with special reference to the control of powdery mildew in barley

by

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Time present and time past

Are both perhaps present in time future,

And time future contained in time past.

If all time is eternally present

All time is unredeemable.

What might have been is an abstraction

Remaining a perpetual possibility

Only in a world of speculation.

T. S. Eliot, Burnt Norton

Acknowledgements

I wish to thank Professor F. R. Bradbury for introducing me to technological economics, and for his particular interest in this project.

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Introduction

The fundamental importance of systematic research for agricultural development has been widely stressed (e.g. by Mellor, 1966; Moseman, 1970). It is therefore surprising that agricultural research has been exposed to so little critical economic appraisal. This is especially true where we might least expect it to be so: in the design of research programmes for the less-developed countries of the Third World. Some of the ways in which agricultural research is deficient have been described recently, in an East African context, by Belshaw and Hall (1972). This effect may be exaggerated by the less well developed capacity of peasant farmers to bear risk: they can not afford to be very far wrong in the decisions they make. However, the phenomenon is a general one, not only in the Third World, but in developed agricultural systems too. Agricultural research must concern itself not only with the provision of technical innovations, such as new types of seed or pesticide, but also with the provision of sufficient information for their economic appraisal, tailored to the conditions on each farm and to the attitude that the individual farmer has towards the risk that the long-run average response will not be realised in any particular year.

This dissertation examines in some detail a particular innovation: the control of the disease, powdery mildew, of spring barley in the United Kingdom. Its approach is that of technological economics (Bradbury, 1969), a point of view peculiar to the Departments of Industrial Science and Economics at Stirling University but particularly concerned with problems of resource allocation under conditions of uncertainty. Its theme is the use, and usefulness, of agricultural research and the experimental data it provides. It confirms many of the deficiencies noted by Belshaw and Hall (*op. cit.*) in the special case of a particular innovation. But it also shows how, in the particular case of agricultural pest control, the micro-economic allocation problems facing the farm firm can be formulated in such a way that they become susceptible to experimental analysis.

A summary account of barley production in the United Kingdom is presented in *Appendix 1*. Data concerning the importance of powdery mildew as a factor limiting yield are discussed in the text. More detailed specifications of the pesticides used against barley mildew are given in *Appendix 2*.

Chapter 1 reviews the literature dealing with the economics of pest control and presents the substance of the farm-level decision models that have been proposed so far.

Chapter 2 discusses the choice of variety, both with and without a systemic mildewcide seed dressing. The decision is formulated as a problem in portfolio selection. A practical approach using linear programming is illustrated.

Chapter 3 extends the farmer's range of choice to whether or not he should apply the pesticide as a spray after the disease has entered his crop. The time of pesticide application is considered as an explicit decision variable.

Chapter 4 considers the aggregate costs and benefits of pest control on the national farm, including the possibility of imposing a legislative ban on the cultivation of winter barley which provides a "green bridge" between successive spring crops. It stresses some of the problems of applying social cost-benefit analysis to any national investment in agricultural pest control.

Chapter 5 summarises the deficiencies in the experimental data provided by agricultural research and described in previous chapters. An attempt is made to construct an analytical framework for research into the economics of pest control. It is suggested that mathematical simulation is the appropriate technique for the analysis of many problems of this nature, and that agricultural research might be more properly directed towards the determination of the coefficients in an analytical model of the situation than to empirical small-plot trials of doubtful relevance. It is not claimed that model building is a novel way of looking at problems (like M. Jourdain in Moliere's "Le Bourgeois Gentilhomme", who found to his amazement that he had been talking prose for more than forty years), only that direct experimentation on the physical yield response at selected locations provides an insufficient model of the economic decision problem facing the farmer.

Chapter 6 discusses the potential usefulness of properly calibrated economic decision models for agricultural pest control to various groups of people. It also considers possible objections to the use of models, and suggests ways in which the preliminary models developed in the text might be extended to other situations such as the control of soil-borne pests and the analysis of complete spray programmes.

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addendum, page 4

It should be stressed right at the start that there is no intention to produce decision models for immediate use in the field (although the portfolio selection model described in Chapter 2 could be used with little or no modification), only to use decision models to structure the problem facing the farmer and to provide guidelines for future research.

Chapter 1

The economics of pest control

George Ordish's book, Untaken Harvest, published in 1952, was an early attempt to indicate the loss that pests of agricultural crops cause in the United Kingdom and the economic basis for crop protection. It is of some interest to compare this with the review by Ordish and Dufour (1969) seventeen years later and to realise what little real progress was made in the interim. However, since 1969 interest in this subject has grown generating several more recent reviews (Carlson and Castle, 1972; Headley, 1972a; Davidson and Norgaard, 1973; Shoemaker, 1973a; Southwood and Norton, 1973; Stern, 1973; James, 1974).

1.1 The economic threshold

Stern et al. emphasised the importance of pest density to indicate the appropriate timing of pesticide application (see Figure 1.1). They defined the economic injury level as the lowest population density that will cause damage equal in money value to the cost of control. Control was recommended when the economic threshold is reached. In Figure 1.1 this is at times t_1 and t_2. The economic threshold is lower than the economic injury level to give time for controls to be implemented and to take effect before the pest population reaches the economic injury level.

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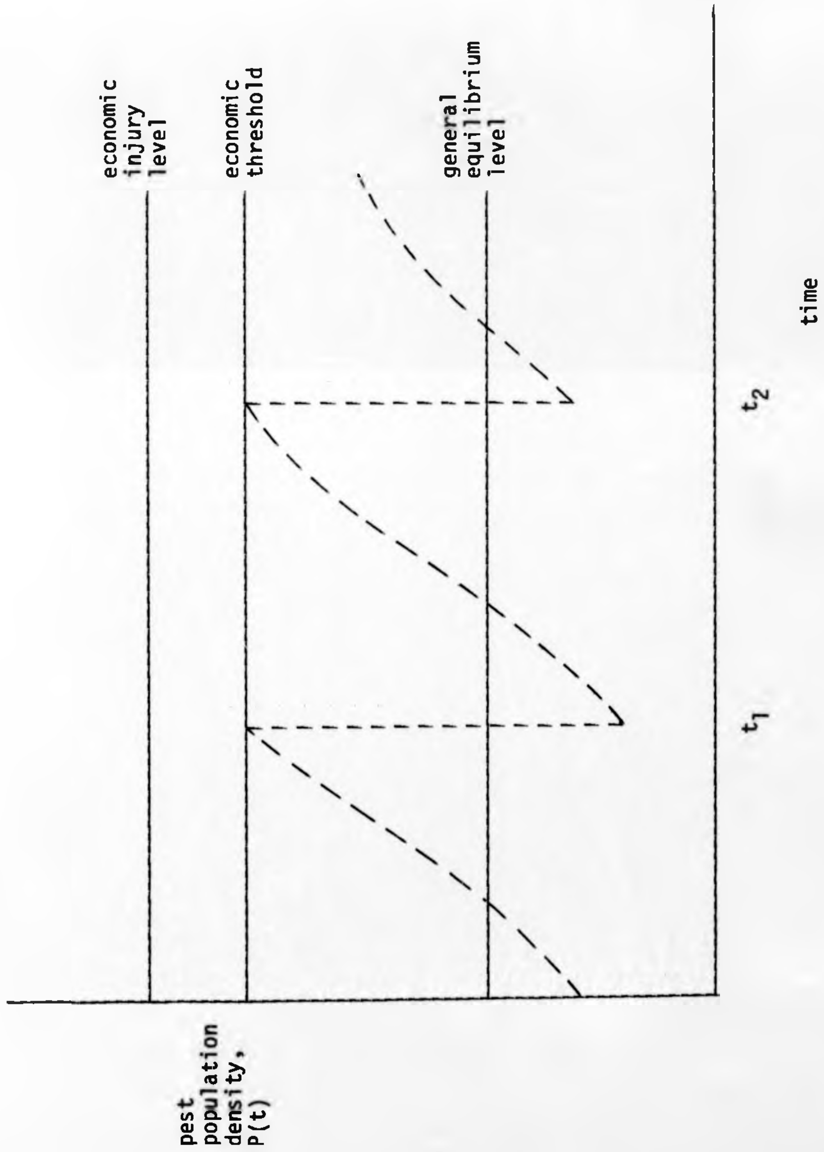
Figure 1.1: Pesticide use over time, according to Stern et al. (1959)



Stern _et al_. did note that the economic injury level can vary "... depending on the crop, season, area, and desire of man". However, no attempt was made to incorporate explicitly in the calculation of the economic threshold such factors as pesticide and crop prices, the effectiveness of controls at reducing the size of the pest population, nor the attitude of the individual farmer towards the riskiness of his investment in pest control.

Headley (1972b) developed the idea of an economic threshold in relation to a simple pest population growth model. His model has four basic elements: a pest population growth function (_Equation 1.1_), a pest damage function (_Equation 1.2_), a product yield function (_Equation 1.3_), and a pest control function (_Equation 1.4_).

Equation 1.1 $P_t = P_{t-n}.(1 + r)^n$ (pest growth)

i.e. the pest population grows at 100.r per cent per period.

Equation 1.2 $D_t = b.P_t^2 - A$ (pest damage)

i.e. the yield is assumed to be proportional to the square of the pest population density at harvest time, above a certain threshold or tolerance level.

Equation 1.3 $Y = N - D_t$ (product yield)

i.e. the actual yield is equal to the potential yield less the loss due to the growth of the pest population.

Equation 1.4 $O = \frac{L}{P_{t-n}}$ (pest control)

i.e. the cost of control is assumed to be inversely proportional to the level to which the pest population is reduced. This is in accordance with the Law of Diminishing Returns in that successive reductions in the size of the pest population at time t-n cost more and more as P_{t-n} gets smaller, but it is an unrealistic model of the cost of control for two reasons: (1) it makes no distinction between fixed and variable costs, and (2) the parameter L is an implicit function of the size of the pest population just before controls are implemented at time $t-n-\Delta$.

where P_t = pest population at time t, the harvest time
P_{t-n} = pest population n periods before t
r = net growth rate of the pest population per time period
D_t = cumulative damage in physical units at time t
A = a constant related to the pest damage tolerance level

b = a parameter relating units of pest population to units of crop damage

Y = realised physical yield at harvest time

N = potential yield at harvest time if no pest damage occurs

O = total cost of reducing the pest population to P_{t-n} at time t-n

L = a parameter relating the reciprocal of the pest population density after controls have been implemented to the cost of controls

By substitution of Equation 1.1 for P_t in Equation 1.2, the damage (D_t) can be expressed as a function of the pest population density after controls have been implemented (P_{t-n}):

Equation 1.5 $$D_t = b.\{P_{t-n}.(1 + r)^n\}^2 - A$$

The substitution of Equation 1.5 for D_t in Equation 1.3 demonstrates the effect of the reduction in size of the pest population on the ultimate yield of the crop:

Equation 1.6 $$Y = N - b.\{P_{t-n}.(1 + r)^n\}^2 + A$$

The marginal change in the money value of the yield produced by an incremental change in the size of the pest population at time t-n is given by the first differential of Equation 1.6 with respect to P_{t-n}, multiplied by the unit price of the crop, β:

Equation 1.7 $$\beta.\frac{dY}{dP_{t-n}} = -2.\beta.b.(1 + r)^{2.n}.P_{t-n}$$

Similarly, the marginal change in the cost of pest control required to produce an incremental change in the size of the pest population at time t-n is given by:

Equation 1.8 $$\frac{dO}{dP_{t-n}} = -\frac{L}{P_{t-n}^{2}}$$

The equation of marginal revenue (Equation 1.7) and marginal cost (Equation 1.8) determines the optimum level to which the size of the pest population should be reduced, since an even greater reduction would require the application of controls costing more than the value of the marginal increase in yield:

Equation 1.9 $$P_{t-n} = \left(\frac{L}{2.\beta.b.(1 + r)^{2.n}}\right)^{1/3}$$

This expression defines the economic threshold. It is important to note that the economic threshold increases as the season progresses (i.e.

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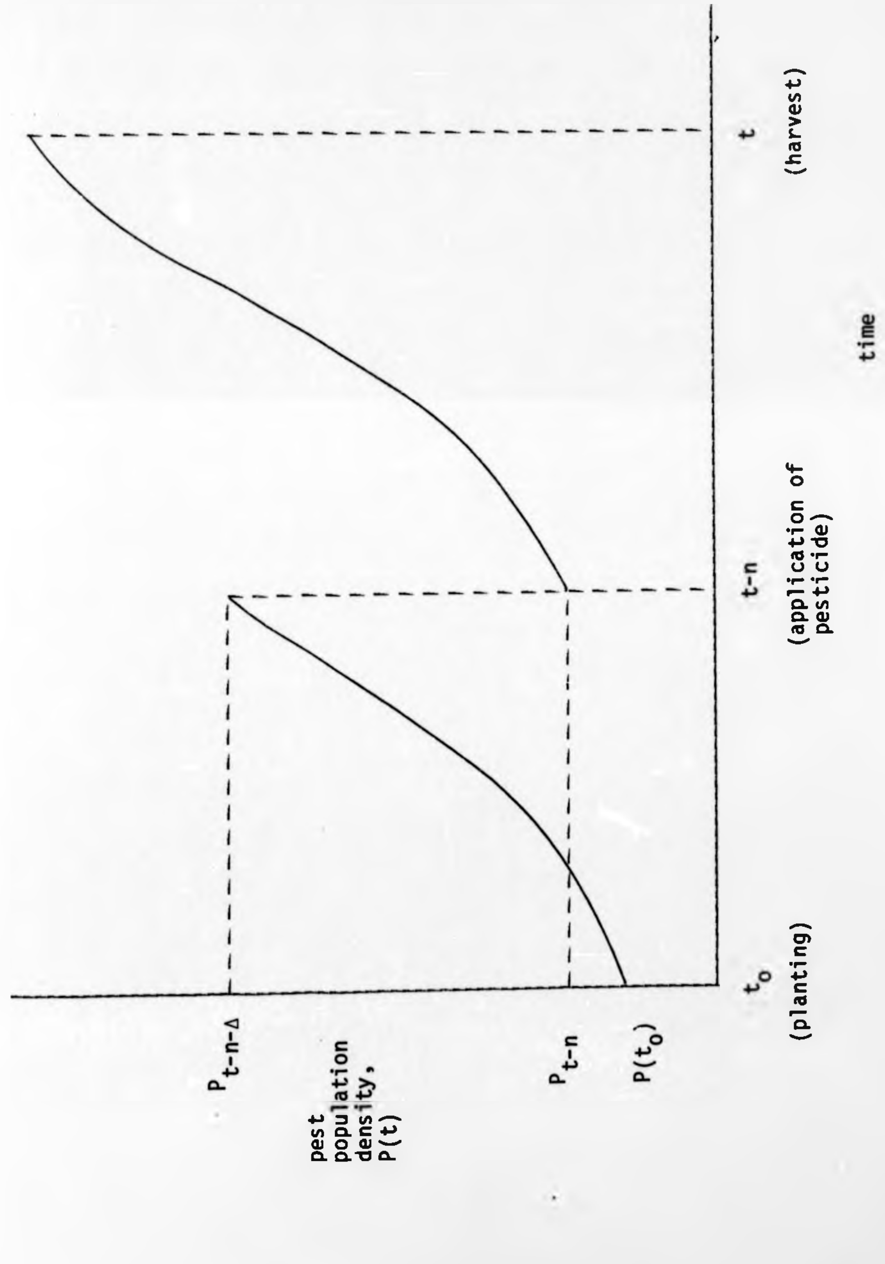
Figure 1.2: Pest population levels over time, according to Headley (1972b)



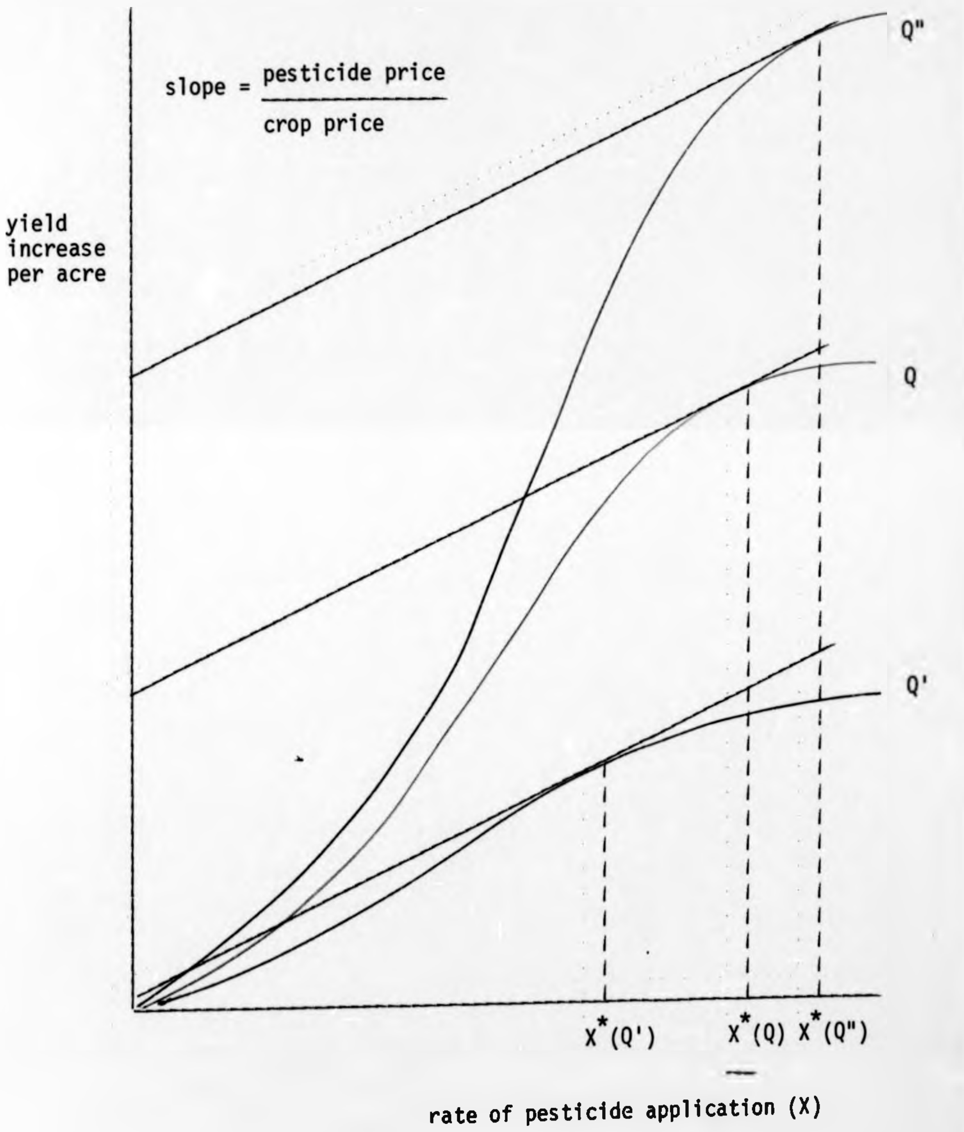
as n approaches zero).

Figure 1.2 illustrates the relation between the size of the pest population and the passage of time in Headley's model. A major defect of the model is its failure to specify the size of the pest population ($P_{t-n-\Delta}$) at which controls should be initiated i.e. it assumes that the time of pesticide application is pre-determined by factors not directly related to the size of the pest population, such as the growth stage of the pest. Even more important perhaps, the equation defining the cost of pest control (Equation 1.4 on page 8) is an implicit function of P_0, the initial size of the pest population, which is not specified in the model. The cost of control depends on the extent of the reduction in size of the pest population rather than on the level to which it is reduced.

1.2 The production function

Hillebrandt (1959) and Headley and Lewis (1967) consider pesticide use within the traditional framework of marginal analysis, see Figure 1.3. The production function, Q, relating the increase in yield to the rate of pesticide application is a sigmoid dosage-response curve. The optimal level of pesticide use, X^*, is where the slope of the dosage-response curve (dQ/dX) is equal to the ratio of pesticide to crop prices since at this point the marginal benefit (= dQ. unit price of the crop) is reduced to the level of the

Figure 1.3: Pesticide use: marginal analysis



marginal cost (= dX. unit price of the pesticide)[1]. In practice, there is a family of dosage-response curves (Q, Q', Q"), one for each level of infestation.

Hall and Norgaard (1973) have presented an analytical model of agricultural pest control which specifies the production function according to the initial size of the pest population (*cf*. the Headley model described above). It consists of five elements: a pest population growth function (*Equation 3.10*), a pest population kill function (*Equation 1.11*), a pest damage function (*Equation 1.12*), a product yield function (*Equation 1.13*), and a pesticide cost function (*Equation 1.14*).

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[1] *i.e.* where the production function is tangential to an iso-revenue curve. The net revenue (R) is the difference between the value of the increase in yield (= $\beta.Q$, where β is the unit price of the crop) and the cost of pesticide treatment required to achieve this (= $\alpha.X$, where α is the unit price of the pesticide). Thus, $R = \beta.Q - \alpha.X$ (if there are zero fixed costs). For a given revenue, the increase in yield (per acre) is related to the rate of pesticide application as follows: $Q = R/\beta + \alpha.X/\beta$ This is the equation of a straight line with slope α/β and intercept on the y axis of R/β.

Equation 1.10 (pest growth)

$$P(t) = P_o.e^{r.t} \qquad \text{for } t_o \leq t \leq t_i$$

$$P(t) = (P_o.e^{r.t_i} - K).e^{r.(t-t_i)} \qquad \text{for } t_i < t \leq t_h$$

where $P(t)$ = size of pest population at time t

P_o = size of pest population at time t_o

t_o = planting time

t_i = time of pesticide application

t_h = harvest time

r = pest population growth rate

i.e. the pest population is assumed to grow in simple exponential fashion both before and after pesticide application. At the time of application, it is assumed to be reduced by K individuals as specified in Equation 1.11.

Equation 1.11 $K = K(X,t_i)$ (pest kill)

where K = number of pests killed by pesticide application

X = pesticide application rate

i.e. the number of pests killed by pesticide application depends, in *a way not analysed by Hall and Norgaard in their original formulation of the model, both on the amount of pesticide used (the concentration of the active ingredient) and on the time of application.*

Equation 1.12 (pest damage)

(i) $$d(t) = b.P(t)$$

(ii) $$D(t_2-t_1) = \int_{t_1}^{t_2} d(t).dt$$

where $d(t)$ = the instantaneous rate of crop damage in physical units per time unit

b = a parameter which specifies the rate of crop damage in physical units per pest per time unit

$D(t_2-t_1)$ = cumulative crop damage between times t_1 and t_2

i.e. the rate of crop damage is determined by the number of pests present in the crop at that time, and the cumulative damage is represented by the area under the rate curve.

Equation 1.13 (crop yield)

$$Y = N - D(t_h-t_o)$$

$$= N - D(t_h)$$

where Y = physical yield at harvest

N = physical yield if no pest damage occurs

t_o = zero

i.e. the actual yield is equal to the potential yield minus the cumulative damage caused by the pest up to harvest time.

Equation 1.14 $C = \alpha.X$ (pesticide cost)

where C = total control cost

α = cost of purchasing and applying each unit of pesticide

i.e. the cost of control is assumed to be directly proportional to the amount of pesticide used. This is a simplification since it ignores the distinction between variable costs, which do vary in direct proportion to the concentration of the active ingredient in the spray, and the fixed costs of actually applying the spray, which do not.

The total damage realised at harvest time can be considered in two parts, one arising before the time of pesticide application, the other after:

Equation 1.15

$$D(t_h - t_i) = \int_{t_o}^{t_i} d(t).dt \; + \; \int_{t_i}^{t_h} d(t).dt$$

By substitution of Equation 1.10, Equation 1.11, and Equation 1.12(i) into Equation 1.15, and setting t_o equal to zero, we get:

Equation 1.16

$$D(t_h - t_i) = \frac{b}{r}.\Big[(e^{r.t_h} - e^{r.t_i}).\{P_o - e^{r.t_i}.K(X,t_i)\} + P_o.(e^{r.t_i} - 1)\Big]$$

i.e. the damage caused by the growth of the pest population is proportional to the area under the pest population growth curve up to the time of pesticide application plus the area under the growth curve of the residual population remaining after pesticide application and up to harvest time.

The profit function (Equation 1.17) can now be written:

Equation 1.17 $\pi = \beta.Y - C$

$$= \beta.(N - D_1 - D_2) - \alpha.X$$

$$= \beta.N - \frac{\beta.b}{r}.\left[(e^{r.t_h} - e^{r.t_i}).\{P_0 - e^{r.t_i}.K(X,t_i)\} + P_0.(e^{r.t_i} - 1)\right] - \alpha.X$$

where π = gross margin

β = unit price of the crop

N.B. (1) all cost and revenue figures refer to one acre of the crop, and (2) any increase in the variable cost of production, apart from the immediate cost of pest control, is assumed to be negligible e.g. the extra cost of bags and twine at harvest because of higher yields.

The economic threshold, $P(t_i)$, is that size of the pest population associated simultaneously with the two decision variables, the optimum time of application (t_i^*) and the optimum quantity of pesticide (X^*), which maximise the gross margin. Equation 1.17 may be solved for the economic threshold if the form of the pesticide kill function is specified. Alternatively, if the parameters in Equation 1.17 are known in any given situation, its solution will trace out the production function.

The use of marginal analysis in this way does not altogether accord with the way in which the decision is presented to the farmer in the real world of the farm firm. The farmer uses (or, at least, the pesticide manufacturer strongly recommends that he use) the application rate suggested on the can. The concentration of the active ingredient in the spray is thus determined by the manufacturer who does not and can not know the intimate details of the dosage-response curve on any given farm. The farmer is more interested in whether or not the pesticide should be used at all (i.e. X is constrained to either zero or X_r, where X_r is the standard rate) than in the optimal incremental level to apply. This is particularly true of the problem of powdery mildew control in spring barley since only a single application of a systemic mildewcide is required for effective control. It is also true when the farmer has to decide whether or not to adopt a spray routine involving several applications if these are presented as a single package. The problem of fixing the concentration of the active ingredient in the spray, or the number of sprays in a routine programme, must then be solved on the basis of a "typical" dosage-response curve. This is a separate problem, although one for which a model of the Hall-Norgaard type could be used (see e.g. Hueth and Regev, 1974).

In Chapter 3, I try to show how the Hall-Norgaard model may be modified for use in a specific context: the use of sprays to control powdery mildew in spring barley. The problem of fixing the concentration of the active ingredient in a routine spray is discussed more fully in Chapter 6.

1.3 Dynamic programming

Shoemaker (1973b, 1973c) has formulated a pest control model in terms of dynamic programming. The basis of dynamic programming is Bellman's Principle of Optimality, which states:

> "An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." (Bellman, 1967)

Thus the approach of dynamic programming differs from that of previous models in that its concern is with multi-period decision problems. In this it may be more appropriate to the analysis of large-scale and long-term investments in agricultural pest control *e.g.* in perennial crops such as trees and of insect/parasite/insecticide/crop systems in which the interactions between the individual components of the system are very much more far-reaching than in the comparatively simple fungus/fungicide/crop system under particular consideration here. Even more important perhaps, it is difficult to see how the multi-period problem can be solved until the behaviour of the system in a single period is properly understood, whether it be week, month, year, growth stage of the pest or crop season.

1.4 Uncertainty

The models presented so far in this chapter are deterministic since no account is taken of any future uncertainty. In general, neither the precise form of the dosage-response curve nor the ultimate sale price of the crop are known for certain at the time when the decision to use pest controls must be made.

Hillebrandt (1960) did discuss uncertainty in her economic theory of pesticide use, basing her analysis on Shackle's Theory of Potential Surprise (see *e.g.* Shackle, 1970). Unfortunately, this is quite ill-suited to our purpose: Shackle's theory is psychological, non-quantitative, and suppresses information in a more or less arbitrary manner by condensing subjective estimates into so-called "focus" gains and losses.

Ghodake *et al*. (1973) formulate production functions for the use of insecticides on cotton in India. Regression analysis was used to examine the relationship between the yield of seed cotton and the factors that affect it: the quantity of pesticide used and the percentage damage. The percentage damage was calculated by subtracting the yield realised in control plots (*i.e.* with no pesticide) from that obtained in the most favourable year. They obtained high values for the index of determination[1] (and thus strong evidence of correlation)

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[1] *index of determination*: the square of the correlation coefficient.

when the parameters were related in the form of a Cobb-Douglas (log-linear) production function:

Equation 1.18 $Y = a.X^{b}.D^{c}$

or $\log(Y) = \log(a) + b.\log(X) + c.\log(D)$

where Y = yield of the crop
X = pesticide application rate
D = percentage damage
a,b,c are constants

Keeping the percentage damage constant at the level of its geometric mean based on historical data, the optimum quantity of pesticide was estimated by equating the marginal physical product (obtained by partial differentiation of the production function with respect to the pesticide application rate) with the price ratio, as described on page 12. This procedure takes care of uncertainty by assuming that the current crop season will be a sample from previous recent seasons weighted with equal probability *i.e.* that this year has as much chance of being like 1974 as like 1970.

It is of some interest that the economic optima identified by Ghodake *et al*. (*i.e.* those application rates for various insecticides that brought the marginal benefit into line with the marginal cost) were less than one fourth of the rates previously recommended.

The treatment of uncertainty in the economics of pest control is a little confused by the idea that some people have of using pesticides as an insurance premium to protect their crops from occasional severe attacks of a pest. Insurance does not produce anything tangible if the premiums are properly calculated. The expected[1] gain from the value of the increase in yield made possible by pesticide applied as insurance would be less than the cost of treatment. The value of insurance is the anticipated reduction of the variance[2] of the gross margin between revenue and variable costs. It will be shown in Chapter 2 that pest control can increase the yield variance and so have no value as insurance. Pest control differs further from insurance in that only losses from a specific cause are considered, whereas approximately 90% of United States Federal crop insurance is "all-risk" (United States Department of Agriculture, 1972).

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[1] expected value or expectation: the quantity obtained by multiplying each possible value of a random variable by the probability of observing that value and adding the products.

[2] variance of a set of values: the arithmetic mean of the squares of the differences between the individual values and the mean value.

addendum, footnote 2, page 24

Strictly speaking, the value of insurance is the anticipated reduction in the negative semi-variance of the gross margin (cf. Markowitz, 1959).

Carlson (1970) has suggested a decision theory approach to crop disease prediction and control. The complete set of possible pesticide input levels can be represented by the actions $a_1 \ldots a_m$. The size of the pest population (or, alternatively, percentage crop losses) can be treated as states of nature $\theta_1 \ldots \theta_n$. There is a crop yield, a monetary yield, and a utility[1] corresponding to each action/state of nature combination. The decision theory approach involves enumerating all possible pay-offs and selecting the action which pays off best. It is suggested that the best guide for decisions is the maximisation of subjective expected utility, as represented by Equation 1.19:

Equation 1.19 $$E(U) = \max_a \left[\sum_\theta U(a,\theta).P(\theta) \right]$$

where $E(U)$ = expected utility

$U(a,\theta)$ = pay-off (utility) derived from each action/state of nature pair

$P(\theta)$ = the decision maker's subjective probability distribution for the random variable θ

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[1] utility: satisfaction, pleasure, need-fulfilment etc., here equated with monetary pay-off. In Chapter 2 the concept of ordinal utility is used to rank projects on the basis of both subjective expected pay-off and the variance of the pay-off.

addendum. footnote, page 25

In decision theory, risky pay-offs may be replaced in the analysis by certain pay-offs of equal utility (see footnote, page 31) to facilitate comparison between pay-offs associated with different levels of risk.

i.e. in order to maximise his subjective expected utility, the decision maker should adopt that course of action which maximises the utility associated with that action in each state of nature multiplied by his estimate of the probability that that state of nature will occur and summed over all possible states.

Carlson computed optimal pesticide use actions for three different objective functions[1]: (1) the simple maximisation of the subjective expected monetary pay-off, although this fails to incorporate survival as an objective of the farm firm since it ignores the farmer's aversion to the risk that any pay-off as good as (or better than) that expected will not be realised that year, (2) the maximisation of the subjective expected monetary pay-off with a minimum income side constraint to ensure survival, and (3) a trade-off between the maximum expected pay-off (E) and its variance (V). This trade-off in E-V space will be considered more fully in Chapter 2.

The analysis was applied to the choice of five common pesticide use actions that a peach grower in California might select in order to control the disease, brown rot: no spray, one or two

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[1] objective function: that which is to be maximised, in the terminology of linear programming; here equated with the maximisation of the subjective expected monetary pay-off subject to either income or variance constraints.

applications of captan, or one or two applications of sulphur. The time of pesticide application was not considered as a decision variable.

In Chapter 2 this form of analysis is applied to the problem of choosing a suitable barley variety in the U.K., and the problem of whether or not to incorporate a systemic mildewcide seed dressing. This overcomes the problem of defining the time of pesticide application since it goes into the ground with the seed at planting time (i.e. $t_1 = t_0$). The procedure is generalised using quadratic programming which considers the possibility of mixed actions in an optimal portfolio. A practical procedure using linear programming is illustrated.

In Chapter 3 I try to show how the empirical approach of statistical decision theory, as developed in this context by Carlson, can be combined with an analytical model of the Hall-Norgaard type to produce a hybrid (techno-economic) prognosis. The development and use of such a model is illustrated by reference to the use of sprays to control barley mildew.

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Chapter 2

The choice of variety and seed dressing

In Chapter 1 the importance of the timing of pest controls was emphasised. The choice of crop variety, with a given complement of genetic resistance factors, and the problem of whether or not to use a pesticidal seed dressing are considered together since these actions are implemented simultaneously and at a particular growth stage of the host crop (t_i = zero). Pesticide application to vegetative plant tissues as a spray or dust takes place subsequently to all decisions concerning the choice of variety and seed dressing (i.e. $t_i > t_0$). Even more important, the timing of spray applications is not fixed relative to the stages in the morphological development of the crop, but is a decision variable under the control of the individual farmer. The choice of variety, with or without a seed dressing, is the subject of this chapter. The problem of whether to apply a subsequent spray is considered in Chapter 3.

As indicated in Appendix 1.4, a farmer interested in growing barley has some fifty named varieties to choose from, each of which could be used with or without a systemic mildewcide seed dressing (ethirimol, see Appendix 2).

2.1 The farmer's objective

I shall assume that the farmer is concerned to maximise his subjective expected monetary pay-off, subject to a constraint describing the riskiness of the project. This concept is discussed at some length by Dillon (1971), and has already been introduced to the economics of pest control by Carlson (1970). The farmer is assumed to hold preferences amongst alternative farm plans solely on the basis of the expected income (E) accruing to each of them and some measure of the risk, such as the variance (V) of E. The appropriate measure of farm income is the gross margin (*i.e.* the gross returns less the variable costs of production), which represents the contribution of each farm plan to the fixed costs of operating the farm. This is so since, at this stage, we are concerned only with planning models of the short run: the farmer has already decided to grow barley rather than some other crop and the choice of pest controls will not affect his fixed production costs.

2.2 Portfolio selection using quadratic programming

Quadratic programming, as developed by Markowitz (1959) for the selection of optimal portfolios[1], has been suggested as a useful method for incorporating the risk attached to gross margins

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[1] portfolio: the collection of securities held by an investor.

in farm planning (e.g. by Cran, 1961; McFarquhar, 1961; Camm, 1962; Stovall, 1966; Bauer, 1971). It has been applied by these authors to the choice of alternative farming enterprises, such as different crops, but has not been used so far to analyse the problem of choosing varieties within a given crop species nor the choice of pest controls (with the single exception of Carlson's work described on page 26).

The use of quadratic programming to construct a portfolio of different crop varieties more nearly resembles its use by Markowitz for the choice of financial securities, such as bonds and shares, than its subsequent use by agricultural economists for whole-farm planning since the objective function (i.e. the minimisation of the variance for a given expected gross margin) is constrained only by non-negativity conditions[1] and by the requirement that the portfolios be composed entirely from the varieties under consideration[2]. There are no extra constraints related to the allocation of other scarce farm resources such as labour, machinery, irrigation capacity, or storage space. In fact, its use in this context is more realistic than the use proposed by Markowitz since the choice necessarily relates to a single cropping period, whereas the management of a portfolio of financial securities is a multi-period problem involving consideration

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[1] $x_i \geq 0$ for all i, where x_i represents the proportion of security i

[2] $\sum x_i = 1$

of how long a security should be held before selling and of when the entire portfolio should be reviewed.

Quadratic programming assumes that the farmer's iso-utility[1] curves in E-V space are convex to the origin *i.e.* that along every iso-utility curve the slope is positive[2] (the farmer would prefer a farm plan that was more risky only if the expected gross margin were also greater) and that the slope gets steeper as V increases[3] (the increase in expected gross margin necessary to compensate the farmer for an increase in risk itself increases as the risk gets bigger). This is equivalent to supposing the farmer to be risk-averse. A set of iso-utility curves in E-V space, ranked on an ordinal scale, is illustrated in *Figure 2.1*.

Also illustrated in *Figure 2.1* is the set of feasible farm plans from which the choice must be made. Each has a characteristic pay-off and risk associated with it. Quadratic programming identifies efficient E-V pairs within the set of feasible farm plans. An E-V efficient plan is one for which the variance is minimal for a given expected gross margin and the expected gross margin

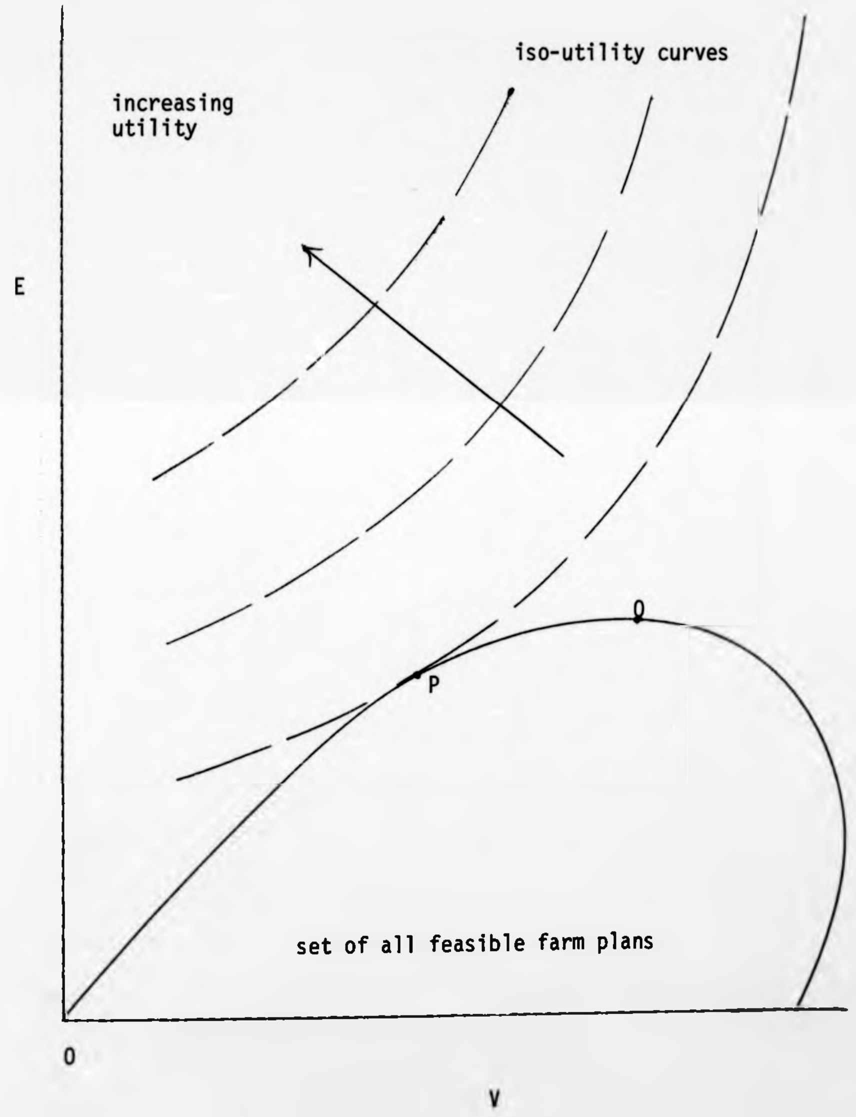
---

[1] *iso-utility*: it is assumed that the investor can trade-off in his own mind between the potential gain and the risk and identify combinations of these between which he is indifferent.

[2] *i.e.* $dE/dV > 0$

[3] *i.e.* $d^2E/dV^2 > 0$

Figure 2.1: The optimal E-V farm plan



is maximal for a given variance. The set of E-V efficient farm plans is represented by the segment OQ of the set of all feasible farm plans in Figure 2.1.

The practical procedure of quadratic programming is summarised in Equation 2.1:

Equation 2.1

$$\text{minimise } V = \sum_i \sum_j x_i . x_j . \sigma_{ij}$$

$$\text{for } E = \sum_i x_i . \mu_i = \lambda \qquad (\lambda = \mu_{min} \text{ to } \mu_{max})$$

$$\text{subject to} \quad \sum_i x_i = 1$$

$$\text{and} \quad x_i \geq 0 \quad \text{for all } i$$

where x_i = proportion of variety i in the portfolio

μ_i = expected gross margin associated with the cultivation of variety i

σ_{ij} = covariance between the gross margins of the i^{th} and j^{th} varieties

λ = a scalar

The covariance term is defined by Equation 2.2. It is the product of the standard deviation[1] of the gross margin associated with each of the two varieties and the correlation coefficient[2] between the respective gross margins in a time series.

Equation 2.2 $\sigma_{ij} = \sigma_i . c_{ij} . \sigma_j$

where σ_i = standard deviation of the gross margin associated with cultivation of the i^{th} variety

c_{ij} = correlation coefficient between the gross margins of the i^{th} and j^{th} varieties in a time series

It can be seen from Equation 2.1 that the variance of the gross margin associated with the portfolio as a whole depends on the sum of the variances of the individual gross margins (weighted according to their proportion in the portfolio) and the covariances between them. If the gross margins associated with each of two varieties

---

[1] standard deviation: the square root of the variance

[2] correlation coefficient: an index of association between two variables x and y, defined by the relation $c_{xy} = \left[\sum(x-\bar{x})(y-\bar{y})\right] / \sqrt{\left[\sum(x-\bar{x})^2 . \sum(y-\bar{y})^2\right]}$ where $\bar{x}$, $\bar{y}$ are the mean values of x, y. It can vary from +1 (perfect correlation), through zero (no correlation) to -1 (perfect inverse correlation).

are not closely correlated (i.e. $0 < c_{ij} < +1$) or, better still, if they are negatively correlated (i.e. $-1 < c_{ij} < 0$) the variance associated with the gross margin of the whole portfolio of varieties will be that much less.

The objective function in Equation 2.1 is quadratic in the decision variables, x_i. By parameterising the term for the expected value of the gross margin (E) from the minimum value associated with any variety (μ_{min}) to the maximum associated with any variety (μ_{max}) a series of solutions is obtained of increasing gross margin (E) and variance (V). Turning point solutions are sufficient to define the efficient E-V boundary since efficient portfolios for intermediate levels of E can be derived by linear interpolation.

The portfolio which maximises the farmer's expected utility is defined within the efficient set determined by quadratic programming if the shape of his iso-utility curve in E-V space is specified. In Figure 2.1 this is represented by the point P since at this point the farmer's utility indifference curve is tangential to the efficient frontier of the feasible set. However, it is considered sufficient to identify the efficient set for practical purposes and to let the farmer make the final choice between them.

2.3 A linear programming model

Although quadratic programming routines are available, such as MPCODE (Land and Powell, 1973; Land *et al*., 1974), they are not readily available as packages on most computer installations. This contrasts with the universal availability of linear programming (LP) packages. A linear alternative to portfolio selection using quadratic programming has been proposed by Hazell (1971), the so-called MOTAD model (for Minimisation Of Total Absolute Deviations)[1]. The MOTAD formulation defines an efficient set in E-A space such that the total negative absolute deviation of the gross margin (as sampled by a time series of historical data) from the arithmetic mean (*i.e.* the expected gross margin, if each sample is given equal weight *cf*. Section 2.5) is minimised for any given level of expected gross margin. This is illustrated by Equation 2.3:

Equation 2.3

$$\text{minimise } A = \sum_h y_h^-$$

$$\text{for } E = \sum_i x_i \cdot \mu_i = \lambda \qquad (\lambda = \mu_{\min} \text{ to } \mu_{\max})$$

---

[1] The reliability of using the mean absolute deviation to derive efficient E-V farm plans has been further investigated by Thomson and Hazell (1972).

subject to the constraints:

(1) $\sum_i (s_{hi} - \mu_i).x_i \; + y_h^- \geq 0$

i.e. the sum of the positive deviations about the sample mean is equal to the sum of the negative deviations, as required by the definition of the arithmetic mean.

(2) $\sum_i x_i = 1$

i.e. the portfolio must consist entirely of those varieties under consideration.

(3) $x_i, y_h^- \geq 0$ for all i, h

i.e. the non-negativity conditions.

where y_h^- = total negative absolute deviation in sample h from the mean sample gross margin[1]

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[1] i.e. $y_h^- = \sum_i (\mu_i - s_{hi}).x_i$

x_i = the proportion of variety i in the portfolio
h = random sample of gross margins associated with each variety i
s_{hi} = observed gross margin of variety i in sample h
μ_i = mean sample gross margin of variety i
λ = a scalar

This can be solved using a conventional linear programming[1] package. Hardaker (1971) gives a general account of the application of linear programming to farm planning. The calculation of E-A efficient portfolios of barley varieties in this chapter were performed on an Elliott 4100 machine using the LP4100 package.

Figure 2.3 illustrates the form of the LP matrix for the calculation of E-A efficient portfolios of barley varieties chosen from amongst those marked with an asterisk in Figure 2.2[2]. Each

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[1] linear programming: a mathematical procedure used to find the maximum value of a linear objective function subject to linear constraints, cf. the quadratic formulation of portfolio selection in which the objective function is quadratic in the decision variables although subject to linear constraints.

[2] Yield data are used here in place of data about the respective gross margins since yield is the primary determinant of the gross margin, see Section 2.4.

Figure 2.2: Varietal yields in N.I.A.B. spring barley trials at Cockle Park, 1970 to 1973

variety	yield (cwt/acre)				
	1970[a]	1971[b]	1972[c]	1973[d]	
Proctor	34.2	35.6	42.6	41.0	*
Zephyr	42.6	34.8	43.4	44.4	*
Sultan	42.6	34.1	-	-	
Gerkra	44.2	-	-	-	
Imber	34.9	-	-	-	
Midas	47.2	39.4	-	-	
Berac	42.2	-	42.1	-	
Felda	43.0	-	-	-	
Lofa Abed	42.6	-	42.6	45.7	
Clermont	34.6	35.2	-	-	
Hassan	47.2	38.7	42.6	-	
Wing	43.8	39.1	38.3	-	
Feronia	43.8	40.8	-	-	
Mazurka	46.5	44.4	43.0	52.1	*
Julia	-	35.9	43.9	43.1	*
Universe	-	46.8	42.6	47.0	*
Ansgar	-	39.8	-	-	
Maris Mink	-	46.8	40.0	51.7	*

[a] data from Fiddian (1970)

[b] data from Fiddian (1971)

[c,d] N.I.A.B. unpublished reports

* varieties included in the LP matrix in Figure 2.3

Figure 2.3: The LP matrix

	X_1	X_2	X_3	X_4	X_5	X_6	Y1	Y2	Y3	sign	RHS
SUM	1	1	1	1	1	1				=	1
T1	-4.1	-6.1	-2.1	-5.1	1.3	0.6	1			≥	0
T2	2.9	2.5	-3.5	2.9	-2.9	-6.2		1		≥	0
T3	1.3	3.5	5.6	2.1	1.5	5.5			1	≥	0
E	39.7	40.9	46.5	41.0	45.5	46.2				=	λ
OBJ							-1	-1	-1		

X_1 = Proctor; X_2 = Zephyr; X_3 = Mazurka; X_4 = Julia; X_5 = Universe; X_6 = Maris Mink variety (i) defines a column in the matrix, the remaining columns being defined by the number of samples (h). Rows in the matrix are defined by the constraints identified in Equation 2.3. The first row (SUM) is the requirement that the portfolio comprise some combination of the varieties (i). Below this is an h (row) by i (column) matrix of the positive deviations of the gross margin[1] of each variety (i) about the mean sample gross margin for that variety (μ_i, recorded in row E) for each sample year (h). The total negative deviation of the entire portfolio of varieties in each sample year (y_h^-) is defined by the square (h by h) matrix to the right of this, with non-zero elements along the diagonal. The expected value of the portfolio (E) is defined by specifying the parameter λ on the right-hand side (RHS) of row E. The objective function (OBJ) is the minimisation of the negative deviations in the value of the portfolio summed over the sample periods. (The sign reversal in the objective function is necessary because LP4100 is a maximisation package.) It is solved by adjusting the proportion of each variety included in the portfolio. This is done by the LP package which prints out the composition of the portfolio which minimises the total negative absolute deviation of the portfolio gross margin over the sampled years, together with the location of the portfolio in E-A space. However, the portfolio defined in this

---

[1] see Section 2.4, page 42.

variety (i) defines a column in the matrix, the remaining columns being defined by the number of samples (h). Rows in the matrix are defined by the constraints identified in Equation 2.3. The first row (SUM) is the requirement that the portfolio comprise some combination of the varieties (i). Below this is an h (row) by i (column) matrix of the positive deviations of the gross margin[1] of each variety (i) about the mean sample gross margin for that variety (μ_i, recorded in row E) for each sample year (h). The total negative deviation of the entire portfolio of varieties in each sample year (y_h^-) is defined by the square (h by h) matrix to the right of this, with non-zero elements along the diagonal. The expected value of the portfolio (E) is defined by specifying the parameter λ on the right-hand side (RHS) of row E. The objective function (OBJ) is the minimisation of the negative deviations in the value of the portfolio summed over the sample periods. (The sign reversal in the objective function is necessary because LP4100 is a maximisation package.) It is solved by adjusting the proportion of each variety included in the portfolio. This is done by the LP package which prints out the composition of the portfolio which minimises the total negative absolute deviation of the portfolio gross margin over the sampled years, together with the location of the portfolio in E-A space. However, the portfolio defined in this

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[1] see Section 2.4, page 42.

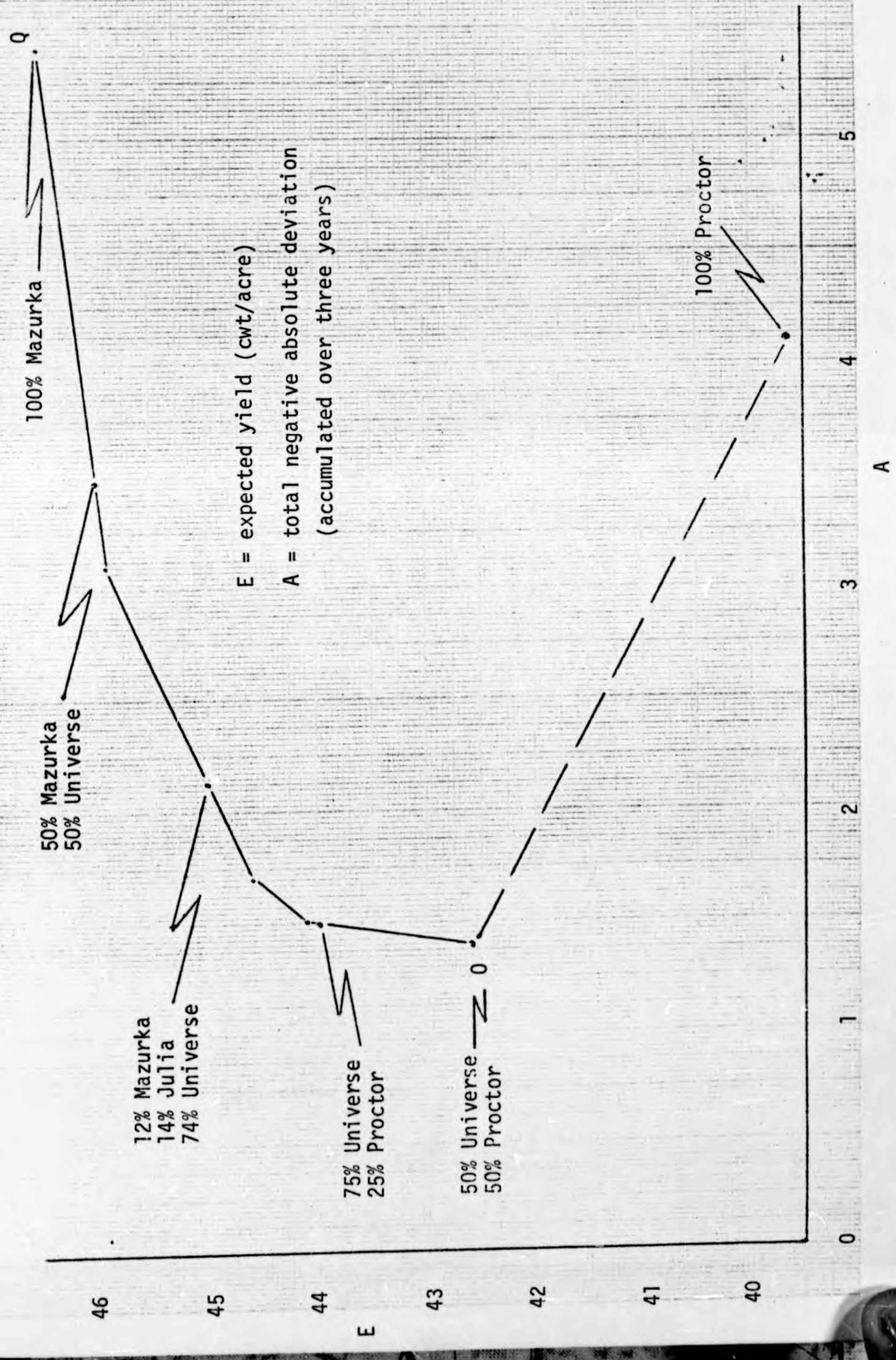
way may not be an efficient one since two portfolios with different expected gross margins may have the same total negative absolute deviation.

This is illustrated in Figure 2.4 which is the solution to the portfolio selection problem set up in Figure 2.3. A portfolio with minimum expected gross margin (corresponding to a yield of 39.7 cwt/acre) would comprise 100% Proctor. As more and more Universe is introduced into the portfolio, the expected gross margin increases and the deviation gets less until a portfolio with minimum deviation is achieved (50% Proctor + 50% Universe) with a gross margin corresponding to an expected yield of 42.6 cwt/acre. This is an efficient portfolio since both the gross margin is maximised for a given deviation and the deviation is minimised for a given expected gross margin. With increasing E-A, first Julia, then Mazurka, are introduced into the efficient set defined in Figure 2.4 by the boundary OQ of the feasible set. The portfolio with maximum expected gross margin (corresponding to a yield of 46.5 cwt/acre) comprises 100% Mazurka.

2.4 The use of yield as a proxy for the gross margin

Figure 2.2 shows the results of spring barley variety trials carried out by the National Institute of Agricultural Botany at just one site (Cockle Park) over the period 1970 to 1973.

Figure 2.4: An E-A efficient set of barley portfolios



The mean trial yield for each variety at that site and in that year was used in the illustration above as a proxy variable for the gross margin associated with that action/state of nature combination. This is acceptable if there are no differences in the variable costs associated with the cultivation of any of the varieties (e.g. the cost of seed or the cost of harvesting a larger crop), nor any differences in the ultimate sale price (e.g. malting barley may command a premium over feeding barley). In general, the physical yield of the crop is the primary determinant of the gross margin:

Equation 2.4 $$\pi_i = \beta . Y_i - (\underline{C} + \Delta C_i)$$

where π_i = gross margin per acre of variety i

Y_i = physical yield per acre of variety i

β = expected sale price of the crop (in the case of barley, either for malting or feed)

$\underline{C}$ = base variable costs per acre of crop e.g. ploughing, sowing, spraying, harvesting

ΔC_i = increase in variable costs per acre associated with the cultivation of variety i

The seed of some varieties may cost more than that of others e.g. Mazurka (see Figure 2.5). In such cases, the actual yield in each sample year should be deflated as shown in Equation 2.5:

Figure 2.5: Prices of spring barley seed (after Miln Masters, 1973)

variety	price per cwt (£)	royalty (£)	total price (£/cwt)
Berac	4.75	0.20	4.95
Deba Abed	4.75	0.20	4.95
Golden Promise	4.75	-	4.75
Hassan	5.25	included	5.25
Julia	4.75	0.20	4.95
Lofa Abed	4.75	0.20	4.95
Mazurka	6.30	included	6.30
Midas	4.75	-	4.75
Proctor	4.75	-	4.75
Vada	4.75	-	4.75
Zephyr	4.75	0.20	4.95

Equation 2.5 $Y'_i = Y_i - (\gamma_i - \gamma).s/\beta$

where Y'_i = corrected yield per acre of variety i
Y_i = actual yield per acre of variety i in the sample year
γ_i = seed price per cwt of variety i
γ = base price of seed
s = sowing rate in cwt per acre
β = estimated sale price of the crop

A similar correction factor could be specified to take into account predictable differences in the sale price of the crop depending on the particular variety, although if many such corrections were needed it would be easier to work directly in terms of the actual gross margin associated with each variety. The use of corrected yields in place of estimates of the gross margin in the MOTAD model will not influence the composition of the efficient set of varietal portfolios since the total negative deviation of the corrected yield and that of the resulting gross margin will be directly related by the farmer's estimate of the sale price of the crop less the base variable production costs.

The shape of the farmer's iso-utility curve (i.e. his attitude to the risk that the expected yield per acre will not be realised) will be affected however by his forecast of the price that

<u>Equation 2.5</u> $Y_i' = Y_i - (\gamma_i - \gamma).s/\beta$

where Y_i' = corrected yield per acre of variety i

Y_i = actual yield per acre of variety i in the sample year

γ_i = seed price per cwt of variety i

γ = base price of seed

s = sowing rate in cwt per acre

β = estimated sale price of the crop

A similar correction factor could be specified to take into account predictable differences in the sale price of the crop depending on the particular variety, although if many such corrections were needed it would be easier to work directly in terms of the actual gross margin associated with each variety. The use of corrected yields in place of estimates of the gross margin in the MOTAD model will not influence the composition of the efficient set of varietal portfolios since the total negative deviation of the corrected yield and that of the resulting gross margin will be directly related by the farmer's estimate of the sale price of the crop less the base variable production costs.

The shape of the farmer's iso-utility curve (<u>i.e.</u> his attitude to the risk that the expected yield per acre will not be realised) will be affected however by his forecast of the price that the crop will fetch and by the size of the total acreage that he intends to put down to the crop.

2.5 The use of subjective probabilities

There is an implicit assumption in the MOTAD model that was not stressed by Hazell (op. cit.). The use of the samples (h in Equation 2.3 on page 36) implies a particular probability distribution of the states of nature represented by the samples: each is given equal weight i.e. the probability that this year will be like 1973 is assumed to be equal to the probability that it will be like 1972 and to the probability that it will be like 1971 (= 0.33). This is a particularly dangerous assumption for the economics of pest control since the availability of data permits only a limited number of samples of alternative states e.g. it may be that P(1973) = P(1972) = P(1971) = 0.1 with a residual probability of 0.7 that this year will not be like any of the years for which data are available.

The introduction of statistical decision theory into Markowitz's original quadratic programming formulation of portfolio selection has been described by Mao and Särndal (1966). The incorporation of an a priori probability distribution of the states of nature on the basis of the farmer's subjective appreciation of the situation is quite straightforward in the MOTAD model. Using the same data as Figure 2.3, Figure 2.6 illustrates the LP matrix for the subjective notion which a

Figure 2.6: The LP matrix with a modified probability distribution

	X_1	X_2	X_3	X_4	X_5	X_6	Y1	Y2	Y3	sign	RHS
SUM	1	1	1	1	1	1				=	1
T1	-5.0	-7.7	-3.4	-6.3	1.3	-0.2	1			≥	0
T2	2.0	0.9	-4.8	1.7	-2.9	-7.0		1		≥	0
T3	0.4	1.9	4.3	0.9	1.5	4.7			1	≥	0
E	40.6	42.5	47.8	42.2	45.5	47.0				=	λ
OBJ							-1	-1	-1		

X_1 = Proctor; X_2 = Zephyr; X_3 = Mazurka; X_4 = Julia; X_5 = Universe; X_6 = Maris Mink

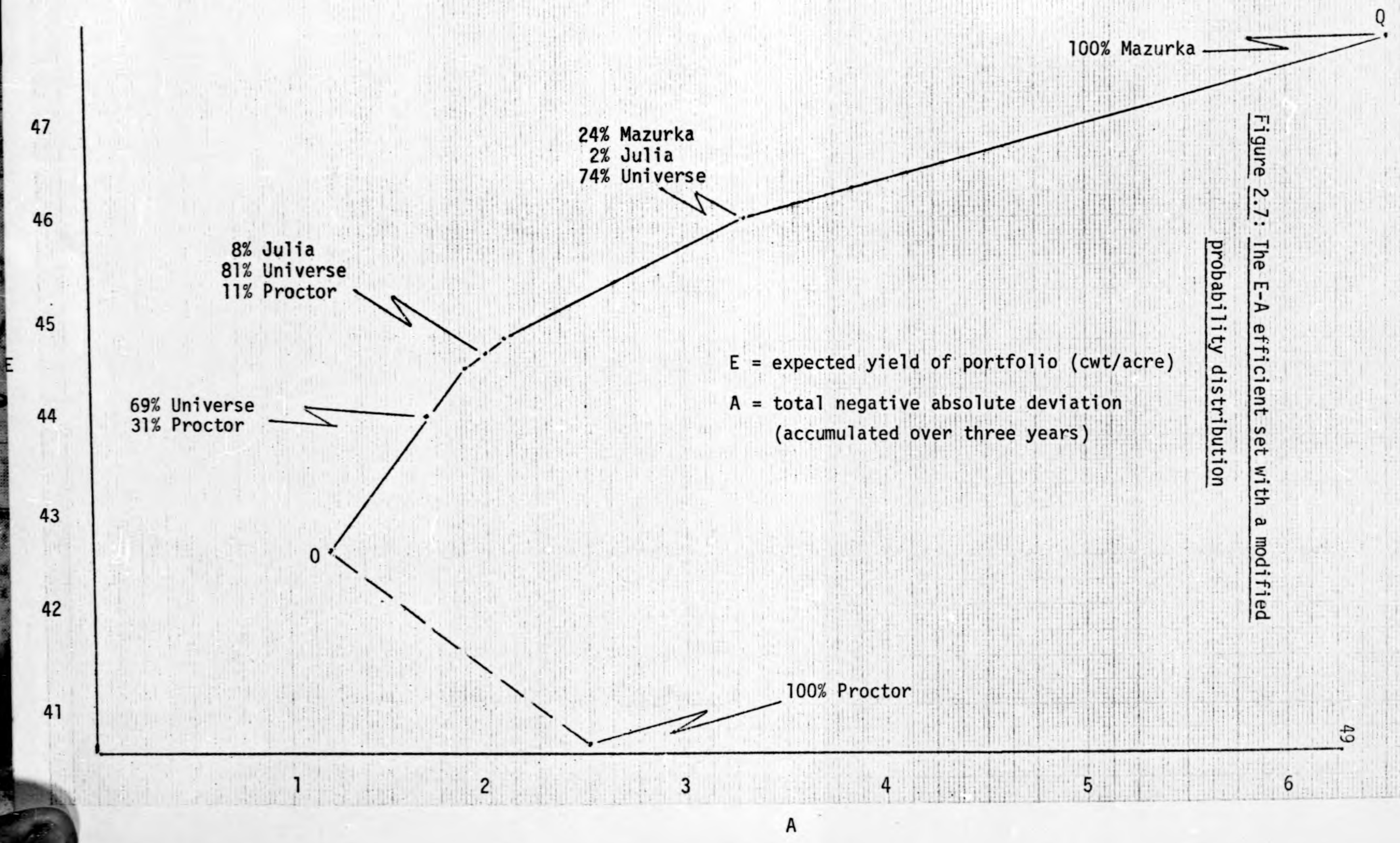


Figure 2.7: The E-A efficient set with a modified probability distribution

farmer has that the coming year has a 50% chance of being like 1973, a 33% chance of being like 1972, and only a 17% chance of being like 1971. The corresponding E-A efficient set of varietal portfolios is shown in Figure 2.7. (N.B. The values of "A" generated by the LP package refer to the expected value of the total negative absolute deviation accumulated over three years.)

The yield data from routine small-plot trials, such as those provided by the national agricultural research agency and illustrated in Figure 2.2, may not represent the states of nature facing any individual farmer let alone provide an estimate of their relative frequency. This is so both because yield tends to be location-specific (depending on the particular physical and chemical characteristics of the soil, and on the weather, and on the level of farm management) and because of interactions between varieties (an effect which is exaggerated when the plots are small). If the farm-level yields are related in direct proportion to the experimental yields, and the coefficient of proportionality remains constant between varieties and from year to year, then the research data would define the E-A efficient set of varietal portfolios just as well as a time series of farm-level yield data.

Neither set of data would define the efficient set if there were systematic changes in the yield of particular varieties.

If certain of the varieties under consideration for inclusion in the portfolios exhibit vertical resistance[1] (see Van der Plank, 1968; Robinson, 1971), consequent upon their possession of only a small number of genes for resistance, we should anticipate the development of physiologic races of the pest capable of attacking them since this would generate a differential yield reduction compared with those varieties with a broader genetic base for resistance *i.e.* with horizontal resistance[2]. It would be necessary in such cases to incorporate a correction factor in successive sample yields to take into account either historical or expected changes in the virulence of the pest population. Alternatively, more recent data may be given greater subjective weight by the farmer when he considers the probability that this year will be like any preceding one in order to reflect any change in the trend of the historical yield response.

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[1] vertical resistance: when a variety is more resistant to some races of a pest than to others the resistance is called "vertical".

[2] horizontal resistance: when the resistance is evenly spread against all races of the pest it is called "horizontal". Vertical resistance implies a differential interaction between varieties of the host and races of the pest. In horizontal resistance there is no such differential interaction.

2.6 The choice of seed dressing

The problem of whether or not to incorporate a seed dressing, and on which varieties, is readily considered by the procedure for risk programming described above. It makes little difference to the form of the problem whether pest control is effected through the mechanism of the plant's own genetic system or by the routine application of a chemical pesticide.

There is some confusion in the literature concerning the effect of pesticide use on the yield variance, and thus on the variance of the gross margin. Strong (1970) has suggested that the typical response is an increase in the yield (gross margin) and a decrease in the yield (and gross margin) variance. If this were so, a seed dressing would be included automatically in the efficient set of varietal portfolios if the expected money value of the increase in yield were greater than the cost of treatment. Unfortunately, this is not necessarily the case.

The situation described by Strong would be realised if the potential yield were constant between samples and the actual yield varied because of differences in the size of the pest population from sample to sample (see Figure 2.8). This behaviour might be considered typical of the space variance[1] of the yield. The alternative

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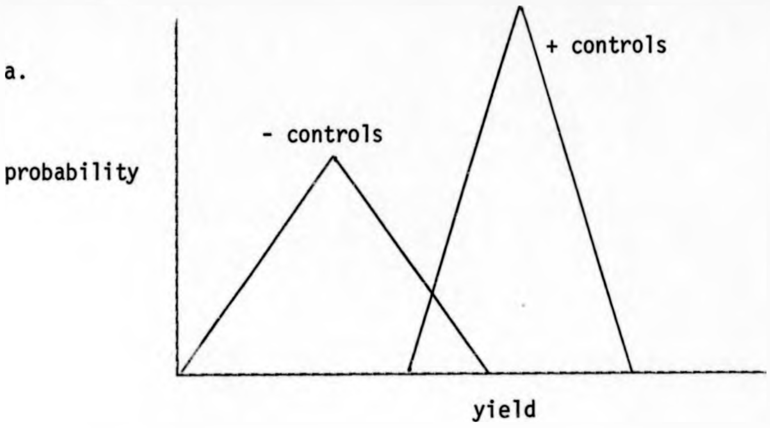
[1] space variance: the variance of cross-sectional data relating to the same time period.

Figure 2.8: The effect of pest control on the space variance of yield

a.



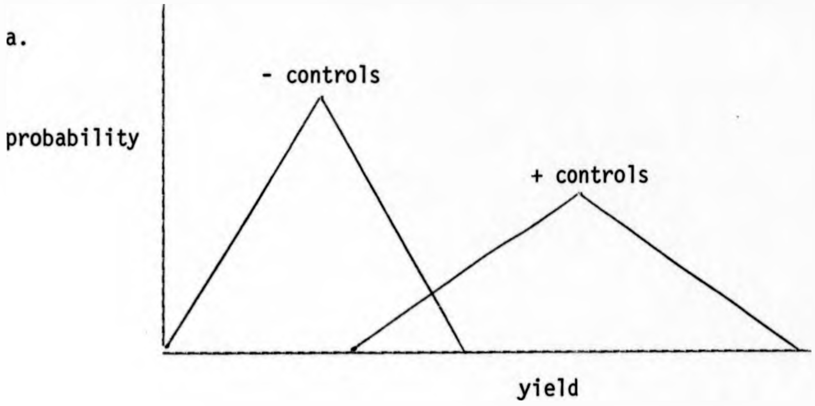
b.

	samples			mean	A[1]
	area 1	area 2	area 3		
base yield	50	50	50		
actual yield (with disease)	30	40	20	30	10
actual yield (with disease, + 50% control)	40	45	35	40	5

[1] A = total negative absolute deviation from the mean

Figure 2.9: The effect of pest control on the time variance of yield

a.



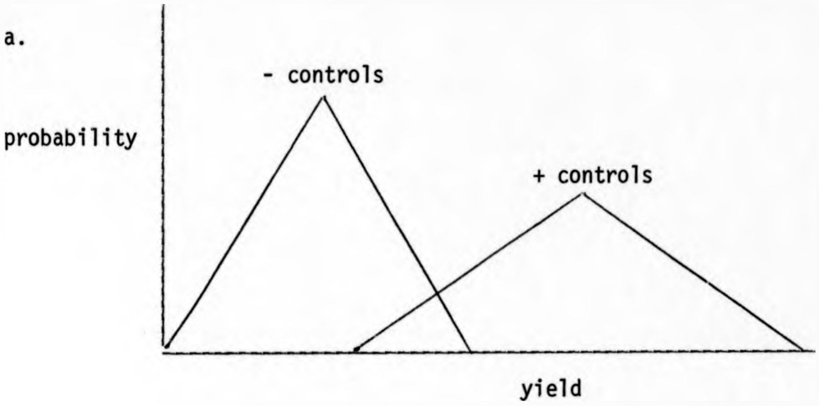
b.

	samples			mean	A[1]
	time 1	time 2	time 3		
base yield	40	20	60		
actual yield (with disease causing 50% loss)	20	10	30	20	10
actual yield (with 50% disease control)	30	15	45	30	15

[1] A = total negative absolute deviation from the mean

Figure 2.9: The effect of pest control on the time variance of yield

a.



b.

	samples			mean	A[1]
	time 1	time 2	time 3		
base yield	40	20	60		
actual yield (with disease causing 50% loss)	20	10	30	20	10
actual yield (with 50% disease control)	30	15	45	30	15

[1] A = total negative absolute deviation from the mean

case (i.e. an increase in the yield variance) is illustrated in Figure 2.9. If we consider the potential yield to vary from sample to sample but assume that the pest always takes a constant proportion of the crop, then pest control will increase the yield variance. This behaviour might be considered typical of the time variance[1] of the yield. The proper concern of the farmer in his choice of pest controls is with their effect on the time variance of the gross margin (and thus on the time variance of the yield) on his own farm and not with their effect on the space variance: he has no direct concern with the difference between the yield he achieves and that on his neighbour's farm.

The application of pest controls may increase the time variance of the physical yield (as in Figure 2.9) but still decrease the time variance of the gross margin. This could be so even if the farm firm faces a perfectly elastic demand curve for its product (i.e. it can sell all it has at the going market price) if the total demand for the crop is inelastic in response to any change in the unit price. In the face of an inelastic demand curve, large crops will be sold for a lower total revenue (= quantity sold times the unit price) than short ones because of the lower price at which the market is cleared. On a particular farm, and assuming that there is significant correlation between the farm yield and the size of the total crop from all farms, pest control may reduce the time variance of the gross margin since

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[1] time variance: the variance of time series data relating to the same location.

the increase in yield will be small when the price is high (i.e. the total crop is short) and large when the price is low (because of a glut).

In the real world, both the potential yield and the level of pest infestation may vary simultaneously, both from farm to farm and from year to year, and any simple analysis of this sort will be rendered inappropriate. As a first approximation, it is suggested that corrected yields still be used in the calculation of E-A efficient varietal portfolios which incorporate specific routine procedures for pest control.

Figure 2.10 illustrates yield data compiled by Little and Doodson (1972) for nine varieties of barley both with and without complete mildew control, obtained by the use of both seed dressing and spray. The mean yield (averaged over the two years, 1971 and 1972) and the total negative absolute deviation (A) are shown for three varieties with different levels of mildew resistance ranging from Golden Promise (susceptible), through Zephyr (moderately susceptible), to Vada (resistant) (see National Institute of Agricultural Botany, 1974). It is clear that both the absolute and the proportional yield increase achieved by pest control are less in a resistant variety than in a susceptible one. This is just as one might expect since the disease has already been partly controlled by intrinsic genetic factors. The yield deviation is

Figure 2.10: Yield data for nine spring barley varieties, both with (+) and without (-) mildew control (after Little and Doodson, 1972)

variety	yield (cwt/acre)			
	1971	1972	mean	A[1]
Golden Promise -	30.0	35.9	33.0	3.0
Golden Promise +	34.9	41.6	38.3	3.4
Proctor -	33.8	37.1		
Proctor +	36.3	40.1		
Zephyr -	36.7	39.4	38.1	1.4
Zephyr +	39.8	43.2	41.5	1.7
Sultan -	34.2	38.2		
Sultan +	36.3	41.2		
Midas -	33.5	39.0		
Midas +	34.6	42.4		
Julia -	39.8	41.2		
Julia +	42.3	43.9		
Vada -	40.9	40.1	40.5	0.4
Vada +	43.7	42.4	43.1	0.7
Mazurka -	-	42.0		
Mazurka +	-	43.2		
Feronia -	37.4	-		
Feronia +	37.7	-		

[1] A = total negative absolute deviation of the yield from the mean

consistently increased through the use of controls. This effect is exaggerated in the case of barley powdery mildew by the tendency for the disease to be most severe (and the proportional damage greater) when the potential yield is high.

It is most important to stress that, if a seed dressing is to be incorporated in the efficient set of varietal portfolios on the basis of yield data such as these, it should be used on resistant varieties such as *Vada* rather than on susceptible ones like *Golden Promise* since both the expected yield is greater and the time variance of the yield is less.

This conclusion contrasts with that implied by Gilmour and Fawcett (1973) in their risk analysis of this situation. Quite apart from ignoring the possibility either of the farmer being able to formulate an *a priori* probability distribution of alternative states of nature or of systematic changes in the yield of particular varieties, presenting their analysis in neo-classical (Waldian) terms, Gilmour and Fawcett assess the risk by calculating the returns to pesticide application alone rather than to the unit, variety *plus* pesticide. Although this is acceptable if the decision of whether or not to apply a spray is subsequent to the choice of variety and independent of it, such a procedure will generate a sub-optimal solution for the choice of a seed dressing (or other routine control programme) when this is made simultaneously with the choice of variety. This is so since the financial return to pesticide application alone is greater when the pesticide is applied to a susceptible variety.

A seed dressing should be incorporated, if at all, with a resistant variety if that combination (after a yield correction for the cost of seed and seed treatment, and after taking into account the farmer's subjective estimate of the probability that this year will be like any other for which yield data are available) is a component of the efficient set of varietal portfolios, since this will maximise the overall expected gross margin for a given deviation and thus maximise the farmer's subjective expected utility.

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addendum, page 59

The decision model presented in Chapter 2 aims to derive an optimal portfolio of varieties (together with other routine procedures for pest control) on the basis of existing information. It does not consider the possibility of selecting varieties to provide better information for future decisions. It is a single period model, not a multi-period one.

Chapter 3

The choice of spraying

The problem of deciding whether or not to spray a crop is easier in some ways than the choice of variety or seed dressing since the variety of the crop has already been chosen and the farmer knows by this time whether the pest is attacking his crop or not. The problem is more difficult in that the timing of pesticide application is not fixed relative to the stages in crop development. This complication militates against the empirical approach adopted in the last chapter. However, since more information is available, an analytical approach which takes account of the variable time base is appropriate. I propose to show how the Hall-Norgaard model described in Chapter 1 can be simplified if the form of the kill function is specified, how the model must be modified if it is to be used to describe a real situation such as the control of barley mildew, and how it can be combined with statistical decision theory to take into account the uncertainty associated with the precise values of the critical parameters.

3.1 The re-definition of the kill function

In their original formulation of the model, Hall and Norgaard (1973) did not specify the form of the pesticide kill function *i.e.* how the number of pests killed by the pesticide is related to the rate of pesticide application. However, in most bio-assay

Chapter 3

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3.1 The re-definition of the kill function

In their original formulation of the model, Hall and Norgaard (1973) did not specify the form of the pesticide kill function *i.e.* how the number of pests killed by the pesticide is related to the rate of pesticide application. However, in most bio-assay procedures, the percentage kill depends on the pesticide concentration alone and not on the size of the pest population. Indeed, when dose against percentage kill is plotted on log-probit (Gaddum, 1933; Bliss, 1935) or log-probability (Wilcoxon and McCallan, 1939; Dimond et al., 1941) paper, a straight line relationship may obtain. The pest population kill function (Equation 1.11 on page 15) can be re-written thus:

Equation 3.1 $K = K(X)$

where K = the proportion of pests killed by pesticide application

X = the pesticide application rate

The pest population growth function (Equation 1.10) becomes:

Equation 3.2 $P(t) = P_o.e^{r.t}$ for $t_o \leq t \leq t_i$

$$P(t) = P_o.e^{r.t_i}.(1-K).e^{r.(t-t_i)} \quad \text{for } t_i < t \leq t_h$$

$$= P_o.(1-K).e^{r.t}$$

where $P(t)$ = size of the pest population at time t

P_0 = initial size of the pest population at t_0 (t_0 = zero)
t_i = time of pesticide application
t_h = harvest time
r = pest population growth rate

i.e. the size of the pest population after pesticide application does not depend on the time of application.

If we introduce this into the total damage function (Equation 1.16 on page 18), we get:

Equation 3.3

$$D(t_h - t_0) = \int_{t_0}^{t_i} \{b.P_0.e^{r.t}\}.dt \; + \int_{t_i}^{t_h} \{b.P_0.(1-K).e^{r.t}\}.dt$$

$$= \frac{b.P_0}{r}.\left[K.e^{r.t_i} + (1-K).e^{r.t_h} - 1\right]$$

where b = damage coefficient, the rate of loss of yield per pest
$D(t_h - t_0)$ = cumulative crop damage at time t_h

By comparison with the original formulation of the total damage function, it is evident that a considerable simplification is achieved if the pesticide kill is expressed as a proportion of the

pest population rather than in terms of the number of pests killed.

3.2 A solution of the Hall-Norgaard model

The cost of purchasing and applying a pesticidal spray has a fixed component (*e.g.* the cost of putting a tractor through a field) that was not included in the original model (*cf.* Equation 1.14 on page 17):

Equation 3.4 $$C = Z + \alpha.X$$

where
C = total control cost
Z = fixed cost of applying the pesticide to the field
α = unit price of the pesticide
X = pesticide application rate

The profit function (Equation 1.17 on page 19) can now be re-written to incorporate the simplified pesticide kill function:

Equation 3.5 $$\pi = \beta.N - \frac{\beta.b.P_0}{r}.\left(K.e^{r.t_i} + (1-K).e^{r.t_h} - 1\right) - (Z + \alpha.X)$$

where
π = gross margin per acre
β = unit price of the crop
N = physical yield if no pest damage occurs

The first differential of the profit function with respect to the pesticide application rate (X) is given by:

<u>Equation 3.6</u> $$\pi_X = \frac{\beta.b.P_0}{r}.\left\{e^{r.t_h} - e^{r.t_i}\right\}.K_X - \alpha$$

It is further evident from the form of <u>Equation 3.5</u> that the gross margin is maximised, for a given pesticide concentration, when the pesticide is applied as soon as possible after the pest enters the crop (when $t_i = t_0$). Thus, if the precise form of the pesticide kill function is specified, <u>Equation 3.6</u> may be solved for the optimal rate of pesticide application (X^*), that which maximises the gross margin.

If, for example, the proportional kill is a simple monomolecular function of the pesticide application rate according to <u>Equation 3.7</u>, then K_X, the rate of change of the proportional kill

<u>Equation 3.7</u> $$K = 1 - e^{-n.X}$$, where n is a constant

i.e. the proportional kill equals zero when no pesticide is applied, and approaches 100% as the application rate is increased.

with respect to the pesticide application rate, is given by <u>Equation 3.8</u>:

<u>Equation 3.8</u> $$K_X = dK/dX = n.e^{-n.X}$$

<u>amendment, page 64, paragraph 2</u>

It has been pointed out by Borosh and Talpaz (1974) that, if the pesticide kill function is of the same form as <u>Equation 3.1</u> on page 61, the solution of the Hall-Norgaard model indicates that the spray should be applied at once if at all. In the barley mildew situation, it is better in general to spray sooner rather than later after the pest has entered the crop, although it may pay to delay spray application for a week or two (see Figure 3.7 on page 87). The explanation for this effect may be found in a more complex model of the kill function as described in Section 3.4.3 (page 83). However, the problem for most barley growers must be not when to spray but whether or not to spray the crop at all and most attention must be given to the consideration of information relevant to this decision, summarised in the decision model, Equation 3.16 on page 90.

By substitution of Equation 3.8 for K_X in Equation 3.6, and setting π_X equal to zero for a maximum, we get:

Equation 3.9

$$X^* = \frac{1}{n}.\left\{\ln\{n.\beta.b.P_0.(e^{r.t_h} - e^{r.t_i})\} - \ln\{\alpha.r\}\right\}$$

i.e. the optimal rate of pesticide application is greater the higher the unit price of the crop, the greater the damage coefficient, the greater the initial size of the pest population, the higher the rate of growth of the pest population, the longer the time between pesticide application and harvest, and the lower the unit price of the pesticide. This is a special case of the Talpaz-Borosh solution of the Hall-Norgaard model (Talpaz and Borosh, 1974)[1].

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[1] In the Talpaz-Borosh solution of the Hall-Norgaard model, the proportional kill (K) is defined by the relation: $K = 1 - e^{-a.X^{\lambda}}$, where X is the pesticide application rate, a and λ are constants. This gives a sigmoid dosage-response curve if $\lambda > 1$ (cf. page 12). However, the optimum application rate is unlikely to be less than that at the point of inflection, since up to this point pesticide application gives increasing returns. The detailed specification of the dosage-response curve for low rates of application is an unnecessary sophistication. In any case, in the example presented by Talpaz and Borosh (op. cit.), concerning the effect of methyl-parathion on tobacco budworm larvae in the cotton field, $\lambda = 1.025$ which is very little different from unity.

However, if we assume as we did previously (on page 20), that the application rate has been pre-selected by the pesticide manufacturer or by the national research agency, then the proportional kill (K) has also been fixed. It remains for the farmer to decide whether or not it is going to be worthwhile to apply the pesticide at that concentration. This is represented by Equation 3.10. The left-hand side of the inequality describes the yield loss offset by pesticide application (derived by subtraction from Equation 3.3, which represents the yield loss realised in spite of pesticide application). The right-hand side describes the cost (fixed plus variable) of pesticide application. The decision model, Equation 3.10, states that it is rational for the farmer to spray his crop if the left-hand side is greater than the right-hand side.

Equation 3.10

$$\frac{\beta.b.P_o.K}{r}.(e^{r.t_h} - e^{r.t_i}) \geq Z + \alpha.X$$

Equation 3.10 is derived directly from the decision model proposed by Hall and Norgaard (1973) and described in Chapter 1. Apart from the correction to the cost function, only two additional assumptions have been made: (1) that the proportional kill achieved by pesticide application does not depend on the time of application, and (2) that it is fixed by the pesticide manufacturer if the pesticide is used according to his instructions. Unfortunately, certain of its assumptions (ones made by Hall and Norgaard) do not bear comparison with a real world decision problem such as the choice of mildew control in spring barley. I try to show in Sections 3.3 through 3.5 how the decision model, Equation 3.10, must be modified in the light of this comparison.

3.3 Defining the pest

The first problem concerns the definition of what constitutes "a pest". This is straightforward enough if the pest is an insect or vertebrate, or even a weed, since individuals are large, separate, and easily counted. It might even be possible (and may be necessary) to distinguish different types of individual (*e.g.* successive instars in an insect population), each with a characteristic growth rate or damage coefficient, and to count these separately. It is not so easy if the pest is a fungus, such as *Erysiphe graminis*, causing a disease, like powdery mildew of barley. The definition of an individual in a microscopic, asexually reproducing, mycelioid organism with a short generation time is indeed a philosophical conundrum.

I propose to use a disease index of the type illustrated by James (1971), and reproduced in Appendix 1, as an indirect measure of the growth of the fungus population. It might be possible to relate the disease index to the dry weight of fungus within the plant body estimated in some other way *e.g.* by biochemical or histochemical assay. Alternatively, the disease index may be treated as though it were a direct measure of some pest population (*i.e.* the disease itself) rather than an estimate of the extent of host-parasite interaction.

In the case of a foliar disease like barley mildew, a unit pest is thus defined to be 1% of the area of a specified leaf affected by the disease. The importance of using a specific leaf (numbering from the top in cereals, flag leaf = 1) should be stressed since the disease index varies from leaf to leaf. However, the size of the disease population may be estimated by sampling the disease index on that leaf on different plants chosen at random throughout the field if the ratio of the disease index on successive leaves along the plant axis is a stable parameter.

This assumption appears to be justified in the case of mildew on barley. King (1972) found that the ratio of the disease index on leaf 2 to that on leaf 1 at GS11.1[1] varied from about 3.5 in

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[1] *GS*: the growth stage of the crop on the Large-Feekes scale, see Large (1954) and *Appendix 1*.

1967 and 1970 to about 5.7 in 1968 and 1969. Also, he was able to demonstrate significant correlation between the disease index on leaf 3 at GS10.5 and that on leaf 2 at GS11.1. The slope of the regression line was approximately constant over several sites in each of two successive years (+0.94 in 1969, +1.18 in 1970). The disease index on leaf 3 will be used here to estimate the size of the pest population.

According to the Hall-Norgaard formulation of the pest population growth function (Equation 1.10 on page 15), the pest population is free to grow exponentially without limit. If the pest population is defined by a disease index, it is free to grow exponentially until it reaches 100% after which the growth rate is constrained to zero. This is comparable to the logistic function used by Van der Plank (1963) to describe the growth of the disease index.

3.4 The pest population growth rate

The second problem associated with the use of Equation 3.10 as a practical guide to action is the implicit assumption that the growth rate of the pest population (r) is constant. This is a necessary assumption if the area under the growth curve is to be calculated by simple integration between the limits defined by the time of pesticide application and harvest time. This is not justified in a real life situation. The problem of defining a variable growth rate for the pest population on a particular variety and at a particular time is discussed in Subsection 3.4.1. In Subsection 3.4.2, the effect of allowing the growth rate to vary on the definition of the damage index (*i.e.* the area under the pest population growth curve) is described. The final Subsection (3.4.3) considers the possibility of defining the kill function in a slightly different way. Taken together with a variable growth rate, this helps to explain the behaviour of the disease index as the time of pesticide application is postponed.

3.4.1 Defining the pest population growth rate

The growth rate of the pest population can be decomposed into two components as shown in Equation 3.11:

Equation 3.11 $r = A.W$

where A = a variety specific activity coefficient *i.e.* specific to a given combination of resistance genes in the host and genes for virulence in the pest. It might also vary with changes in the nutrient status of the host *e.g.* in response to nitrogen application.

W = a weather oscillator, which expresses the variation in the growth rate as a function of all the various external (*i.e.* weather) forces that affect it *e.g.* temperature, atmospheric moisture (relative humidity), light, and wind.

If we assume once more that the particular variety of the host crop has been pre-selected, and that the variety specific activity coefficient is constant over a particular crop season, it only remains to express the growth rate as a function of critical environmental parameters (W). There are two practical procedures to consider: (1) the construction of a table of expected[1] weekly growth rates (or net growth rates over whatever is a convenient interval) on the basis of empirical data obtained from historical field trials, and (2) the development of an analytical model of the growth rate that will generate estimates of successive weekly growth rates on the basis of historical meteorological data.

There are certain advantages associated with the analytical approach to estimation of the growth rate: (1) meteorological data are readily available for a great many sites and going back over a great many years, and (2) meteorological forecasting is much better developed than direct forecasting of the pest population growth rate. This means that estimates of the parameter W can be made on the basis of sample data much more extensive than direct estimates of the growth rate, more suited to local conditions, and incorporating a prediction of the value it will take at a particular site in a particular year.

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[1] expected: see footnote (1) on page 24.

Estimates of the growth rate could also be constructed in this way for regions where the host has never been grown before or where the pest has not previously been noticed.

The construction of an analytical model of the growth rate of the pest population has been nicely done for Helminthosporium maydis on maize by Waggoner, Horsfall and Lukens (1972) with their EPIMAY programme. I want to describe a much simplified model of the growth rate of barley mildew as a function of temperature alone in order to demonstrate how one could be built and how it could be incorporated into the overall decision model.

Many authors (e.g. Rosser, 1969; Gilmour, 1971; Polley and King, 1973) have stressed that the development of barley mildew is responsive to changes in the ambient temperature over the range commonly observed in the field. Figure 3.1 illustrates the cardinal temperatures[1] of Erysiphe graminis in several different situations (see Yarwood et al., 1954, for the references). The typical response appears to be maximum activity at about 20°C, decreasing sharply at higher and lower temperatures. The production of conidia[2] (examined by Ward and Manners, 1974) exhibits a similar form of response.

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[1] cardinal temperatures: the range and optimum for physiological activity.

[2] conidia: asexual (vegetative) spores.

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[1] cardinal temperatures: the range and optimum for physiological activity.

[2] conidia: asexual (vegetative) spores.

Figure 3.1: Cardinal temperatures for *Erysiphe graminis* (after Yarwood et al., 1954)

host	criterion of activity	cardinal temperature (^{o}C)			authority
		min.	optimum	max.	
barley	% germination on glass	0	6	35	a
barley	% germination on glass	5	13	33	b
barley	% germination on glass	5	19	29	c
wheat	% germination on glass	0	10	35	a
wheat	% germination on glass	2	17	35	d
barley	length of germ tubes	5	21	33	b
wheat	length of germ tubes	2	19	30	d
barley	disease development	-	15-20	-	a
barley	disease development	5	18	29	c
wheat	disease development	-2	20	30	d
wheat	disease development	-	15-20	-	e

a = Cherewick, 1944

b = Graf-Marin, 1934

c = Corneli, 1934

d = Pratt, 1943

e = Hammarlund, 1925

N.B. See Yarwood *et al.* (1954) for details of the references to this work.

Pratt (1943) and Last (1963) have traced the spore-to-spore incubation period of *E. graminis* as a function of temperature, as shown in Figure 3.2. Their descriptions of the response are very similar in spite of differences in host (wheat, barley), location (N. America, Europe), time (20 years), and experimental method. By analogy with the procedure suggested by Waggoner (1968), we can approximate this function with the parabola (fitted by eye):

Equation 3.12
$$i = 3 + 5.10^{-2}.(T - 20)^2$$

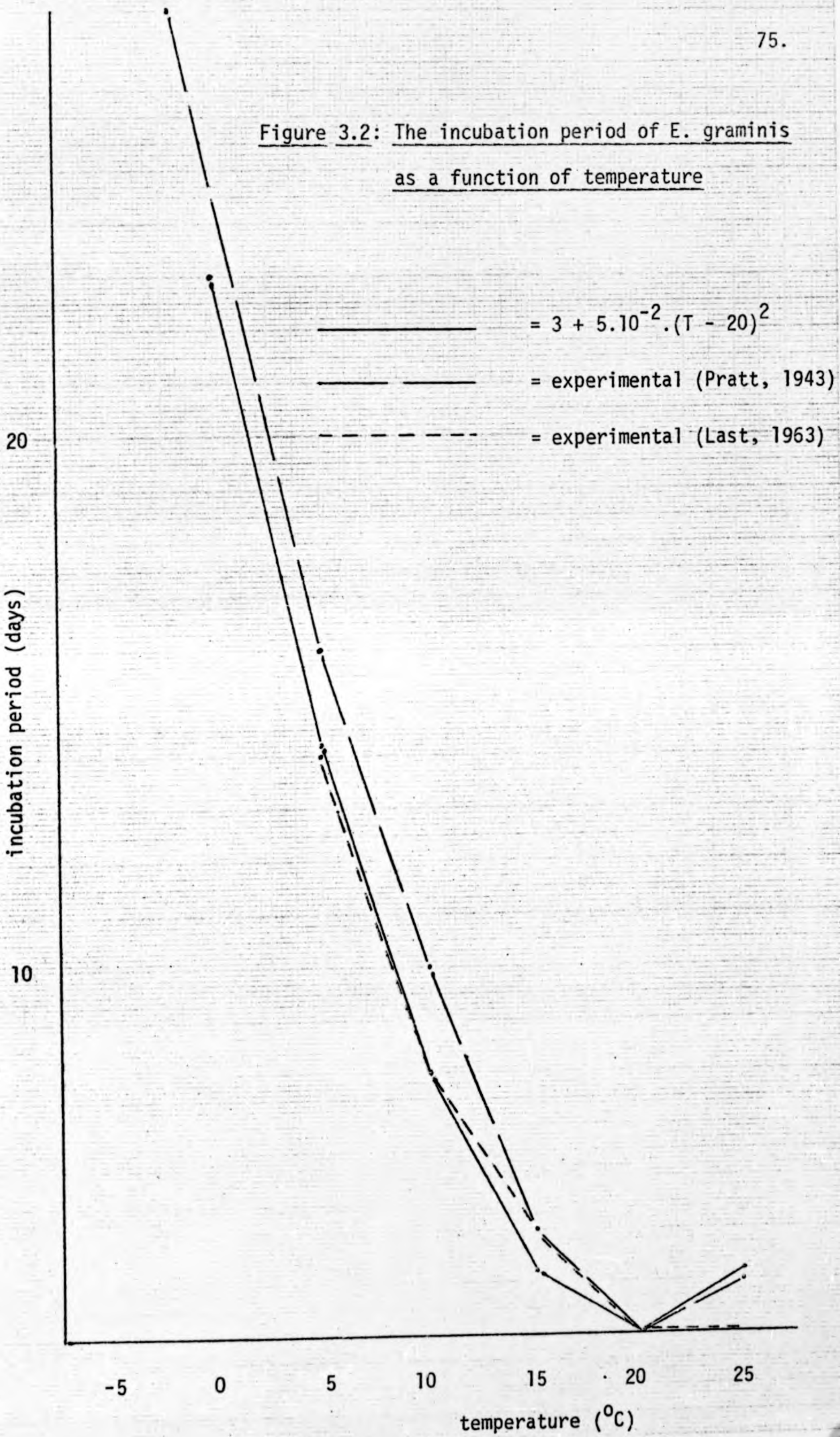
where i = incubation period in days
T = ambient temperature in ^{o}C

i.e. the incubation period is shortest (3 days) when the temperature is kept at 20°C.

Thus we have a simple model of pest development as a function of the ambient temperature:

Equation 3.13
$$P(t) = P_0.e^{\frac{A.t}{3 + 5.10^{-2}.(T - 20)^2}}$$

Figure 3.2: The incubation period of E. graminis as a function of temperature



i.e. the size of the pest population grows faster the closer the temperature is to 20°C[1].

It is important to stress that this is a gross over-simplification of the development of a plant disease as limited by environmental constraints. It is assumed that, under all environmental conditions, the development of the disease is limited solely by the level of the ambient temperature. This is likely to be so only at the extremes of the temperature range. Further, it is assumed that disease development is restricted by the single process

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[1] In the Talpaz-Borosh model (Talpaz and Borosh, 1974), the growth rate of the pest population is assumed to be constant in "physiological time". Physiological time is counted in degree-days by accumulating the excess of the temperature over a minimum threshold temperature depending on the pest. There are severe disadvantages with this approach: (1) it provides a poor model of the pest population growth rate, even as a simple function of temperature, since each temperature-degree is given equal weight (cf. Equation 3.13 in which each temperature-degree is given greater weight the closer it is to 20°C, the physiological optimum for the pest), and (2) the Talpaz-Borosh model assumes that both the pest population growth rate and the rate of crop damage per pest are constant in the same physiological time - this is unlikely to be the case. It seems to me more useful to express all rates in absolute time and to take explicit account of any variation in response to changes in environmental parameters such as temperature.

of incubation within the plant body i.e. that neither the number of conidia produced per lesion, nor the speed and extent of spore transmission, nor any other stage in the asexual developmental cycle, apart from incubation, is at any time a bottle-neck limiting the overall rate of growth of the pest population.

Since the temperature varies continuously, with a circadian periodicity and a trend from spring towards summer, it is necessary to update the growth rate at frequent intervals e.g. every three hours as in EPIMAY.

Using data kindly supplied by the Meteorological Office, weekly growth rates (WGR's) for the six weeks starting May 1, over a ten year period, have been constructed for several sites, and the mean and standard deviation of each weekly growth rate at each site calculated, see Figure 3.3. These estimates of successive weekly growth rates are based on Equation 3.13 (for A = 0.5), updated every six hours.

It is interesting to note that, if the weekly growth rates for the six weeks starting May 1, 1967, are multiplied together for a site in each of the main administrative regions of the Ministry of Agriculture, Fisheries and Food in England, then the products rank these regions in exactly the same order as the average disease index found in disease surveys described by King (1972, 1973), as illustrated

Figure 3.3: Weekly growth rates based on dry bulb temperatures accumulated according to Equation 3.13 every six hours (A = 0.5)

location 244: Acklington (North Region)

year	week no. (starting May 1)					
	1	2	3	4	5	6
1963	1.43	1.59	1.51	1.57	1.64	1.74
1964	1.66	1.79	1.72	1.73	1.57	2.08
1965	1.47	1.78	1.53	1.58	1.56	1.65
1966	1.52	1.52	1.61	1.56	1.87	1.81
1967	1.33	1.51	1.42	1.55	1.75	1.69
1968	1.35	1.38	1.37	1.46	1.73	1.85
1969	1.32	1.69	1.42	1.51	1.54	1.70
1970	1.57	1.39	1.62	1.89	1.79	1.94
1971	1.48	1.84	1.61	1.56	1.62	1.50
1972	1.47	1.46	1.46	1.73	1.58	1.61
mean	1.46	1.59	1.53	1.61	1.66	1.76
s.d.	0.11	0.17	0.11	0.13	0.11	0.17

location 776: Gatwick (South East Region)

1963	1.52	1.60	1.64	1.73	2.13	2.24
1964	1.73	1.88	1.95	2.20	1.99	2.22
1965	1.66	1.92	1.74	1.76	1.69	1.92
1966	1.71	1.59	1.88	1.73	1.95	2.34
1967	1.43	1.96	1.59	1.75	1.98	2.06
1968	1.50	1.57	1.53	1.84	2.12	1.99
1969	1.73	1.92	1.57	1.87	1.84	2.01
1970	2.05	1.89	1.82	1.99	2.21	2.36
1971	1.73	2.03	1.82	1.67	2.03	1.76
1972	1.75	1.53	1.61	1.74	1.65	1.73
mean	1.68	1.79	1.72	1.83	1.96	2.06
s.d.	0.17	0.19	0.15	0.16	0.19	0.22

in Figure 3.4. This is equivalent to a Spearman rank correlation coefficient[1] of +1.0. The probability of achieving this precise arrangement by random assortment of seven items is 1 in 7 factorial (= 7.6.5.4.3.2.1) i.e. 5,040 to 1 against. Unfortunately, this degree of correlation is not maintained in other years for which data are available (1968 through 1973, except 1971).

There are several possible reasons for this: (1) the value of the aggregate parameter A will vary between regions since susceptible varieties are not likely to be grown in areas liable to the disease (e.g. Golden Promise is widely grown in Scotland, but not in England), (2) the average time when the disease enters the crop will vary from region to region (e.g. because of differences in winter severity, or the availability of susceptible host tissue on which to over-winter), (3) the site at which the weather measurements were taken may not be representative of the region as a whole or of those areas where the crop is grown, and (4) the model of the growth rate is insufficient.

---

[1] Spearman rank correlation coefficient: $\rho = 1 - \frac{3.Sd}{n^2-1}$

where Sd is the sum of the differences in rank, and n is the total number of individuals (see Spearman, 1904).

Figure 3.4: Regional disease levels of barley mildew, 1967

region[1]	disease index[2]	site[3] (region)	disease index[4]
North	6.8	244 (North)	13.0
Yorks & Lancs	8.7	318 (Yorks & Lancs)	20.9
East Midlands	11.7	354 (East Midlands)	22.2
West Midlands	15.6	414 (West Midlands)	23.7
South West	18.4	839 (South West)	30.8
East	20.4	495 (East)	31.1
South East	27.1	776 (South East)	31.7

[1] Ministry of Agriculture, Fisheries and Food Administrative Region

[2] average percentage lamina area affected on the second leaf, after King (1972)

[3] 244 = Acklington; 318 = Blackpool; 354 = Watnall; 414 = Shawbury; 839 = Exeter; 495 = Coltishall; 776 = Gatwick

[4] the disease index calculated for the six week period starting May 1 using the model of the growth rate, Equation 3.13, to accumulate the dry bulb temperature every six hours

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3.4.2 The damage index

The reduction in the damage index (ΔG) achieved as a result of pesticide application must be re-defined if the pest population growth rate is allowed to vary. It may be represented by the sum of the areas of successive trapezia[1] between the growth curves of the treated and untreated populations:

Equation 3.14
$$\Delta G = \sum_{t=t_i}^{t=t_e-1} \tfrac{1}{2}.K.P(t).t.(e^{r_t.t} + 1)$$

where $P(t)$ = size of the pest population at the beginning of each time interval, in the absence of control

K = proportional kill achieved by pesticide application

r_t = growth rate of the pest population over the time interval t

t_i = time of spraying

t_e = end-point for effective crop damage, not necessarily corresponding to t_h (harvest time) in the original Hall-Norgaard model

t = an increment of time *e.g.* a week

This is illustrated in Figure 3.5. The summation ends at time t_e-1 since the calculation of the area of the trapezium

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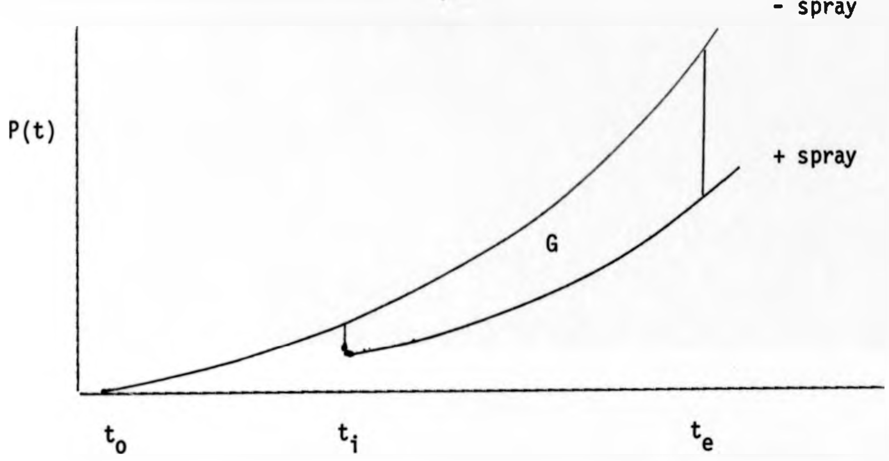
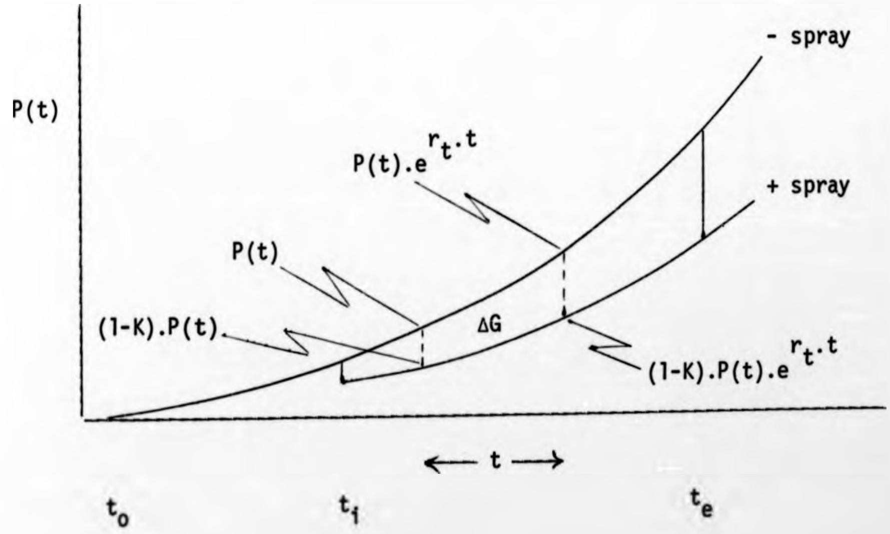
[1] area of a trapezium: half the sum of the parallel sides times the perpendicular distance between them.

Figure 3.5: The damage index

a. The area "G" represents the reduction in the damage index achieved by pesticide application at time "t_i".



b. The area "G" is calculated by the summation of the areas of successive trapezia such as "ΔG".



between the two growth curves is based on the size of the pest population at the beginning of each time interval. The formulation of the damage index in terms of pest-days is identical to the procedure adopted by Norton and Evans (1974) in their study of frog-hopper control in sugar-cane.

3.4.3 An alternative model of the kill function

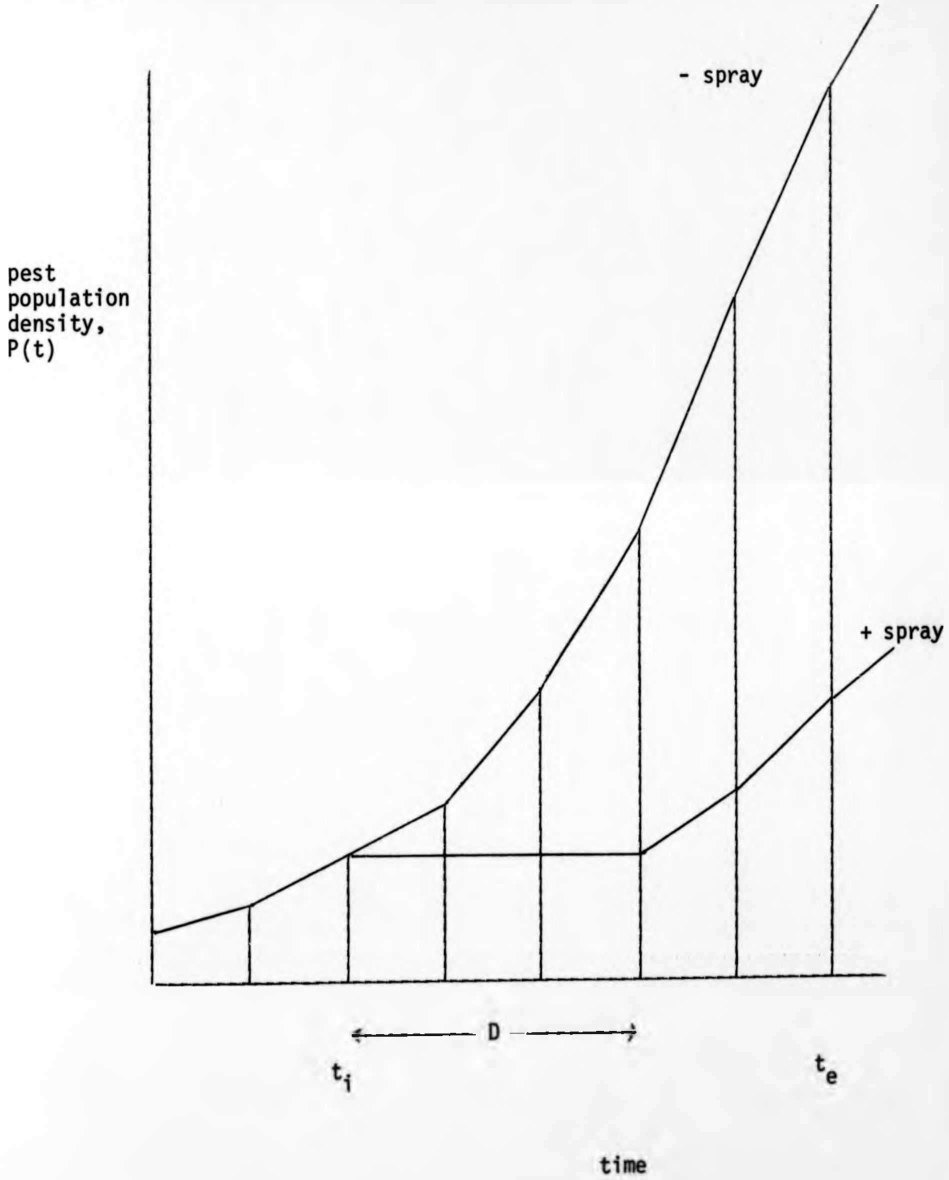
The admission of a variable growth rate into the calculus has a further implication for the extent of the reduction in the disease index as a function of the time of pesticide application. Figure 3.6 illustrates an alternative model of the kill function according to which no pests are actually killed but the growth rate of the entire pest population is constrained to zero for a finite period D, after which the constraint is instantaneously removed and the pest population free to grow at its natural rate (r). If $t > t_i+D$, and the natural rate of growth is constant, then the size of the pest population after spraying, P(t), is independent of the time of pesticide application (t_i) just as before:

Equation 3.15 $$P(t) = P_o.e^{r.t_i}.e^{r.(t-t_i-D)}$$

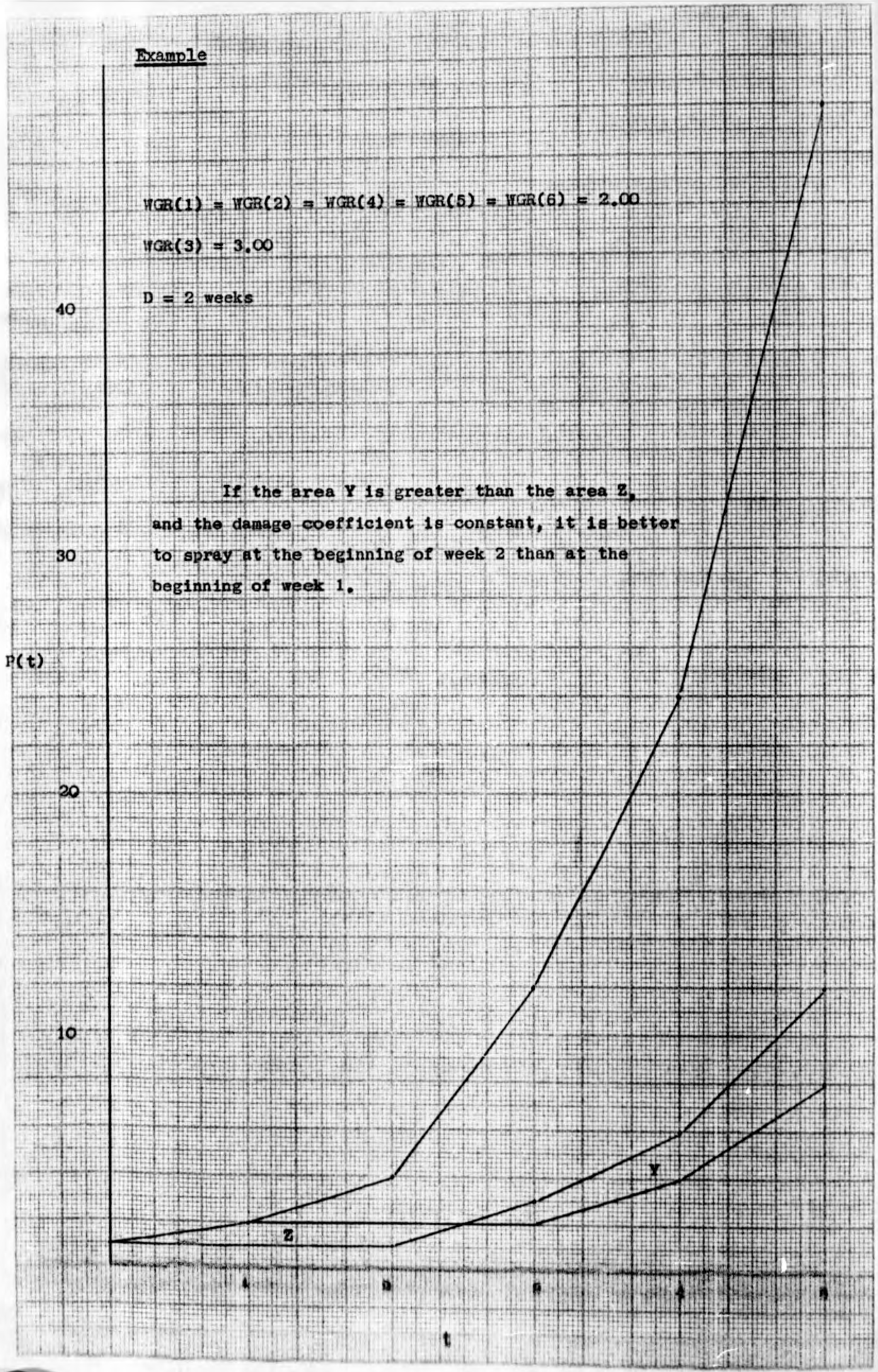
$$= P_o.e^{r.(t-D)} \qquad \text{for } t > t_i+D$$

Under these circumstances, we can thus define a notional kill directly

Figure 3.6: An alternative model of the kill function



Example

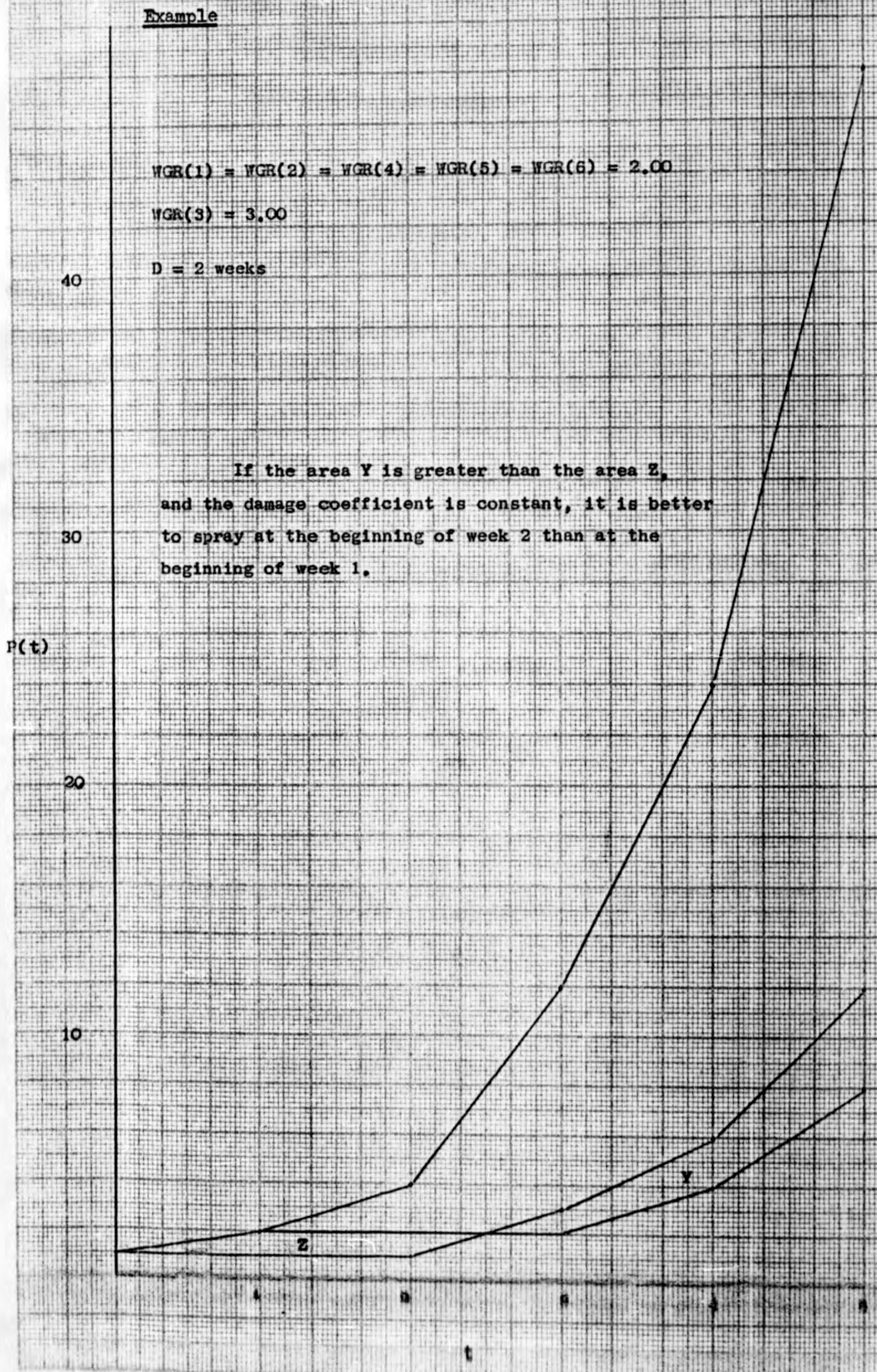


WGR(1) = WGR(2) = WGR(4) = WGR(5) = WGR(6) = 2.00

WGR(3) = 3.00

D = 2 weeks

If the area Y is greater than the area Z, and the damage coefficient is constant, it is better to spray at the beginning of week 2 than at the beginning of week 1.



Example

WGR(1) = WGR(2) = WGR(4) = WGR(5) = WGR(6) = 2.00

WGR(3) = 3.00

D = 2 weeks

If the area Y is greater than the area Z, and the damage coefficient is constant, it is better to spray at the beginning of week 2 than at the beginning of week 1.

analogous to the actual kill in the original formulation.

If the natural rate of growth of the pest population increases continuously (and $D < t-t_0$), then the size of the pest population at time t, as a function of the time of pesticide application, first decreases (from $t_i = t_0$ up to $t_i = t-D$), reaches a turning point at $t_i = t-D$, then increases as far as $t_i = t$. Also, since the shape of the area between the pest population growth curves with and without pesticide treatment changes as t_i is postponed, the reduction in the damage index is not necessarily greatest when the pesticide is applied as early as possible (*i.e.* when $t_i = t_0$).

In the Hall-Norgaard model, the time of pesticide application was a decision variable because the effective kill was a function of the size of the pest population. If the proportional kill is constant (as assumed earlier in this chapter), then the pesticide should be applied as soon as possible in order to maximise the reduction in the damage index. However, according to this alternative model of the kill function, the time of pesticide application may still be a decision variable even though the proportional kill is assumed to be independent of the size of the pest population (since the notional proportional kill remains constant if the growth rate does, as assumed by Hall and Norgaard), but this depends on the way in which the pesticide works and on how the growth rate of the pest population varies over time[1].

The data in Figure 3.7 (taken from BASF, 1972) demonstrate the superficial resemblance between the behaviour of barley mildew and that predicted by the alternative model of the kill function. The disease index read on June 21, expressed as a function of the time of spraying, first decreases (from 5.5 when the spray is applied on May 5), reaches a minimum (0.5 when the spray is applied on May 31), then increases again (reaching 13.9 for a crop not yet sprayed). Thus, tne value of "D" is about 3 weeks.

It is also of interest to note that the increase in the yield of the crop is not greatest when the spray is applied as soon as possible after the disease enters the crop (if we assume that the disease was present on May 10 even though it was not noticed until May 14), but rather in response to a spray put on either one week (on May 17) or two weeks (May 24) later. This is readily understandable if the pesticide works according to the alternative model of the kill function and the rate of growth of the pest population was temporarily

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[1] An interior solution of the Hall-Norgaard Model has been described by Borosh and Talpaz (1974). The alternative model of the kill function described here provides a physical explanation of this effect.

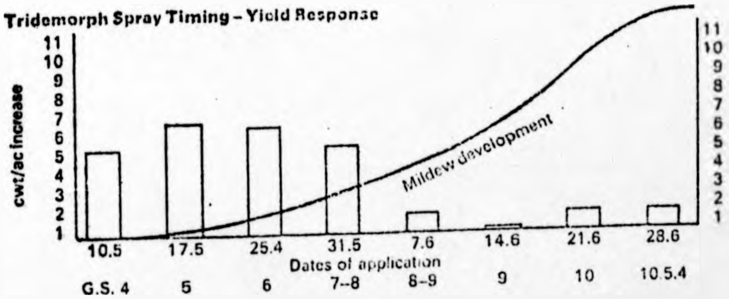
Figure 3.7: The effect of spray timing on the yield response of barley affected with powdery mildew (after BASF, 1972)

Spray Timing Trial – Northants College of Agriculture
Variety – Sultan

Date of Spraying	Growth Stage	Mildew	Yield cwt/ac	Increase	Mildew Assessment 21.6.71 mean % cover 3rd leaf
10.5.71 10.5.71	4	No mildew: first mildew 14th/15th	48.6	+5.3	5.5
17.5.71	5	Very rapid mildew build up	49.2	+5.9	3.4
24.5.71	6		49.2	+5.9	2.0
31.5.71	7–8	Damper cooler weather with some heavy rain. Rate of increase slowed but severe infection present	48.0	+4.7	0.5
7.6.71	8–9		44.1	+0.8	4.9
14.6.71	9		43.3	+0.0	8.3
21.6.71	10		44.1	+0.8	12.4*
28.6.71	10.5.4	Warmer conditions and rapid spread again	44.1	+0.8	13.5*
17.5.71 + 14.6.71	5+9		51.9	+8.6	1.4
Control	—	—	43.3	—	11.4

* not yet sprayed

4.



increased at some time after the end of the first week (cf. the weekly growth rates illustrated in Figure 3.3 on page 78).

However, in the absence of detailed epiphytological evidence in favour of this formulation, the simpler (and more general) model will be adopted here for the sake of convenience of exposition, and the level of kill achieved by pesticide application in the field estimated ex post[1] from the proportional reduction in the damage index in experimental trials.

3.5 The damage coefficient

The final problem associated with the practical use of Equation 3.10 as a decision model lies in the definition of the damage coefficient (b), the rate of loss of yield per pest, which relates the damage index (i.e. the area under the growth curve) to the total yield loss. In those cases where the pest feeds directly on the crop (e.g. insect pests of stored products), the expression of "b" in absolute terms may be justified. However, in the case of a leaf disease like barley mildew, the loss of yield is indirect and a function of the potential yield. It is thus necessary to re-define "b" as "B", the rate of per cent loss of yield per pest. This is comparable to the Large and

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[1] ex post: the value which some variable actually takes in the event cf. the ex ante value, which is the expected or intended value.

Doling (1962) formula relating the percentage loss of yield in barley as a result of infection by the powdery mildew fungus to 2.7 times the square root of the average disease index on the top four leaves at GS10.5. However, their use of a one-dimensional damage index (in fact, a spurious compound disease index) is misleading and of little use when the time of pesticide application is variable. The analysis of such a situation requires at least a two-dimensional damage index (*i.e.* pest-days), and quite possibly a complex sub-model of the parameter B if the rate of percentage loss of yield is not effectively constant over the relevant stages in host crop development. I shall make the simplest assumption, that the percentage yield loss is directly proportional to the area under the pest population growth curve *i.e.* that B is constant.

It is of some interest that, if damage indices are calculated from the weekly growth rates for the six week period starting May 1 (themselves calculated according to Equation 3.13 and illustrated in Figure 3.3 on page 78), and the relation between the accumulated damage indices and disease indices (represented by the product of the successive weekly growth rates) investigated using regression analysis[1]

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[1] *e.g.* at site 244 (Acklington), $Y = 27.2 \cdot X^{0.73}$ (index of determination = 0.907), where Y is the damage index and X is the disease index. The regression analysis was performed using the CURFT$*** package available on the time-sharing system.

then the damage index is given approximately by a constant times the disease index raised to the power of 0.7. This has a striking resemblance to the Large and Doling (*op. cit.*) formula in which the percentage yield loss is given by a constant times some disease index (see page 89) raised to the power of 0.5, and is consistent with a direct proportional relationship between the percentage yield loss and the damage index.

3.6 The decision model

The preliminary decision model based directly on that presented by Hall and Norgaard, *Equation 3.10*, can thus be replaced by the inequality, *Equation 3.16*, which expresses the same notion: that it is rational for the farmer to spray his crop if the left-hand side is greater than the right-hand side.

Equation 3.16

$$\frac{\beta.B.N}{100}.\left[\sum_{t=t_i}^{t=t_e-1} \tfrac{1}{2}.K.P(t).t.(e^{r_t.t} + 1)\right] \geq Z + \alpha.X$$

3.7 Calibration of the model

The data in *Figure 3.7* on page 87 may be used to illustrate how the decision model, *Equation 3.16*, can be calibrated. The disease index increased from a (notional) 1.0 on May 15 to 11.4 by

June 21 (37 days later). The average growth rate, which must be used in the absence of detailed epiphytological data concerning the levels of successive weekly growth rates, thus equals $\ln(11.4)/37 = 0.066 \text{ day}^{-1}$.

The end-point for effective crop damage (t_e) is taken to be at GS9 ($t_e = 28$ days) since pesticide application after this stage produces only a small residual response. It is of particular interest that the end-point occurs before the grain has filled out, whereas the yield component most affected by mildew infection is grain size (i.e. the 1000 grain weight) not the number of grains. This implies that mildew affects the capacity of the grain to fill out rather than directly influencing the actual process of filling out after GS10.

The effective kill (K) achieved by pesticide application may be estimated indirectly by the proportional reduction in the damage index:

Equation 3.17
$$K = \frac{Y_1 - Y}{Y_s - Y}$$

where K = proportional kill achieved by pesticide application

Y = crop yield (cwt/acre) if no spray applied

Y_1 = crop yield if a single spray is applied as soon as the disease enters the crop (e.g. when the disease index = 1.0)

Y_s = crop yield if the disease is completely controlled by a regular spray programme

According to the data given in Figure 3.7, K = (49.2 - 43.3)/(51.9 - 43.3) = 0.7 approx..

The damage coefficient, B, may be estimated from Equation 3.18. This is equivalent to Equation 3.3 (page 62), solved for "b" given data about the cases K = 1 (complete control) and K = 0 (no control) and expressed as a percentage of the potential yield.

Equation 3.18
$$B = \frac{r.(Y_s - Y)}{P_o.(e^{r.t_e} - 1)} . \frac{100}{Y_s}$$

$$\text{Accordingly, } B = 0.066 \,.\, (51.9 - 43.3) \,.\, 100/\{(e^{0.066 \,.\, 28} - 1) \,.\, 51.9\}$$
$$= 0.21\ \%.\text{pest}^{-1}.\text{day}^{-1}$$

The graph in Figure 3.8 illustrates the comparison between the calculated yield response to pesticide application in successive weeks and the response actually realised in this experiment. The exponential decline in the yield response (from a level corresponding to a fraction of the potential response) as the time of application is postponed is observed in the experimental data as predicted by the model, which provides an explanation of this effect. This result appears

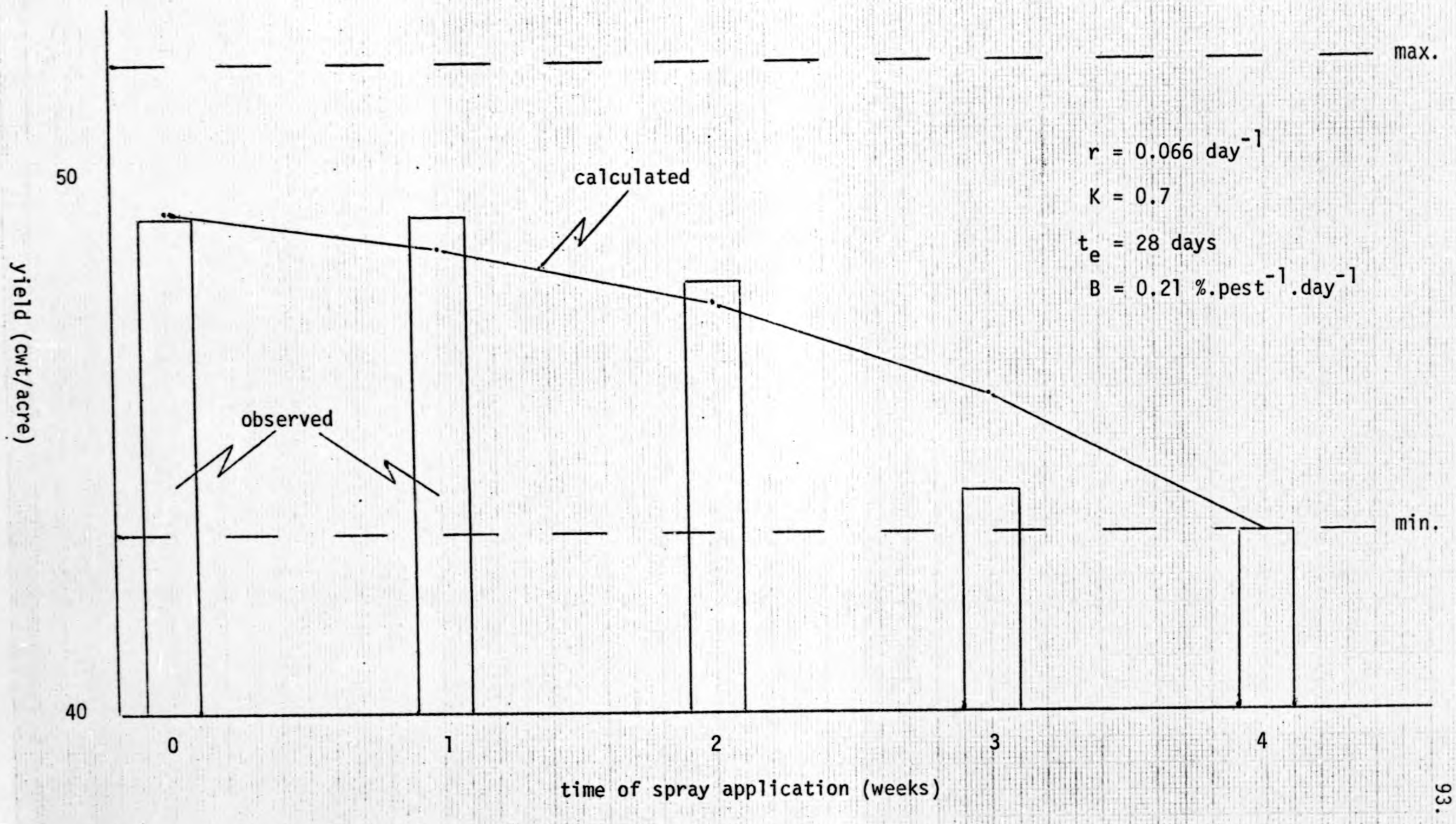

Figure 3.8: The effect of spray timing on the yield response, a comparison of theoretical and observed results

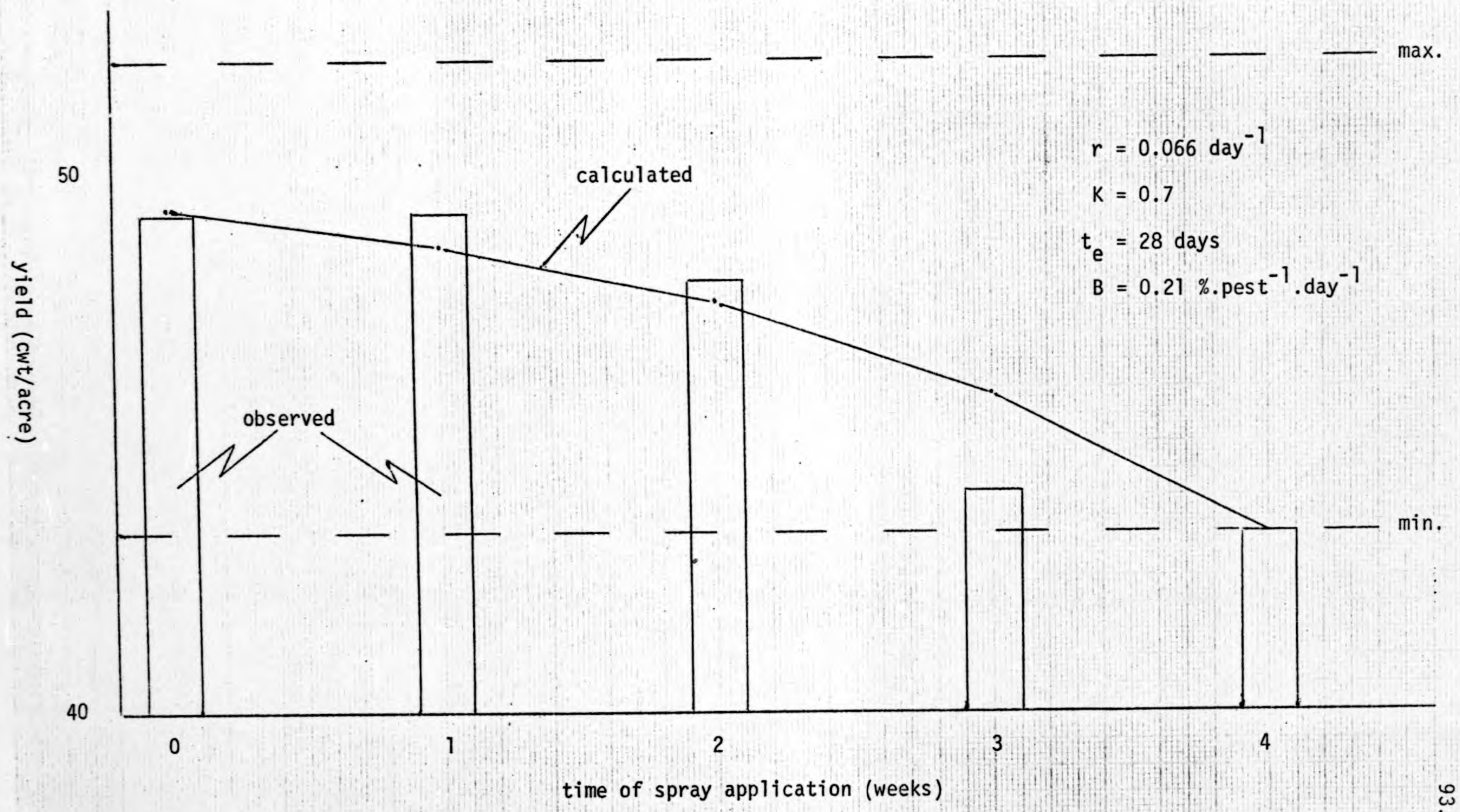

Figure 3.8: The effect of spray timing on the yield response, a comparison of theoretical and observed results

to be a general one in the barley/powdery mildew system (similar results were obtained by Evans and Hawkins, 1971), but insufficient data are available in the published literature to provide good estimates of the model parameters or even to indicate their stability.

The variety specific component (A) of the pest population growth rate may be determined for each variety in relation to a varietal standard if they are grown at the same time and under the same conditions since the weather effect (W, see Equation 3.11 on page 70) will then be the same for both:

Equation 3.19

$$P_1(t) = P_{1,0}.e^{A_1.W.t}$$

$$P_2(t) = P_{2,0}.e^{A_2.W.t}$$

therefore $$A_2 = A_1.\log\{P_2(t)\}/\log\{P_1(t)\}$$

where A_1 = variety specific activity coefficient for a standard variety e.g. Proctor

$P_{1,0} = P_{2,0}$ = the initial pest population density on each variety

The expected effect of weather on the growth rate may be estimated either by a study of historical growth rates on a particular variety or by the use of an analytical model of the growth rate such as that described in Section 3.4.1. The growth rate may be adjusted to fit any other variety by use of Equation 3.19, and a vector of expected weekly growth rates constructed such as those illustrated in Figure 3.3 on page 78.

It is assumed that the farmer can form an estimate both of the crop yield in the absence of the pest (N) and of the final sale price of the crop (β) on the basis of his own experience. The use of a subjective model of host crop development is necessary since we have no realistic analytical model either of crop growth on a particular farm (to provide an estimate of "N") or of that on the national farm (to the extent that aggregate supply is a partial determinant of the sale price). The use of an analytical model of the response to pesticide application in conjunction with a subjective model of the potential yield may be justified both on the basis of expediency and to the extent that the micro-environment of the pest (in the case of mildew in barley, the host epidermis) is much more stable than that of the host, thus reducing the number of system parameters required to describe the growth of the pest population to those environmental forces not regulated by the host *e.g.* temperature.

The fixed (Z) and variable ($\alpha.X$) costs of pesticide application can be presumed to be known with certainty prior to the decision.

3.8 Uncertainty

Just as in Chapter 2 (Section 2.1, page 29) where the choice of variety was considered, so the choice of whether or not to apply a pesticide in response to the presence of the pest in the crop must be presumed to be made in such a way that the farmer maximises his subjective expected utility. Since the pay-off is uncertain, the utility he attaches to it will depend both on its expected value and on its variance. The higher the variance (*i.e.* the more risky the project), the greater must be the expected monetary pay-off to compensate for this. The solution to the left-hand side of the decision model, Equation 3.16 on page 90, can only be represented by a probability distribution for the pay-off since certain of the parameters defining it are stochastic variables. Thus the decision model must be solved both for the expected value of the pay-off and for its variance.

The potential yield of the crop (N) and the sale price (β) have already been portrayed as subjective estimates in Section 3.7 when discussing the calibration of the model. To take account of the uncertainty associated with the precise values of these parameters, it may be considered sufficient if the farmer can identify three points in each probability distribution: the minimum, the maximum, and the expected value.

It is not quite so obvious perhaps that some of the other model parameters must also be described by subjective *a priori* probability distributions rather than considered as constants adequately described by historical ("objective") estimates. This applies both to the variety specific activity coefficient (A) and to the proportional kill (K).

A change in the value of a variety specific activity coefficient is exemplified by the history of the barley variety *Impala* described by Wolfe (1968). *Impala* has two genes for resistance, Mlg and Mla6. Its use increased from zero to 15% of the total (England and Wales) spring barley acreage between the time it was introduced in the early 1960's and 1967. Almost simultaneously with the diffusion of this varietal innovation through the host population, the proportion of physiologic races of the powdery mildew fungus capable of attacking *Impala* (and therefore possessing the virulence genes Vg and Va6 in accordance with the gene-for-gene hypothesis) increased from zero in 1964 to 75% in 1967 of all the mildew samples examined by Wolfe. Thus, in the space of only three years, the activity of the fungus population on *Impala* had increased dramatically. The sales of *Impala* seed in 1967 amounted to 35,399 tons, second only to the sales of *Zephyr* (Anon., 1967). By 1969/70, sales had shrunk to under 2,000 tons, and in 1971/2 it was the 33rd most popular variety (Anon., 1972; Home-grown Cereals Authority, 1972).

Thus the value of the variety specific activity coefficient should properly be represented by a subjective probability distribution skewed towards higher values than those realised in historical field trials if the resistance of the variety has a narrow genetic base (cf. page 51). This would incorporate the farmer's anticipation of the development of new races of the pest and the partial breakdown of genetic resistance in the crop.

Similarly, the proportional kill (K) should also be represented by a subjective probability distribution skewed towards lower values than experience might suggest if the farmer anticipates a loss of pesticidal potency as the pest population adapts to the presence of the pesticide in the environment.

I have already considered the effect of variable weather on the growth rate of the pest population in constructing a table of expected weekly growth rates as in Figure 3.3 on page 78. The analysis of historical data would provide an "objective" probability distribution of the parameter W, described (for a given value of "A") by the mean and variance of successive weekly growth rates. The straightforward use of historical probability distributions in this way implies that possible weather sets are considered to be distributed at random amongst successive years.

3.9 /SPRAY/

The various probability distributions identified in Section 3.8 can be incorporated into the decision model, Equation 3.16, using a Monte Carlo routine. In this, a particular value is chosen at random from each probability distribution and the model solved based on these values. This is repeated a number of times, each time selecting a fresh value from each probability distribution. The number of times a particular value is selected depends on the probability density assigned to it by the probability distribution read in with the model. The output thus identifies alternative pay-offs according to their probability of being realised. The arithmetic mean of successive outputs is the expected pay-off, and the variance of these about the mean is the variance of the expected pay-off. This procedure has been described as a technique for risk analysis by Hertz (1964).

The decision model, Equation 3.16, has been re-written as a Monte Carlo simulation model, /SPRAY/, to take account of the uncertainty associated with some of the model parameters described in the last section. /SPRAY/ is written in the Fortran-based simulation language SIMON, as developed at Imperial College and Stirling University for use on the Elliott 4100 series computer. It is illustrated in Appendix 3.

Wheeling damage to a barley crop because of late spraying has been incorporated into /SPRAY/ on the basis of unpublished data from Gleadthorpe Experimental Husbandry Farm (1971). As written, it is a stepped function depending on the growth stage of the crop at the time of spraying. If the pesticide is to be applied at the same time as another routine spray, then the incremental track damage, like the other fixed costs of pesticide application, is zero.

/SPRAY/ calculates two indices of the financial pay-off resulting from the use of a fungicidal spray against barley powdery mildew: (1) the per cent return per annum on the cost of treatment[1], and (2) the potential benefit-cost ratio[2]. The use of a rate of return enables direct comparison of the investment in pest controls with the farmer's cost of capital, such as the cost of a bank overdraft. However, since the project life is short and the variance of the return is large, it may be more convenient to express

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[1] per cent return per annum: $\left[\frac{\text{value of yield increase}}{\text{cost of treatment}} - 1\right] \cdot \frac{100}{t}$

where t = time after expenditure on pest controls to receipt of crop revenue (as a fraction of a year). The internal rate of return criterion has also been used by De Janvry (1972) in his study of the comparable problem of optimal fertilisation levels on maize and wheat in Argentina.

[2] benefit-cost ratio: $\frac{\text{value of yield increase}}{\text{cost of treatment}}$

the return as a benefit-cost ratio in the conventional way, ignoring the rate at which it is accumulated.

/SPRAY/ must still be considered a preliminary decision model until the functional relationships which it comprises have been established by experiment. Also, it does not take into account either serial correlation (*e.g.* in successive weekly growth rates of the pest population[1]) or inter-parametric correlation (*e.g.* between the growth rate of the pest population and the yield of the crop in the absence of pest infestation). It does demonstrate that an analytical approach to the economic decision problem relating to pesticide use is feasible.

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[1] *e.g.* regression analysis of the calculated weekly growth rates in any week against those the preceding week, using the data in Figure 3.3 on page 78 for location 244 (Acklington), generates the following vector of correlation coefficients: week 2 *vs* 1, 0.23; week 3 *vs* 2, 0.44; week 4 *vs* 3, 0.57; week 5 *vs* 4, 0.05; week 6 *vs* 5, 0.27.

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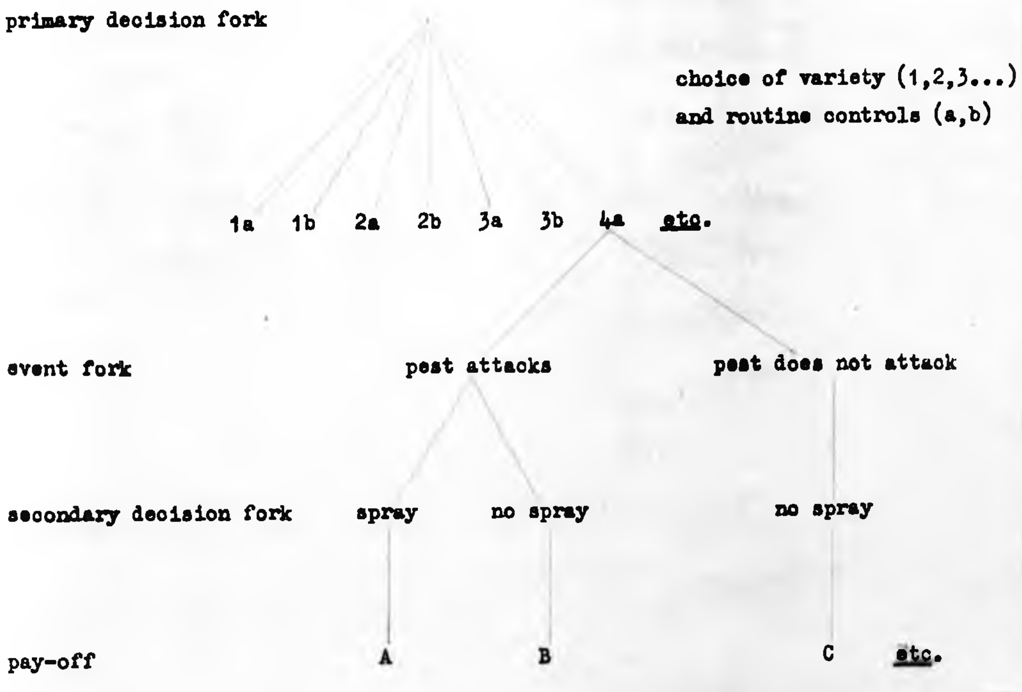
[1] *e.g.* regression analysis of the calculated weekly growth rates in any week against those the preceding week, using the data in *Figure 3.3* on page 78 for location 244 (Acklington), generates the following vector of correlation coefficients: week 2 *vs* 1, 0.23; week 3 *vs* 2, 0.44; week 4 *vs* 3, 0.57; week 5 *vs* 4, 0.05; week 6 *vs* 5, 0.27.

addendum, page 101

The decision problems considered in *Chapters 2* and *3* are of course connected. This can be illustrated by means of a decision tree as shown below. The primary decision fork (discussed in *Chapter 2*) involves the choice of variety (1,2,3...) both with and without a routine pesticide treatment such as a fungicide seed dressing (a = treatment applied, b = no treatment). The primary event fork is whether or not the pest attacks the growing crop that year. If a pest attack occurs, the farmer may (or may not) decide to spray his crop against the pest (the secondary decision fork, discussed in *Chapter 3*). Each action/state of nature/action sequence is shown associated with a characteristic pay-off (A,B,C...). If the alternative pay-offs can be specified, and if a probability distribution can be attached to the alternative states of nature at the event fork, then an expected pay-off and its variance could be calculated for each action/state of nature/action sequence. In this way, the conditional problem of whether or not to spray if the pest enters the crop might be considered simultaneously with the unconditional choice of variety and other routine measures. However, as stressed in *Chapter 3*, it is very difficult at present to specify the pay-off from spraying even if the time of pest attack is known; it is even more difficult if it is not. The event fork - pest attacks, pest does not attack - is a major simplification and it seems preferable to me to keep the two decision problems distinct until more is known about the distribution of the pay-off as a function of the time of pest attack.



Chapter 4

Pest control in aggregate

The problem of the economics of pest control at an aggregated level, at the level of a geographical region or the nation state, is much more complex than that of the farm-level decision considered in previous chapters. This is so whether controls are imposed blanket-fashion by a central authority, such as a legislative ban on the cultivation of a particularly susceptible crop variety or of an alternative host that may harbour the pest, or whether the mechanism of control is merely provided by a central agency, such as a pesticide manufacturer, with all decisions concerning its implementation being de-centralised and adapted to local conditions.

In Section 4.1, the distinction between investment appraisal and social cost-benefit analysis is considered. A simple economic decision model for investment appraisal by a pesticide manufacturer is presented in Section 4.2. A model for the estimation of the social return to any national investment in agricultural pest control is described in Section 4.3, which includes a discussion of some of the problems that may be met if one tries to solve the model for a particular case. The problem of winter barley, which provides a "green bridge" between successive spring crops helping pests to survive the winter, is considered in the final section.

4.1 Investment appraisal and social cost-benefit analysis

Bradbury and Loasby (1974) have distinguished between investment appraisal and social cost-benefit analysis (CBA) in relation to pest control measures. The distinction is an important one and deserves reiteration.

Investment appraisal (see *e.g.* Merrett and Sykes, 1973) is concerned exclusively with the net cash flow at a single investment locus, whether farm firm or pesticide manufacturer. The economic decision models discussed in *Chapters 2* and *3* are techniques for investment appraisal at the level of the individual farm firm. Investment appraisal by the pesticide manufacturer is considered in this chapter together with CBA because both are multi-period decision problems. This contrasts with the single-period models developed for use at farm level. A rider of this is that the decision problems considered in this chapter only need to be solved very infrequently, whereas the farm level allocation problems are solved every year on every farm.

Any effects resulting from the decision that are not expected by the decision maker either to augment or to restrict the net cash flow through the investment locus over which he has control, and for which he has responsibility, will not be taken into account by investment appraisal. Such effects might include the contamination of the environment with pesticide residues (upsetting the balance of nature in an arbitrary and unspecified way), or the destruction of non-target species of organism which may or may not be of economic significance at other investment loci (people, farm animals, and pollinating insects are, some birds or wild flowers might not be). However, if damage at other investment loci can be proved (and fault allocated), the law may force the decision maker to internalise any such costs in his investment appraisal. In practice, the possibility of substantial external diseconomies[1] is restricted by the legal requirements for the registration of new agro-chemicals. Any uncorrected external diseconomies would be included together with any external economies as costs and benefits respectively in social cost-benefit analysis, which tries to identify and measure the gain or loss in economic welfare by society as a whole (in a given geographical region) if the project is undertaken. Thus, investment appraisal and CBA differ in the form of the function to be maximised.

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[1] *externalities*: production externalities exist when the production activities of one firm directly affect those of another. Private investment appraisal, which determines the size of the externality-generating activity, does not take account either of external economies (*i.e.* benefits received by somebody else) or external diseconomies (*i.e.* costs borne by someone else).

addendum, footnote, page 104

The direct nature of technological externalities should be stressed: they do not operate merely through changes in the factor or product markets.

Investment appraisal and CBA differ further in the value they attach to the same physical transformations. This has two aspects: (1) the evaluation of costs, and (2) the treatment of transfer payments[1]. Costs are a measure of what has to be given up in order to achieve some objective: in economics, cost is reckoned by the value of alternatives foregone *i.e.* the opportunity cost. This applies both to raw materials and to manpower *e.g.* a pesticide manufacturer will have to pay the institutional wage rate to chemists with experience in pesticide research even though this might greatly exaggerate their value in any other capacity (because of their degree of specialisation). Competition between pesticide manufacturers for a scarce factor of production, such as a pesticide chemist, may force the total payments to it above its transfer earnings[2]. The factor will receive an economic rent for its services. In the case of chemists, this will be a "quasi-rent" arising because the system is not in long-run equilibrium (in the absence of institutional forces restricting the

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[1] *transfer payments*: payments which are not made in return for some productive service but which redistribute income *e.g.* pensions, social security payments, and taxes.

[2] *transfer earnings*: the earnings of a factor of production which are just sufficient to keep it in its present employment. Any excess of actual earnings over transfer earnings is known as "economic rent".

downward movement in the real earnings of pesticide chemists, the quasi-rent element will disappear as more are trained).

The treatment of transfer payments is analogous to that of costs. In investment appraisal, tax is indeed considered to be a cost and is treated as a negative cash flow. In CBA, tax is a transfer payment of part of the net benefit from the individual firm to the state. This applies both to corporation tax made on company profits (*i.e.* direct taxes) and to indirect taxes such as import tariffs.

Investment appraisal and CBA are alike in their use of discounting[1]. Both are multi-period decision problems (although unlike those discussed in Section 1.3 on page 21, only a single decision has to be made): costs are borne and benefits received at various times in the future. Since money can be invested in other projects and earn interest, the value of the net benefit will be that much greater if it is received sooner rather than later. It will also be more certain.

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[1] discounting: the present value of money received in n years time is calculated by discounting the amount (R) at a rate of interest (r) at which it could be invested: $R/\{(1 + r)^n\}$

In investment appraisal, the discounted cash flow technique (D.C.F.) estimates the net present value (NPV[1]) of the stream of net cash flows. If the discount rate used is the same as the firm's opportunity cost of capital, then the decision model will define an acceptable project as one with a positive NPV.

The same procedure is used in CBA: the net benefit in successive years of the project is discounted back to year zero (the year of the decision) at a rate depending on the social rate of time preference. There may be apparent anomalies in social cost-benefit analysis if some of the costs or benefits of the proposed project are "intangible" in that they are not readily expressed in money terms _e.g._ it is more important to me that there will be elephants in 20 years time (for my children to see) than that there are elephants now (because I have already seen them). Thus, the value of elephants _qua_ elephants may increase with time (depending on the proportion of adults to children in the population, and on how we weight their different kinds of satisfaction) even though the unit value of the numéraire falls: discounting can only be applied to money equivalents of intangibles calculated on some commonly agreed basis (_e.g._ a proportion of zoo takings plus the cost of

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[1] $$\underline{NPV} = \frac{R_1}{(1 + r)} + \frac{R_2}{(1 + r)^2} + \ldots + \frac{R_n}{(1 + r)^n} - C_o$$

where C_o is the present value of capital expenditure.

people travelling to and from zoos) not to the intangibles themselves. In the social cost-benefit analysis of agricultural pest control, a problem of this kind might arise if pesticide residues are toxic to wildlife, or if the pests themselves have an aesthetic or cultural value to some section of the community (apart from farmers). Further, the choice of a social discount rate is more likely in practice to reflect planners' preferences (and prejudices) than the social rate of time preference.

4.2 Investment appraisal by the pesticide manufacturer

The application of the discounted cash flow technique for investment appraisal by a pesticide manufacturer considering the development and introduction of a new product is straightforward enough provided that he can specify the size and timing of the cash flows. It may reasonably be assumed that the pesticide manufacturer can form good estimates of his production costs (fixed plus variable) for any specified level of future output. However, the contribution[1] towards fixed costs that he will receive in successive years of the project will be known with much less certainty. Accordingly, the economic decision model may be re-cast to demonstrate the problem

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[1] contribution: the difference between total revenue and total variable costs is the contribution to fixed costs.

of pricing policy: at what level should the unit price of the pesticide be set in order to maximise the NPV of the project? This is illustrated by Equation 4.1, although it is a gross simplification of the problem since it assumes that the unit price of the product remains fixed (in real terms) throughout the life of the project.

Equation 4.1

$$\max_{\alpha} \sum_{i=1}^{i=I} \left[\frac{1}{(1+r)^i} \, . \, (1 - t_m).\{J(i).X_r.(\alpha - c_i) \; - \; C_i\} \right]$$

where α = unit price of the pesticide

c_i = unit variable costs of production, distribution, and marketing in year i

C_i = capital expenditure on new plant and equipment etc. in year i

X_r = recommended pesticide application rate (assumed to be constant throughout the life of the project)[1]

I = project life in years

$J(i)$ = area to which the pesticide is applied in year i

r = opportunity cost of capital to the pesticide manufacturer

t_m = marginal rate of tax on gross profits

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[1] i.e. that X_r is constant from site to site, from year to year, and is independent of the unit price (α). This may be a realistic assumption (e.g. in the case of an ethirimol seed dressing), but it is certainly not then true that $X_r = X_{ij}^*$ (for all i, j) i.e. the optimum rate at each site (j) in each year (i) for any given unit price.

However, *Equation 4.1* can not be used as it stands to solve the problem of pricing policy since c_i, C_i, and J(i) are all implicit functions of the unit price of the pesticide (a). If the level of production in each year of the project can be specified (*i.e.* X_r.J(i), for all i), then the pesticide manufacturer can plan his production programme and provide good estimates both of the variable production costs (c_i, for all i) and of capital expenditure (C_i, for all i). It thus remains to specify the project life (I) and the area treated with the pesticide in successive years of the project (J(i), for all i).

The project life will depend partly on the degree of patent protection that the pesticide manufacturer can secure for his product. This will be equivalent to the number of years before the patent expires if patent-jumping is considered unlikely. The project may also be curtailed prematurely if the pest population develops resistance to the product or if a rival product displaces it.

The area treated with the pesticide in any year will depend partly on the price of the pesticide in so far as the actual farm-level does take cognizance of it (*cf.* the economic decision models developed in *Chapters 2* and *3*). The lower the price, the higher the ceiling level of adoption and the higher the rate of diffusion of the innovation through the crop, thus increasing the present value of any given unit contribution by bringing it forward in time. On the other hand, if the price is low, then so is the unit contribution: the pesticide manufacturer must trade-off these effects one against the other by adjusting the unit price until the present value of the total contribution to the fixed costs of being in the pesticide business at all is at a maximum.

The rate of diffusion and the ceiling level of adoption will also depend on many factors other than the price of the pesticide, only some of which are "economic" e.g. the value of any increase in the yield of the crop to the farmer, the chance of getting this increase, and the availability of credit to fund his use of the pesticide. Other factors include: the farmers' awareness of the product and what it can do for them (as modified by advertising in trade journals, demonstrations at agricultural shows, research reports, the experiences of their neighbours, and energetic selling in the field by the pesticide manufacturer), their previous experience with other pesticides, and their attitude to the company "image".

The simultaneous existence of two or more pesticide manufacturers with separate products, each with patent protection and all doing the same job, does not provide for competitive price-cutting. The rational behaviour in such a situation of oligopoly is for them all to set similar prices so that joint profits are maximised, although this behaviour does indeed amount to collusion through "conscious parallelism of action" (*cf*. Triangle Conduit and Cable Co. *vs* U.S. Federal Trade Commission, Seventh Circuit Court of Appeals, 1948). Each firm may attempt to increase its market share by non-price competition *e.g*. by advertising. Even more important perhaps, the simultaneous use of different products against the same pest at various different sites throughout the national farm might prolong the project life of all of them by restricting the development of resistance to any one *i.e*. they have something of the character of complementary goods[1] rather than substitutes.

If the solution of Equation 4.1 is positive (after adjusting the unit price of the pesticide so as to maximise the present value of the contribution that the pesticide manufacturer receives towards his other fixed costs), then the project should be allowed to proceed. This assumes that there are no extra budget constraints requiring the ranking of alternative projects according to their respective NPV's.

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[1] complementary goods: two or more products are said to be complementary in demand when an increase in the demand for one is generally associated with an increase in the demand for the other *e.g*. automobiles and petrol.

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[1] complementary goods: two or more products are said to be complementary in demand when an increase in the demand for one is generally associated with an increase in the demand for the other e.g. automobiles and petrol.

4.3 Social cost-benefit analysis and pesticide use

The application of CBA to the national investment in agricultural pest control involves the concept of economic surplus described in Subsection 4.3.1. The actual decision model is presented in Subsection 4.3.2. In Subsection 4.3.3, I have tried to outline some of the problems associated with the practical use of the decision model. However, some conclusions have been drawn from the model in Subsection 4.3.4.

4.3.1 The concept of economic surplus

The concept of economic surplus has been reviewed recently by Currie, Murphy and Schmitz (1971). It has been used by Griliches (1958) in his study of the social returns from hybrid maize, by Tintner and Patel (1966) in their appraisal of Indian fertiliser projects, by Peterson (1967) with regard to poultry research, by Schmitz and Seckler (1970) in their analysis of the welfare effects of the mechanical tomato harvester, and by Ayer and Schuh (1972) in their study of the social rate of return to cotton research in Brazil.

The introduction of pest controls is an innovation which induces a shift in the market supply curve[1] of the crop *e.g.* from

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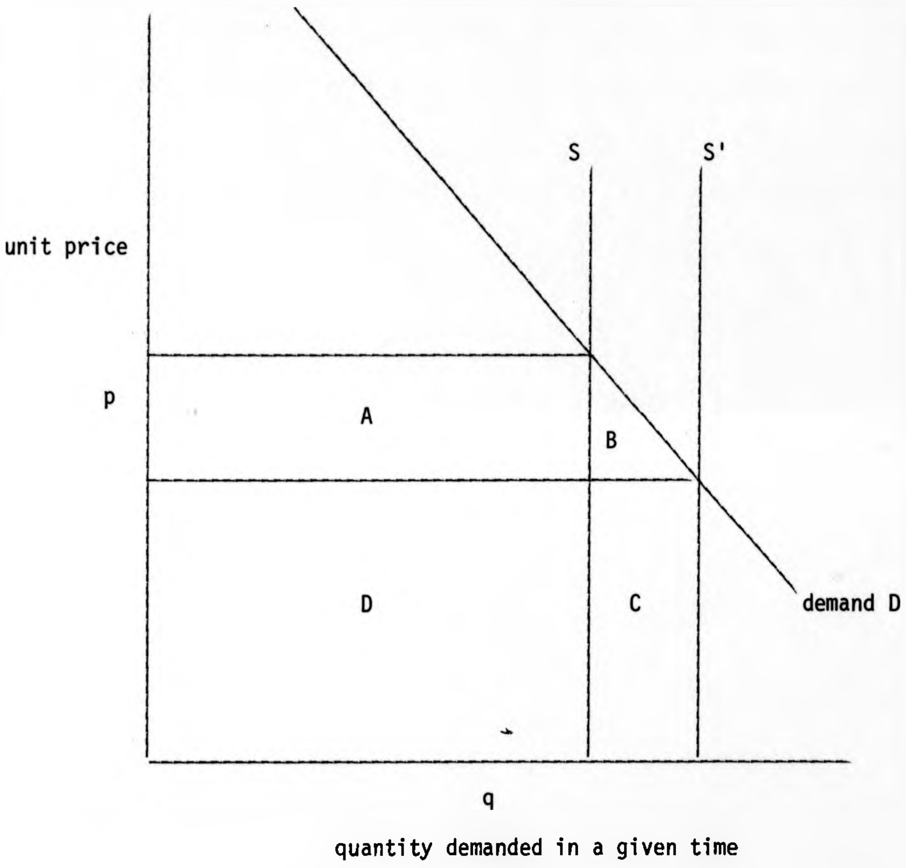
[1] supply curve: the market supply curve relates the quantity of a good supplied in a stated time interval to the unit price.

Figure 4.1: Economic surplus with an inelastic demand curve



S to S' in Figure 4.1. (This is initially assumed to be a cost-less transition e.g. if the yield of a crop is increased by the diffusion through it of a new variety costing no more to produce than the old one and in which the resistance factors responsible for the increase in yield are self-propagating within the plant body.) The increase in consumer surplus (where consumer surplus is represented by the area between the demand curve[1] and the price line) is given by A + B. The increase in producer surplus (where producer surplus is represented by the area between the supply curve and the price line) is given by (C + D) - (A + D) i.e. by C - A. The total increase in economic surplus is represented by the sum of the increases in consumer and producer surpluses i.e. by B + C, the area enclosed by the base supply curve, the new supply curve, the demand curve, and the axis. This may be used to estimate the total direct annual benefit to society resulting from the introduction of agricultural pest controls, although it does ignore any external economies not realised as an increase in the yield of the particular crop (i.e. economies external to the industry not ones merely external to a particular farm).

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[1] demand curve: a curve relating the total amount of a good which consumers will buy in a stated time interval to the unit price.

N.B. Supply and demand curves are usually drawn with price on the y axis.

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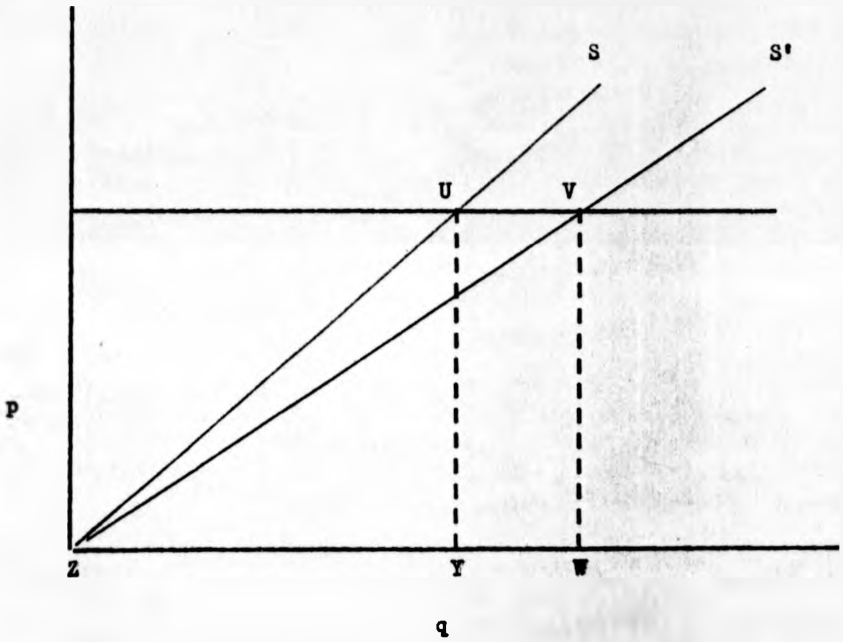
In Figures 4.1 and 4.2 the supply curves have been drawn perpendicular to the x axis i.e. with zero price elasticity. This is a reasonable description of the short-term supply response (after planting) and also facilitates calculation of the economic surplus defined by the area between the old and new supply curves, the demand curve and the axis. This procedure has been adopted by several previous writers including Griliches (1958). However, it is likely to produce an upper bound estimate of the economic surplus since the supply does adjust to changes in price through the acreage response:



The old supply curve (S) describes the quantity (q) that would be produced at each price (p) without the innovation. The new supply curve (S') describes the quantity that would be produced with the innovation. It is evident that the rectangle YUVW is exactly twice the area of the triangle ZUV if the supply curves are drawn through the origin. However, this treatment confuses a pure acreage response (S) with a mixed acreage plus innovation response (S'). A procedure for distinguishing that part of the total increase in supply directly attributable to adoption of the innovation from that generated by an increase in crop acreage has been suggested by Musalem (1974). But it seems to me to be simpler to take the annual acreage of the crop as given, for a first approximation, and to include as benefit any increase in the value of the quantity produced from that acreage.

In the short term (i.e. a single crop season, after planting), the supply of an agricultural crop from a particular region is inelastic[1] in response to any changes in its unit price. This is illustrated in Figure 4.1 by drawing both the base and the new supply curves perpendicular to the x axis i.e. with zero elasticity. The position of the base supply curve in successive years depends both on the yield of the crop per acre and on the total acreage. The acreage in any year depends in a complex way (as described by Colman, 1972, for the case of cereals in the U.K.) partly on that the previous year, partly on concomitant acreage decisions (e.g. the acreage of barley depends on that of wheat in the same year), and partly on the relative financial advantage of the crop at farm level (e.g. there may be competition between cereals and dairying). Thus, the base supply curve S moves back and forth along the x axis from year to year.

The position of the base supply curve in a particular year will also depend on the distance S' - S the previous year i.e. on the previous success of the innovation in augmenting the yield. If the demand for the crop is inelastic in response to a change in its price (i.e. the demand curve is more nearly vertical), as in Figure 4.1, then

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[1] elasticity: a measure of the responsiveness of one variable to changes in another, given by the proportional change in the dependent variable (e.g. the quantity supplied) divided by the proportional change in the independent variable (e.g. price) which brought it about.

the total revenue[1] received by the industry will be less for the supply augmented by the use of controls (S') than for the base supply (S) without controls, by an amount equal to the area C - A. The benefit will have been passed on to the consumer through a reduction in price and an increase in consumer surplus represented by the area A + B. The base supply line will move to the left (*ceteris paribus*) as the gross margin per acre of untreated crop is reduced and the total acreage of the crop contracts. Pest control will have been substituted for land.

If the demand curve for the crop is elastic in response to price changes (*i.e.* it is more nearly horizontal, like the perfectly elastic demand curve shown in *Figure 4.2*), then the total revenue received by the industry will increase as the supply of the crop is augmented by the use of pest controls. The base supply line S may move to the right if the increase in total revenue is such that the average gross margin per acre of crop is also increased.

The position of S' (*i.e.* the distance S' - S, that part of the total supply generated directly by the innovation) will in turn depend on the position of the base supply curve, related by

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[1] *total revenue*: quantity supplied times the unit price of the crop, here equated with producer surplus only because the short period supply curve is assumed to have zero elasticity.

Figure 4.2: Economic surplus with an elastic demand curve

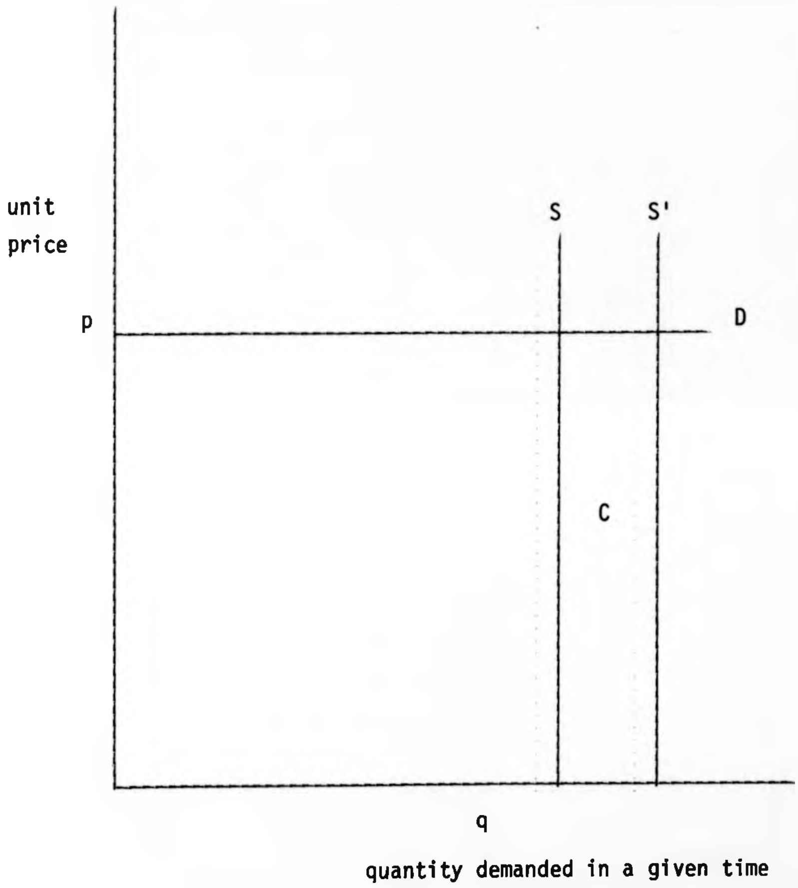
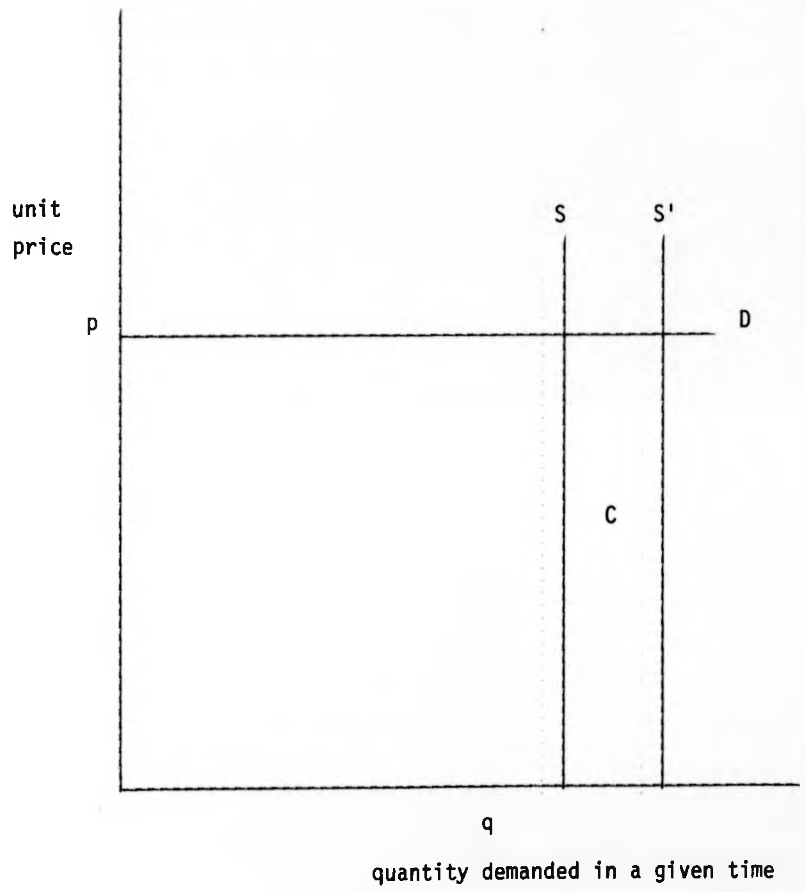


Figure 4.2: Economic surplus with an elastic demand curve



parameters describing the extent of the diffusion of the innovation through the crop and its effectiveness at augmenting the yield.

The positions of both S and S' in any historical time series will also depend on any changes in the varietal mix or the weather in each region, and on the correlation of such changes between regions within the national farm, since these will generate erratic fluctuations in the yield component of the total supply.

The annual increase in economic surplus is defined not only by the positions of the base and new supply curves, but also by the slope and position of the demand curve. In the case of a crop like barley, for which a well-organised commodity market exists in the world outside, the state can buy as much as it wants or sell as much as it over-produces at the prevailing world (i.e. border) price. It is therefore proposed (following Gittinger, 1972, and Little and Mirrlees, 1974) to use the border price of an agricultural crop to value the increase in production made possible by the use of pest controls. If the country is a net exporter of the crop, this will be the f.o.b.[1] price. If a net importer, it will be the c.i.f.[2] price. If the historical price

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[1] f.o.b. (free on board): a term applied to the valuation of goods up to the point of embarkation.

[2] c.i.f. (charged in full or cost-insurance-freight): the valuation of goods including all transport costs and insurance to destination. U.K. imports are entered by H.M. Customs in the overseas trade accounts as c.i.f., and exports as f.o.b..

of the commodity exhibits cyclical variation, the lowest price in the annual cycle should be taken i.e. the price just after harvest. Actual prices should be deflated by a price index to take account of any changes in the purchasing power of money. In Figure 4.2, the line D represents a perfectly elastic demand curve at the border price p[1]. The increase in economic surplus generated by the innovation is thus represented by the area C and consists entirely of producer surplus: there can be no increase in consumer surplus if the domestic price remains unchanged.

If the demand for the crop is inelastic in response to any change in price (as shown by the demand curve D in Figure 4.1 on page 114), e.g. if pest controls are used on a market garden crop which is sold locally, perishes easily, and has no export market, any increase in economic surplus generated by the innovation will be appropriated in the short term by the consumer. The estimated demand curve at local prices may be used to define the total increase in economic surplus represented by the area B + C.

The net social benefit resulting from the adoption of the innovation is represented by the total increase in economic surplus less the cost of generating it, and must be calculated for each

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[1] If foreign demand and supply are not perfectly elastic, the marginal export revenue or the marginal import cost should be substituted for f.o.b. or c.i.f. prices.

year of the project. There are two kinds of cost to consider: (1) the opportunity cost of any resources used, ignoring transfer payments, and (2) the loss of factor rents sustained by any people consequent on the shift to the left of the base supply curve if the demand for the crop is inelastic.

The loss of factor income is likely to be most pronounced where pest control is directly substituted for labour e.g. if chemical herbicides are used in place of hand-weeding. The increase in total economic surplus must be sufficient to compensate anyone affected in this way, although it is not usually considered necessary for the purpose of social cost-benefit analysis that such compensation actually be paid.

In the particular case considered here, the control of powdery mildew in spring barley, there is no direct substitution of novel pest control techniques for labour, and the possibility of a major supply readjustment through the acreage response is not thought to be significant: it is assumed that the acreage is determined by extraneous forces, and that any increase in production can be valued at its border price in the year of its realisation. Nevertheless, this treatment does ignore: (1) any loss of consumer surplus resulting from the migration of resources into the progressive sector, and away from alternative activities, as the average gross margin per acre is increased, and (2) any increase in the welfare cost of disequilibrium between supply and demand (see Musalem, 1974)[1].

4.3.2 The decision model

The present value of the increase in net social benefit resulting from the development and introduction of a new technique for agricultural pest control is represented by Equation 4.2.

Equation 4.2

$$\mathrm{NPV} = \sum_{i=1}^{i=I} \left\{ \frac{1}{(1+r)^i} \cdot \{ \sum_{\text{all } j} (\beta_i . N_{ij} . B . \Delta G_{ij}) - \sum_{j=1}^{j=J(i)} c_{ij} \} \right\} - C_0$$

where NPV = net present value of the increase in net social benefit

N_{ij} = potential yield of the crop in the absence of the pest in year i, acre j

ΔG_{ij} = reduction in the damage index achieved by pest control in year i, acre j

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[1] Currie, Murphy and Schmitz (1971), in their comprehensive review of economic surplus, justify the use of partial equilibrium analysis by stating, "This is virtually inevitable, for the economist's limited knowledge of the complex interrelationships characterizing any economic system precludes any possibility of allowing for all the ramifications generally associated with a change in one particular industry" (pp. 787-788).

B = rate of percentage yield loss per pest

β_i = border price of the crop in year i

c_{ij} = variable cost of control per acre, as accumulated by *e.g.* the pesticide manufacturer, the agricultural merchant, and the farmer, but excluding any taxes appropriated by the state

r = social discount rate, a measure of the social preference for present as opposed to future consumption

I = project life in years

$J(i)$ = area to which pest controls are applied in year i

C_0 = present value of the initial investment required to develop the technique and go into production

This formulation of the decision model for social cost-benefit analysis is based on the model of pesticide application developed in Chapter 3 summed over all the fields in the national farm and, discounted to the present, over the expected life of the project. It ignores any external diseconomies associated with pesticide production and use which have not been circumscribed by legislation and the loss of factor income sustained by anyone as a direct result of acreage readjustment. If the NPV is positive (in the absence of any budget constraint), the decision model, Equation 4.2, would allow the project to proceed since the benefit to society would outweigh the cost.

The term in *Equation 4.2* for the annual benefit might be approximated as shown in *Equation 4.3*:

Equation 4.3

$$\sum_{\text{all } j} (\beta_i . N_{ij} . B . \Delta G_{ij}) = \frac{Y_i . l_i . k_i . v_i . \beta_i}{1 - l_i}$$

where Y_i = estimated total crop production in year i

l_i = estimated proportional loss of crop through pest damage, calculated on the basis of the average severity of pest damage on untreated plots in year i

k_i = estimated average proportional kill (*i.e.* reduction in the damage index) achieved by pest control in year i

v_i = estimated proportion of the total crop treated in year i, for which the estimated proportion of the total area of the crop treated in year i may be used as a proxy variable

However, it is probable that the right-hand side of *Equation 4.3* will underestimate the left-hand side, and this for two reasons: (1) as shown in *Chapter 3*, controls will tend to be used *ceteris paribus* where the potential yield is higher, so that the proportion of the area treated will be lower than the proportion of the total crop treated, and (2) control of an air-borne pest in one field will help to delay the onset of the epiphytotic in neighbouring fields both generating an external economy, included on the left-hand side of Equation 4.3 but not on the right, and reducing the estimated proportional yield loss in untreated plots.

4.3.3 Some problems with the decision model

There are some problems associated with the straightforward use of Equation 4.2 as an economic decision model: problems of estimation and problems of sufficiency.

I have stressed in Chapter 3 some of the problems of estimating *ex ante* both the potential yield (N_{ij}) and the extent of the reduction in the damage index (ΔG_{ij}) at a single location (j) in a given year (i). Their summation over space and time confounds the problem. It is worse confounded by the uncertainty associated with J(i), the value of which in a given year depends on the rate of diffusion of the innovation, and with the project life (I), which may be truncated earlier than it might have been by the development of resistance to the pesticide in the pest population.

The problem of estimating the increase in economic surplus *ex post* is almost as bad. Although disease surveys, such as those conducted by King (1972, 1973), can be used to estimate the extent of yield loss through disease, they can not be used directly to estimate the yield loss offset by disease control. Indeed, if the time of an external economy, included on the left-hand side of Equation 4.3 but not on the right, and reducing the estimated proportional yield loss in untreated plots.

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The problem of estimating the increase in economic surplus *ex post* is almost as bad. Although disease surveys, such as those conducted by King (1972, 1973), can be used to estimate the extent of yield loss through disease, they can not be used directly to estimate the yield loss offset by disease control. Indeed, if the time of pesticide application is variable, it is doubtful whether they can even be used to estimate the residual loss since the implicit assumption that the disease index can be used to estimate the damage index (*cf.* Large and Doling, 1962) is violated.

The allocation of research costs to a particular project (involved in the calculation of C_0 in *Equation 4.2*) is difficult when the search for controls is empirical and non-purposive in the sense that all candidate pesticides are screened for activity against many different pests. The search for novel pest control techniques has a substantial fixed component which represents the cost of being in the pest control business at all, and it would be inappropriate to allocate this to particular projects. Only those development costs incurred after the discovery of a particular pesticide should be allocated to that project, although in the long run the accumulated net surplus (aggregated over all the successful projects) must be sufficient to cover the fixed costs of pesticide research and development if the on-going search for novel pesticidal activity is to be justified. Even more important perhaps, the opportunity cost of using research personnel and facilities on a particular project may be very much less than an allocation of their actual money cost on the basis of usage time just because of the extent of their specialisation.

However, even if we could estimate the annual increase in economic surplus, if we ignored sunk costs, and if we used accounting prices to reflect opportunity costs, the solution of Equation 4.2 may not represent very well the net social benefit provided by any innovation in agricultural pest control: it is still insufficient. There are two problems here: (1) how to incorporate the cost of any increase in the variance of the annual total yield of the crop, and (2) how the benefit should be weighted depending on who gets it.

The increase in yield generated by pest control may be accompanied by an increase in the time variance of the yield. We have seen that this can occur when controls are applied at a single site in Chapter 2. Since the space variance is typically decreased by the use of controls, the summation of the time variance over all sites is also increased[1]. This is illustrated in Figure 4.3, from which it can be seen that correction of the actual U.K. barley production figures for the estimated losses caused by powdery mildew demonstrates not only a substantial increase in yield, but also a 30% (approx.) increase in the

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[1] If the space variance is not simultaneously decreased, then the time variance of the national yield would not be increased even though the time variance of the yield is higher on each individual farm, because of the law of large numbers.

Figure 4.3: The estimated annual loss of barley production in the United Kingdom from powdery mildew

year	% yield loss[1]	actual production[2] (thousand tons)	potential production[3] (thousand tons)
1967	13	9,069	10,424
1968	14	8,140	9,465
1969	6	8,527	9,071
1970	9	7,410	8,143
1971	-	(8,441)	-
1972	(8)	-	-
1973	(13)	-	-
mean	10.5	8,286	9,276
A[4]		1,022	1,338

[1] after King (1973). N.B. King's survey data refer to England and Wales.

[2] after Home-grown Cereals Authority (1972)

[3] potential production = $\frac{\text{actual production}}{100 - \%\ \text{yield loss}} \cdot 100$

[4] A = the total negative absolute deviation (see Chapter 2)

total negative absolute deviation of the national yield. Pest control increases the variability of the national yield by destroying a natural homeostatic mechanism maintaining the yield. If it is accepted as a valid objective for society to reduce the variability of the physical yield of a basic commodity such as barley (*e.g.* to reduce the strategic cost of perennial short-falls, or to ease agricultural planning), it may be necessary to incorporate the increase in yield variance as a cost of the expected increase in net social benefit by defining a national iso-utility curve in E-V space, just as I did for the individual farmer in *Chapter 2*.

The concept of an input-output matrix of donors (who bear the cost) and recipients (of any benefits) has been proposed by Bradbury and Loasby (*op. cit.*). In the case of a chemical pesticide, these may include the pesticide manufacturer, the agricultural merchant, the farmer, the consumer of the crop, and the state. However, these multifarious agents exist in various states of aggregation. In particular, the pesticide manufacturer (as prime mover in the process of innovation, and as a monopolist maintained by patent protection) has control of the market for a new pesticide through the price he charges for his product.

The objective of any one agent in the matrix (with the possible exception of the state) will not correspond in general with the overall social objective of maximising the present value of the net social benefit as defined by Equation 4.2. The proper objective of a self-interested pesticide manufacturer has already been discussed in Section 4.2. To the extent that he does have price-fixing monopoly power, he will increase both the proportional and the absolute amount of the total increase in economic surplus that he appropriates, simultaneously restricting the overall magnitude of the total surplus. (After the expiry of patent protection, competition from secondary manufacturers will reduce the transfer price of the pesticide to the next agent in the matrix, so augmenting the annual increase in economic surplus as the pesticide is more widely used and reducing the proportion of the total surplus appropriated by pesticide manufacturers as a group. But this effect will be heavily discounted by the decision model since it occurs far in the future.)

The use of the patent laws to restrict the diffusion of the initial surplus generated by the innovation away from the prime mover in the donor-recipient matrix will contain a substantial proportion of it in an organised environment, where it retains the potential to finance other innovations. This will be so just because of its accumulation at an investment locus that has already demonstrated its capacity for successful innovation. The subsequent dis-aggregation of the surplus across the matrix dissipates this potential.

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It is thus necessary to weight the annual net surplus depending on who (or what) gets it. (This has recently been noted in the literature by Bieri *et al*., 1972.) Its concentration by the pesticide manufacturer restricts the size of the total surplus and is of doubtful virtue from considerations of equity. The provision both of the capacity and of the incentive for the pesticide manufacturer to generate further innovations might however be applauded. The final weighting attributed for the purpose of social cost-benefit analysis to that part of the annual net surplus appropriated by the pesticide manufacturer will depend on which of these properties is held in greatest esteem.

So, for all of these reasons (the difficulty of estimating *ex ante* or even *ex post* the value of the parameters defining the present value of the increase in economic surplus, the difficulty of incorporating the cost of any increase in the variance of the total annual yield of the crop, and the differential utility of the generated surplus depending on where it is accumulated in the donor-recipient matrix, together with its ultimate diffusion across the matrix), the relation between the estimated present value of the increase in net economic surplus and the potential gain in real social benefit is doubtful.

4.3.4 Some conclusions from the model

Notwithstanding the problems associated with the use of Equation 4.2 (page 122) as a decision model for social cost-benefit analysis, certain conclusions can be drawn from the comparison between Equation 4.2 and the farm-level decision model developed in Chapter 3 (Equation 3.16 on page 90).

If it is agreed that any increase in the annual net surplus is a good thing worth having, then many pesticides in current use[1] will be under-used from the point of view of social cost-benefit analysis if, at farm level, they are applied according to the economic decision model, Equation 3.16. There are several reasons for this:

(1) The monopoly power of the pesticide manufacturer (provided by patent protection) enables him to maintain the transfer price of the pesticide to the next agent in the matrix above its marginal cost of production. This restricts pesticide usage by reducing the potential benefit-cost ratio at farm level. The adoption of short-run marginal cost pricing for a pesticide already in production would necessitate the separate appraisal of appropriate rewards for the development of novel pesticides.

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[1] *i.e.* those not associated with substantial external diseconomies through the deleterious effects of their residues. This problem is ignored here (see page 104) but has been considered by Edwards *et al.* (1970).

(2) The pesticide application rate is, in practice, indivisible, being determined by the strong recommendation of the manufacturer. This restricts the use of the pesticide at some fraction or multiple of the standard rate even though it may give an economic return.

(3) The individual farmer is risk-averse and requires a marginal potential benefit/cost ratio very much greater than unity to induce him to use controls at all, because of the variability of the return. This is quite rational for the individual (cf. Lipton, 1968), but less so for the state because of the law of large numbers[1] even though the national yield may still be de-stabilised by the use of controls (see Figure 4.3 on page 128).

(4) Not all of the benefits of pest control are appropriated by the farmer who invests in them i.e. there are economies external to any particular farm. This may happen if the application of controls on one farm helps to delay the progress of an epiphytotic through the region and reduces the need for controls to be applied elsewhere. However, this additional benefit is not included in the farm-level decision model, Equation 3.16, and is not taken into account by the farmer in his choice of pest controls.

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[1] law of large numbers: the tendency for peculiarities of individual members of a group to cancel out, which becomes stronger the larger the size of the group cf. portfolio selection described in Chapter 2.

A similar conclusion has been reached by Headley (1968) on the basis of empirical studies of the aggregate agricultural production function: that the marginal factor product of pesticide use exceeds the marginal factor cost by a substantial amount. This inequality between marginal social benefit and marginal social cost represents the cost of de-centralised decision making. It does suggest that far better use could be made of present generation pesticides through the development and application of economic decision models, such as Equation 3.16, together with control of the transfer prices of the pesticides through the donor-recipient matrix.

The demand for more selective pesticides, with a narrow spectrum of activity, as well as more potent ones (both of which characteristics are likely to make them unattractive propositions to a potential pesticide manufacturer, the first because it restricts the size of the market in a particular year, the second because it may restrict the project life by reducing the size of the pest population managing to over-winter), may also provide a case for public investment in the pesticide industry. It should be sufficient to demonstrate that the net social benefit will be greater than the private return appropriated by a potential manufacturer, and that the private return is likely to be less than that provided by alternative investments in the private sector. The state might contract out the necessary research and development to a private agency, or purchase successful patents, or subsidize their exploitation.

4.4 The problem of winter barley

Some strategies for agricultural pest control can only be implemented and analysed at a regional level. This is so with the possible strategy for controlling powdery mildew in spring barley in the U.K. by means of a legislative ban on the cultivation of the winter barley crop.

Traditionally, the barley crop in Britain is sown in the spring. In the years between the two World Wars, the better chance of getting a malting sample and the possibility of higher yields from barley sown in the autumn provided stimuli for autumn sowing. Bell (1944) describes the breeding of *Pioneer*, the first two-row winter-hardy malting variety grown in this country and the only one available until the introduction of *Maris Otter* in 1965. Jenkins (1970) gives a general account of winter barley in Britain.

The evidence concerning the yield advantage of winter barley over the spring crop is confusing. In eight comparisons of *Maris Otter* winter-sown with *Zephyr* and *Impala* sown in the spring in trials carried out by the National Institute of Agricultural Botany between 1965 and 1969, the winter barley out-yielded the spring crop by 6% (reported by Jenkins, *op. cit.*). At a single location, Cambridge, *Pioneer* yielded 29% more than spring-sown *Rika* in 1956, but 14% less in 1955. The average yield of spring-sown *Rika* over five centres in

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1958 was 99% of winter-sown Pioneer, and 98% over six centres in 1959.

Some trials conducted with the spring barley variety, Proctor, at the Norfolk Agricultural Experiment Station at Sprowston between 1960 and 1964 demonstrated the yield advantage from autumn sowing if no severe winter killing occurred (Anon., 1965). It was concluded that the yield advantage depended largely on the amount and distribution of rainfall in May and June and that winter-sown barley can be expected to give substantially higher yields if there is a spring drought.

The hazards of using a spring variety for autumn sowing are well illustrated by the yields following the severe winter of 1962/3 when, from autumn and spring sowings respectively, Proctor gave 14 and 36 cwt/acre compared with yields of 38 and 35 cwt/acre from Maris Otter (Anon., 1964).

The statistics published by the Ministry of Agriculture, Fisheries and Food do not distinguish between acreages of winter and spring cereals. Jenkins (op. cit.) estimated the acreage of winter barley from cereal seed sales returns for 1958/9 to 1968/9. (In 1958, Pioneer accounted for 95% of the winter barley acreage; by 1969, Pioneer had virtually disappeared and been replaced by Maris Otter, for malting, and Senta, for feeding.) Over this period, the proportion of the total barley acreage that was winter-sown remained fairly constant between 5% and 7%. The sales of Maris Otter plus Senta as a proportion of the total barley seed sales amounted to 6.8% in 1969/70 and to 7.6% in 1970/71 and 1971/72 (Anon., 1972). These figures refer to England and Wales only. There were considerable fluctuations in winter barley as a proportion of the total crop in some counties, particularly in the West Midlands. In the North and West, the ratio of winter to spring barley was less than over the rest of the country.

The attraction of winter barley (i.e. higher yield, malting quality, and more evenly spread labour requirements) must be balanced against the cost of the consequent build-up in pest population levels. Since the spread of soil-borne pests is restricted, the costs associated with them are largely internalised in the production decisions of the farm firm. This is not so with air-borne foliage pathogens which cause diseases such as leaf blotch, brown rust, and powdery mildew in barley.

Yarham and Pye (1969) have shown the importance of winter barley as a source of inoculum for early mildew infection of neighbouring spring-sown crops in Cambridgeshire. However, no direct relationship was found between the nearness to winter barley and the level of disease in the spring crop in the later stages of growth, nor between earlier differences in mildew levels and the yield of the crop or the quality of the grain.

Yarham, Bacon and Hayward (1971) report the results of a collaborative exercise undertaken in 1970/71 by Plant Protection Ltd., Miln Masters, and the Advisory Service of the Ministry of Agriculture, Fisheries and Food in which some 25 square miles of north-west Norfolk were sown with ethirimol-treated winter barley. This did delay slightly the development of mildew on the spring crop in the area, but the winter was very mild and mildew still developed on the treated crop. Mildew levels were much lower in spring crops distant from winter barley irrespective of whether these crops were in the treated or untreated area.

In Denmark, the government banned the cultivation of winter barley for an experimental period of five years starting in 1968 (Stapel and Hermansen, 1968). This seems to have protected spring crops from mildew infection for an extra two to four weeks even though much inoculum originates outside Denmark. (In 1971, widespread and severe outbreaks of powdery mildew were reported for the first time on the spring variety Emir in Jutland. Stapel and Hermansen (1972) suggest that the primary inoculum originated in England on the widely-cultivated, genetically-similar, mildew-susceptible variety Sultan.)

The present value of the net social benefit that might result if the cultivation of winter barley were banned in the U.K. by administrative decree can be represented by Equation 4.2 on page 122. The problems of performing such a calculation have been discussed already in Subsection 4.3.3. However, the decision problem might be approached in a slightly different way. Let us suppose: (1) that winter barley occupies 8% of the total U.K. barley acreage (= 8% of 5.6 million acres in 1972: Home-grown Cereals Authority, 1972, see Appendix 1.3), (2) that, if the cultivation of winter barley were banned, all this land would be put down to the spring crop, (3) that the yield advantage of the winter over the spring crop amounts to some 10% of the average (winter plus spring) barley yield (= 10% of 29.9 cwt/acre in 1972), and (4) that powdery mildew alone takes 10% of the present spring crop (see Figure 4.3 on page 128).

Thus a ban on the cultivation of winter barley would involve an immediate yield loss of about 0.8% of the total crop (= $6.7 \cdot 10^4$ tons in 1972). This represents the breakeven increase in the average yield of the spring crop necessary to justify the ban. Let us assume further: (1) that the breakeven yield increase for an all-spring crop is 1% (this is just being cautious), and (2) that any yield increase in the new, all-spring, crop is completely delocalised throughout the national barley crop.

How long must the mildew epiphytotic be delayed in order to realise a 1% increase in yield? Let us assume that this complex process can be represented by a typical disease scenario such as the example discussed in Chapter 3 (Section 3.7, page 90). The reduction in the damage index resulting from a delay in the onset of the disease may be represented by Equation 4.4:

Equation 4.4 $$\Delta G = \frac{1}{r} \cdot \left(e^{r.t_e} - e^{r.(t_e - \Delta t)} \right)$$

where ΔG = the reduction in the damage index which results from the delay (pest-days)

r = average rate of growth of the pest population (day^{-1})

t_e = end-point for effective crop damage (days)

Δt = the delay in the onset of the disease (days)

If we assume that the damage coefficient, relating the percentage yield loss to the damage index (see Section 3.5, page 88), equals 0.2 $\%.\text{pest}^{-1}.\text{day}^{-1}$, and that the rate of growth of the pest population equals 0.07 day^{-1}, as defined by the typical scenario[1], then

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[1] N.B. The growth rate of the pest population must be adjusted if the behaviour on the variety Sultan in the experiment is not considered "typical".

the end-point for effective crop damage (t_e) may be adjusted until the percentage yield loss equals 10%, the average national yield loss in spring barley due to infection by the mildew fungus. This is illustrated in Equation 4.5:

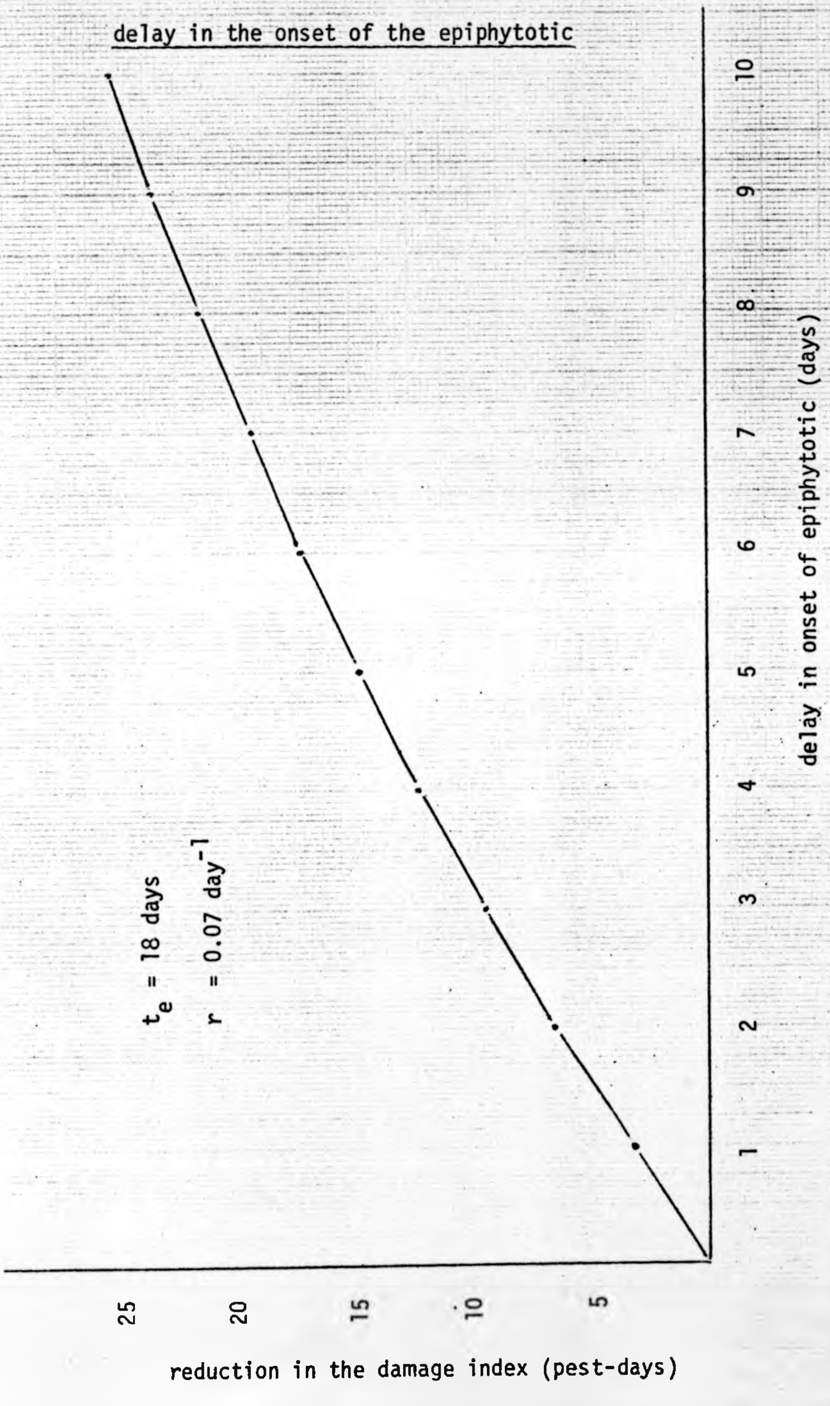
Equation 4.5 $$t_e = \frac{1}{r} \cdot \ln\left(\frac{r \cdot 10}{B}\right) = \frac{1}{0.07} \cdot \ln\left(\frac{0.07 \cdot 10}{0.2}\right)$$

= 18 days approx.

The estimated average end-point can be substituted for "t_e" in Equation 4.4, the reduction in the damage index set at 5 pest-days (corresponding to a yield loss of 1%), and Equation 4.4 solved for the delay required to achieve this, see Figure 4.4. Reading from the graph, the breakeven increase in yield would be achieved by a delay of about 1.5 days. This should be compared with the actual delay of two to four weeks realised in Denmark.

Of course, such an analysis ignores many factors. On the cost side, these include: the loss of the larger proportion of malting barley (which can be sold at a premium) in the winter crop, the increased lumpiness of the requirements for labour and machinery to grow an all-spring crop, and the cost of administering and policing such a scheme. On the benefit side, it ignores: any increase in yield that

Figure 4.4: The reduction in the damage index as a function of the delay in the onset of the epiphytotic



might result from the control of pests other than the mildew fungus, and any increase in the overall malting quality due to mildew control. There is also some doubt concerning the importance of volunteer barley plants as an alternative source of inoculum, and about the precise way in which the yield loss is related to the growth of the pest population.

Nevertheless, it does show that a nationwide delay of as little as two days in the progress of the mildew epiphytotic could more than compensate for a generous allowance imputed to the supposed advantage of the autumn-sown over the spring-sown barley crop.

Chapter 5

Research for pest control

The importance of systematic research for agricultural development is widely recognised (*e.g.* by Mellor, 1966; Moseman, 1970). The particular importance of pest control research is also appreciated (*e.g.* by Pradhan, 1971). It is therefore surprising that agricultural research should be deficient in providing proper information to guide the use of its technical innovations. Nevertheless, deficient it is, as discussed in Section 5.1. The necessity to construct properly calibrated analytical models of farm-level decision problems in place of empirical investigation of the yield response in order to rectify these deficiencies is considered in Section 5.2. An analytical framework for experimental research to provide adequate data to guide the rational use of practical techniques for agricultural pest control is developed in Section 5.3.

5.1 Deficiencies in the data provided by agricultural research

Belshaw and Hall (1972) have discussed the usefulness of agricultural research data for the solution of farm-level decision problems and have noted many ways in which they are deficient. I want only to mention three points of general application: (1) they fail to take account of the fact that the physical yield response of a crop to an innovation in the technique of husbandry is very much location-specific,

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Although the detailed design of crop protection field trials has been considered quite extensively in the literature (*e.g.* Unterstenhöfer, 1963; Van der Plank, 1963), the problem of what to measure, and what for, has not. Several examples to illustrate these deficiences can be quoted:-

(1a) Jenkyn and Bainbridge (1974) have demonstrated the importance of edge effects in small plot experiments involving barley powdery mildew. Substantial edge effects would indeed be expected when dealing with air-borne infectious particles under field conditions *e.g.* a resistant variety would appear to be much less resistant when grown in close juxtaposition with a susceptible one, just because of the high level of inoculum accumulating there. Such an experimental design might be appropriate if the objective is the invention of a resistant variety since the candidates will be subjected to maximum stress and this will provide an effective screen, albeit one with a small mesh. It is quite inappropriate if the objective is to determine the yield response of a variety prior to its adoption on a large scale *i.e.* to provide information to guide innovation at farm level.

(1b) The yield data in Figure 2.2 (page 39) should be compared with the national average barley yield of under 30 cwt/acre (see Appendix 1.3): the experimental yield of each variety is consistently higher, in some cases very much higher, than that realised under farm conditions. In general, the yield of control plots (i.e. ones not receiving the new treatment) should be commensurate with simultaneous farm-level yields if the yield response is to be at all meaningful.

(2) The leaflet published by the National Institute of Agricultural Botany for farmers, and giving recommended varieties of cereals (National Institute of Agricultural Botany, 1974), ignores: (i) the absolute yield of each variety, giving the yield as a proportion of a variable base yield (the yield of a standard variety grown in control plots), (ii) the time variance of the yield of any variety, and (iii) the co-variance between the yields of different varieties (cf. Chapter 2, page 34). According to the decision model developed in Chapter 2, the farmer needs to form some idea both of the absolute level of the expected yield and of the time variance of the yield if he is to make a rational decision concerning the use of a particular crop variety. He also needs some idea of the co-variance between the yields of various different varieties that may be available if he is to identify an efficient portfolio amongst them.

(3) As mentioned in Chapter 1 (page 23), the economic optimum for the rate of pesticide application (i.e. that which equates

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(3) As mentioned in Chapter 1 (page 23), the economic optimum for the rate of pesticide application (*i.e.* that which equates

the marginal expected benefit with the marginal cost of treatment[1]) may be very much less than the technical optimum (*i.e.* that which gives the maximum physical response). This was exemplified by the work of Ghodake *et al*. (1973) concerning the use of insecticides on the cotton crop in India. It is of the utmost importance that economic variables be included in any analysis of these problems which forms the basis of a practical recommendation. It is quite untrue, incidentally, that economic variables are any more unstable than some of the parameters defining the physical yield response *e.g.* the variety specific activity coefficient (see page 97).

5.2 The necessity for using analytical models

Direct investigation of the physical yield response using empirical small-plot trials only represents the first stage in the construction of an economic decision model to guide the actions of individual farmers: by itself, it is insufficient. There are several reasons for this, reasons which also explain the superiority of properly calibrated analytical models of agricultural pest control over conventional research data in overcoming the deficiencies described in the last section.

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[1] *N.B.* This ignores aversion to risk: the pesticide application rate which maximises the farmer's utility would be even less, see *Chapter 2*.

Firstly, as I tried to show in Chapter 3, the pay-off is affected by many factors not under the direct control of the farmer *e.g.* the time when the pest enters the crop, and the various components of weather. Thus, the pay-off is likely to vary a lot from year to year and from site to site. It would require many years of empirical experimentation on the physical yield response at a particular location to provide good estimates of the expected yield and its variance, even if the functional relationships that comprise the system remained unchanged. Analytical modelling, by taking account of more information relating to a particular site/year (*e.g.* the size of the pest population at the time of spraying, in relation to the growth stage of the crop), reduces the amount of empirical experimentation needed.

Secondly, although the form of the functional relationships between system parameters may be assumed to remain unchanged over long periods, the levels at which such parameters are set do not. Some changes of this kind are allowed for by direct investigation of the physical yield response *e.g.* changes in pesticide and crop prices, which are not taken into account at all but left for the farmer to adjust for himself. Any change in a parameter regulating the physical response is not. The rapidity with which the variety specific activity coefficient (a component of the pest population growth rate) can change has been described previously (page 97) with reference to the history of the barley variety *Impala*. The same may well be true of the proportional kill achieved by pesticide application. Empirical investigation of the yield response has hardly had time to form an estimate of the expected pay-off and its variance under one set of conditions before the conditions change and the experiments must be repeated. Analytical modelling, by considering each component function separately, makes full use of all the information available. Really good estimates of some functions (*e.g.* the effect of weather on the growth rate of the pest population, those which remain stable) can be combined with the latest estimates (or, indeed, forecasts) of those which change (*e.g.* the effect of variety).

Thirdly, it is necessary to use analytical models rather than empirical ones where the system is complex in Forrester's sense (Forrester, 1969) *i.e.* characterised by "counter-intuitive" behaviour. This point has been made previously by Watt (1970). It is likely to apply to large-scale and long-term programmes for pest control and, more especially, to programmes for insect control which upset established predator/prey relationships. In this sense, the control of powdery mildew in spring barley is not a complex system as regards the annual farm-level decision problem: its behaviour is not counter-intuitive, only vexed by the large number of state variables defining the system. If the system is long-term or large-scale, direct experimentation on the physical response is unlikely to be a feasible proposition anyway.

5.3 An analytical framework for pest control research

After the invention of a new pesticide or crop variety, research is needed to provide information to guide the adoption of the innovation by individual farmers. It has been argued here that empirical data, provided by direct investigation of the yield response, could be better used than hitherto *e.g.* to construct efficient portfolios of different crop varieties, taking into account the co-variance between the individual yield responses. It was further argued that the development of a properly calibrated analytical decision model, in which the factors affecting the yield response are considered separately, is a significant improvement on empirical field investigation under certain circumstances: where the response is very location-specific, where it is very variable from year to year, and where one or more of the functions regulating the yield response changes from one year to the next.

The use of abstract models in agricultural research has been considered by several authors (*e.g.* Watt, 1966; Jones, 1970; Dent and Anderson, 1971). Their use in the particular context of research for pest control has also been given some attention (*e.g.* by Watt, 1970; Conway and Murdie, 1972; Van der Plank, 1972). I want to outline in a general way the procedure involved in the construction of an analytical economic decision model for agricultural pest control.

The model must be sufficient to explain the behaviour of irreducible and stubborn facts in particular field experiments (*cf*. the calibration of the model described in *Chapter 3*, Section 3.7, page 90). If the model is sufficient, then: (1) the form and level of the yield response should be defined by the model (*e.g*. the exponential decline in the yield response from a level corresponding to a fraction of the potential response, as the time of pesticide application is postponed), (2) the relationship between the various functions defining the yield response must be logical and non-arbitrary (this is where the use of small-plot trials as iconic models of the farm-level yield response is insufficient: the relation between the two is arbitrary), and (3) the level of certain of the parameters defining the model should be stable between experiments *e.g*. the damage coefficient and the end-point for effective crop damage. If these conditions are met, location-specific behaviour can be modelled by adjusting the level of certain critical parameters to suit the occasion *e.g*. the time when the pest enters the crop and the rate of growth of the pest population.

It should be remembered that economic decision models are prescriptive not predictive: they help people to decide what to do, they do not describe what is going to happen. Nevertheless, predictions can be incorporated in the decision model. Dillon and Officer (1971) recommend the use of Bayes' theorem to incorporate a prediction (Z) with an *a priori* probability distribution, P(θ), to give an *a posteriori* probability distribution of that state of nature, $P(\theta|Z)$. The use of Bayes' theorem has been described by Schlaifer (1959); it has also been introduced to the subject of pest control economics by Carlson (1970). It is illustrated by Equation 5.1:

Equation 5.1

$$P(\theta|Z) = \frac{P(\theta).P(Z|\theta)}{P(Z)}$$

where $P(\theta|Z)$ = *a posteriori* probability distribution of a state of nature (θ) given a prediction (Z)

$P(\theta)$ = *a priori* probability distribution of θ

$P(Z|\theta)$ = conditional probability of observing the prediction (Z) given that θ occurs

$P(Z)$ = probability of observing Z

The use of a subjective probability distribution of a state of nature was described in Chapters 1 through 3. The use of Bayes' theorem to combine a subjective *a priori* probability distribution of θ with a prediction of the particular value it will take in the period to which the decision relates is the second major characteristic of Bayesian (*i.e.* statistical) decision theory. The resulting *a posteriori* probability distribution of θ should be used in place of the *a priori* distribution in the economic decision model *e.g.* in determining the subjective weighting to give to historical yield response data in the LP model for portfolio selection described in Chapter 2, and in the estimation of the variety specific activity coefficient (A), the proportional kill (K), and the weather oscillator (W) in the analytical model of pesticide use developed in Chapter 3.

Unfortunately, the papers both by Dillon and Officer (1971) and by Carlson (1970) suggest the use of yield response data from neighbourhood experimental small-plot trials, of necessity from the previous year, as the prediction (Z) of the response on a particular farm. The use of experimental data in this way is not likely to provide a very good prediction of a farm-level yield response which is highly location-specific, such as the response to pesticide application. Even more important perhaps, the use of Bayes' theorem must be considered spurious as applied to a system which changes substantially from one year to the next. It would be acceptable, however, to apply Bayes' theorem in the estimation of individual response functions in an analytical model of pesticide application *e.g.* the use of meteorological forecasts to predict the effect of weather on the growth rate of the pest population.

The development and use of a prediction is not necessarily worthwhile. Polley and King (1973) have presented a preliminary model for forecasting barley mildew infection periods on subjective weighting to give to historical yield response data in the LP model for portfolio selection described in Chapter 2, and in the estimation of the variety specific activity coefficient (A), the proportional kill (K), and the weather oscillator (W) in the analytical model of pesticide use developed in Chapter 3.

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The development and use of a prediction is not necessarily worthwhile. Polley and King (1973) have presented a preliminary model for forecasting barley mildew infection periods on the basis of gross weather data. They suggest that the minimum daily requirements for a barley mildew infection period are: (1) maximum temperature > 60°F (15.6°C), (2) sunshine > 5 hours, (3) rainfall < 1 mm, and (4) run-of-wind > 153 miles (246 km). Predicted peaks were obtained when all four criteria were satisfied on any one day, when at least three out of four on two or more consecutive days, and when at least two out of four were satisfied on three or more consecutive days. There are however a number of limitations affecting the use of this information: (1) a prediction is of little use unless it can be incorporated into a prescriptive model to provide a better guide to action (*cf*. a forecast of how warm the weather is going to be may be incorporated in the estimates of the expected weekly growth rates of the pest population calculated on the basis of the temperature model described in *Chapter 3*), (2) it ignores both the accuracy of the forecast (*i.e*. $P\{Z|\theta\}$), and the probability of observing the forecast (*i.e*. $P\{Z\}$), both required to incorporate a prediction with an *a priori* probability distribution of that state of nature according to Bayes' theorem, and (3) it ignores the cost of operating a forecasting service, which would be included in any social cost-benefit analysis of the project (*cf*. *Chapter 4*).

This raises the more general question of just how much time and effort should be spent in getting more accurate estimates of the parameters defining the decision model in a particular application. This will depend on the sensitivity of prescribed activity to changes in the variable: it may matter very little to the farmer whether the potential benefit/cost ratio is 3.5 or 3.9, the project will still be adopted. In the case of barley powdery mildew, it may be possible to construct an analytical model of the pest population growth rate (itself a component of the economic decision model described in Chapter 3) as a function of critical weather parameters such as temperature, relative humidity, light, and wind, just like the EPIMAY programme described by Waggoner, Horsfall and Lukens (1972). Really good estimates of the pest population growth rate at a particular site would then be obtained using the extensive meteorological data available to build up an *a priori* probability distribution defining each weekly growth rate; meteorological forecasts may be combined with these using Bayes' theorem, thus providing corresponding *a posteriori* estimates of successive weekly growth rates. However, the expense of the fundamental research required to tease out the relationships between pest growth and the various environmental parameters that regulate it would only be justified if the activity prescribed by an economic decision model of agricultural pest control were peculiarly sensitive to the actual rate of growth achieved by the pest population.

Although this is a necessary condition, it is not in itself sufficient. The level of any activity in the field (*e.g.* the extent of pesticide use) will depend not only on the level of prescribed activity, but also on numerous other factors that influence the behaviour of individual farmers (this is discussed a little more fully in Chapter 6). The research expenditure would only be justified if the level of real activity were also sensitive to any change in the level of prescribed activity.

Chapter 6

The usefulness of economic decision models for agricultural pest control

This chapter is intended to be rather more speculative and suggestive than previous ones. The question of who might be interested in the development and use of economic decision models for agricultural pest control is considered in Section 6.1. A number of possible objections to their use are considered (and dismissed) in Section 6.2. In the following section, the application of analytical modelling to situations other than the use of a single spray to control an air-borne pest is discussed. The final section serves as both summary and conclusion.

6.1 Who might be interested?

In previous chapters, the interests of several different groups of people have been considered: individual farmers (Chapters 2 and 3), a pesticide manufacturer (Section 4.2, page 108), and society at large as embodied in the state (Section 4.3, page 113). The decision models developed for their use were normative in that they provided a rational basis for future activity. They were also economic in that they seeked to maximise utility, and utility was equated with the monetary pay-off (subject to constraints describing the riskiness of the project): either the annual gross margin (for the farmer), the net present value of the cash flow (for the pesticide manufacturer), or the net present value of the overall social benefit (for the state).

The interest of farmers in normative economic decision models for agricultural pest control is pretty much self-evident: they need help in deciding whether or not to adopt a new crop variety or to use a pesticide in a particular situation. However, the inner workings of any realistic model are likely to appear too complex for the ordinary farmer to work it through for himself. Also, it would require more data than is readily available from his own experience (e.g. a vector of expected weekly growth rates on a crop variety that he has never grown before). He would be interested in the recommendations of a decision model (i.e. in the advice) rather than in the conceptual framework on which that advice was based. The solution of the model in a particular situation must take account nevertheless of the farmer's appreciation of that situation e.g. his estimation of the yield of the crop in the absence of the pest, of the price that the crop will fetch, and of the possible loss of potency by the pesticide. The model should help the farmer make his decision, not force a pre-digested solution upon him.

The pesticide manufacturer is interested in all of the forces that may influence farmers to buy his product, only some of which are "economic" and taken into account by the normative decision manufacturer), or the net present value of the overall social benefit (for the state).

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The pesticide manufacturer is interested in all of the forces that may influence farmers to buy his product, only some of which are "economic" and taken into account by the normative decision models described above: he needs a model of actual farm-level behaviour, not one to rationalise that behaviour. If he knows what these forces are, and how they influence farmers' decisions, he can adapt his marketing programme accordingly in order to maximise the project NPV *e.g.* adjust the strength of the pesticide (the recommended dose) and its price to give an average potential benefit/cost ratio at farm level of 3.0 say, and deploy demonstrations at agricultural shows, advertisements in trade journals, and technical representatives in the field.

It seems to me probable that the application rate suggested by a pesticide manufacturer for a novel pesticide protected by a patent would be the technical optimum in "typical" field experiments *i.e.* that concentration of the active ingredient which generates the maximum physical response, where the marginal increase in yield resulting from pest control is just balanced by the marginal yield reduction through phyto-toxicity. There is a certain economic justification for this: (1) one of the factors in a behavioural model of pesticide use would be the farmer's fondness of owning a pest-free crop irrespective of whether the increase in yield justified the expense[1], thus favouring over-kill, and (2) the transfer price of the pesticide

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[1] *i.e.* the utility of pest control to a farmer is not simply the monetary pay-off subject to risk or income constraints as assumed in the decision models developed in *Chapters 2* and *3*.

from the manufacturer to the farmer is greater than the marginal variable cost of production since patent protection allows him to make super-normal profits *i.e.* the price can be adjusted independently of the recommended dose rate.

However, the increasing cost of petrochemical products in the wake of the global energy crisis must mean both that the transfer price of the pesticide to the farmer is increased and that the variable cost of production as a proportion of the transfer price is increased. The farm-level potential benefit/cost ratio will become more nearly marginal and require greater consideration before a pesticide is used. Increasingly therefore, the pesticide manufacturer must be concerned with how his product is used by farmers for their own economic benefit. More and more, the manufacturer will be selling information about pesticide use together with his product, and recommending application rates less than the technical optimum in order to secure a sale. The recommended rate will depend on the solution of a normative economic decision model of the farm-level problem such as I have described. Only in this way will he be able to maximise the contribution that he appropriates in accordance with *Equation 4.1* (page 109): the pesticide manufacturer will no longer be in the chemical industry, but in the pest control business.

The state has considerable interest in normative economic decision models for agricultural pest control at several different levels. At the level of the national planning agency, it is concerned with the solution of the model for social cost-benefit analysis, Equation 4.2 on page 122. This will indicate whether national investment in agricultural pest control is worthwhile compared with alternative investments. It will also indicate whether or not the net social benefit might be increased even further if the state interfered more in the operation of the free-market system governing pesticide development and use *e.g.* by introducing subsidies to reduce the transfer price of the pesticide to the farmer and encourage its use or taxes to penalise the pesticide manufacturer and the farmer for any external diseconomies associated with pesticide manufacture or use but not considered sufficiently distressing to warrant legislative control. As shown in Chapter 4, social cost-benefit analysis involves the summation of the results of many separate farm-level decisions: it pre-supposes the availability of an analytical model of pesticide use at farm-level. The state is also directly concerned that farmers use pesticides wisely (*i.e.* in accordance with rational normative economic decision models) since both under-use and over-use represent a waste of national resources as well as private ones.

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The national agricultural research agency should be allocating research budgets according to the potential usefulness of the data obtained. If research for pest control were performed within an analytical framework such as that outlined in Section 5.3, the potential usefulness of alternative projects would be more readily appreciated and the allocation of the research budget adjusted accordingly. It would also preclude the funding of esoteric projects of little direct relevance to farm-level decision problems in the real world. It would even be easier (hence cheaper) to monitor the research findings of the pesticide manufacturer since some of the critical parameters defined by the model (e.g. the effective kill achieved by pesticide application) are much more stable than the yield response realised in experimental trials.

6.2 Objections to the use of models

There are three general types of objection to the development and use of economic decision models for agricultural pest control: (1) that they are too complex, (2) that they are too simple, and (3) that they are irrelevant.

The accusation that the models presented here are too complex is difficult to appreciate. It is the system which they describe that is involved. The appearance of complexity helps one to understand the intricate inter-dependencies that obtain amongst various aspects of the natural world, and between these and the humdrum world of economic reality. To say that these models are complex is to admit their realism.

The contrary accusation, that the models are too simple, is almost as difficult to appreciate. I recommend the following quotation from Bourke (1970):-

"The main problem is to steer a safe course between the Scylla of stripping the model to a stark simplicity which throws out the baby with the bath water, and the Charybdis of clogging the machinery with irrelevancies which stop just short of the kitchen sink...

"It can be argued that, at least at this stage of the game, simple models handled in an enlightened way can yield at least as good results in practical disease predictions as complex models with inflexible characteristics - apart perhaps from the satisfaction, in difficult seasons, of being wrong for more sophisticated reasons."

To say that these models are too simple is to admit, in so far as they do work, that they are good models.

The objection that economic decision models are irrelevant, because farmers do not make their decisions in this way, is based on a mis-understanding. I have not tried to describe the way in which farmers make decisions, only to indicate how we can help them to make better ones. To say that these models are irrelevant is to claim that technological economics has nothing useful to contribute. I can not allow that this is so.

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6.3 Some extensions to the use of analytical models

In Chapter 3, an analytical model was developed of the use of a single pesticide application to control an air-borne pest, *Erysiphe graminis* f.sp. *hordei* on spring barley in the U.K.. The barley powdery mildew system is comparatively straightforward to analyse in this way, as well as being of topical interest and extensively documented: (1) powdery mildew occurs regularly throughout the country, (2) it is readily controlled by the single application of a chemical mildewcide, (3) *Erysiphe* is an obligate parasite with no alternative host, and (4) the host crop, barley, is widely grown (see Appendix 1.1), it can be stored, and traded abroad (*cf*. page 119). These are all simplifications which may not apply in other disease triangles[1].

If the pest occurs only infrequently, or if the yield loss is not directly proportional to the potential yield that year, then pest control may both increase the expected yield and decrease the time variance of the yield. Pest control would then be included automatically in the efficient portfolios of crop varieties according to the decision model developed in Chapter 2 if the expected value of the increase in gross margin exceeded the cost of pesticide application.

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[1] disease triangle: pest + host + environment (see Van der Plank, 1972).

This will be so with facultative (especially wound) parasites which attack the crop when the potential yield that year is already low because the plants themselves are debilitated.

Where the pest has an alternative host (another plant species in the case of an obligate parasite, the soil in the case of a soil-borne facultative parasite), there may be a substantial reservoir of inoculum not treated by a pesticidal spray applied to the host crop. This is likely to make the definition both of the pest population growth rate and of the proportional kill achieved by pesticide application rather more difficult.

With soil-borne pests, the benefits of control are only realised in successive years after the initial application of an eradication programme such as complete soil sterilisation; these must be discounted back to the time of the decision (at the farmer's opportunity cost of capital) and summed for comparison with the cost of control. There may be difficulty in specifying the rate at which the soil is re-infested.

In many pest control situations, more than one spray application is included in the annual spray programme. If the programme is to be applied routinely, then the decision model described in Chapter 2 may be used to assess its value. The identification of an optimal spray programme will require the use of marginal analysis as described in Chapter 1, but not in the simple way suggested by Hillebrandt (1959) and by Hall and Norgaard (1973) since successive increments of pest control are spaced out through time and operate under different conditions of both host crop and pest development and of weather. The dose rate at each application, and the number and timing of the applications, may all be important decision variables. Just as in Chapter 3, where I tried to show that the time of pesticide application can be a decision variable depending on the way in which the pesticide works and on how the growth rate of the pest population varies over the growing season, mathematical simulation can be used to identify an optimal spray programme.[1]

It will also be necessary to study the effect of interaction between the pay-off from pest control and that from other agricultural inputs *e.g.* nitrogen application.

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[1] Multiple treatment models have been considered by Chatterjee (1973), Hueth and Regev (1974), and Talpaz and Borosh (1974). In all three papers a method of solution is indicated, but only in the last named are the functions involved stated explicitly and any numerical computation performed on even a semi-realistic pest control system, the use of pesticides on cotton.

6.4 Summary and conclusion

In Chapter 2, I have shown how technological economics can be used to develop an empirical basis for the farm-level choice of a portfolio of different crop varieties, with or without an additional routine for pest control.

In Chapter 3, the use of mathematical simulation to analyse the problem of whether or not to use pest controls in response to the appearance of the pest in the crop is considered.

The economic decisions faced by a pesticide manufacturer contemplating the introduction of a new pesticide, and by the state with its special responsibility to control the use of national resources, are both multi-period problems in contrast with the annual farm-level decision problems. Decision models were formulated for their solution in Chapter 4.

The value of analytical decision models as devices to regulate the experiments performed by the national agricultural research agency, to make experimental data more meaningful in terms of the real problems facing farmers, is stressed in Chapter 5.

The more general considerations, of who might be interested in economic decision models for agricultural pest control anyway, and of possible objections to the use of models, have been dealt with earlier in this chapter.

Technological economics demonstrates the necessity for developing economic decision models, and how this might be done, both to guide rational behaviour in the field and to provide a framework for agricultural research.

References

Anon. (1964)
Rep. Norfolk agric. Stn 1963-4 pp. 14-16

Anon. (1965)
Rep. Norfolk agric. Stn 1964-5 pp. 9-11

Anon. (1967)
Agric. Merch. 48
Cereal and pulse survey.

Anon. (1972)
Agric. Merch. 52 (10) 8
Cereal seeds survey.

Ayer, H.W. and G.E. Schuh (1972)
Am. J. agric. Econ. 54 557-569
Social rates of return and other aspects of agricultural research: the case of cotton research in Sao Paulo, Brazil.

BASF (1972)
Technical manual concerning the activity of tridemorph.
1971 trial results supplement.

Bauer, L. (1971)
Ph.D. thesis, Oregon State Univ., 216 pp.
University Microfilms No. 71-2463
A quadratic programming algorithm for deriving efficient farm plans in a risk setting.

Bebbington, R.M., D.H. Brooks, M.J. Geoghegan and B.K. Snell (1969)
Chemy Ind. 1969 p. 1512
Ethirimol: a new systemic fungicide for the control of cereal powdery mildews.

Bell, G.D.H. (1944)
J. agric. Sci., Camb. 34 223-228
The breeding of two-row winter barley.

Bellman, R.E. (1967)
Introduction to the mathematical theory of control processes, vol. 1
Academic Press

Belshaw, D.G.R. and M. Hall (1972)
E. Afr. J. rur. Dev. 5 (1/2) 39-71
The analysis and use of agricultural experimental data in tropical Africa.

Bieri, J., A. de Janvry and A. Schmitz (1972)
Am. J. agric. Econ. 54 801-808
Agricultural technology and the distribution of welfare gains.

Bland, B.F. (1971)
Crop production: cereals and legumes Ch. 2, pp. 63-120
Barley.
Academic Press

Bliss, C.I. (1935)
Ann. appl. Biol. 22 134-167
The calculation of the dosage-mortality curve.

Borosh, I. and H. Talpaz (1974)
Am. J. agric. Econ. 56 642-643
On the timing and application of pesticides: comment.

Bourke, P.M.A. (1970)
A. Rev. Phytopath. 8 345-370
Use of weather information in the prediction of plant disease epiphytotics.

Bradbury, F.R. (1969)
Chemy Ind. 1969 pp. 1488-1494
Technological economics.

Bradbury, F.R. and Loasby, B.J. (1974)
Proceedings of symposium of the International Atomic Energy Agency on the sterility principle for insect control, Innsbruck, July 22-26, pp.119-133
Economics of the sterility principle for insect control: some general considerations.

Britton, D.K. (1969)
Cereals in the United Kingdom 835 pp.
Pergamon Press

Brooks, D.H. (1972)
in: R.W. Marsh (Ed.), *Systemic Fungicides,* Ch. 10.1, pp. 186-205
Results in practice - I. Cereals.

Camm, B.M. (1962)
Fm Economist 10 89-98
Risk in vegetable production on a fen farm.

Carlson, G.A. (1970)
Am. J. agric. Econ. 52 (2) 216-223
A decision theoretic approach to crop disease prediction and control.

Carlson, G.A. and Castle E.N. (1972)
in: National Academy of Sciences, *Pest control: strategies for the future,* pp. 79-99
Economics of pest control.

Chatterjee, S. (1973)
Biometrics 29 727-734
A mathematical model for pest control.

Bradbury, F.R. (1969)
Chemy Ind. 1969 pp. 1488-1494
Technological economics.

Bradbury, F.R. and Loasby, B.J. (1974)
Proceedings of symposium of the International Atomic Energy Agency on the sterility principle for insect control, Innsbruck, July 22-26, pp.119-133
Economics of the sterility principle for insect control: some general considerations.

Britton, D.K. (1969)
Cereals in the United Kingdom 835 pp.
Pergamon Press

Brooks, D.H. (1972)
in: R.W. Marsh (Ed.), *Systemic Fungicides,* Ch. 10.1, pp. 186-205
Results in practice - I. Cereals.

Camm, B.M. (1962)
Fm Economist 10 89-98
Risk in vegetable production on a fen farm.

Carlson, G.A. (1970)
Am. J. agric. Econ. 52 (2) 216-223
A decision theoretic approach to crop disease prediction and control.

Carlson, G.A. and Castle E.N. (1972)
in: National Academy of Sciences, *Pest control: strategies for the future,* pp. 79-99
Economics of pest control.

Chatterjee, S. (1973)
Biometrics 29 727-734
A mathematical model for pest control.

Colman, D. (1972)
The United Kingdom cereal market 191 pp.
Manchester U.P.

Conway, G.R. and G. Murdie (1972)
in: J.N.R. Jeffers (Ed.), *Mathematical models in ecology*, pp. 195-213
Population models as a basis for pest control.

Cran, J.A. (1961)
M.Sc. dissertation, Cambridge Univ.
Calculating optimum farm plans.

Currie, J.M., J.A. Murphy and A. Schmitz (1971)
Econ. J. 81 741-799
The concept of economic surplus and its use in economic analysis.

Davidson, A. and R.B. Norgaard (1973)
EPPO Bull. 3 (3) 63-75
Economic aspects of pest control.

Davies, M.E., S.M. Weedon and T.J. Martin (1971)
Proc. 6th. Br. Insectic. Fungic. Conf. pp. 42
Studies of powdery mildew control in spring barley using chloraniformethan.

De Janvry, A. (1972)
Am. J. agric. Econ. 54 1-10
Optimal levels of fertilization under risk: the potential for corn
and wheat fertilization under alternative price policies in Argentina.

Dent, J.B. and J.R. Anderson (1971)
Systems analysis in agricultural management 394 pp.
John Wiley and Sons

Dillon, J.L. (1971)
Rev. Mktg agric. Econ., Sydney 39 (1) 3-80
An expository review of Bernouillian decision theory in agriculture: is utility futility?

Dillon, J.L. and R.R. Officer (1971)
Fm Economist 12 31-46
Economic v. statistical significance in agricultural research and extension: a pro-Bayesian view.

Dimond, A.E., J.G. Horsfall, J.W. Heuberger and E.M. Stoddard (1941)
Bull. Conn. agric. Exp. Stn 451 635-667
Role of the dosage-response curve in the evaluation of fungicides.

Edwards, W.F., M.R. Langham and J.C. Headley (1970)
Nat. Resour. J. 10 (4) 719-741
Pesticide residues and environmental economics.

Evans, E.J. and J.H. Hawkins (1971)
Proc. 6th. Br. Insectic. Fungic. Conf. pp. 33-41
Timing of fungicidal sprays for control of mildew on spring barley.

Fiddian, W.E.H. (1970)
J. natn Inst. agric. Bot. 12 165-194
Wheat, barley and oat varieties completing primary trials in 1970.

Fiddian, W.E.H. (1971)
J. natn Inst. agric. Bot. 12 358-384
Wheat, barley and oat varieties completing primary trials in 1971.

Forrester, J.W. (1969)
Urban Dynamics 285 pp.
M.I.T. Press

Gaddum, J.H. (1933)
M.R.C. Spec. Rep. 183 46 pp.
Reports on biological standards.
III. Methods of biological assay depending on quantal response.

Ghodake, R.D., A.S. Sirohi and D. Jha (1973)
Indian J. agric. Econ. 28 (4) 92-99
Economics of the use of pesticides in cotton crop.

Gilmour, J. (1971)
Proc. 6th. Br. Insectic. Fungic. Conf. pp. 63-74
Fungicidal control of mildew on spring barley in south-east Scotland.

Gilmour, J. and R.H. Fawcett (1973)
Proc. 7th. Br. Insectic. Fungic. Conf. pp. 1-10
Risk analysis of the control of barley mildew with fungicides.

Gittinger, J.P. (1972)
Economic analysis of agricultural projects 221 pp.
Johns Hopkins Press

Gleadthorpe Experimental Husbandry Farm (1971)
in: A.D.A.S., *Results of experiments at the experimental husbandry farms 1971, Part 1 (Cereals)*, pp. 109-110

Griliches, Z. (1958)
J. polit. Econ. 66 419-431
Research costs and social returns: hybrid corn and related innovations.

Hall, D.C. and R.B. Norgaard (1973)
Am. J. agric. Econ. 55 (2) 198-201
On the timing and application of pesticides.

Hardaker, J.B. (1971)
M.A.F.F. Tech. Bull. 19 132 pp.
Farm planning by computer.

Hazell, P.B.R. (1971)
Am. J. agric. Econ. 53 53-62
A linear alternative to quadratic and semi-variance programming for farm planning under uncertainty.

Headley, J.C. and J.N. Lewis (1967)
The pesticide problem: an economic approach to public policy.
Resources for the Future Inc.

Headley, J.C. (1968)
Am. J. agric. Econ. 50 13-23
Estimating the productivity of agricultural pesticides.

Headley, J.C. (1972a)
A. Rev. Ent. 17 273-286
Economics of agricultural pest control.

Headley, J.C. (1972b)
in: National Academy of Sciences, *Pest control: strategies for the future,*
pp. 100-108
Defining the economic threshold.

Hertz, D.B. (1964)
Harv. Busin. Rev. 42 (1) 95-106
Risk analysis in capital investment.

Hillebrandt, P.M. (1959)
J. agric. Econ. 13 (4) 464-472
The economic theory of the use of pesticides.
I. The dosage response curve, the rate of application, and the area to be treated.

Hardaker, J.B. (1971)
M.A.F.F. Tech. Bull. 19 132 pp.
Farm planning by computer.

Hazell, P.B.R. (1971)
Am. J. agric. Econ. 53 53-62
A linear alternative to quadratic and semi-variance programming for farm planning under uncertainty.

Headley, J.C. and J.N. Lewis (1967)
The pesticide problem: an economic approach to public policy.
Resources for the Future Inc.

Headley, J.C. (1968)
Am. J. agric. Econ. 50 13-23
Estimating the productivity of agricultural pesticides.

Headley, J.C. (1972a)
A. Rev. Ent. 17 273-286
Economics of agricultural pest control.

Headley, J.C. (1972b)
in: National Academy of Sciences, *Pest control: strategies for the future,* pp. 100-108
Defining the economic threshold.

Hertz, D.B. (1964)
Harv. Busin. Rev. 42 (1) 95-106
Risk analysis in capital investment.

Hillebrandt, P.M. (1959)
J. agric. Econ. 13 (4) 464-472
The economic theory of the use of pesticides.
I. The dosage response curve, the rate of application, and the area to be treated.

Hillebrandt, P.M. (1960)
J. agric. Econ. 14 (1) 52-61
The economic theory of the use of pesticides.
II. Uncertainty.

Home-grown Cereals Authority (1972)
Seventh Annual Report 126 pp.
H.M.S.O.

Hueth, D. and U. Regev (1974)
Am. J. agric. Econ. 56 543-552
Optimal agricultural pest management with increasing pest resistance.

James, C. (1971)
Canada Dept. of Agric. Publ. No. 1458 80 pp.
A manual of assessment keys for plant diseases.

James, W.C. (1974)
A. Rev. Phytopath. 12 27-48
Assessment of plant diseases and losses.

Jenkins, G. (1970)
N.A.A.S. Quart. Rev. 90 74-83
Winter barley in Britain.

Jenkyn, J.F. and A. Bainbridge (1974)
Ann. appl. Biol. 76 269-279
Disease gradients and small plot experiments on barley mildew.

Jones, J.G.W. (Ed.) (1970)
The use of models in agricultural and biological research.
Grassland Research Institute

King, J.E. (1972)
Pl. Path. 21 23-35
Surveys of foliar diseases of spring barley in England and Wales 1967-70.

King, J.E. (1973)
Proc. 7th. Br. Insectic. Fungic. Conf. pp. 771-780
Cereal foliar disease surveys.

Kradel, J., E.H. Pommer and H. Effland (1969)
Proc. 5th. Br. Insectic. Fungic. Conf. pp. 16-19
Response of barley varieties to the control of powdery mildew with cyclomorph and tridemorph.

Land, A. and S. Powell (1973)
Fortran codes for mathematical programming 249 pp.
John Wiley and Sons

Land, A.H., S. Powell, N.J. Paulley and M.R. Wigan (1974)
Transport and Road Research Laboratory Suppl. Rep. 17UC 42 pp.
MPCODE: a versatile linear and quadratic mathematical programming system.

Large, E.C. (1954)
Pl. Path. 3 128-129
Growth stages in cereals. Illustrations of the Feekes scale.

Large, E.C. and D.A. Doling (1962)
Pl. Path. 11 47-57
The measurement of cereal mildew and its effect on yield.

Last, F.T. (1963)
Pl. Path. 12 132-133
Effect of temperature on cereal powdery mildews.

Lipton, M. (1968)
J. Dev. Stud. 4 327-351
The theory of the optimising peasant.

Little, I.M.D. and J.A. Mirrlees (1974)
Project appraisal and planning for developing countries 388 pp.
Heinemann Educational Books

Little, R. and J.K. Doodson (1972)
J. natn Inst. agric. Bot. 12 447-455
The reaction of spring barley cultivars to mildew, their disease resistance rating and an interim report on their yield response to mildew control.

Mao, J.C.T. and C.E. Särndal (1966)
Mgmt Sci. 12 (8) B323-B333
A decision theory approach to portfolio selection.

Markowitz, H.M. (1959)
Cowles Foundation Monograph No. 16 344 pp.
Portfolio Selection.

Marshall, J. (1972)
Fisons Agricultural and Technical Information 1972 pp. 36-40
Cereal mildew and lucel.

Martin, H. (Ed.) (1971)
Pesticide Manual, 2nd. edition
British Crop Protection Council

McFarquhar, A.M.M. (1961)
J. agric. Econ. 14 552-563
Rational decision making and risk in farm planning - an application of quadratic programming in British arable farming.

Mellor, J.W. (1966)
The economics of agricultural development 402 pp.
Cornell U.P.

Merrett, A.J. and A. Sykes (1973)
The finance and analysis of capital projects, 2nd. edition 573 pp.
Longman

Miln Masters (1973)
Cereal Yearbook 1973 16 pp.

Moseman, A.H. (1970)
Building agricultural research systems in the developing nations 137 pp.
Agricultural Development Council

Musalem, A.R. (1974)
Am. J. agric. Econ. 56 837-839
Social rates of return and other aspects of agricultural research: the case of cotton research in Sao Paulo, Brazil: comment.

National Institute of Agricultural Botany (1974)
Farmer's Leaflet No. 8 17 pp.
Recommended varieties of cereals.

Norton, G.A. and D.E. Evans (1974)
Bull. ent. Res. 63 619-627
The economics of controlling froghopper on sugar-cane in Trinidad.

Ordish, G. (1952)
Untaken Harvest
Constable

Ordish, G. and D. Dufour (1969)
A. Rev. Phytopath. 7 31-50
Economic bases for protection against plant diseases.

Peterson, W.L. (1967)
J. Fm Econ. 49 656-669
Return to poultry research in the United States.

Polley, R.W. and J.E. King (1973)
Pl. Path. 22 11-16
A preliminary proposal for the detection of barley mildew infection periods.

Pommer, E.H., S. Otto and J. Kradel (1969)
Proc. 5th. Br. Insectic. Fungic. Conf. pp. 347-353
Some results concerning the systemic action of tridemorph.

Pradhan, S. (1971)
Indian J. Ent. 33 (3) 233-259
In tropics, protection research more needed than production research.

Pratt, R. (1943)
Bull. Torrey bot. Club 70 (4) 378-385
Influence of temperature on the infection of wheat by the powdery mildew Erysiphe graminis tritici.

Robinson, R.A. (1971)
Rev. Pl. Path. 50 (5) 233-239
Vertical resistance.

Rosser, W.R. (1969)
Proc. 5th. Br. Insectic. Fungic. Conf. pp. 20-24
Spray timing and the control of mildew in spring barley.

Schlaifer, R. (1959)
Probability and statistics for business decisions 732 pp.
McGraw-Hill

Schmitz, A. and D. Seckler (1970)
Am. J. agric. Econ. 52 569-577
Mechanised agriculture and social welfare: the case of the tomato harvester.

Shackle, G.L.S. (1970)
Expectation, enterprise and profit 160 pp.
George Allen and Unwin

Shoemaker, C. (1973a)
Mathl Biosci. 16 143-175
Optimization of agricultural pest management.
I. Biological and mathematical background.

Shoemaker, C. (1973b)
Mathl Biosci. 17 357-365
Optimization of agricultural pest management.
II. Formulation of a control model.

Shoemaker, C. (1973c)
Mathl Biosci. 18 1-22
Optimization of agricultural pest management.
III. Results and extensions of a model.

Southwood, T.R.E. and G.A. Norton (1973)
in: P.W. Geier, L.R. Clark, D.J. Anderson and H.A. Nix (Ed.),
Ecol. Soc. Aust. (memoirs 1), Insects: studies in population management
pp. 168-184
Economic aspects of pest management strategies and decisions.

Spearman, C. (1904)
Am. J. Psychol. 15 72-101
The proof and measurement of association between two things.

Stapel, C. and J.E. Hermansen (1968)
Tidsskr. f. Landøkon. 155 218-230
Forbud mod dyrkning af vinterbyg - en farlig afgrøde for vårbyg.

Stapel, C. and J.E. Hermansen (1972)
Tolvmandsbladet 4 205-216
(Mildew in cereals in Denmark with special reference to 1971.)

Stern, V.M., R.F. Smith, R. van den Bosch and K.S. Hagen (1959)
Hilgardia 29 (2) 81-101
The integrated control concept.

Stern, V.M. (1973)
A. Rev. Ent. 18 259-280
Economic thresholds.

Stovall, J.G. (1966)
J. Fm Econ. 48 1575-1579
Income variation and selection of enterprises.

Strong, W.M. (1970)
Soc. Chem. Ind. Monograph No. 36 pp. 33-41
Pesticides as an agricultural input.

Talpaz, H. and I. Borosh (1974)
Am. J. agric. Econ. 56 769-775
Strategy for pesticide use: frequency and applications.

Thomson, K.J. and P.B.R. Hazell (1972)
Am. J. agric. Econ. 54 503-506
Reliability of using the mean absolute deviation to derive efficient
E,V farm plans.

Tintner, G. and M. Patel (1966)
J. Fm Econ. 48 704-710
Evaluation of Indian fertilizer projects: an application of consumer's
and producer's surplus.

Unterstenhöfer, G. (1963)
Pflanzenschutz Nachrichten 16 81-164
The basic principles of crop protection field trials.

United States Department of Agriculture (1972)
PA-408 27 pp.
Federal crop insurance - a description.

Van der Plank, J.E. (1963)
Plant diseases: epidemics and control 349 pp.
Academic Press

Van der Plank, J.E. (1968)
Disease resistance in plants 206 pp.
Academic Press

Van der Plank, J.E. (1972)
in: National Academy of Sciences, *Pest control: strategies for the future*
pp. 109-118
Basic principles of ecosystems analysis.

Waggoner, P.E. (1968)
in: W.P. Lowry (Ed.), *Proc. 28th. ann. Biol. Coll., Corvallis: Biometeorology*
Weather and the rise and fall of fungi.

Waggoner, P.E., J.G. Horsfall and R.J. Lukens (1972)
Bull. Conn. agric. Exp. Stn 729 84 pp.
EPIMAY: a simulator of southern corn leaf blight.

Ward, S.V. and J.G. Manners (1974)
Trans. Brit. mycol. Soc. 62 (1) 119-128
Environmental effects on the quantity and viability of conidia
produced by Erysiphe graminis.

Watt, K.E.F. (1966)
Systems analysis in ecology 276 pp.
Academic Press

Watt, K.E.F. (1970)
in: R.L. Rabb and F.E. Guthrie (Ed.), *Concepts of pest management* pp. 71-79
The systems point of view in pest management.

Wilcoxon, F. and S.E.A. McCallan (1939)
Contr. Boyce Thompson Inst. Pl. Res. 10 329-338
Theoretical principles underlying laboratory toxicity tests of fungicides.

Wolfe, M.S. (1968)
Pl. Path. 17 82-87
Physiologic race changes in barley mildew 1964-67.

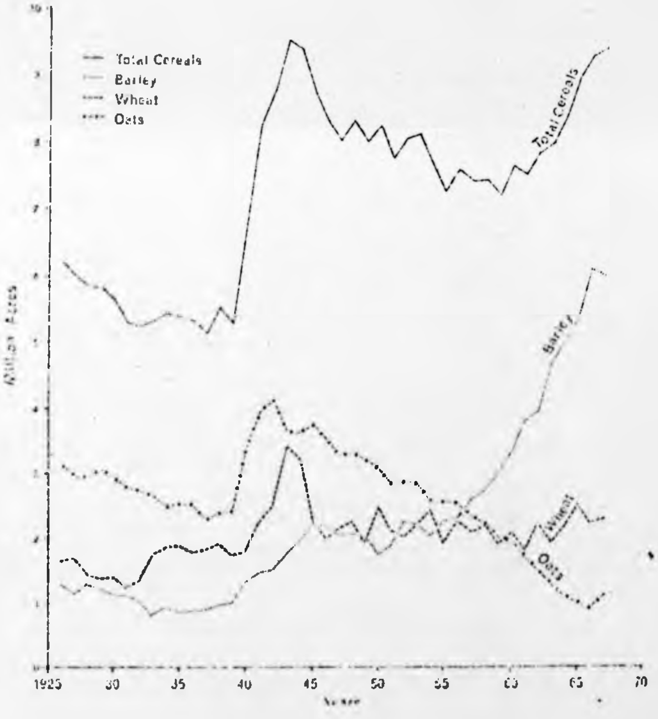
Yarham, D.J. and D. Pye (1969)
Proc. 5th. Br. Insectic. Fungic. Conf. pp. 25-33
Winter barley as a source of inoculum for spring barley crops.

Yarham, D.J., E.T.G. Bacon and C.F. Hayward (1971)
Proc. 6th. Br. Insectic. Fungic. Conf. pp. 15-25
The effect on mildew development of the widespread use of fungicide
on winter barley.

Yarwood, C.E., S. Sidky, M. Cohen and V. Santilli (1954)
Hilgardia 22 (17) 603-622
Temperature relations of powdery mildews.

Appendix 1.1: The distribution of the barley acreage in the United Kingdom in June, 1967 (after Britton, 1969)

Appendix 1.2: The acreages of barley, wheat, oats, and total cereals in the United Kingdom, 1926-1967 (after Britton, 1969)



Appendix 1.3: The United Kingdom production of barley, wheat, oats, and total cereals, 1961-1972 (after Home-grown Cereals Authority, 1972)

UNITED KINGDOM PRODUCTION
WHEAT, BARLEY, OATS, RYE AND MIXED CORN

July/June Years

Acreage — Thousand Acres
Yield — Cwts. per Acre
Production — Thousand Tons

		1961/62	1962/63	1963/64	1964/65	1965/66	1966/67	1967/68	1968/69	1969/70	1970/71	1971/72 (a)	1972/73
WHEAT	Acreage ...	1,827	2,256	1,928	2,206	2,535	2,238	2,305	2,417	2,059	2,495	2,710	
	Yield	28·2	34·7	31·1	33·8	32·4	30·6	33·3	28·2	32·2	33·4	35·0	
	Production ...	2,573	3,911	2,998	3,733	4,105	3,420	3,841	3,414	3,311	4,169	4,748	
BARLEY	Acreage ...	3,828	3,987	4,713	5,032	5,395	6,130	6,027	5,933	5,962	5,542	5,654	
	Yield	26·0	29·0	28·0	29·4	29·9	28·0	30·1	27·4	28·6	26·7	29·9	
	Production ...	4,974	5,773	6,599	7,404	8,062	8,586	9,069	8,140	8,527	7,410	8,441	
OATS	Acreage ...	1,730	1,515	1,291	1,123	1,009	904	1,010	940	942	926	895	
	Yield	21·1	23·1	22·3	23·6	24·0	24·4	27·0	25·6	27·3	25·9	30·1	
	Production ...	1,822	1,747	1,438	1,325	1,213	1,102	1,364	1,205	1,287	1,198	1,346	
TOTAL	Acreage ...	7,385	7,758	7,932	8,361	8,939	9,272	9,342	9,291	8,963	8,963	9,259	
	Production ...	9,369	11,431	11,035	12,461	13,381	13,108	14,274	12,759	13,125	12.777	14,535	

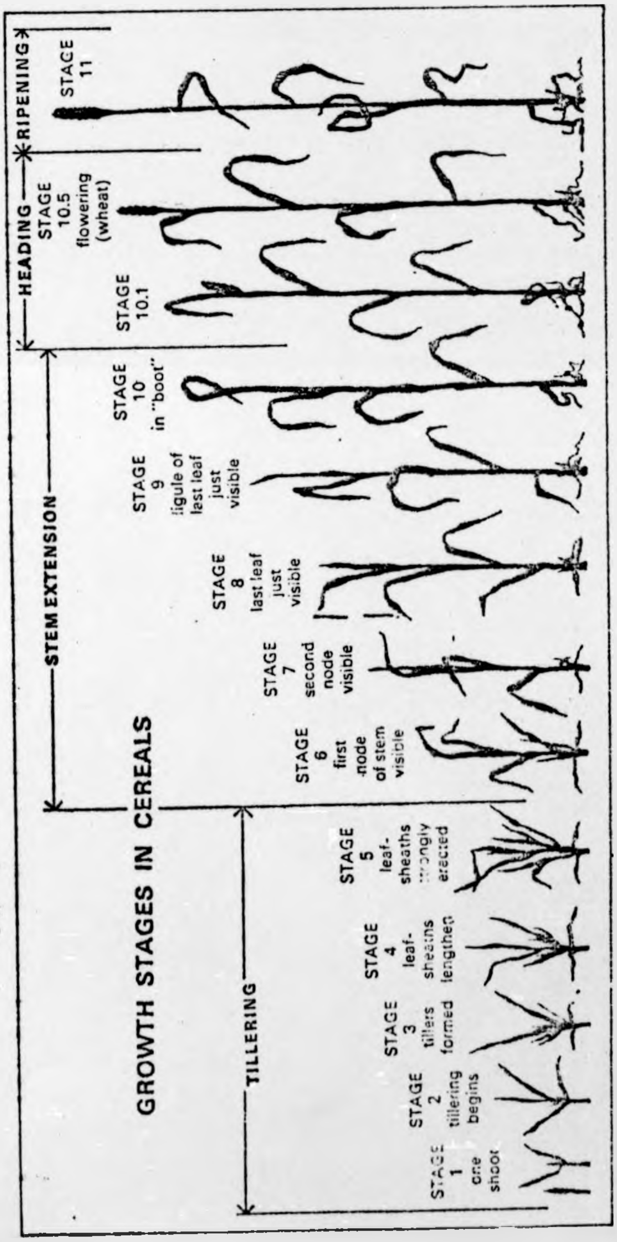
Appendix 1.4: The sales of barley seed in tons, 1969/70 to 1971/72 (after Anon., 1972; Home-grown Cereals Authority, 1972)

variety	1969/70	1970/71	1971/72
Akka	1,161	1,480	474
Astrix	-	-	83
Banba	33	57	-
Beorna	60	32	-
Berac	-	1,200	6,015
Bonus	140	152	60
Brevia	320	145	-
Clermont	-	2,039	1,317
Crusader	1,242	1,009	119
Dea	41	19	-
Deba Abed	14,150	9,048	4,515
Delisa	192	84	-
Emir	183	81	52
Freegold	-	28	387
Freja	187	122	59
Gerkra	410	2,022	2,591
Golden Promise	17,229	22,598	19,233
Hassan	-	22	155
Hunter	68	55	-
Imber	-	675	3,838
Impala	1,929	408	69
Ingrid	23	24	-
Inis	174	179	-
Julia	17,015	37,938	58,952
Lofa Abed	-	509	5,679

continued...

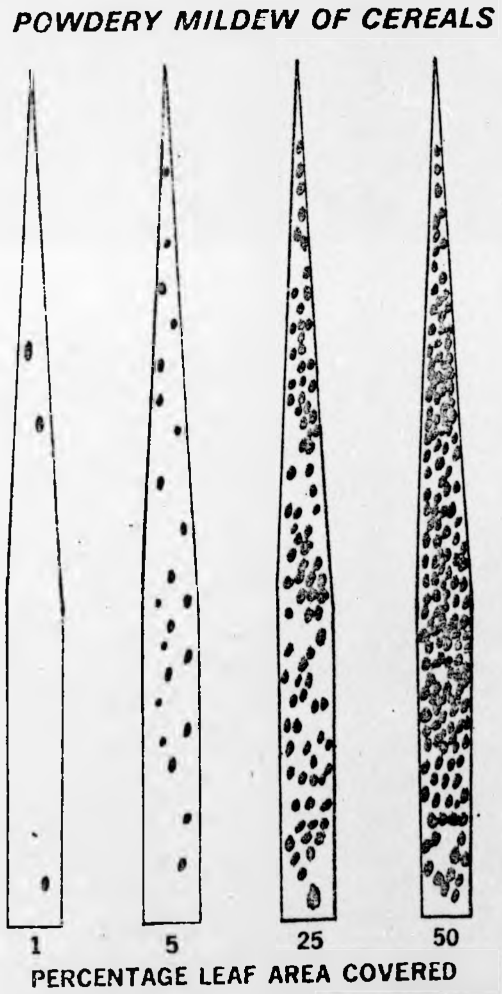
variety	1969/70	1970/71	1971/72
Malta	383	1,202	1,455
Mari	51	33	-
Maris Badger	591	122	-
Maris Baldric	989	790	114
Maris Otter	13,528	16,202	14,113
Maythorpe	6	29	-
Midas	846	10,519	8,374
Mirra	-	41	404
Mosano	2,516	2,146	1,932
Nackta	-	35	-
Pallas	687	1,309	457
Pella	416	574	868
Pioneer	34	12	-
Pirkka	7	462	-
Proctor	32,081	30,540	25,049
Rika	1,249	1,144	336
Ruby	2,093	2,953	1,687
Sabarlis	-	77	-
Senta	4,659	6,397	3,909
Sultan	72,250	54,581	11,397
Tern	1,005	1,273	3,241
Union	107	9	-
Vada	18,479	33,556	30,312
Wing	-	-	18
Ymer	11,698	13,384	7,243
Zephyr	48,765	39,004	22,445
others	190	256	159
total	267,187	296,576	237,293

Appendix 1.5: An illustration of the Large-Feekes scale for growth stages in cereals (after Large, 1954)



Feekes-Large Scale (Reproduced from Plant Pathology 3, 1954 by permission of Her Britannic Majesty's Stationery Office.) CROWN COPYRIGHT.

Appendix 1.6: A disease assessment key for cereal powdery mildew (after James, 1971)



Appendix 2: The chemical mildewcides

Ethirimol

Ethirimol is the common name for 5-butyl-2-ethylamino-6-hydroxy-4-methylpyrimidine. It was introduced by Plant Protection Ltd. in 1968 as a selective systemic fungicide under the trademark "Milstem" and the protection of BP 1,182,584. It is described by Bebbington *et al*. (1969), Martin (1971), Brooks (1972), and in the technical data sheet and information bulletins available from Plant Protection.

Ethirimol is active against powdery mildew fungi on grasses, including cereals, especially when applied to the soil in the root zone from where it can be taken up by the roots and translocated in the xylem. It is also active as a foliar spray but, since it does not move in the phloem, unsprayed growth is not protected. The seed dressing is ineffective in organic soils.

Tridemorph

Tridemorph is the common name for 2,6-dimethyl-4-tridecylmorpholine which was introduced in 1969 by Badische Anilin- & Soda-Fabrik (BASF) under the trademark "Calixin". Its fungicidal properties are described by Kradel, Pommer and Effland (1969), Pommer, Otto and Kradel (1969), and BASF (1972).

Like ethirimol, tridemorph is a systemic fungicide but is usually applied as a spray. It has controlled cereal mildews when applied at ½ pint in not less than 25 gal. water/acre, which gives protective action for 3 to 4 weeks when a second application may be made.

Chloraniformethan

Chloraniformethan is the common name for 1-(3,4-dichloroanilino)-1-formylamino-2,2,2-trichloroethane, introduced by Bayer under the trademark "Milfaron". Like ethirimol and tridemorph, it is a systemic fungicide, applied as a spray. It is described by Davies *et al*. (1971).

Tetrachloroquinoxaline

Tetrachloroquinoxaline was patented by Fisons in 1962. Its activity against barley powdery mildew was demonstrated in 1963/4 but the material was shelved at that time because resistant varieties were achieving acceptable control. It was re-examined over the period 1968 to 1971, and marketed under the trademark "Lucel" in 1972. It is non-systemic, and is described by Marshall (1972).

Appendix 3: /SPRAY/

/SPRAY/ is written in Fortran IV. The subroutines, DISTR, RANDR, SAMPL, HISTO, ADDTO and WRITE, are based on the corresponding SIMON subroutines (see S.C. Mathewson, 1970: *A programming manual for SIMON simulation, in Fortran,* Management Engineering Section, Imperial College of Science and Technology), re-written for use on the Elliott 4100 machine.

```
C /SPRAY/ IS A MONTE CARLO ROUTINE WHICH ESTIMATES THE FINANCIAL
C RETURN TO SPRAY APPLICATION AGAINST BARLEY POWDERY MILDEW CAUSED BY
C THE FUNGUS /ERYSIPHE GRAMINIS F. SP. HORDEI/, GIVEN DATA ABOUT THE
C LOCATION, THE GROWTH STAGE OF THE CROP, THE LEVEL OF DISEASE IN THE
C CROP (ASSUMED TO BE 1% AT THE TIME THE DECISION TO SPRAY HAS TO BE
C MADE), APPLICATION COSTS, THE PRICE AND REQUIRED DOSAGE OF THE
C PESTICIDE, THE ESTIMATED YIELD OF THE CROP IN THE ABSENCE OF DISEASE,
C AN ESTIMATE OF THE RESISTANCE OF THE CROP, AN ESTIMATE OF THE TIME
C THE CROP WILL NEED TO REACH GS9 ON THE LARGE-FEEKES SCALE, THE
C ESTIMATED PRICE OF THE CROP AT THE TIME OF SALE, AND THE
C ESTIMATED TIME OF SALE.
C VERSION 8.3.75
      DIMENSION I1(21),I2(21),I3(21),I4(21),I5(21),I6(21),
     &          KILL(21),ICROP(21),IBETA(21),IVSAC(21),ITH(21),
     &          N1(21),N2(21),
     &          GS(10),WGR(10)
      DOUBLE PRECISION AJRAND
      INTEGER SAMPL
      LOGICAL SPRAY, L1
      AJRAND = 2.3269396OD8
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```
      B = 0.002
C /K/ IS LOCATION REFERENCE
      READ (7,10) K
   10 FORMAT (I3)
C /GS(I)/ IDENTIFIES GROWTH STAGE OF HOST ON LARGE-FEEKES SCALE
      READ (7,15) (GS(I), I = 1,6)
   15 FORMAT (6F4.1)
C /Z/     IS FIXED COST OF SPRAYING (EXCLUDING TRACK DAMAGE) IN
C £ PER ACRE
C /ALPHA/ IS PESTICIDE PRICE IN £ PER UNIT
C /RATE/  IS PESTICIDE APPLICATION RATE IN UNITS PER ACRE
      READ (7,20) Z,ALPHA,RATE
   20 FORMAT (3F4.2)
      COST = Z + ALPHA*RATE
C /J1/   IS WEEK NO. WHEN DISEASE REACHES 1% ON 3RD LEAF
C /J/    IS WEEK NO. WHEN SPRAY IS TO BE APPLIED
C /PER/  IS TIME TO SALE OF CROP IN WEEKS
C /NSIM/ IS NUMBER OF SIMULATED SEQUENCES REQUIRED
      READ (7,25) J1,J,PER,NSIM
   25 FORMAT (2I2,F4.1,I3)
      PERYR = PER/52.
C /I1 TO I6/ ARE WEEKLY GROWTH RATES, A = 0.5
      CALL DISTR(I1,100)
      CALL DISTR(I2,200)
      CALL DISTR(I3,300)
      CALL DISTR(I4,400)
      CALL DISTR(I5,500)
      CALL DISTR(I6,600)
C /KILL/  IS ESTIMATED PER CENT KILL IF PESTICIDE IS APPLIED
      CALL DISTR(KILL,010)
C /ICROP/ IS ESTIMATED CROP YIELD IF NO DISEASE OCCURS (IN CWT
C PER ACRE)
      CALL DISTR(ICROP,020)
C /IBETA/ IS ESTIMATED CROP PRICE IN PENCE PER CWT
      CALL DISTR(IBETA,030)
```

```
      B = 0.002
C /K/ IS LOCATION REFERENCE
      READ (7,10) K
   10 FORMAT (I3)
C /GS(I)/ IDENTIFIES GROWTH STAGE OF HOST ON LARGE-FEEKES SCALE
      READ (7,15) (GS(I), I = 1,6)
   15 FORMAT (6F4.1)
C /Z/     IS FIXED COST OF SPRAYING (EXCLUDING TRACK DAMAGE) IN
C £ PER ACRE
C /ALPHA/ IS PESTICIDE PRICE IN £ PER UNIT
C /RATE/  IS PESTICIDE APPLICATION RATE IN UNITS PER ACRE
      READ (7,20) Z,ALPHA,RATE
   20 FORMAT (3F4.2)
      COST = Z + ALPHA*RATE
C /J1/   IS WEEK NO. WHEN DISEASE REACHES 1% ON 3RD LEAF
C /J/    IS WEEK NO. WHEN SPRAY IS TO BE APPLIED
C /PER/  IS TIME TO SALE OF CROP IN WEEKS
C /NSIM/ IS NUMBER OF SIMULATED SEQUENCES REQUIRED
      READ (7,25) J1,J,PER,NSIM
   25 FORMAT (2I2,F4.1,I3)
      PERYR = PER/52.
C /I1 TO I6/ ARE WEEKLY GROWTH RATES, A = 0.5
      CALL DISTR(I1,100)
      CALL DISTR(I2,200)
      CALL DISTR(I3,300)
      CALL DISTR(I4,400)
      CALL DISTR(I5,500)
      CALL DISTR(I6,600)
C /KILL/  IS ESTIMATED PER CENT KILL IF PESTICIDE IS APPLIED
      CALL DISTR(KILL,010)
C /ICROP/ IS ESTIMATED CROP YIELD IF NO DISEASE OCCURS (IN CWT
C PER ACRE)
      CALL DISTR(ICROP,020)
C /IBETA/ IS ESTIMATED CROP PRICE IN PENCE PER CWT
      CALL DISTR(IBETA,030)
```

```
C /IVSAC/ IS ESTIMATED VALUE OF /A/ TIMES 100
      CALL DISTR(IVSAC,040)
C /ITH/   IS ESTIMATED END-POINT IN DAYS FROM MAY 1
      CALL DISTR(ITH,050)
C HISTOGRAM N1 REGISTERS THE RATE OF RETURN IN PER CENT PER ANNUM
      CALL HISTO(N1,-100,100)
C HISTOGRAM N2 REGISTERS THE BENEFIT-COST RATIO
      CALL HISTO(N2,0,1)
      WRITE (2,27)
   27 FORMAT (1H1,50X,7H/SPRAY/)
      WRITE (2,28)
   28 FORMAT (1H0,2X,4HKILL,5X,5HYIELD,6X,5HPRICE,6X,
     &        1HA,6X,9HEND-POINT,4X,4HGAIN//)
      DO 40 N = 1,NSIM
      G = 0.
      X = 1.
      DAMAGE = 0.
      XKILL = SAMPL(KILL,AJRAND)/100.
      CROP = SAMPL(ICROP,AJRAND)
      BETA = SAMPL(IBETA,AJRAND)/100.
      A = SAMPL(IVSAC,AJRAND)/100.
      TH = SAMPL(ITH,AJRAND)
      WGR(1) = SAMPL(I1,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      WGR(2) = SAMPL(I2,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      WGR(3) = SAMPL(I3,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      WGR(4) = SAMPL(I4,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      WGR(5) = SAMPL(I5,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      WGR(6) = SAMPL(I6,AJRAND)*(10.**(-2.))*EXP(A)/EXP(0.5)
      L1 = .FALSE.
      DO 30 I = J1,6
C /SPRAY/ INDICATES WHETHER A SPRAY IS TO BE APPLIED IN WEEK /I/
      SPRAY = J.EQ.I
C /L1/    INDICATES WHETHER A SPRAY HAS BEEN APPLIED
      IF (SPRAY) L1 = .TRUE.
C CHECK END-POINT
```

```
      T = TIME(I,TH)
C CHECK DISEASE INDEX
      TEST = X*WGR(I)*EXP(T)/EXP(7.)
      IF (TEST.GE.100.) TEST = 100.
C UPDATE DAMAGE INDEX OFFSET BY SPRAYING
      IF (L1.AND.X.LT.100.) G = G + 0.5*X*XKILL*T*(TEST/X + 1.)
      IF (L1.AND.X.GE.100.) G = G + 0.5*T*100.*XKILL
      IF (X.GE.100.) GO TO 33
C UPDATE DISEASE INDEX ON UNSPRAYED CROP
      X = X*WGR(I)
      IF (X.GE.100.) X = 100.
C CHECK FOR WHEELING DAMAGE
      IF (SPRAY) DAMAGE = TRACK(GS,I,CROP)
   30 CONTINUE
   33 GAIN = (G*B*CROP - DAMAGE)*BETA
      WRITE (2,35) XKILL,CROP,BETA,A,TH,GAIN
   35 FORMAT (1X,6(F6.2,4X))
      RR = (GAIN - COST)*100./(COST*PERYR)
      IRR = RR
      CALL ADDTO(N1,IRR)
      IBCR = IFIX(GAIN/COST)
      CALL ADDTO(N2,IBCR)
   40 CONTINUE
      WRITE (2,45)
   45 FORMAT (1H1,50X,7H/SPRAY/)
      WRITE (2,50) K
   50 FORMAT (1H0,8HLOCATION,2X,I3)
      WRITE (2,55) J1,J
   55 FORMAT (1H0,32HDISEASE INDEX REACHES 1% IN WEEK,2X,I2,
     &        10X,21HSPRAY APPLIED IN WEEK,2X,I2)
      WRITE (2,60) COST
   60 FORMAT (1H0,6HCOST =,2X,1H£,F5.2,2X,8HPER ACRE)
      WRITE (2,65) PER
   65 FORMAT (1H0,18HCROP TO BE SOLD IN,2X,F4.1,2X,5HWEEKS)
      WRITE (2,70)
```

```
   70 FORMAT (1H0,33X,39H% RETURN PER ANNUM TO SPRAY APPLICATION//)
      CALL WRITE (N1,1)
      WRITE (2,75)
   75 FORMAT (1H0,33X,18HBENEFIT-COST RATIO//)
      CALL WRITE (N2,2)
      STOP
      END


      FUNCTION TRACK(GS,I,CROP)
C WHEELING DAMAGE BASED ON DATA FROM GLEADTHORPE EHF (1971)
C USING A 40 FOOT SPRAY BOOM
      DIMENSION GS(10)
      IF (GS(I) - 5.) 10,20,20
   10 TRACK = 0.
      RETURN
   20 IF (GS(I) - 7.) 30,40,40
   30 TRACK = 0.66*CROP/100.
      RETURN
   40 IF (GS(I) - 10.) 50,60,70
   50 TRACK = 2.31*CROP/100.
      RETURN
   60 TRACK = 2.97*CROP/100.
      RETURN
   70 TRACK = 4.62*CROP/100.
      RETURN
      END


      FUNCTION TIME(I,TH)
      J2 = TH/7 + 1
      IF (I - J2) 10,20,30
C IF THE END-POINT COMES AFTER WEEK /I/
   10 TIME = 7.
      RETURN
```

```
C IF THE END-POINT COMES DURING WEEK /I/
   20 TIME = TH - 7*(I - 1)
      RETURN
C IF THE END-POINT COMES BEFORE WEEK /I/
   30 TIME = 0.
      RETURN
      END


      SUBROUTINE DISTR(IA,N)
      DIMENSION IA(21)
      READ (7,10) IDUM, (IA(I), I = 1,20)
   10 FORMAT (21I3)
      IF (IDUM - N) 20,30,20
   20 WRITE (2,25)
   25 FORMAT (1X,34HWRONG DATA NUMBER FOR DISTRIBUTION)
      STOP
   30 RETURN
      END


      SUBROUTINE RANDR(RAND,AJRAND)
      DOUBLE PRECISION AJRAND
      X = 1.27D2*AJRAND
      Z = X/5.36870912D8
      I = Z
      F = FLOAT(I)
      AJRAND = X - 5.36870912D8*F
      B = AJRAND/1.0D4
      I = B
      C = I
      C = C*1.0D4
      D = AJRAND - C
      E = D + 1.0D-3
      J = E
```

```
      H = J
      AJRAND = C + H
      RAND = AJRAND/5.36870912D8
      RETURN
      END


      INTEGER FUNCTION SAMPL(IA,AJRAND)
      DOUBLE PRECISION AJRAND
      DIMENSION IA(21)
      CALL RANDR(RAND,AJRAND)
      M = IFIX(100.*RAND)
      DO 10 I = 4,20,2
      IF (M - IA(I)) 20,10,10
   10 CONTINUE
   20 SAMPL = IA(I-3) + (M-IA(I-2))*(IA(I-1)-IA(I-3))/(IA(I)-IA(I-2))
      RETURN
      END


      SUBROUTINE HISTO(N,L,IW)
      DIMENSION N(21)
      DO 10 J = 1,19
   10 N(J) = 0
      N(14) = 27147
      N(21) = L
      N(20) = IW
      RETURN
      END


      SUBROUTINE ADDTO(N,IV)
      DIMENSION N(21)
      K = N(21)
      DO 30 J = 1,10
      IF (IV - K) 10,20,20
```

```
 10 N(J) = N(J) + 1
    GO TO 40
 20 K = K + N(20)
 30 CONTINUE
    N(11) = N(11) + 1
 40 N(13) = N(13) + IV
    IF (IV - N(14)) 50,60,60
 50 N(14) = IV
    GO TO 80
 60 IF (IV - N(15)) 80,80,70
 70 N(15) = IV
 80 N(18) = N(18) + 1
    RETURN
    END


    SUBROUTINE WRITE(N,IT)
    DIMENSION KK(11), N(21)
    WRITE (2,10) IT
 10 FORMAT (1X,12HHISTOGRAM NO,2X,I2)
    IF (N(18)) 20,20,40
 20 WRITE (2,30)
 30 FORMAT (1X,10HNO ENTRIES)
    GO TO 100
 40 DO 50 I = 1,10
    KK(I) = N(21) + N(20)*(I-1)
 50 CONTINUE
    WRITE (2,60) (KK(I), I = 1,10), (N(I), I = 1,11)
 60 FORMAT (1X,6HRANGES,2X,10I8/4HFREQ,11I8//)
    SUM = 0.
    DO 65 L = 1,10
    SUM = SUM + (KK(L) - 0.5*N(20))*N(L)
 65 CONTINUE
    SUM = SUM + N(11)*(KK(10) + 0.5*(N(15) - KK(10)))
    XMEAN = SUM/N(18)
```

```
      WRITE (2,70) XMEAN,N(14),N(15)
   70 FORMAT (1X,4HMEAN,2X,F8.2,10X,14HSMALLEST VALUE,2X,I6,10X,
     &        13HLARGEST VALUE,2X,I6//)
      SUM = 0.
      DO 80 J = 1,10
      DIFF = KK(J) - 0.5*N(20)
      DIFF = N(J)*((ABS(DIFF - XMEAN))**2.)
      SUM = SUM + DIFF
   80 CONTINUE
      DIFF1 = KK(10) + 0.5*N(20)
      DIFF1 = N(11)*((ABS(DIFF1 - XMEAN))**2.)
      SUM1 = SUM + DIFF1
      DEV1 = SQRT(SUM1/(N(18) - 1))
      DIFF2 = KK(10) + 0.5*(N(15) - KK(10))
      DIFF2 = N(11)*((ABS(DIFF2 - XMEAN))**2.)
      SUM2 = SUM + DIFF2
      DEV2 = SQRT(SUM2/(N(18) - 1))
      WRITE (2,90) DEV1,DEV2
   90 FORMAT (10X,12HSTD DEV(LOW),2X,F7.2,10X,13HSTD DEV(HIGH),2X,
     &        F7.2//)
  100 RETURN
      END
```

EXAMPLE

DATA CARD 1:354

i.e. location 354 (= Watnall).

DATA CARD 2: 05.007.009.010.0

i.e. the growth stage of the crop is expected to reach GS5 in week3, GS7 in week 4, GS9 in week 5, and GS10.0 in week 6.

DATA CARD 3:2. 2. 1.

i.e. the fixed cost of pesticide application is £2/acre, the variable cost is £2/unit of pesticide, and the application rate is 1 unit/acre.

DATA CARD 4: 3 316. 100

i.e. the disease index on the third leaf reaches 1% at the beginning of week 3, the spray is to be applied at this time, it is 16 weeks before the crop can be sold, and 100 simulated sequences are required.

```
DATA CARD  5:100105000124002143016162050181084200098219100
DATA CARD  6:200114000134002154016174050194084214098234100
DATA CARD  7:300117000133002149016165050181084197098213100
DATA CARD  8:400128000145002162016179050196084213098230100
DATA CARD  9:500128000149002170016191050212084233098254100
DATA CARD 10:600129000153002177016201050225084249098273100
```

i.e. the cumulative distribution of the weekly growth rate (A = 0.5) based on the mean and standard deviation, for each of the weeks 1 through 6 (*e.g.* 96% of the distribution is assumed to be within two standard deviations either side of the mean).

DATA CARD 2: 05.007.009.010.0

i.e. the growth stage of the crop is expected to reach GS5 in week3, GS7 in week 4, GS9 in week 5, and GS10.0 in week 6.

DATA CARD 3:2. 2. 1.

i.e. the fixed cost of pesticide application is £2/acre, the variable cost is £2/unit of pesticide, and the application rate is 1 unit/acre.

DATA CARD 4: 3 316. 100

i.e. the disease index on the third leaf reaches 1% at the beginning of week 3, the spray is to be applied at this time, it is 16 weeks before the crop can be sold, and 100 simulated sequences are required.

DATA CARD 5:100105000124002143016162050181084200098219100
DATA CARD 6:200114000134002154016174050194084214098234100
DATA CARD 7:300117000133002149016165050181084197098213100
DATA CARD 8:400128000145002162016179050196084213098230100
DATA CARD 9:500128000149002170016191050212084233098254100
DATA CARD 10:600129000153002177016201050225084249098273100

i.e. the cumulative distribution of the weekly growth rate (A = 0.5) based on the mean and standard deviation, for each of the weeks 1 through 6 (*e.g.* 96% of the distribution is assumed to be within two standard deviations either side of the mean).

DATA CARD 11:010060000065050070100

i.e. the percentage kill achieved by pesticide application is thought to be between 60% and 70%, and expected to be 65%.

DATA CARD 12:020030000035050040100

i.e. the yield of the crop in the absence of disease is thought to be between 30 cwt/acre and 40 cwt/acre, and expected to be 35 cwt/acre.

DATA CARD 13:030180000200050220100

i.e. it is thought that the crop will fetch a price of between £1.80 and £2.20/cwt, and expected to fetch £2.00/cwt.

DATA CARD 14:040055000060050065100

i.e. the variety specific activity coefficient (Λ) is thought to be between 0.55 and 0.65, and expected to be 0.6.

DATA CARD 15:050038000040050042100

i.e. the end-point for effective crop damage (t_e, GS9) is thought to occur between 38 and 42 days after May 1, and expected to occur 40 days after.

The solution to /SPRAY/ using these data is illustrated in *Figure A3.1* (the *per cent* return *per annum*) and *Figure A3.2* (the potential benefit-cost ratio).

Figure A3.1: The rate of return

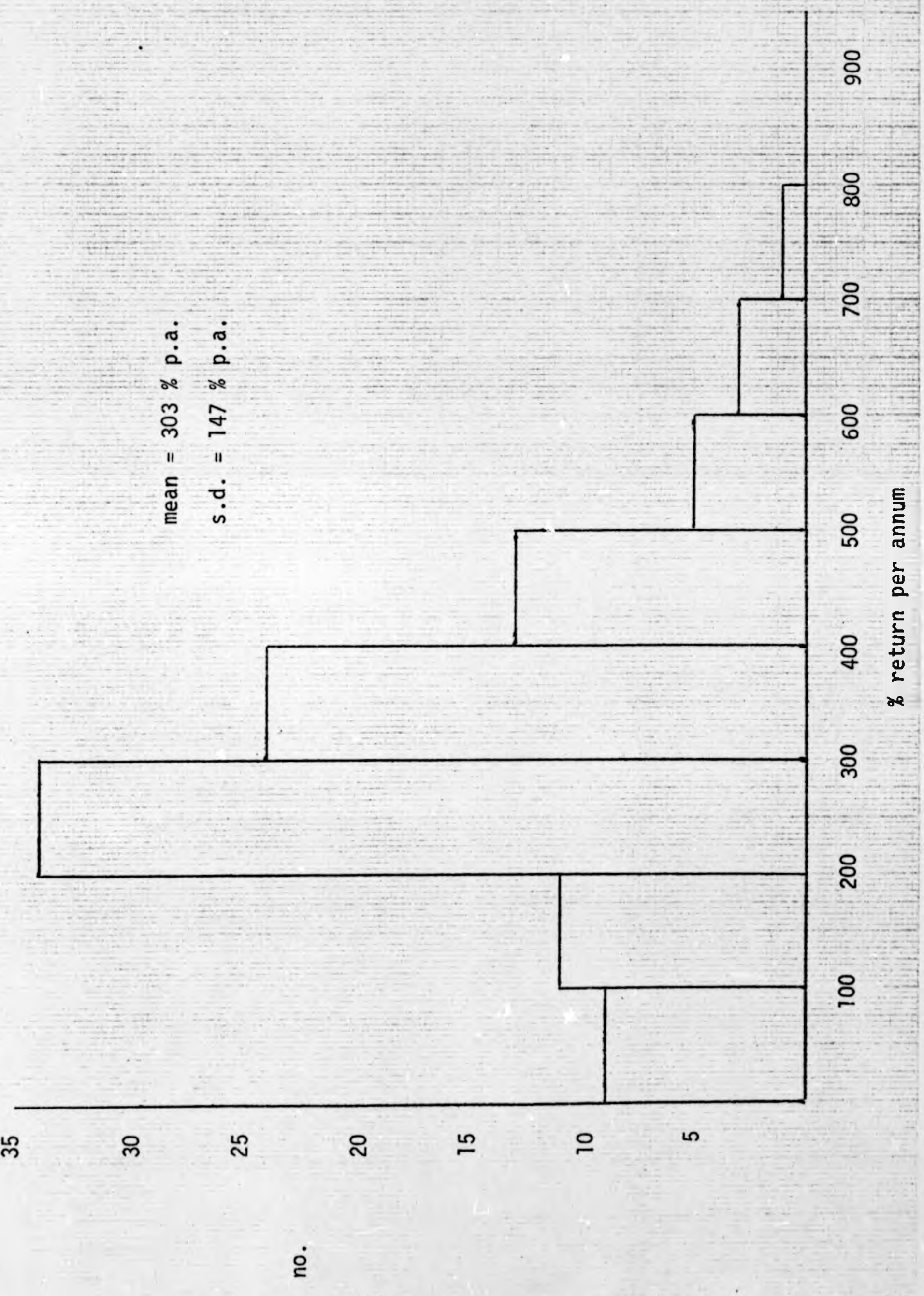

Figure A3.2: The benefit-cost ratio