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A Dynamic Programming Approach to the Economic Control of Weed and Disease Infestations in Wheat

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Weeds and fungal diseases cause significant losses to grain crops in Australia. In many cases cultural methods of control are effective. However, it is often difficult for farm decision-makers to select the optimum crop rotation, from an economic point of view, given the technical constraints they face. A decision to plant a particular crop will have implications for both current and future profitability because the current decision will alter the constraints faced by the decision-maker in subsequent periods. Dynamic programming is used to solve the rotation problem faced by grain growers in north-western New South Wales in areas where the weed, wild oats (*Avena fatua* or *Avena ludoviciana*), and the disease, crown rot (*Fusarium graminearum* Group 1), have a significant effect on wheat yields. The solutions to the dynamic programming problem suggest that in many circumstances a stable rotational pattern is appropriate. In the present case the model is solved for a set of conditions which is relevant to only a small part of the wheat-belt of New South Wales. However, the method can be applied to aid decision-making in individual cases where the user may wish to change the underlying agronomic assumptions of the model.

Introduction

Graingrowers are faced not only with the problem of deciding which crop will give the best return in a particular year but also with the problem that the choice of a particular enterprise may affect the future returns from the farm. For example, a crop of sorghum will deplete soil moisture levels and will, in most cases, make it impossible to grow a crop of wheat during the following winter. The production of wheat, on the other hand, may lead to an increased infestation of the weed wild oats (*Avena fatua* or *Avena ludoviciana*) which will seriously affect the yield of wheat crops in future years unless control measures are taken.[1] Similarly, the yield of wheat may be decreased by soil-borne diseases such as crown rot (*Fusarium graminearum* Group 1) or take-all (*Gaeumannomyces graminis*). As is the case with wild oats, the decision to grow wheat may result in a more serious disease infestation in later years and therefore reduce yields.

The aim of this paper is to illustrate how the optimal economic rotation can be found for cropping land in the north-west of New South Wales, given the initial soil moisture level and initial infestations of crown rot and wild oats. It was assumed that the farmer could choose to grow wheat both with and without the application of post-emergence herbicide to control wild oats, a summer crop (in this case sorghum), or to maintain a weed-free fallow. The approach taken is quite general and the computer program could be adapted easily to analyze other farming systems or to incorporate different constraints. For purposes of the present analysis it was assumed that the decision-making problem on the farm was separable, that is, an optimal decision could be made about the crop rotation to be followed on a specific area of land without reference to other parts of the farm plan. Therefore the solutions

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[1] Wilson (1978) has claimed that wild oats is the most serious weed which affects the Australian wheat crop. The weed occurs in almost all wheat-growing areas. *Avena fatua* is prevalent in southern Australia while *Avena ludoviciana* is more important in the summer rainfall areas of northern New South Wales and Queensland.

provided will not be useful in cases where there are severe cash-flow problems which may force the farmer to take a short-run approach to the effects of current cropping decisions on the future state of the soil.

The decision-making problem discussed above can be solved using dynamic programming, an optimization technique which is applicable in many cases where it is necessary to make a series of interrelated decisions.[2] This technique was chosen in preference to simulation which is often used in solving agricultural decision-making problems where there are several stochastic variables. The advantage of dynamic programming is that random variables can be incorporated and an optimal policy can be found whereas there is no guarantee of finding the optimal policy using simulation. The return or optimal value function which was maximized was the net present value of current and future returns from cropping operations. In order to make use of dynamic programming it is necessary to divide the problem into stages. The stage variable in the rotation problem is time. In the present case the year was divided into a summer (November to April) and a winter (May to October) cropping period of six months duration. Therefore if the rotation is computed for a period of ten years the problem has twenty stages. Dynamic programming is computationally efficient because the optimal solution can be obtained by decomposing the problem into stages which can be treated separately even though the stages are dependent. This is achieved using the concept of the state. The state variables in a dynamic programming problem summarize the current status of the system with respect to the constraints that link the stages. In the problem discussed here there are three state variables which describe the moisture status of the soil, the level of crown rot infestation and the population of wild oats in the area.[3] The following section outlines the interaction between the state variables in the system and the decision variables.

Agronomic Considerations

Soil Moisture

The assumptions built into the model presented here are applicable for the wheat-growing area between Narrabri and Moree in north-western New South Wales. This area receives a large proportion of its rainfall in the summer months and therefore dryland winter crops, such as wheat, are heavily dependent on moisture stored in the soil before the crop is planted. The amount of stored moisture depends, among other things, on the type of soil and the effective rainfall. Despite the high water-holding capacity of the dark swelling clay soils on the north-western plains, water absorption at the soil surface is reduced significantly once the soil is wet. Waring, Fox and Teakle (1958) found that approximately 17 per cent of moisture was retained by the maintenance of a summer fallow. Fawcett (1972) suggested that water retention is closer to 20 per cent of rainfall while Holford and Doyle (1978) used a figure of 25 per cent. For the purposes of the present study it was assumed that, on average, 20 per cent of summer rainfall and 25 per cent of winter rainfall was accumulated in summer and winter fallows respectively. For an average year at Narrabri this implied that the soil was wet to a depth of 58 centimetres after a six month summer fallow given that the soil was dry at the beginning of the period. Moisture retention during a winter fallow was assumed to result in wet soil to a depth of 54 centimetres by the end of the season.

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[2] For a description of the dynamic programming technique see Taha (1971). For a complete coverage see Dreyfus and Law (1977) and for a review of uses in agriculture see Kennedy (1981).

[3] Similar work has been done in the United States by Burt and Allison (1963)and Burt and Johnson (1967). Both studies were concerned with optimum wheat/fallow decision strategies given a stochastic soil moisture state variable.

The relationship between grain yield and the depth of wet soil at sowing time presented by Fawcett, Gidley and Doyle (1976) was used as the basis for estimating the relationship between wheat yield and soil moisture status that is presented in Table 1.[4] As can be seen from Table 1 the state variable representing soil moisture has seven discrete values.[5] It was assumed that both a crop of wheat and a crop of sorghum depleted the available soil moisture by harvest time. Table 1 shows the assumed values of the moisture state variable after cropping or after a winter or summer fallow.

The Effect of Crown Rot

Crown rot is common on the black and grey soils of the north-western plains of New South Wales. The occurrence of this disease is an important factor in long-term farm decision-making because the fungal spores build up with successive crops of wheat and, in some years, cause severe losses. The crown rot fungus survives from year to year in the stubble remains of affected wheat or barley crops and in host plants such as canary grass *(Phalaris paradoxa).* The crown rot fungus invades the lower parts of the stem of diseased plants and interrupts the flow of water from the roots. In severe cases the result is premature ripening and whitehead formation. The percentage of whiteheads in the crop is used as a guide to the severity of the disease in the field. Table 2 illustrates the progress of the disease in a case where wheat is grown continuously for five years.

In the absence of a susceptible crop such as wheat or a pasture species such as canary grass the number of viable fungal spores in the soil will decline. For example, an 18-month fallow will result in a significant decline in the level of crown rot. The inclusion of a summer crop in the rotation will have a similar result provided that the winter fallow is kept free from weeds. Table 3 shows the extent to which crown rot may be controlled by the maintenance of a weed-free fallow of 18 months duration. The data contained in Tables 2 and 3 were used to assess the impact of various decisions on the state variable representing crown rot. Changes in the value of the crown rot state variable given the alternative decisions are shown in Table 4.

Weed Competition

In north-western New South Wales, where it has been traditional to maintain a fallow over the summer months in an attempt to accumulate soil moisture, cultural methods have been the main approach to weed control. Most broad-leafed weeds are adequately controlled by pre-sowing cultivation. However, serious infestations of wild oats (mainly *Avena ludoviciana)* can develop in areas used to grow wheat. The wild oat seeds germinate during the autumn and some control during pre-sowing cultivation is possible. However, the oat plant matures more quickly than wheat and sheds most of its seed before the wheat harvest. The result is that the population of wild oats increases rapidly unless effective control measures are taken. This is particularly the case where successive crops of wheat are grown in the one paddock for a number of years. Unfortunately the data available on both the rate of growth of wild oat populations and the weed's subsequent effect on the yield of wheat are highly variable. The assumptions used in the present study about the population growth rates of wild oats are based on the work by Quail (1968). Table 5 shows the assumed relationship between the density of wild oats and wheat yields. The effect of wild oats on wheat yields assumed here is considerably less severe than that suggested by Philpotts (1975) but slightly more severe than that given by Quail (1968).

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[4] The relationship between sorghum yield and soil moisture was estimated by B. G. Sutton, Department of Agronomy and Horticultural Science, University of Sydney (Personal communication).

[5] In all cases the state variables were assumed to take a limited number of discrete values. The agronomic data that were available were not precise enough to warrant the specification of more complex functions.

Table 1: The Relationship between Moisture and Crop Yields and the Soil Moisture State Transformation Process[a]

Value of Moisture State Variable	Depth of Soil Moisture (cm)	Yield Index (per cent of mean yield)		Effect on Moisture State Variable of		
		Wheat	Sorghum	Wheat	Sorghum	6-Month Fallow
1	>120	175	125	7	7	1
2	90 - 119	150	100	7	7	1
3	70 - 89	125	75	7	7	1
4	50 - 69	100	50	7	7	2
5	30 - 49	75	25	7	7	2
6	10 - 29	50	0	7	7	3
7	0 - 9	25	0	7	7	4

[a] The contents of the table can be interpreted as follows: if the initial value of the moisture state variable is 7 (corresponding to a depth of wet soil of 0-9 cm) then a 6-month fallow will have the effect of moving the soil moisture status to level 4.

Table 2: The Progress of Crown Rot (Fusarium graminearum Group 1) under Continuous Wheat (Measured as a percentage of whiteheads in the crop)

Year	1	2	3	4	5
Per cent Whiteheads	<1	1 - 5	10 - 25	25 - 50	50 - 100

Source: L. W. Burgess, Department of Plant Pathology and Agricultural Entomology, University of Sydney, April, 1981 (Personal communication).

Table 3: The Effect of an Eighteen Month Weed-free Fallow on Crown Rot (Fusarium graminearum Group 1)

Before Fallow (Per cent whiteheads)	After Fallow (Per cent whiteheads)
0 - 1	<0.1
5	< 1
10	< 1
25	1 - 5
50	10
100	25 - 50

Source: L. W. Burgess, Department of Plant Pathology and Agricultural Entomology, University of Sydney, April, 1981 (Personal communication).

Table 4: The Crown Rot State Transformation Process

Initial Level of the State Variable	Wheat Yield (per cent of normal)	Effect on Crown Rot of	
		Wheat	Winter Fallow
1	100	2	1
2	99	3	1
3	95	4	2
4	90	5	3
5	75	6	4
6	50	7	5
7	10	7	6

Several factors such as seed disposal patterns and the size of the initial population affect the spread of a particular weed.[6] However, in the present case it was assumed that the only important factor governing the spread of wild oats was the number of seeds which germinated. Two alternate assumptions were made about establishment. In the first instance it was assumed that a single wild oat plant produced 200 seeds and that 40 per cent of those seeds germinated in the following year. The second assumption made was that a single plant produced 100 seeds and that 30 per cent of those germinated the following year. The first assumption was consistent with an environment which was favourable for the growth of wild oats while the second related to a case where wild oats were a relatively minor problem.

Apart from cultural control the population of wild oats can now be effectively reduced by the application of post-emergence herbicide (it was assumed that pre-emergence herbicide was always applied). Post-emergence herbicides such as "Hoegrass" are relatively expensive. The use of post-emergence herbicide adds approximately $31 to the variable cost per hectare of growing a crop of wheat (Bailey and Buffier 1981, p.102). It was assumed that conventional preparation and sowing with the application of pre-emergence herbicide resulted in the control of 95 per cent of the expected wild oats seedlings and that an application of post-emergence herbicide gave 99.5 per cent control. The effects of the alternative cropping decisions on the wild oats state variable are shown in Table 5. It was assumed that a summer fallow or a crop of sorghum had no effect on the population of wild oats in the following season and that a winter fallow resulted in two separate controls with an effectiveness of 95 per cent on both occasions.

Model Formulation

The model can be described succinctly by the recursive equation used to obtain the optimal solutions. The recursive equation which was used to find the maximum net present value of the revenue stream over a finite planning horizon was a follows.

$$(1) \quad f_{T+1}(M_{T+1}, C_{T+1}) = 0$$

$$(2) \quad f_t\,(M_t, C_t, W_t) = \max_{j_t} \pi\; M_t, C_t, W_t, j_t) + \alpha f_{t+1}\,(M_{t+1}, C_{t+1}, W_{t+1});$$

$$t = T, \ldots\ldots, 1$$

where f_t = maximum present value given by following the optimal policy from period t to the final period, T.

M_t = level of soil moisture
C_t = level of crown rot
W_t = level of wild oats
j_t = crop selection number = 1 for wheat
= 2 for wheat plus post-emergence herbicide
= 3 for sorghum
= 4 for winter fallow
= 5 for summer fallow

α = discount factor = $1/(1+r)$ where r is the chosen discount rate.
$\pi\ (M_t, C_t, W_t, j_t)$ = net returns

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[6] For a general discussion of the factors which govern the spread of a plant species see Auld, Menz and Monaghan (1978/1979).

Table 5: The Relationship between Wheat Yield and Wild Oat Density and the Wild Oat State Transformation Processes

Value of Wild Oat State Variable	Density of Wild Oats (number m^{-2})	Wheat Yield (per cent of mean yield)	Effect on Wild Oat Population					
			Assumption 1 Severe Problem			Assumption 2 Moderate Problem		
			Wheat	Wheat Plus Post-emergence Spray	Winter Fallow	Wheat	Wheat Plus Post-emergence Spray	Winter Fallow
1	<1	100	2	1	1	2	1	1
2	1 - 9	99	4	2	2	2	1	1
3	10 - 19	96	6	2	2	4	2	2
4	20 - 39	92	7	3	2	5	2	2
5	40 - 59	85	8	4	3	6	2	2
6	60 - 99	75	9	4	3	7	3	2
7	100 - 199	65	10	6	4	8	4	3
8	200 - 299	55	10	7	5	9	4	3
9	300 - 499	40	11	7	6	10	6	4
10	500 - 1000	20	11	9	7	11	7	5
11	>1000	10	11	10	8	11	9	6

The state transformation functions are described in various tables as follows.

(3) $M_{t+1} = g_m(M_t, j_t)$ – Table 1
(4) $C_{t+1} = g_c(C_t, j_t)$ – Table 4
(5) $W_{t+1} = g_w(W_t, j_t)$ – Table 5
(6) $\pi(M_t, C_t, W_t, j_t) = P(j_t)\ Y(M_t, C_t, W_t, j_t)\ SI\ (j_t) - VC\ (j_t)$
where $P(j)$ = price of the jth crop
$Y(j)$ = yield of the jth crop
$SI\ (j)$ = seasonal index for the jth crop and
$P(j) = Y(j) = 0$ for $j = 4, 5$.

The seasonal indexes were used to ensure that crops were not grown out of season. For example, the seasonal index for wheat took a value of unity in the winter period. A large penalty was incurred for growing wheat in the summer.

A computer program was written to perform the necessary calculations needed to obtain the optimal policy.[7] The recursive equation and the computer program can be easily changed to incorporate extra decision variables to describe a more complex farming system. An additional state variable could be added to take account of a liquidity constraint faced by the decision-maker. In solving the problem it was assumed that product prices and variable costs were not stochastic. The above formulation also treats yields as deterministic. However, given the nature of the objective function, the optimum control policy obtained by solving the deterministic problem with rainfall set equal to its expected value was the same as the policy that would have been obtained by solving the stochastic problem where soil moisture was specified as a function of a stochastic rainfall variable. This result, known as certainty equivalence (Dreyfus and Law 1977, pp. 188-192), held because a critical part of the objective function was linear.

Results

For the results presented below it was assumed that the variable costs per hectare of growing a crop of wheat, wheat with an application of post-emergence herbicide, and sorghum were \$63, \$94 and \$54 respectively. The variable cost of maintaining a weed-free fallow for six months was assumed to be \$15.[8] The estimated variable costs were based on data given by Bailey and Buffier (1981). In an attempt to gauge the sensitivity of the optimum policies the model was solved for a range of prices, discount rates, planning horizons and average crop yields. It should be noted that the optimal policies presented below are valid only in cases where the agronomic constraints are consistent with those already presented.

For illustrative purposes the optimal policies are shown for two sets of initial agronomic conditions and two sets of gross returns. The first set of physical conditions represents a case where there is a minor crown rot and wild oat problem and where the soil is wet to a depth of 120 centimetres, while the second set of conditions represents a case where the soil is dry and the levels of crown rot and wild oats are such that it is not possible to successfully grow a crop of wheat. The problem was solved for a planning period of ten years. The optimal policies for each set of conditions are given in Tables 6 and 7.

The solutions presented in Table 6 are based on the assumption that the prices of wheat and sorghum were \$150 and \$125 per tonne respectively while the average yields were assumed to be 2.0 tonnes per hectare for wheat and 1.3 tonnes per hectare for sorghum. Inspection of the table shows that, for the above assumptions, the optimal policy involved a crop of wheat followed by an 18-month period of fallow. This pattern

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[7] A copy of the computer program, which is written in Fortran 5, is available from the authors upon request.

[8] Note that the dynamic programming algorithm takes account of the opportunity cost of a fallow in selecting the optimum policy. A fallow (with a net return of −\$15) will only be selected when the future benefit of the fallow, in terms of higher crop yields, outweighs the net returns from growing a crop.

Table 6: Optimum Policies for a Ten-Year Planning Horizon Given a High Wheat Price[a]

Year	Optimum Policy[b]							
	Case 1		Case 2		Case 3		Case 4	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
1	Wheat + Spray[c]	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
2	Fallow	Fallow	Fallow	Sorghum	Fallow	Fallow	Fallow	Sorghum
3	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
4	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow
5	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
6	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow
7	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
8	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow
9	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
10	Wheat	Fallow	Wheat	Fallow	Wheat	Fallow	Wheat	Fallow
Net Present Value of Policy ($ha^{-1})	1477		832		1526		874	

[a] The prices of wheat and sorghum were assumed to be $150 and $125 per tonne respectively. The average yields were assumed to be 2.0 and 1.3 tonnes per hectare for wheat and sorghum respectively.

[b] Cases 1 and 2 represent an environment in which the wild oat problem is severe (assumption 1) while cases 3 and 4 represent an environment in which the wild oat problem is moderate (assumption 2). The initial conditions for cases 1 and 3 were: M=1; C=2; W=4. The initial conditions for cases 2 and 4 were: M=7; C=7; W=11.

[c] Wheat + spray represents wheat with an application of post-emergence herbicide.

always developed for the given gross returns regardless of the initial agronomic conditions, the length of the planning horizon or the selected discount rate.[9] Wheat with an application of post-emergence herbicide to control wild oats was only selected on one occasion. This selection was made when the price of wheat was much higher than that for sorghum and when the number of wild oat plants in the paddock was initially between 20 and 39 per square metre. When the initial population of wild oat plants was greater than 1000 it became profitable to forgo all cropping for 18 months and then to plant a crop of sorghum. The sorghum crop was followed by a 12-month fallow after which the wheat/18-month fallow rotation was established. It must be emphasized that the optimal policies which have been presented are only valid for cropping on soils with a high moisture-holding capacity and where crown rot is a major problem.

The results for a case where the prices of wheat and sorghum were set equal to $130 and $135 per tonne respectively and where the average yields were assumed to be 1.5 and 2.0 tonnes per hectare are presented in Table 7. Once the effect of the initial agronomic conditions were overcome the optimal policy for the given price regime always involved a wheat/12-month fallow/sorghum/12-month fallow/wheat rotation. Experimentation indicated that the gross margin for sorghum had to exceed that for wheat by approximately $30 per hectare before sorghum was included in the stable rotation. This result was expected because of the assumption made about the way in which each crop responded to additional soil moisture (see Table 1).

In general the optimal policies appeared to be insensitive to changes in the discount rate and the length of the planning horizon. However, large changes in prices and changes in the initial values of the state variables do lead to changes in the optimal policy. The computer program was written to allow for changes to be made in the initial agronomic conditions, prices, yields, variable costs, the discount rate and the length of the planning horizon. If necessary decision makers could also change the underlying agronomic assumptions to make the model consistent with their actual experience for particular farms.

Conclusions

The present paper has illustrated how the dynamic programming technique can be used to determine economic control measures that can be applied to limit the effects of pests and diseases in crops. The optimal solutions involved fallows of 12 or 18 months duration. The use of long fallows is becoming more popular in areas of the north-western plains of New South Wales where crown rot is a major problem. It should be noted that the optimal policy did not involve the complete elimination of the pest in any of the cases studied but the choice of some tolerable level of infestation.

No account was taken of the stochastic nature of commodity prices. Although it is possible to incorporate the effects of uncertainty in prices in dynamic programming models this was not done because, first, the current stabilization arrangements for wheat effectively limit the year to year movements in wheat prices and this, in turn, affects the coarse grains markets and, second, experimentation with a range of prices suggested that the optimal policy was not particularly sensitive to changes in prices. Obviously, however, changes in prices affect the net present value of policies.

The solutions for the deterministic model were equivalent to those which would have been obtained from the solution of a model containing a stochastic rainfall variable. Certainty equivalence would not necessarily hold for a model containing a non-linear relationship between yield and soil moisture. If such a relationship were incorporated it would probably become necessary to include a stochastic state variable in the model.

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[9] The model was solved with varying initial agronomic conditions for planning horizons of 20, 30 and 40 periods and discount rates of 10, 12 and 15 per cent.

Table 7: Optimum Policies for a Ten-Year Planning Horizon Given a Low Price of Wheat[a]

Year	Optimum Policy[b]							
	Case 1		Case 2		Case 3		Case 4	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
1	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow
2	Fallow	Sorghum	Fallow	Sorghum	Fallow	Sorghum	Fallow	Sorghum
3	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow
4	Wheat	Fallow	Fallow	Sorghum	Wheat	Fallow	Fallow	Sorghum
5	Fallow	Sorghum	Fallow	Fallow	Fallow	Sorghum	Fallow	Fallow
6	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow
7	Wheat	Fallow	Fallow	Sorghum	Wheat	Fallow	Fallow	Sorghum
8	Fallow	Sorghum	Fallow	Fallow	Fallow	Sorghum	Fallow	Fallow
9	Fallow	Fallow	Wheat	Fallow	Fallow	Fallow	Wheat	Fallow
10	Fallow	Sorghum	Fallow	Sorghum	Fallow	Sorghum	Fallow	Sorghum
Net Present Value of Policy ($\$ha^{-1}$)	967		753		971		756	

[a] The prices of wheat and sorghum were assumed to be $130 and $135 per tonne respectively. The average yields were assumed to be 1.5 and 2.0 tonnes per hectare for wheat and sorghum respectively.

[b] see Table 6.

The approach described and the model itself are applicable in areas of north-western New South Wales where crown rot causes significant losses in wheat crops. With modifications, which can be easily incorporated, the computer program could be used to solve rotation problems applicable in other areas. Unfortunately some of the agronomic data incorporated in the model is only approximate. Despite pleas by agricultural economists (see for example, Anderson 1971, or Dillon 1966) many agronomic experiments have not been designed to provide the type of information necessary for use in economic models. Perhaps one of the most significant outcomes of the research reported is that some of the field and glass-house trials on the effects of crown rot on wheat which are now being conducted by members of the Department of Plant Pathology and Agricultural Entomology at the University of Sydney are designed to provide the type of information needed for the construction of farm decision-making models.

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