Reducing the impact of sclerotinia disease by determining optimum crop rotations using dynamic programming

Bouda Vosough Ahmadi[a*], Fiona J. Burnett[a], Caroline S. Young[b], Mark P. McQuilken[a] and Alistair W. Stott[a]

[a]SRUC, King's Buildings, West Mains Road, Edinburgh, EH9 3JG, UK.
[b]ADAS Consulting Ltd., ADAS Wolverhampton, Woodthorne, Wergs Road, Wolverhampton, WV6 8TQ, UK.

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[*]E-mail address: Bouda.V.Ahmadi@sruc.ac.uk

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Abstract

Sclerotinia rot is a disease caused by the fungus *Sclerotinina sclerotiorum* which affects a wide range of crops and causes major yield and economic losses. Crop rotation is an important strategy for minimising losses. A dynamic programming (DP) model was developed to study the trade-offs between state of the land, severity of sclerotinia and financial impacts as a result of different cropping decisions. Results showed that rotation and treatment against sclerotinia was financially justified yet permitted intensive yet sustainable production of susceptible food crops in the long-run. Allocation of even a small proportion of cropping decisions to break crops coupled with treatments in the rotation mitigated long-term build-up of sclerotia in land. However in the short-run, high proportions and high frequencies of cropping decisions need to be either allocated to break crops or treated-susceptible crops in order to avoid the disease and to generate profit. Results showed that DP methodology provides a useful framework to explore the trade-offs between crop rotation and growing high value susceptible crops in the long- and short-term in relation to plant diseases in arable agriculture that are at the heart of sustainable food production and land use.

Keywords sclerotinia, crop rotation, dynamic programming, optimisation, agriculture

JEL code C61, Q12

Introduction

Sclerotinia rot is a disease caused by the fungus *Sclerotinia sclerotiorum* which affects a wide range of arable and horticultural crops including oilseed rape, peas, spring beans, potatoes, lettuce and carrots. The pathogen causes major yield and economic losses in susceptible crops (Kora et al., 2003). Sclerotinia survives in the soil as sclerotia (resting bodies) for up to 10 years, so a high level of inoculum built up in the soil in one crop can have a significant impact on subsequent susceptible crops in a rotation. Crop rotation can be used to minimise the impact of the disease. Crop rotation is defined as planting different crops on the same piece of land in sequential seasons. Crop rotation gives many benefits, including maintaining soil structure and fertility, reducing agricultural chemical usage, reducing flood losses and avoiding build-up of pathogens and pests but here our interest is restricted to the effect of rotation on the temporal dynamics of disease.

Long-term and short-term management decisions such as crop rotation have an impact on the epidemiology of plant disease and therefore on farm economics. Reducing sclerotinia disease while maximising profit is more complicated than simply lengthening rotations for susceptible crops, hence this study. Bio-economic models provide useful frameworks to investigate the trade-offs between the state of the land, severity of sclerotinia and financial impacts as a result of different cropping decisions. We therefore developed a dynamic programming (DP) model of the crop rotation decision problem to study these trade-offs. The objective was to find the cropping decision sequence that maximises the net present value of cropping on a unit of land over both the long- and short-term time horizons. By changing key parameters in the DP and re-optimising, the impact of alternative assumptions and crop rotations could be explored.

Materials and methods

Structure of Model

DP (Bellman, 1957) is a mathematical technique which is especially of value in a situation where a sequence of interdependent decisions has to be made, e.g. livestock replacement, forest management and crop rotations. The basic principles of DP were fully explained by Kennedy (1986) and their use in determining optimum crop rotations has been described by several authors (Onstad and Rabbinge, 1985; Stott et al., 1996; Trengove and Manson, 2003; Cai et al., 2011). In this study a DP model was developed using Microsoft Excel and Visual Basic version 6.5 for Windows (Microsoft Corporation, 2007). The model was run separately using the general purpose dynamic programming (GPDP) software (Kennedy, 1986). The objective of the DP was to find the cropping decision sequence that maximises the net present value (i.e., current value of current and future net returns from one hectare of farming land expressed as an annuity) of cropping on that land over the short-term and long-term time horizons. Land was represented by 25 states including 5 sclerotinia states (S1-S5, based on numbers of sclerotia in the soil) and 5 break crop states (G1-G5) representing the number of years since last non-susceptible crop decision. In total a maximum of 6 cropping decision options (i.e. a combination of susceptible crops, break crops and treated -susceptible crops) could be included in each run of the model. The DP calculates which combination and sequence of crops is required to be included in the optimal solution to reduce sclerotinia to the extent that maximises profit. Susceptible crops considered were: carrots, oilseed rape, spring beans, spring peas, lettuce and potatoes. It was assumed that growing susceptible crops raises the number of sclerotia in soil but subsequent break crop (non-susceptible) decisions will reduce it at differential rates. Fig 1 illustrates the event time line and the decision tree structure of the DP model.

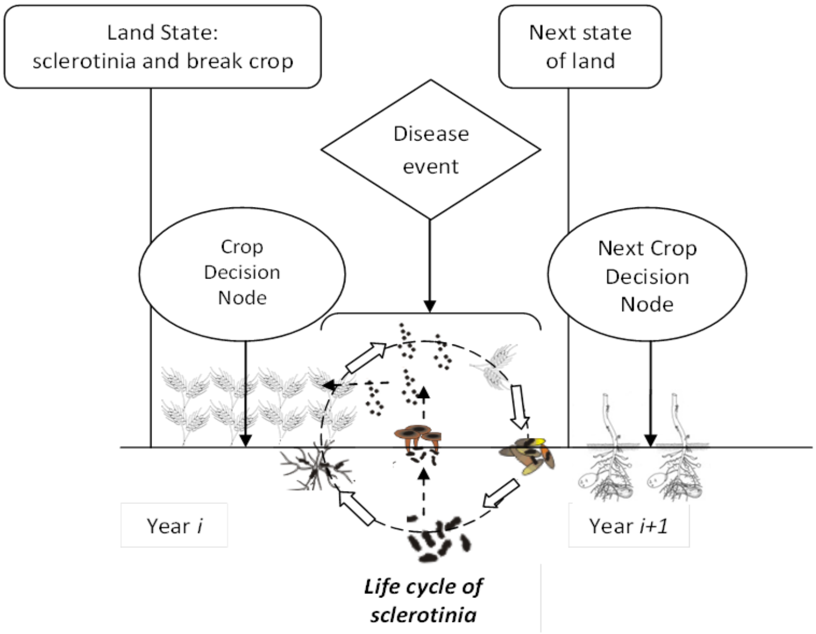

Figure 1. Cropping decision and sclerotinia disease event time line that represents the Decision Tree structure used in the DP model. In this figure *i* equals to 1-4 for short-term runs of the model (year 1 to year 5) and it equals to 1 to >20 for long-term runs of the model.

Model inputs and assumptions

<u>Stage return</u>

The assumptions and figures mentioned in Table 1 were used to determine the gross output for each possible state. In Table 1 the yields and prices of each susceptible and break crop are based on figures reported in the farm management handbook (SAC, 2011/12) except figures for lettuce.

Table 1. Yields and output prices used in the model.

Crop	Yield[1] (t/ha)		Price[1] (£/ha)		Reference
	Produce	Straw	Produce	Straw	
Carrots (C)	64	8	120	15	SAC 2008/09
Winter wheat (WW)	8	4.2	155	28	SAC 2011/12
Spring wheat (SW)	6.5	3.6	175	28	SAC 2011/12
Winter barley (WB)	7.5	4.1	145	40	SAC 2011/12
Spring barley (SB)	5.5	2.9	145	40	SAC 2011/12
Winter oilseed rape (WOSR)	4	-	350	-	SAC 2011/12
Spring oilseed rape (SOSR)	2.5	-	350	-	SAC 2011/12
Spring beans (SB)	5	-	200	-	SAC 2011/12
Spring peas (SP)	4	-	200	-	SAC 2011/12
Potato -early ware (P)	39.2	-	175	-	SAC 2011/12
Lettuce (L)[1]	48750	-	0.21	-	Young et al., 2007

[1] Lettuce yield and price are head/ha and £/head respectively.

The variable costs associated with each state were based on figures presented in Table 4 (SAC, 2011). By subtracting variable costs from gross outputs, the gross margins were calculated. The stage returns were calculated based on the gross margin of the current cropping decision but with a yield and variable cost adjustment function dependent on the state of the land at the current stage.

Table 2. Variable costs of included crops (£/ha).

	C	WW	SW	WB	SB	WOSR	SOSR	SB	SP	P	L
Seed	520	91	87	84	72	63	80	130	130	840	2,010
Fertiliser and salt	406	294	243	274	186	276	137	64	73	410	720
Polythene		-	-	-	-	-	-	-	-	800	-
Topper, harvest, tractor	358	-	-	-	-	-	-	-	-	-	-
Labour & tractor	115	-	-	-	-	-	-	-	-	-	-
Pesticides (sprays)	853	128	88	88	58	142	49	98	109	75	980
Other crop expenses		-	-	-	-	-	-	-	-	41	675
Straw	2000	-	-	-	-	-	-	-	-	-	-
Market commission	768	-	-	-	-	-	-	-	-	-	-
TOTAL	5,020	513	418	446	316	481	266	292	312	2,166	4,385

Yield loss assumptions

The build-up and decline curves of sclerotinia in soil as a result of cropping decisions and their impacts on marketable yields were obtained from previous experiments and from expert opinion mentioned below. It was assumed that the yields of susceptible crops are lowered at a rate inversely proportional to sclerotinia level (i.e. S1-S5 states, S1 being worst and S5 best states) and are raised by growing break crop (i.e. G1-G5 states) in a similar manner. An estimated function (Equation 1) of marketable yield loss (t/ha) and sclerotinia root disease incidence for carrots (McRoberts et al., 2007) was used to estimate the proportion of disease-free yield lost to the disease in successive years of susceptible cropping:

$$Yld = 120.96 - 0.927 * srr\% \qquad \text{Equation (1)}$$

where *Yld* represents annual marketable yield of susceptible crops (t/ha) and *srr* denotes sclerotinia root disease incidence (%). It was assumed that sclerotinia survives in the soil as sclerotia for up to 5 years. The build-up rate of sclerotia in land (that was assumed to be equal to *srr*), as a result of continuous susceptible cropping, was estimated by the experts in the project at 0%, 10%, 30%, 90%, 100% for year 1 to year 5 respectively. By replacing these rates for s*rr* rates in Equation 1, the yield losses for years 1-5 were calculated and the proportion of yield loss determined as: 0%, 7.7%, 23%, 69% and 76% for years 1-5 respectively. The yield figures presented in Table 3 are the outcome of multiplying the yields from healthy crops (Table 1) by the annual yield loss rate calculated above. The annual yield loss of continuously cropping the break crops (i.e. winter wheat, spring wheat, winter barley and spring barley) were estimated by the experts and used in the model. These were: 0%, 2.25%, 5.25%, 11.25% and 22.50% for years 1-5 respectively (Table 4).

Spraying was considered as a possible treatment option. For all the susceptible crops an annual effectiveness rate of 18.5% (20% effectiveness (McRoberts, 2007) minus 1.5% wheeling loss) of improving marketable yield was assumed. Therefore an annual extra variable cost of £76 (two extra sprays at £38 each) for treatment was considered in the scenarios that treatment options made available for the DP model.

Table 3. Assumed yield loss due to the impact of sclerotinia on susceptible crops.

Crop	Yield loss (t or head*/ha) based on time span of continuous growing susceptible crops (Year 1 to Year 5)				
	Y1	Y2	Y3	Y4	Y5
Carrots	0.0	4.9	14.7	44.1	49.0
Winter oilseed rape	0.0	0.3	0.9	2.8	3.1
Spring oilseed rape	0.0	0.2	0.6	1.7	1.9
Spring beans	0.0	0.4	1.1	3.4	3.8
Spring peas	0.0	0.3	0.9	2.8	3.1
Potato -early ware	0.0	3.0	9.0	27.0	30.0
Lettuce*	0.0	3736.0	11208.1	33624.4	37360.5

Table 4. Assumed yield loss due to continuous growing of break crops.

Crop	Yield loss (t/ha) based on time elapsed since last break crop for Year 1 to Year 5				
	Y1	Y2	Y3	Y4	Y5
Winter wheat	0.0	0.2	0.4	0.9	1.8
Spring wheat	0.0	0.1	0.3	0.7	1.5
Winter barley	0.0	0.2	0.4	0.8	1.7
Spring barley	0.0	0.1	0.3	0.6	1.2

Transition probabilities

Two transition probability matrices were used, one for the susceptible crops and one for the break crops. These matrices define the probabilities of moving from a current state of land, in terms of infestation and the time elapsed since the last break crop for a unit of land, to the next state by deciding to grow a certain crop from the decision set. They also regulate the transitions from one state to another by preventing or allowing certain movements. In other words they reflect the life cycle of the disease in the format of transition probabilities based on cropping decision. The probabilities used are based on the authors' assumptions. Two transition probability tables were considered, one for susceptible crops and one for break crops. Table A1 of the appendix presents the probability of next stage given the current states for the susceptible crops (i.e. carrots, winter oilseed rape, spring oilseed rape, spring beans, spring peas, potatoes and lettuce). For example if the land is currently at state 7 (G2, S2), deciding to grow a susceptible crop will shift the land state in the next year to states 2, 3, 4 or 5 with probabilities of 10%, 50%, 30% and 10% respectively. Table A2 of the appendix presents the probability of next stage given the current states for the break crops (i.e. winter wheat, spring wheat, winter barley and spring barley).

DP model runs

The data described in the previous sections provided the input required for the general purpose dynamic programming (GPDP) software (Kennedy, 1986) that was used separately to run the model. Three main scenarios were examined and the DP runs were undertaken. The scenarios examined were:

Scenario 1: Only susceptible crops (i.e. carrots, lettuce, potatoes, winter oilseed rape, spring peas and spring beans) provided to the DP as decision choice set.

Scenario 2: Including a break crop to susceptible crops in the decision choice set.

Scenario 3: Including a treatment option for susceptible crops and a break crop to susceptible crops in the decision choice set. The above-mentioned susceptible crops and a break crop plus a treatment option for carrots, as an example of this scenario, is presented in this paper.

For each of the three scenarios a long-term time horizon and a short-term (five-year) time horizon were considered and investigated. In scenario 1-3 for a long-term time horizon, only one susceptible crop in each run was added to the decision choice set (i.e. continuous cropping). The DP model was run for a long-term time horizon using a discounting factor of 5%, and expected net present values (ENPV) expressed as annuities were estimated by the model. In DP runs considering a short-term time horizon six susceptible crops (i.e. carrots, lettuce, potatoes, winter oilseed rape, spring peas and spring beans) were added to the decision choice set and the DP decided on which crops to be included in the optimal decision.

Results

Model runs in long-term

In scenario 1, continuous susceptible cropping led to financial losses in the long-term (results for four susceptible crops are presented in Fig 2). Carrots and lettuce made higher losses than winter oilseed rape and potatoes in this run of the model (scenario 1). However, one break crop (i.e. winter wheat) in the rotation in scenario 2 mitigated long-term build-up of sclerotia in land and major financial losses (Fig 2). Adding a treatment option for the susceptible crops to the rotation of susceptible and break crop in scenario 3 further enhanced the financial returns and reduced the adverse effect of sclerotinia on outputs.

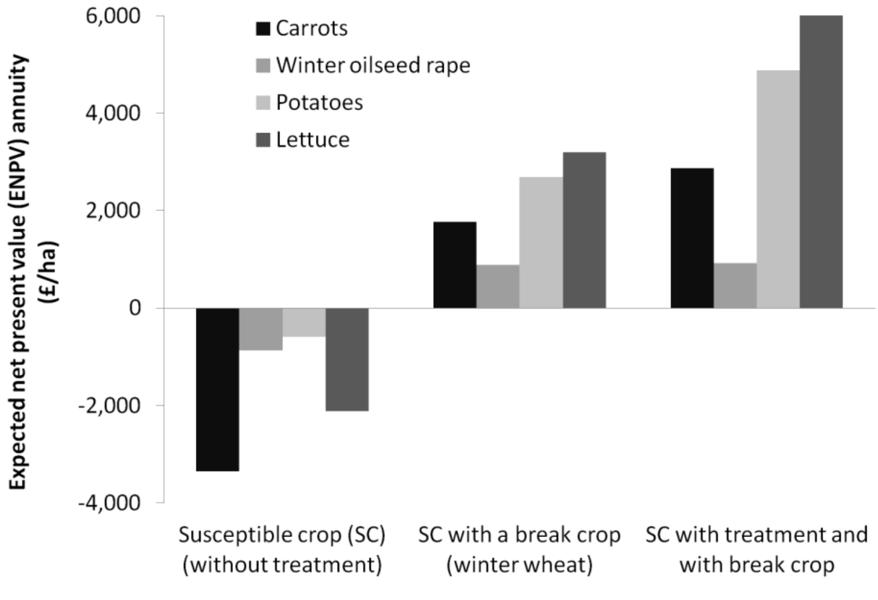

Figure 2. Effect of management decisions of three different scenarios: i) continuously growing only susceptible crops (SC), ii) susceptible and break crops and, iii) susceptible crop and applying treatment on financial outcomes of carrots, winter oilseed rape, potatoes and lettuce in a long-run time horizon.

For oilseed rape the results of long-term runs showed that continuously growing oilseed rape generated a financial loss (ENPV of -£866/ha). Including winter wheat as a break crop to the decision set, featured both oilseed rape and winter wheat in the optimal decision that generated financial profit (ENPV) of £882/ha. By adding a treatment option to the decision set, the optimal decision predicted by the DP included all the three crop decisions oilseed rape, treated oilseed rape and winter wheat that generated an ENPV of £919/ha that was equal to the gross margin of a healthy oilseed rape crop. The long-run state probabilities of the optimal decision in this case were 45% for oilseed rape in S5, 53% for treated oilseed rape in S4, and 2% of winter wheat in S3. Sclerotinia states S1 to S2 did not featured in the optimal decision (i.e. long-run probabilities of 0.0) indicating that the DP limits the land infestation by including a break crop in the rotation.

Model runs in short-term

Results of the DP short-term run for scenario 1 showed that the optimal decision consisted of spring peas (20% of the states) for the highest sclerotinia states (i.e. S1-S2), potatoes in moderate sclerotinia state (S2, 20% of the states), and lettuce for low sclerotina states (S3-S5, 60% of the states) (Table 5). The model minimised the impact of the disease and therefore avoided great financial losses in highly- and moderately-infested states (S1 and S2) by including spring peas and potatoes (ENPV of −£29 per ha and −£9 per ha for S1 and S2 respectively) in the optimal decision (Fig 3). Results showed no difference in financial returns in year 1 to year 5 for the high- and moderately-infested land states (i.e. states 1-15). However, for the low-infested land states (i.e. states 16-25) lower financial returns were predicted for years 1 and 2 compared to the last three years 3-5 (Fig 3).

By inclusion of winter wheat as a break crop in the decision choice set in scenario 2, the DP's optimal decision crops were lettuce and winter wheat. The optimal decision in year 1 consisted of winter wheat for the states S1 to S2 (40%) and lettuce for S3 to S5 (60% of the states). In year 2, winter wheat was the optimal decision for S1 to S3 (60%) and lettuce for S4 to S5 (40%). For year 3 to year 5, winter wheat accounted for 80% of the optimal decision in S1 to S4 and lettuce was the best decision for S5 (20%) (Table 5 and Fig 4).

Table 5. Optimal rotations and proportion of cropping decisions in each state for year 1 to year 5 of a short-term time horizon.

Scenarios	Proportion of decisions and state numbers for year 1 to year 5					
Susceptible crop only						
	Year 1-5					
Crop	Proportion	State				
Spring peas	0.20	1-5				
Potatoes	0.20	6-10				
Lettuce	0.60	11-25				
Susceptible and break crop						
	Year 1		Year 2		Year 3-5	
Crop	Proportion	State	Proportion	State	Proportion	State
Winter wheat	0.40	1-10	0.60	1-15	0.80	1-20
Lettuce	0.60	11-25	0.40	16-25	0.20	21-25
Susceptible crop and treatment and break crop						
	Year 1		Year 2		Year 3-5	
Crop	Proportion	State	Proportion	State	Proportion	State
Winter wheat	0.40	1-10	0.40	1-10	0.40	1-10
Treated carrots	0.00	-	0.24	11-16	0.40	11-20
Lettuce	0.60	11-25	0.36	17-25	0.20	21-25

In scenario 3, where a treatment option for carrots was added to the decision choice set of crops, the optimal decision in year 1 remained similar to scenario 2 with winter wheat and lettuce as the best options (Table 5). In years 2-5, lettuce in moderate- and low-infested states was replaced by treated carrots to improve the state of sclerotinia. The optimal decision in year 1 consisted of winter wheat in sclerotinia states of S1 to S2 (40%), and lettuce for S3 to S5 (60%). In year 2, winter wheat remained the best decision for S1 to S2 states. For S2 to S3 and one state in S4 (24% of all the states) treated carrots provides the highest benefit, and lettuce was the optimal decision for the lowest sclerotinia state S5 (36%). In year 3 to year 5, winter wheat remained the best decision for the highest sclerotinia states of S1 and S2 (40%). Treated carrots chosen as the best decision in S3 and S4 states (40%) and lettuce was the optimum decision for the lowest sclerotinia state S5 (20%).

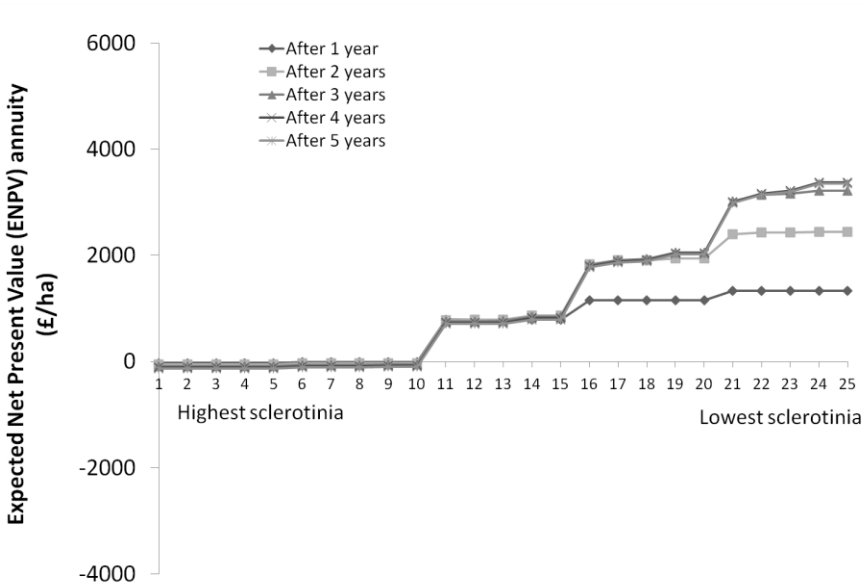

Figure 3. Financial outcomes of the optimal solution of growing only susceptible crops (scenario 1) in a five-year time horizon.

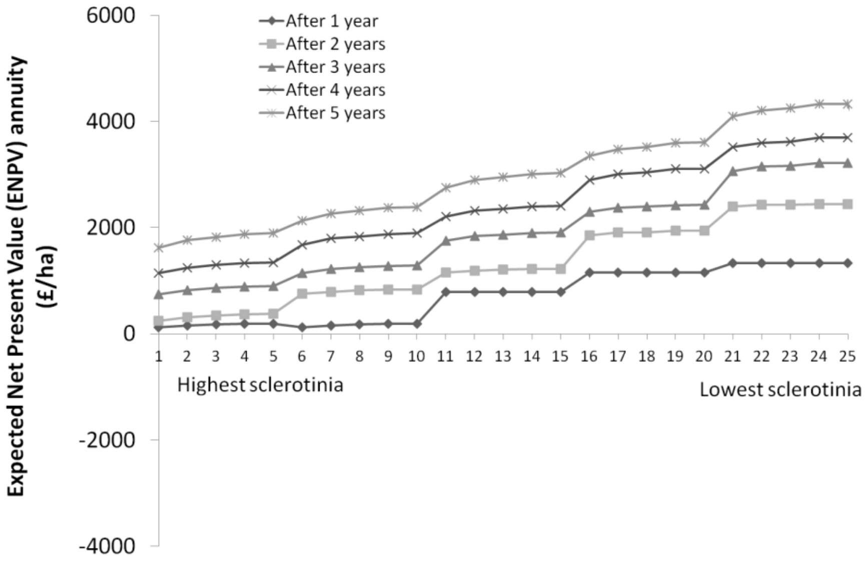

Figure 4. Financial outcomes of the optimal solution of growing susceptible crops and a break crop (i.e. winter wheat) (scenario 2) in a five-year time horizon.

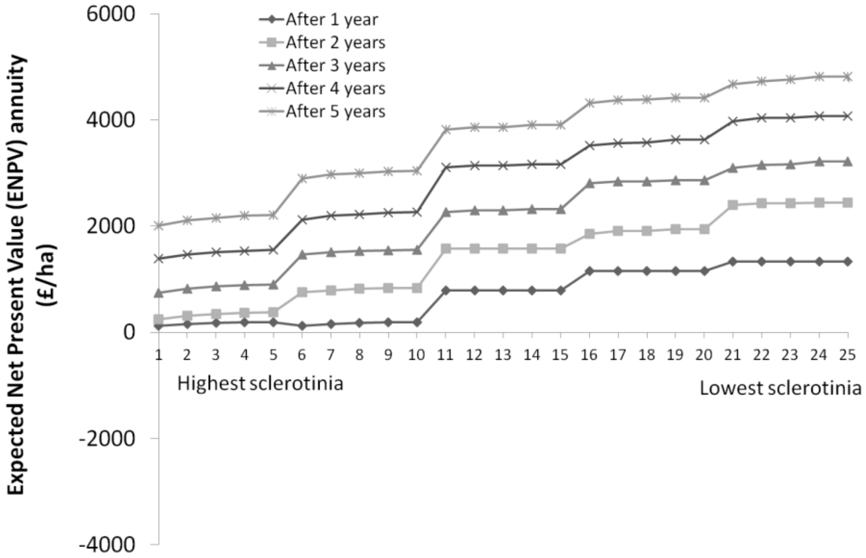

Figure 5. Financial outcomes of the optimal solution of growing susceptible crops and providing a treatment option (scenarios 3) in a five-year time horizon.

Results showed that when sclerotinia is at the highest level (i.e. S1), inclusion of a break crop in rotation and/or treatment did not improve the average financial returns of the all 25 states in year 1 (Fig 6). However, including a break crop in rotation and adding treatment improved the average returns of all the states in year 2-5.

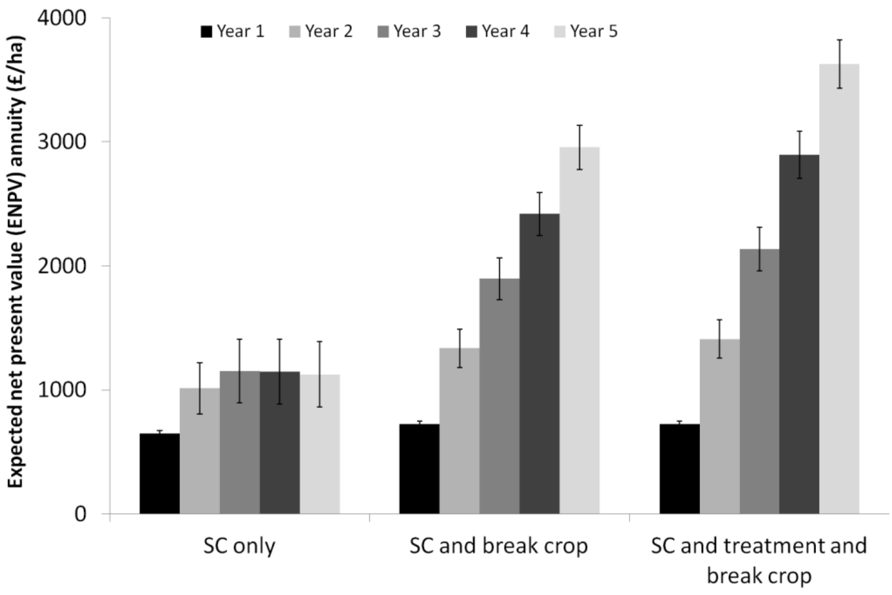

Figure 6. Financial outcome of optimal solutions of three scenarios calculated by DP for year 1 to year 5. Presented figures are Mean±SE (error bars) of 25 modelled states (sample size of 25 in one run of the model).

For oilseed rape including winter wheat as a break crop to the decision set in short-term runs showed that in year 1, in worst- and moderately infested land states (S1 to S3 and 3 states in S4) winter wheat was the best decision (72% of all states). In 2 states of S4 and all states of

S5 (i.e. minimum infestation) oilseed rape featured as best decision (28% of the states). However, in year 2 to year 5 the optimal decision consisted of winter wheat for sclerotinia states S1 to S4 (80% of states) and oilseed rape featured only in sclerotinia states S5 (20% of states). The average ENPVs of all the states for year 1, year 2, year 3, year 4 and year 5 were predicted at: £180, £517, £678, and £834 respectively. These results showed that in short-term oilseed rape could be the best choice only if the land infestation with sclerotia is its minimum. In moderate to high level of land infestation the optimum decision is to grow a non-susceptible crop.

Discussion

Continuous susceptible cropping in the long-term resulted not only in substantial financial losses but also a great accumulation and build-up of sclerotia in land over time, a build-up that poses a great risk to susceptible future crops. Despite a profitable outcome for continuously growing susceptible crops in some land states (moderate to low sclerotia infestation) in the early years of a short-term time horizon (5 years), the model confirms that major losses would be expected for the majority of land states in the last years (year 4 and 5). Including one break crop in the rotation in the long-term reduced build-up of sclerotia in soil and improved the financial returns that were reflected in positive probability-adjusted ENPVs. The financial improvement calculated by the model were 64%, 96%, 57% and 55% of the gross margins of healthy crops for carrots, winter oilseed rape, potatoes and lettuce respectively. Combination of rotation with a break crop plus treatment showed the highest effectiveness in minimising the impact of the disease. It should be noted that although the DP can handle the stochastic nature of the disease and the long-term cyclical cropping decision, calibrating the model to mimic certain (short-term) rotations is difficult if not impossible.

Running the model with the 6 susceptible crops in the decision choice set, the optimum rotation in the short-term featured a high proportion of lettuce (60%) in the low infested states and an equal proportion of spring peas and potatoes (20% each) in high- and moderately-infested states of land. With no break crop in the rotation, highly-infested land states could not be improved and therefore generated a loss that was minimised by choosing spring peas, potatoes and lettuce. However it was still possible to make positive financial return for the land with moderate to low levels of infestation (i.e. state 10 to state 25). Adding winter wheat to the decision choice altered the optimum crop rotation in that winter wheat and lettuce featured in the optimal rotation. The proportion of winter wheat decisions predicted by the model increased from 40% in year 1 to 80% in year 5 aiming at minimising accumulation of the sclerotia in land by the end of the short-term time horizon (year 5). The financial returns in year 1 were the lowest and in year 5 were the highest predicted. Despite the low financial returns, particularly in year 1 and year 2, in the highly-infested land states, the inclusion of a break crop in the rotation mitigated losses in these states. Minor improvements (10%) observed in the average financial figures of the all states in year 1 were achieved by adding a break crop or a break crop and treatment. The improvement in average figures was higher in subsequent years and in year 5 reached to its maximum of 62% and 69% for scenario 2 and scenario 3 respectively.

In the current model, two transition probability matrices were used, one for the susceptible crops and one for the break crops. Ideally crop-specific transition probability matrices are needed to capture the differences between the crops. These matrices regulate the transitions from one state to another by preventing or allowing certain transitions and therefore play a crucial role in characterizing the optimal decisions of the DP. In the absence of field data that could inform these matrices, we used our best assumptions in reflecting the transitions of land state based on the disease status and type of the crop (susceptible or break crop). We considered it as one of the limitations of the current model that needs further attention and improvement. The modelling work helped with identifying these data gaps and the areas that more research is needed. Another limitation of the current model was the relationship of the level of disease (sclerotia) and the potential yield loss. In the absence of crop-specific data, a disease-yield loss relationship from a carrot experiment was used for all the 6 crops included in the model. Therefore, the relationships between the number, size and frequency of sclerotia and the yield loss as well as the build-up and decay curves of sclerotia by continuously growing susceptible and/or break crop needs to be investigated in future research projects. Further development of the model is required to improve the input data and assumptions used in the model and to expand the scope and test alternative scenarios.

Conclusions

Under the assumptions made in the presented DP model we showed that rotation and treatment of the land against sclerotia build up was financially justified yet permitted intensive yet sustainable production of susceptible food crops in the long run. Allocation of even a small proportion of cropping decisions to break crops coupled with treatments in the rotation will mitigate long-term build-up of sclerotia in land, reduce the financial losses and keep the land at a low level of sclerotia infestation. This provides the opportunity of gaining higher benefits by growing susceptible crops in less infested land while avoiding susceptible cropping in highly-infested land or the need for long periods of break cropping. However in the short-run, high proportions and high frequencies of cropping decisions need to be either allocated to break crops or treated-susceptible crops in order to avoid accumulation of the disease and to generate profit. In the examined scenarios, rotation gave the greatest financial benefits when sclerotinia pressure was higher, but it was also the best financial strategy for land with low sclerotia. The examples presented show that DP methodology provides a useful framework to explore the trade-offs between crop rotation and growing high value susceptible crops in the long and short term in relation to plant diseases in arable agriculture that are at the heart of sustainable food production and land use.

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Appendix

Table A1. Probability of Next States given Current States for susceptible crops (i.e. C, WOSR, SOSR, B, P, P and L).

State No.	Land States		Next State																								
	G[a]	S[b]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	1	0.10	0.50	0.30	0.10																					
2	2	1	0.10	0.50	0.30	0.10																					
3	3	1	0.10	0.50	0.30	0.10																					
4	4	1	0.10	0.50	0.30	0.10																					
5	5	1	0.10	0.50	0.30	0.10																					
6	1	2	0.10	0.50	0.30	0.10																					
7	2	2		0.10	0.50	0.30	0.10																				
8	3	2			0.10	0.50	0.30	0.10																			
9	4	2				0.10	0.50	0.30	0.10																		
10	5	2				0.10	0.50	0.30	0.10																		
11	1	3					0.10	0.50	0.30	0.10																	
12	2	3						0.10	0.50	0.30	0.10																
13	3	3							0.10	0.50	0.30	0.10															
14	4	3								0.10	0.50	0.30	0.10														
15	5	3								0.10	0.50	0.30	0.10														
16	1	4										0.10	0.50	0.30	0.10												
17	2	4											0.10	0.50	0.30	0.10											
18	3	4												0.10	0.50	0.30	0.10										
19	4	4													0.10	0.50	0.30	0.10									
20	5	4													0.10	0.50	0.30	0.10									
21	1	5															0.10	0.50	0.30	0.10							
22	2	5																0.10	0.50	0.30	0.10						
23	3	5																	0.10	0.50	0.30	0.10					
24	4	5																		0.10	0.50	0.30	0.10				
25	5	5																		0.10	0.50	0.30	0.10				

[a]G: represents the time (number of years) elapsed since the last break crop.
[b]S: represents the sclerotinia state

Table A2. Probability of Next States given Current States for break crops (i.e. WW, SW, WB and SB).

State No.	Land States		Next State																								
	G[a]	S[b]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	1	0.20					0.80																			
2	2	1		0.20					0.80																		
3	3	1			0.20					0.80																	
4	4	1				0.20					0.80																
5	5	1					0.20					0.80															
6	1	2						0.20					0.80														
7	2	2							0.20					0.80													
8	3	2								0.20					0.80												
9	4	2									0.20					0.80											
10	5	2										0.20					0.80										
11	1	3											0.20					0.80									
12	2	3												0.20					0.80								
13	3	3													0.20					0.80							
14	4	3														0.20					0.80						
15	5	3															0.20					0.80					
16	1	4																0.20					0.80				
17	2	4																	0.20					0.80			
18	3	4																		0.20					0.80		
19	4	4																			0.20					0.80	
20	5	4																				0.20					0.80
21	1	5																					1.00				
22	2	5																						1.00			
23	3	5																							1.00		
24	4	5																								1.00	
25	5	5																									1.00

[a]G: represents the time (number of years) elapsed since the last break crop.

[b]S: represents the sclerotinia state.