A Decision Process to Determine Optimal Rotations When There is Plant Disease

by

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Abstract

The root disease *Aphanomyces euteiches* is a major yield depressing disease in lentil and field pea production in the Canadian Prairies. The only control measure for producers of these crops is to have more break-years between growing susceptible crops. The disease is also highly variable. This study used a stochastic dynamic programming framework to determine the optimal lentil-based rotation when the disease *A. euteiches* is present. Disease severity in the model was probabilistic. The probabilities depended on past disease severity, the pulse break-years in the rotation, and yield potential. It was determined that when the disease severity rating was high enough for noticeable yield damage, a 7-yr rotation was optimal over that of shorter rotations with more frequent lentil production. The cost of a one unit increase in disease severity rating ranged from \$6 (average lentil price) to \$22 (high lentil price) ha^{-1} yr^{-1}, when the crop rotation was optimal. Using shorter rotations with fewer break-years in pulse production resulted in higher future disease, imposing costs in the present and future.

Introduction

Plant disease can occur above ground on plant stems and leaves, or on plant roots and emerging seedlings. The pulse root disease *Aphanomyces euteiches* is now a major disease of western Canadian pea and lentil crops. Unlike leaf diseases, there are no methods of pre-season nor in-crop control for this disease. The incidence and severity of this disease can be influenced by producer actions, such as crop rotations. Another major factor in disease expression is weather conditions, for which the producer has no control. Without action to lessen the disease, crop yield will be reduced. The yield damage will depend on the incidence and severity of the disease, the plant growth stage at which disease becomes severe, and environmental conditions. The recommended long-term action to manage this disease is to reduce the frequency of growing the susceptible crop to one in seven years by adopting diverse crop rotations.

A. euteiches is a fungus-like pathogen. It appears to be native and widespread as it has been detected in prairie soils that have never been cultivated (Karppinen et al., 2019). The disease can also affect some other annual and perennial leguminous crops and weeds, such as alfalfa, faba, snap and red kidney beans, red and white clover, and black medic. The infected root tissue initially appears gray and water soaked (Chatterton et al., 2019). With disease progression, the tissue becomes soft and honey-brown or blackish brown in appearance. Both root volume and its functionality are reduced. The upper plant when severely infected can be easily pulled out of the ground, leaving the outer cortical tissue in the soil. With very severe infection, plants wilt and yellow from the bottom of the stem upward, and ultimately die. In peas and lentils, moderate levels of *A. euteiches* severity reduces the number and size of pods, and the seed size. Recorded yield losses range from 10% to 100%. Disease severity is rated on a scale, and for this study a scale of 1 to 7 (Chatterton et al., 2019) was used. Yield damage starts to appear at a severity rating of 3 and plants are dead at a rating of 7.

Wet and soggy soils provide an ideal environment for *A. euteiches* root infection and spread. An infection early in the growing season generally results in a higher disease rating (Pfender and Hagedorn, 1983). Disease symptoms and yield loss are most evident if conditions are warm and dry following infection. Plants become stressed by both the disease reduced rooting system functionality and limited available soil moisture. The disease and inoculum level are not uniform across a field. *A. euteiches* typically develops first in low spots with saturated soil. Disease appears to be influenced by soil texture, topsoil depth, organic matter and soil nutrient content. Yield loss is generally evident in fields with moderate *A. euteiches* disease. With longer breaks in growing susceptible crops, inoculum levels and disease severity will eventually decline, mitigating yield damage. But once disease is in the field it will always be present, and disease can be high in any year when environmental conditions are favourable for its development and spread.

There are many unknown factors that influence the severity of *A. euteiches* in any cropping year. The one action that producers have in their control is the sequence of crops grown. This study determined the optimal cropping strategy for a producer with evidence of *A. euteiches* in their fields for lentil-based rotations. The objective of the study was to determine the optimal lentil-based rotation at different levels of disease severity in the previous lentil crop, given uncertainty about future disease severity. The expected cost of disease and associated yield damage imposed into the future was estimated under the condition of using the optimal crop rotation. The producer was assumed to maximize the net present value (*NPV*) of net cash flow (*NCF*) over time from crop production. Long-term disease management was by crop rotation selection, determining the number of break-years between lentil crops.

Model

A multi-year model capable of addressing long-term decision making in an uncertain environment was used in the analysis. A dynamic programing (*DP*) model with a Markovian process (Dreyfus and Law, 1977) for the stochastic disease component was specified. A stochastic *DP* problem solves the problem at each stage and is entirely independent of the outcome from previous decisions. The current state and the probabilities of future states for the actions available are all that is required to make a decision. The optimal value function of the stochastic *DP* model can be specified as

$$V_\alpha(i,k) = \max_{a}\left[NCF(i,a) + \alpha \sum_j^J P_{ij}(a) V_\alpha(j,k-1)\right] \qquad \text{(k=1, 2, …, n)}$$

and the boundary condition is

$$V_\alpha(i,0) = B_i$$

where the optimal value function, V_α, is the maximum discounted *NCF* at the discount rate α for k periods given the process starts in state i, a is the action (rotation selection), *NCF(i,a)* is the net cash flow for disease severity rating in state *i* the last time lentil was grown, and action *a*, $P_{ij}(a)$ is the probability transition matrix, and B_i is the boundary value at the last period for state *i*. The probability transition matrix contains the probability the system in state *i*, the previous lentil crop disease severity rating, will be in state *j* at period *t+1*, given the action at *t* is *a*. The sum of the probabilities for any state i over all *j* states will sum to 1.0; $\sum_j P_{ij} = 1 \; and \; 0 \leq P_{ij} \leq 1$. The probabilities in the transition matrix are independent of the period or prior history. Further, for a given state and action, the *NCF* is bounded. The use of a Markovian process in a stochastic *DP* model will determine the maximum expected discounted returns for *k* periods given the process starts in state *i*. The solution procedure to obtain the optimal policy is backward solving from the last to the first period.

The Markovian process was used to describe agricultural production that contained a degree of uncertainty, in this model the root disease *A. euteiches*. The yearly climatic differences (precipitation, humidity, solar radiation, etc.) that influence disease were expressed in the disease severity. Once *A. euteiches* is in a field, there is a probability for considerable yield damage. The probability of disease and yield damage can only be reduced by less frequent planting of the susceptible crop, lentil in this study. The only management practice available is the cropping system. To date, plant genetic resistance has not been found that could be bred into these crops to provide genetic disease resistance. For this problem, the number of actions and the states were independent.

Data and Analysis

Based on crops grown in the Brown Soil Zone of Saskatchewan, four crop rotations were specified. These were *L-D* (lentil-durum), *L-C-D* (lentil-canola-durum), *L-D-C-D*, and *L-W-C-D-K-D-M* (lentil-hard red spring wheat-canola-durum-Kabuli chickpea-durum-yellow mustard). The shorter rotations were commonly used by producers prior to *A. euteiches* disease damage becoming evident. The longer rotation was a more diverse rotation with lentil once every seven years, as is the recommendation when *A. euteiches* is present and has caused yield loss. Average weekly crop prices since 2015 (PDQ, 2021) were used in the model. Yields were from select municipalities in the region (GoS, 2021b). Production costs were based on provincial crop budgets (GoS, 2021a). Prices, yields and costs were used to determine the *NCF* from the rotations. Respectively for lentil, durum, canola, chickpea, wheat and flax; the prices were ($\$ \, t^{-1}$) 582, 294, 493, 597, 250 and 860; yields were ($kg \, ha^{-1}$) 1402, 2257, 1535, 1434, 2080 and 874; and production costs were ($\$ \, ha^{-1}$) 509, 511, 657, 766, 482 and 474. The discount rate used in the analysis was 5%.

The transition probability matrix was derived from a disease model (Smith et al. 2022). The disease model was based on studies by Pfender and Hagedorn (1983), Malvik et al. (1994), and Moussart et al. (2012). Because there was limited information from the Canadian Prairies, disease information from the three studies was synthesized to provide a prediction of disease severity rating as a function of the number of break-years between lentil crops, the previous level of disease, and a random component correlated with crop yield. The oospore inoculum in the soil was modelled to break down over time at a 20% decay rate (personal communication), which was lower than the predicted rate of 45% by Pfender and Hagedorn (1983). Previous disease rating net of its decay was used as an indicator of inoculum in the soil and the potential for early infection and high disease. The more break-years in growing a susceptible crop, the lower the oospore inoculum count and the lower the likelihood of early disease and disease severity. The higher (lower) disease in the past, the higher (lower) disease was likely to be in the current period. The final factor was a random component to account for disease severity rating being associated with many unknown environmental conditions during the growing season. Disease will generally be higher when moisture is plentiful – also a condition that contributes to higher disease-free yield. Disease in the model was correlated with potential crop yield. Disease severity rating was probabilistic, and predicted using a PERT (modified triangular) distribution. The higher past disease, the higher the yield potential, and the fewer years between susceptible lentil crops, the higher was the probability of a high disease severity rating. The mean of the PERT distribution was the previous disease rating, decayed to the present period. The minimum was set to 0.1 and the maximum to 7.0. The random component was a uniform random variate (0 to 1). The disease model was used to simulate disease ratings for 500 iterations, and the estimates were summarized into transition probability matrices for each of the four rotations. There were seven disease rating states in the model (Table 1). The reported states were the midpoint of the modelled disease severity ratings. The transition probability matrix for the *L-D* rotation was reported in Table 1 to illustrate the matrix. The probabilities across j (rows) for each i (column) summed to 1.0. If the initial period disease level was low (high), there was a higher probability the next period disease level would also be low (high). For longer rotations, the probabilities were higher for low disease in the next period (j) than those reported in Table 1.

Table 1. Transition probability matrix for the *L-D* rotation.

Next period	Current disease severity rating (i)						
disease rating (j)	2.5	3.0	3.5	4.0	4.5	5.5	6.5
2.5	0.664	0.572	0.480	0.388	0.30	0.160	0.070
3.0	0.128	0.142	0.152	0.152	0.146	0.112	0.068
3.5	0.088	0.112	0.126	0.140	0.146	0.132	0.094
4.0	0.056	0.076	0.098	0.116	0.130	0.140	0.116
4.5	0.046	0.068	0.092	0.122	0.152	0.198	0.206
5.5	0.018	0.028	0.046	0.070	0.106	0.194	0.282
6.5	0	0.002	0.006	0.012	0.020	0.064	0.164

Solving the model was by a macro program written in Excel VBA. The standard solution procedure for the *DP* program was coded to read in data, compute the optimum path, and output results to a worksheet. There were 15 time periods. A major factor that will influence *NCF* by rotation was crop price. The optimal rotation, and consequently the frequency that lentil was optimal, would depend on the price of lentil relative to other crops. The major non-pulse crops in the region were durum wheat, and to a lesser extent hard red spring wheat and canola. The base model price ratio of durum to lentil was 0.51, spring wheat to lentil was 0.43, and canola to lentil was 0.85. Four additional lentil prices were examined, 15% lower, 15% higher, 30% higher, and 45% higher than the base price. At the different lentil prices, the associated durum/lentil price ratios would be 0.59, 0.44, 0.39 and 0.35, respectively, for -15%, +15%, +30% and +45%. The altered price ratios made lentil less (higher ratio) or more (lower ratio) profitable for a producer to grow. The price ranges and ratios closely reflected recent historical values. Crop prices in 2021 to 2022 were higher for all crops, but the price ratios were similar to the longer-term averages. The discount rate could also affect the optimal solution, a rate of 10% was used with the base prices to determine its influence.

An estimate of the cost imposed on the production system from a higher *A. euteiches* disease severity rating, the marginal user cost (*MUC*) of the disease, was estimated from the difference in the optimal value function at the initial year. The optimal value function used a rotation sequence over time that was optimal for the given state and prices. The comparison to estimate the *MUC* used the optimal crop rotation sequence, not a fixed rotation. The *MUC* was the change in annualized *NCF*, for a one unit increase in disease severity rating, for each of the discrete disease rating states in the analysis, evaluated at the first period.

Results

The model determined the optimal crop rotation at each period for seven levels of previous disease severity rating, five lentil prices, and a higher discount rate. The value of the optimal value function was converted to an annualized value by the appropriate annuity factor. The optimal decision depended on the previous lentil crop disease rating (Table 2). When the previous disease rating was less than 3.0, the *L-D* rotation was optimal. With previous disease rating 3.0 and the *L-D* rotation, there was a probability of 0.3 the disease severity would be higher than 3.0 resulting in expected yield damage of 8%. Yield damage of 8% reduced the lentil *NCF* about \$ 26 ha^{-1}, negating most of the *NCF* return advantage of lentil over all other crops. When previous disease rating was 3.5, or higher, the *L-W-C-D-K-D-M* rotation was optimal. A disease severity rating for the previous lentil crop of just over 3.0 was high enough that the optimal path over time was the 7-yr rotation. At these low disease severity ratings, the long-term expected *NCF* from the 7-yr rotation exceeded that from shorter rotations where disease damage would be higher. The *NCF* of rotations *L-C-D* and *L-D-C-D* was never as high as for the *L-D* or *L-W-C-D-K-D-M* rotations, so were never optimal. Lentil price influenced the optimal cropping (Table 2). With a lower lentil price (-15%), when previous disease rating was greater than 2.5, the 7-yr rotation was optimal. The lentil price needed to be up to 30% higher than the base before the *L-D* rotation would be optimal at a previous disease rating of 3.5. A higher discount rate of 10% had no affect on the optimal cropping system. The value of the optimal value function was lower at the higher discount rate, but when annualized it was similar to the annualized *NCF* for the base discount rate. A discount rate of 0% did not alter the optimal cropping system (data not shown).

Table 2. Expected annualized net cash flow (\$ ha^{-1}) by scenario and previous disease severity rating

	Previous disease severity rating						
Scenario	2.5	3	3.5	4	4.5	5.5	6.5
Base	213*	209*	206	204	202	200	198
Lentil price -15%	164*	162	160	159	158	155	154
Lentil price +15%	262*	258*	251	249	248	245	242
Lentil price +30%	312*	307*	298*	295	293	290	287
Lentil price +45%	363*	357*	347*	342	340	336	333

Discount rate 10%	224*	219*	214	211	209	207	203

* indicated the *L-D* rotation was optimal, otherwise it was rotation *L-W-C-D-K-D-M*.

With the base prices, the *L-D* rotation had an annualized expected *NCF* of \$213 ha^{-1} with low (2.5) previous disease rating, declining to \$209 ha^{-1} at a disease rating of 3.0. If the previous disease rating was 3.5, or higher, expected yield damage from higher disease with *L-D* exceeded the expected *NCF* benefit from intensive lentil production with low disease. The annualized *NCF* declined for the *L*-D rotation by \$40 ha^{-1} from 2.5 to 3.5 and by \$47 ha^{-1} from 3.5 to 4.5 (data not shown). For the *L-W-C-D-K-D-M* rotation, the decline was \$12 ha^{-1} and \$14 ha^{-1}, respectively, for the same increases in previous disease. At the highest lentil price in the analysis, the annualized *NCF* declined \$58 and \$69 ha^{-1} for the *L-D* rotation, and \$17 and \$20 ha^{-1} for the *L-W-C-D-K-D-M* rotation, when disease increased from 2.5 to 3.5, and from 3.5 to 4.5, respectively (data not shown).

An estimate of the *MUC* of *A. euteiches* disease was presented in Figure 1 for the base lentil price and for the +45% lentil price. As previous disease severity rating increased, it was optimal to move to a longer, more diversified, rotation (Table 2). The *MUC* illustrated in Figure 1 was broken into three components. The first (blue line) was the *MUC* when the optimal rotation was *L-D*, which was when previous disease severity was low. With the *L-D* rotation, the probability of high disease rating in the future was higher, imposing a cost, and with lentil more frequent in the rotation any lentil disease damage had more impact on the annualized *NCF* of the rotation. A one unit increase in the disease severity rating when disease severity was 3.0 and rotation was *L-D*, imposed a cost of \$6 ha^{-1} yr^{-1} at the base lentil price and \$12.50 ha^{-1} yr^{-1} at the high lentil price. The *MUC* increased with a previous disease rating of 3.25 because of higher yield damage. The *L-D* rotation was still optimal for part of this range of disease severity states. The break in the line (red dashes) occurred because there was a shift to the 7-yr

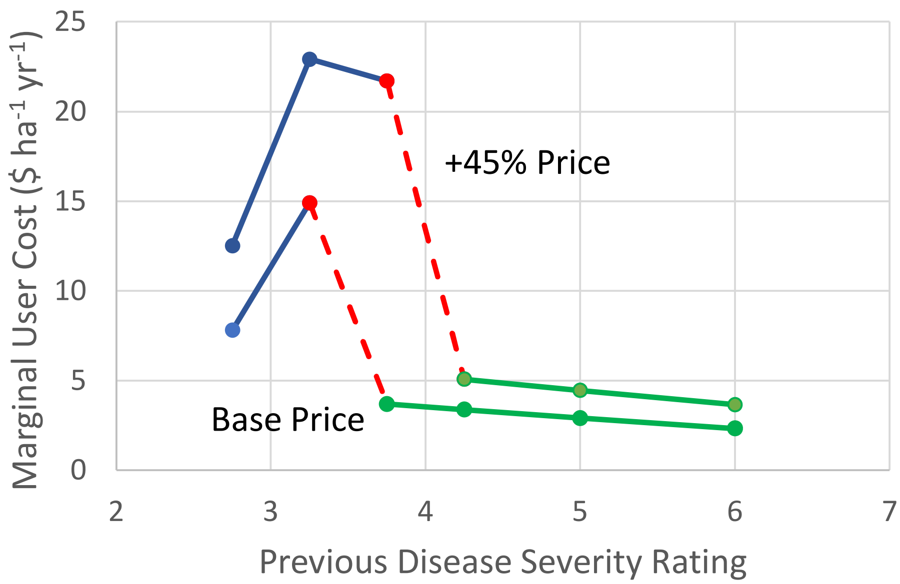

Figure 1. Estimate marginal user cost of *A. euteiches* disease severity in lentil-based cropping, base and +45% lentil price.

rotation *L-W-C-D-K-D-M* with previous disease severity rating of greater than 3.25 for the base price and 3.75 for the +45% lentil price. The *MUC* of a one unit increase in disease severity was \$2.30 to \$3.70 ha^{-1} yr^{-1} for the base price and \$3.65 to \$5.10 ha^{-1} yr^{-1} for the high price. The lower *MUC* with rotation *L-W-C-D-K-D*-M was due to a lower probability of high disease rating and high yield damage, yield damage declining over time with the longer rotation, and the lentil crop was a smaller portion of the rotation so had less effect on the rotation annualized *NCF*.

A similar pattern for *MUC* existed for the other three price scenarios, though the actual *MUC* values differed. When lentil price was 15% lower, the *MUC* was lower because the return to lentil production was lower and as a result future damage to annualized *NCF* from disease was also lower. The higher lentil prices 15% and 30% had *MUC* between the two price scenarios in Figure 1. When previous disease rating was low and it was optimal to use the *L-D* rotation, the probability of higher disease in the future was higher, resulting in a high *MUC*. At a previous disease severity rating of about 3.5, yield damage started to be a deciding factor determining the optimal rotation. If the *L-D* rotation was still optimal because of its higher annualized *NCF*, high future disease would result in yield damage continuing over time, even after switching to the longer rotation with six break-years in lentil production.

Discussion

Lentil production in the semi-arid regions of the Canadian Prairies was historically more profitable than many of the cropping alternatives. As a result, it was profitable to frequently grow lentil, and to have few break-years between lentil crops. The rise of the root disease *A. euteiches*, and its potential devastating yield damage altered the profitability of lentil production. The results of this study indicated that if the disease rating of *A. euteiches* has been about 3.0, or less, the short rotation *L-D* was still the most profitable rotation. Once the disease rating was slightly higher than 3.0, a longer crop rotation, in this study the 7-yr *L-W-C-D-K-D-M* rotation was optimal in the long-term. If disease has been noticeable in the field, the disease severity rating will be greater than 3.0, and longer rotations with more break-years between lentil crops should be adopted. The important component of the longer rotation was the number of break-years between lentil crops to help manage the future disease severity. The longer rotation resulted in reduce disease severity, but it did not eliminate the disease or yield damage. Other rotations and crops with six break-years between lentil crops could also be used to manage disease severity. The selection of six crops to be grown between lentil crops will depend on the producer and the comparative productivity of different crops on their farm.

The lentil price had a relatively minor influence on the optimal cropping system. With higher lentil price relative to competing crops, lentil can be grown every second year at slightly higher disease severity, but not over about 3.5. While a higher lentil price was an incentive to grown lentil more frequently, doing so imposed greater costs in terms of lower future yield and returns. The *L-D* rotation, even at low levels of previous disease severity and high lentil price, imposed costs into the future that ranged from \$6 to \$22 ha^{-1} yr^{-1}, depending on previous disease and lentil price.

The results of the study depended on the disease model and the prediction of disease, given previous disease, the rotation, and a random component. The probability of disease for the *L-D* rotation though did not have high probabilities for high disease in most situations. For example, if previous disease was 3.0, the probability of disease being 3.0, or less, was 71%, and 63% for 3.5, or less. The disease model in all likelihood did not overestimate disease. The relatively low probability of higher future disease was adequate for the 7-yr rotation to be optimal when disease symptoms have been evident in past crops. Altering the model disease estimate by 30%, higher and lower, did not alter the optimal rotation, but did influence the annualized *NCF*. The model results of the optimal cropping system were robust, and would vary little with different disease estimation.

Conclusions

This study determined that in the presence of root disease *A. euteiches* in southwestern Saskatchewan, long-term profitability of lentil-based rotations was higher with six break-years in lentil production than one break-year. Lentil price had little influence on the optimal cropping system. Higher lentil price was an incentive to plant lentil more frequently, but the cost associated with future higher disease damage negated most of the current benefits from a higher lentil price. The expected future cost of a one unit increased in disease severity rating when using the optimal cropping system ranged from \$6 to \$22 ha^{-1} yr^{-1}, the higher cost was associated with a high lentil price. When yield damage to lentil has been evident, more break-years between lentil crops will help manage the future disease severity and yield damage. Continuing to use a short rotation, such as *L-D*, in an attempt to maximize current lentil production, will impose high costs into the future. These results were from a dynamic optimization model that used probabilities of disease based on past disease and the number of break-years between lentil crops. The result were expectations because of an uncertainty future, but results were robust to the disease damage estimates. If *A. euteiches* has been identified in lentil fields, the optimal long-term cropping system to manage the disease and maintain lentil returns is to follow the recommendation of using rotations with six break-years between lentil crops.

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