Everything in the Universe is Either a Potato or not a Potato:
Solving for Optimal Crop Rotations Through Linear Programming

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Authorization to Submit Thesis

This thesis of Henry Wilson, submitted for the degree of Master of Science with a Major in Applied Ecnomics and titled "Everything in the Universe is Either a Potato or not a Potato: Solving for Optimal Crop Rotations Through Linear Programing," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Potatoes are a major commodity for the United States as well as Idaho. However, growing potatoes comes at a cost of diminishing soil quality. Diminished soil quality can impact profits by decreasing yields and quality. Crop rotations help potato growers maintain soil quality, while maximizing average annual returns. Through linear programming, optimal crop rotations are found by maximizing net present value. These optimal crop rotations are then run through a Monte-Carlo simulation to characterize the price risk of these different rotations. The linear programming and Monte-Carlo models are also compiled into a simple dynamic functional excel tool to be used by growers and future researchers.

Each of the highest net return five-year crop rotations consist of potatoes in the first, third, and fifth years. There is little difference in the NPV of these top crop rotations. As potatoes consist of the majority of the rotations' NPV what is grown in the years without potatoes has little impact on the total NPV. This indicates the importance of the crops grown besides potatoes having a positive impact on the soil health and in turn having a positive impact on the yields and quality of the potato harvest. The Monte-Carlo simulation results in small difference in the price risk of these different crop rotations. This again supports the importance of the other crops' impact on potatoes as there is no significant difference in the price risk of the varying crop choices. The dynamic tool created and presented herein will be able to further this research with more information on what the impact crops have on each other in terms of the quality and yields. This tool can by researchers to further the research done within this thesis, as well as by producers as a decision-making tool for helping to find the crop rotations that will maximize NPV.

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1. Introduction

1.1 Potato Industry Overview

The potato industry is worth almost 4 billion dollars in the United States alone, with 50% of this production coming from Washington and Idaho (Shahbandeh, 2018). Because of their substantial value to the economy, potatoes are an extremely important crop for these states and the country as a whole. However, intensive commercial potato production comes at a cost: diminishing soil quality. As soil quality decreases crop yields, generally, also decrease (Karlen, 2005). Growing potatoes requires considerable tillage and fumigation, which disturbs the soil, affects soil biodiversity, and may cause a loss of nutrients that other crops can help restore. Crop rotations have traditionally been used to combat soil disturbance and manage pests. Different crops uptake different nutrients from the soil as well as put different nutrients back into the soil (Carter, 2003). Thus, using certain crop rotations (as well as irrigation, tillage, soil amendments and other practices) can restore the soil quality, reduce pests, and improve the yields and profits of potato producers (Carter 2003; Chaparro 2012; Hills 2018).

From a neoclassical economics and practical perspective, the goal of most producers is to maximize profits; a significant component of which relies on cost-effectively increasing yields and quality. As such, understanding how particular rotations affect yield, quality, and profitability is critical in effective management decisions. Given the importance of crop rotations in profitable potato production, this thesis examines optimal crop rotations for maximizing net revenue, accounting for 1-year crop dynamics and includes a sensitivity analysis to account for price uncertainty. The goal of this thesis is to identify optimal crop rotations for potato farmers in Idaho, characterize the risk of these rotations, and create a usable tool such that producers can easily calculate optimal crop rotations for any crop choices with personalized enterprise budgets. Accordingly, this thesis:

1) Identifies the most profitable crop rotations for a "representative" potato grower using a linear programming model that accounts for 1-year dependence among crops.
2) Characterizes the risk of the ten most profitable rotations and examines how outcomes change with different assumptions around price.

3) Presents a decision support tool using a customizable, dynamic enterprise budget.

1.2 Funding Source and Broader Project

This thesis is an extension of the Potato Soil Health Project established to: identify reliable indicators of soil health and effective methods for increasing soil health in potato cropping systems, understand what determines growers' adaption of soil health management practices, and ultimately, improve soil health in potato cropping systems across the United States (UMN, 2019). This project is funded by the USDA Specialty Crops Research Initiative Coordinated Agriculture Project (CAP) #2018-51181-28704 (USDA). This project is a consortium of nine universities, as well as technical and industrial advisors that is currently running crop rotation research to see the impact that different crops and rotations have on soil health, as measured by yields and quality of crops such as different potato size classifications. As part of these experimental crop rotations, researchers are collecting detailed information on the impact that different crops within the rotation have on yields, potato sizes, and overall crop quality. For the average potato producer, potatoes are their primary source of on-farm revenue, but these producers cannot grow potatoes every year because this would be hard on the soil and increase the chance of pests taking over, or other factors hurting their yields and net revenue in the long run (Scholte 1992; Emmond 1972). For example, field studies found that continuous potato rotations have stem lesions on 58% of plants, while simple rotations reduce these infections to as low as 12% (Honeycutt et al. 1996). Therefore, potato growers must balance annual net revenues from rotational crops with the needs to improve soil health and nutrient concentrations between potato years. For example, sugar beets also have high annual net returns at over $700 per acre but do little to improve soil health for subsequent potato production. Potatoes are known for being a favorite for many pests and many of these pests that eat potatoes also will eat sugar beets and some of pests known to be potato pests actually prefer sugar beets (Roderus, 1908). The crops that are grown in non-potato years typically bring in less revenue, so it is important that these crops are setting the soil up to improve the potato yields in future years. Ongoing research as part of the Soil Health project will provide estimates to parameterize our model, based on crop rotations inter-year dependencies, where crops chosen in one year affect the quality and yield of crops in sequential years. While exact biophysical results have not yet been analyzed, this information can then be subsequently included in the decision support tool (presented herein) to help us better find the optimal crop rotations for potato farmers once these dynamics have been estimated.

1.3 Soil Health

In *Soil and Tillage Research,* Carter et al (2003) investigate the effect of long-term 2-year potato rotations on potato yields in Atlantic Canada. Potatoes were rotated with Italian ryegrass, red clover and barley. They found potato tuber yields were highest under Italian ryegrass, where out of the three rotation crops the Italian ryegrass had the largest biomass of both herbage and roots. Difference in yields was hypothesized to be a result of differences in nitrogen levels and nematode activity. Changes in diseases effecting potato yields were also recorded, "The greatest reduction in tuber-borne diseases occurred with the potato-red clover rotation but significant differences were infrequent" (Carter, 2003). It was observed that when looking strictly at soil health Italian ryegrass was the best for maintaining that health, and in turn giving the best potato yields. Potato crop productivity and soil organic matter were maintained in rotations with Italian ryegrass but declined in rotations with red clover and barley. Yields were mostly affected by levels of nitrogen so it is possible that the best crops to have in rotation with potatoes would be crops that put nitrogen back in the soil (Carter, 2003).

Other research highlighted the importance of rotation crops when producing potatoes. "A 2-year study quantified the changes in soil health for each phase of 5-year potato-grain-forage rotations at four organic potato production sites. Changes in soil physical and chemical, and biological properties, microbial quotient, mineralizable calcium, metabolic quotient, and earthworm were assessed" (Nelson, 2009). Nelson found that the potato phase would negatively affect the soil health in many aspects, but the other parts of the rotation were able to restore the health leading to no significant effect on the soils physical and chemical properties. The soil's biological properties were negatively affected by growing potatoes but were able to be recovered in the other years of the rotation. (Nelson, 2009). Understanding the biophysical relationship of crops and soil is necessary to estimate and identify optimal rotations, but it is insufficient without including economics considerations.

The Choice of Crop Rotation: A Modeling Approach and Case Study (McCarl,1986). looks at the economic impact of the choice of crop rotations. This research used linear programming methods to identify an optimum long-run crop rotation strategy. The procedure was implemented for a case study on a northeastern Oregon irrigated farm. The crops considered were wheat, corn, potatoes, and alfalfa. They found that the optimal rotation for maximizing profits was a rotation of wheat-potatoes-wheat-potatoes. More recently a similar optimal rotation was identified by Penny Myers' thesis, finding that the optimal rotation cycle was some form of a four year rotation made up of wheat and potatoes (Myers, 2005) However, a continuous rotation of wheat and potatoes is known to be soil depleting and presumably not optimal in the long run (McCarl, 1986). This rotation could be sustained in the short run and maximize profits in the short run, but eventually a continuous cycle of this rotation may deplete soil health causing an eventual decline in yields that could decrease the potential profits. McCarl found that a better rotation was a seven-year cycle of potato-wheat-potato-corn followed by three years of alfalfa (McCarl, 1986). These conflicting results are relevant to our current research as we attempt to identify profit-maximizing rotations (and other practices), while accounting for soil health and inter-annual dynamics.

Mean profit is only one metric of optimal rotations, as such this thesis also characterizes risk in choosing particular rotations. In McCarl's research it was also found that crops in the rotation have an impact on the returns in crops preceding them. "Growing one year of corn after alfalfa before potatoes raises the potato returns $400 per acre relative to immediately seeding potatoes". The effect of crops on the returns of other crops something that will be implemented into the research explained in this thesis that although some crops such as potatoes are the real money makers, the other parts in the rotation can increase profits even if they aren't directly making those profits (McCarl, 1986).

Overall, past literature suggests that crop rotations are useful and necessary to maintain soil health in potato production and crucial in driving profitability. Other practices are necessary to keep the soil healthy, but crop rotations are a practice that can be done to both maintain the soil health as well as optimize profits for producers. We also saw from the modeling approach a beginning of trying to determine an optimal crop rotation to maximize profits. We were able to use this existing research and expand to include more crop options and the impact of crops on one another to find optimal crop rotations for farmers from all over with different crop options and current soil health. Farmers can use this information to make an informed decision of what crop rotations will best benefit them in the short and long run when it comes to both soil health and profits.

1.4 Objectives

The first objective of this thesis is to find optimal crop rotations for Idaho potato farmers using linear programming techniques. Liner programming is a common method for identifying optimal combinations of inputs and/or outputs (choice variables) under limited resources (constraints) (Seagraves, 1956). In this case, the model includes 6 potential crops to be planted each year, with the limited resource being acres available. After the top optimal crop rotations were found we were able to use them to also examine their risk.

The second objective is to identify and characterize the risk of the most profitable rotations (based on mean net-returns and an interest rate of 5%). This was done by taking the identified ten most profitable crop rotations and conducting a Monte-Carlo simulation using historical crop prices and interest rates to identify the risk associated with the different rotations and compare the results across the different rotations.

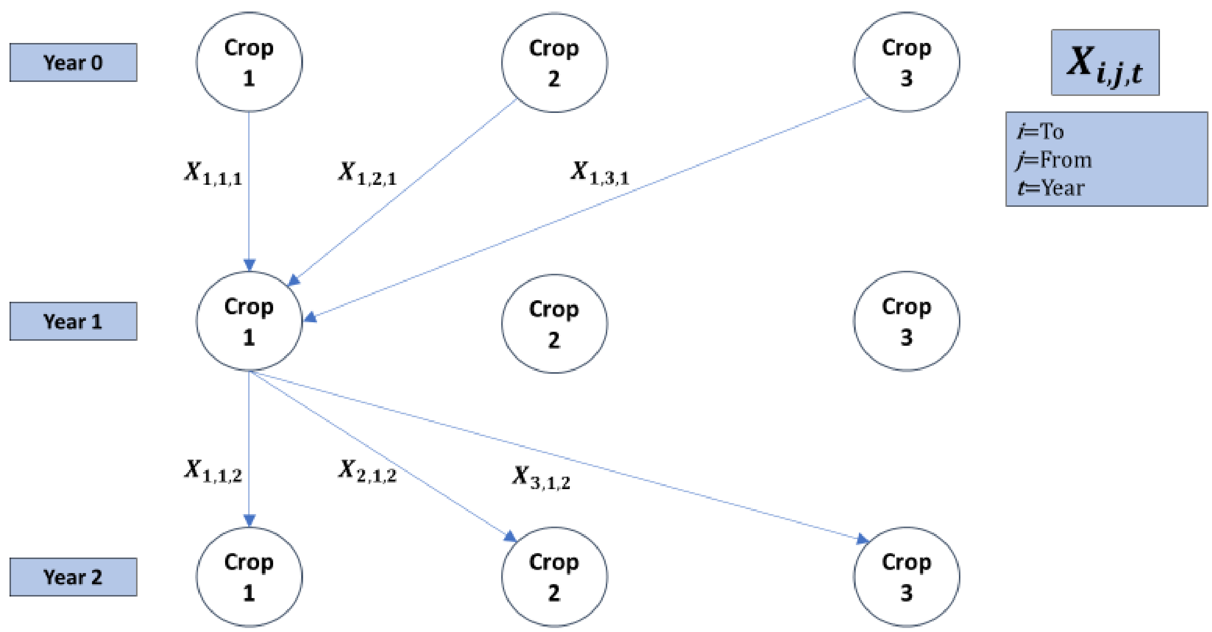
The third and final objective is to create a usable dynamic enterprise budget that allows for individualization. This is a tool that can be used by both farmers as a decision-making tool as well as future researchers to easily add to when more crop impact data is found. This tool is run in excel to keep it easy to use and change according to the needs of each individual producer or researcher.

2. Methods

2.1 Objective 1: Optimal Crop Rotations

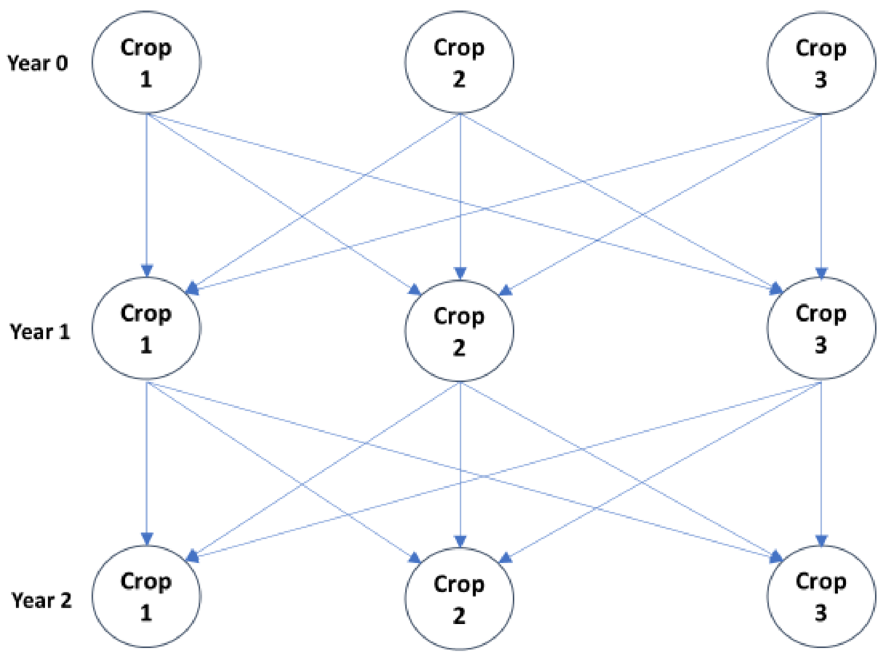
To achieve Objective 1, we solve for the optimal crop rotation through maximizing net revenue via a linear programming model. The problem is modelled using a "network" made up of different nodes and arcs. Where the nodes are the different crop options in each year and the arcs are the pathways from one crop to another between each year (Detlefson, 2004). This network problem is shown in Figure 2.1. For simplicity we are showing just three crops over three years, but the problem can easily be expanded to include additional years and crop choices, although computational constraints will become a problem as we increase choice variables and constraints. As such, out model includes six crops over a five-year planning horizon (discussed below).

Figure 2.1: Simple network flow



Each arc is represented by a $X_{i,j,t}$ where X is the number of acres planted to crop i from crop j in year t. So $X_{1,2,1}$ means that we have X number of acres grown of crop 1 in year 1 after at least X amount of acres of crop 2 were grown in year 0. These arcs are subject to the constraint $\sum_j^3 X_{ijt} \leq \sum_i^3 X_{ijt-1} \; \forall \, i \, , j \, , t > 0$. This means that the sum of acres grown from a given crop (*i*) in any year *t* has to be less than or equal to the sum of acres grown to that same crop (*j*) in year *t*-1. So for example, $\sum_j^3 X_{i,1,2} \leq \sum_i^3 X_{1,j,1}$ this means the sum of acres grown of crop 1 in year 2 has to be less than or equal to the sum of all acres grown to crop 1 in year 1. Another way of stating this is that in year 2 we would be unable to grow crop 2 from crop 1 ($X_{2,1,2}$), if there were no acres of crop 1 grown in year 1 ($X_{1,j,1} = 0$). Every node and arc possible with the entirety of the equation is shown in figure 2.2

Figure 2.2: Full network flow and equation



$$\pi = \sum_{t=0}^{3} \sum_{j=1}^{3} \sum_{i=1}^{3} \frac{X_{ijt}\rho_{ij}}{(1+r)^t}$$

$$\rho_{ij} = \lambda_{ij} Price * \delta_{ij} Yield$$

$$\max_{X_{i,j,t}} \pi$$

s.t.

$$\sum_j^3 X_{i,j,t-1} \geq \sum_i^3 X_{i,j,t}$$

$$X_{i,j,t} \geq 0$$

Profit is solved from the sum product of all $X_{i,j,t}$ for every crop to, crop from, and year, and the crops corresponding ρ_{ij} where $\rho_{ij} = \lambda_{ij} Price * \delta_{ij} Yield$, and λ_{ij} is the price multiplier for moving to crop *i* from crop *j*, and δ_{ij} is the yield multiplier for moving to crop *i* from crop *j*. We then maximize profit by choosing $X_{i,j,t}$ subject to the constraint $\sum_j^3 X_{ijt} \leq \sum_i^3 X_{ijt-1} \; \forall \, i \, , j \, , t > 0$ that was discussed before, and that $X_{i,j,t}$ must be great than zero. Since the first constraint does not apply to year zero there is also a constraint $\sum_{i=1}^6 X_{i,,0} <$

$TA\ for\ t = 0$ that simply says that we cannot grow more acres in year zero than there are acres available.

In this example there are only nine different nodes for the three crops in each of the three years such that 18 different arcs between these nodes represent each choice variable. This set up is identical to our full model, except we use six crop choices and solve for a five-year rotation. There will now be 30 different nodes representing the six crop choices over all five years, and there will now be 144 arcs in between the nodes representing all of the choices. The equation is also similar to before and is shown here in equation 2.1.

Figure 2.3: Linear Programming Equation

$$\pi = \sum_{t=0}^{5}\sum_{j=1}^{6}\sum_{i=1}^{6}\frac{X_{ijt}\rho_{ij}}{(1+r)^t}$$

$$\rho_{ij} = \lambda_{ij}Price * \delta_{ij}Yield$$

$$\max_{X_{i},j,t} \pi$$

St.

$$\sum_{i=1}^{6} X_{i,,0} < TA\ for\ t = 0$$

$$\sum_{j=1}^{6} X_{ijt} \leq \sum_{i=1}^{6} X_{ijt-1}\ \forall\ i\ ,j\ ,t > 0$$

$$X_{ijt}\ \geq\ 0\ \forall\ i\ ,j\ ,t$$

This linear programming problem is set up using these networks of arcs and nodes. The rows of the constraint matrix M of the linear programming problem will correspond to the nodes and the columns of the constraint matrix corresponds to the arcs. Therefore, M is called a node-arc incidence matrix. Solving a linear programming problem with this special structure is very easy and has very nice interpretations. For example, the node-arc incidence matrix is unimodular which means that the determinant of any square-sub-matrix of the incidence matrix is 0, 1, or -1. This is utilized in the algorithm for solving the problem (Detlefson, 2004). In this problem each column in the matrix and the column vector is set up as $X_{i,j,t}$ where *i* is the crop being grown that year, *j* is the crop that was grown the year before, and t is the year ($t \in$ Z: [0,5]), and r is the assumed interest rate. The matrix is the network for the flow of crop rotation, the column vector is the total revenue for each $X_{i,j,t}$ and the constraint is the total acres available. Six crops across five years, with one year dependency results in 144 choice variables represented by the arcs, while acreage and rotational constraints results in 72 total constraints not including non-negativity ($X_{i,j,t} > 0$) constraints. The crop options with their net present value are shown in table 2.1. These crops were chosen because they are all commonly grown in Idaho and we had accurate data for their enterprise budgets. The yields we took from our enterprise budgets, but the prices are from the average Idaho crop price over the last 25 years (NASS, 2020).

Table 2.1: Crop Options

Crop	Yield	Price	Annual Costs	NPV
Wheat	125	$ 4.65	$ 372.87	$ 208.33
Barley	145	$ 4.13	$ 387.54	$ 211.49
Sugar beets	41	$ 43.32	$ 879.90	$ 896.22
Dry Beans	26	$ 25.52	$ 498.52	$ 165.00
Corn	175	$ 4.01	$ 609.59	$ 93.00
Potatoes	460	$ 6.16	$ 1,552.00	$ 1,281.05

Using this model requires several implicit assumptions and includes limitations. In any given year a producer can grow some mixture of crops. We initially assume that “plantable” acres is the only constraint in year 0 such that $\sum X_{i,,0} < Total\ Acres.$ This suggests that planting decisions before year 0 do not meaningfully affect the problem, which may be a limitation since potatoes cannot be grown consecutively and the interannual multipliers on yield and price will not affect production in year 0 (since there is no crop from which the current field is being planted). Another consideration in our modeling choice is how to initialize year zero, since no information on what is grown before year zero is included. As such, there is no multiplier impact on what crop was grown before for the crop that is grown in year zero. Some studies have gone back to year -2 to parameterize the current rotation in year 0. Going back to year -2 mans they also consider not just the crop that was grown the year previously, but the two crops that were grown previously (Detlefson, 2004). They do this to be able to know what the impact previous crops had on the first year of the rotation. This gives an advantage of more accurate values in the first year of the rotation. While we included what impact previous crops have on the later years of the rotation, we did not include the opportunity to identify that impact on the first year of the rotation. Some research has even gone as far as three years back (McCarl, 1986).

The linear programming model is not spatially explicit, and therefore established a crop rotation for a singular "field" where field can be defined as any area (generally, acre). Additionally, the model does not allow for fields to have more than one crop grown on each field in a year, thus it is incompatible with intercropping or other non-traditional planting schedules. Not allowing for split fields and only having one crop choice per year is similar with other research. This is a limitation that does not allow us to account for some crop rotations practices that are commonly used. **"**The modelling approach taken here does not consider specific fields. One could imagine that the above model came up with a solution which will require half a field of one crop and the other half of another crop. The same problem arises in the linear programming model established in Klein Haneveld and Stegeman (2004)" (Detlefson, 2004). These decisions could be made for multiple crops on different acres within one year, but you would have to run a different linear programming problem for each individual field or set of acres.

Additionally, land is the only constraint. This means that all other possible constraints such as labor and water we assume are sufficient under any crop choice. Lastley, we assume constant returns, which is common in most linear programming models. This means that we can grow any amount up to the total acreage available for any crop and use the same relative proportions of all inputs, and get the same relative output (Boles, 1955).

Since solving that many linear equations by hand is infeasible Excel's solver plugin is used. While Excel has limitations when comparted to other optimization programs/languages (MATLAB/R/etc.) it has the advantage of usability and ubiquity among farmers. Given Objective 3, to create a usable decision support tool, Excel (and simple VBA macros) is used to conduct our analysis.

Production information for each crop is taken from enterprise budgets created by the University of Idaho. They create these budgets with crop costs and returns estimated with the goal of providing the Idaho agriculture industry with unbiased estimates for various crops. Input prices are found through an annual survey of agriculture supply companies. The selling price is a historical average (NASS, 2019). Production practices are based on data taken from different agriculture sources throughout Idaho (Eborn, 2019).

We solve to maximize the total annual revenue by changing the matrixes of what crops are grown constrained to the acres available. This will give us the optimal crop rotation given the prices, yields, costs, and acres that are given. We could easily change what any of the crops are or what the price, yield, costs, or acres and find a new optimal solution. We unfortunately cannot add more years or more crops to the problem because excel has constraints of 200 decision variables when running a linear programming problem, and we have 144 decision variables with a six-crop/five-year rotation.

While there is the downside of only getting one crop rotation and not multiple top rotations to choose from, this still seems to have the advantage of choosing the optimal crop rotation and looking at different options with ease. This will help to characterize the risk and conduct sensitivity analysis for these crop rotations.

2.2 Objective 2: Identifying Risk

Objective two characterizes the risk of the ten most profitable rotations and examines the distribution of NPV returns. Once optimal rotations are identified, each of the ten rotations with the highest NPV will be used in a Monte-Carlo simulation where prices, interest, and yields are normally distributed stochastic variables. All yield and price multipliers are set to one within a matrix for both yield and price, so they have no effect on NPV.

Once ten crop rotations with the highest net revenues are identified, we look at the risk associated with the output price fluctuation of the different crops within the rotation. Net revenue for every possible five-year crop rotation with our six given crops is calculated with six annual crop choices and a five-year time horizon; thus 7,776 permutations exist. We use a simple VBA loop in Excel to run through all permutations and report NPV (assuming average prices, yields, and costs) for each one. Excel was used to facilitate our 3rd objective, to create a useable tool. As such, individual growers can enter farm-specific enterprise budgets and easily conduct a similar analysis tailored to their operation.

Impractical or infeasible rotations are removed from the feasible solutions set. These rotations were excluded because they would never be used in actual practice because of the high risk involved with pests, soil health, and lost yields involved with those rotations. Infeasible rotations include any that have the pairings listed in table 2.2.

Table 2.2: Infeasible crop pairings

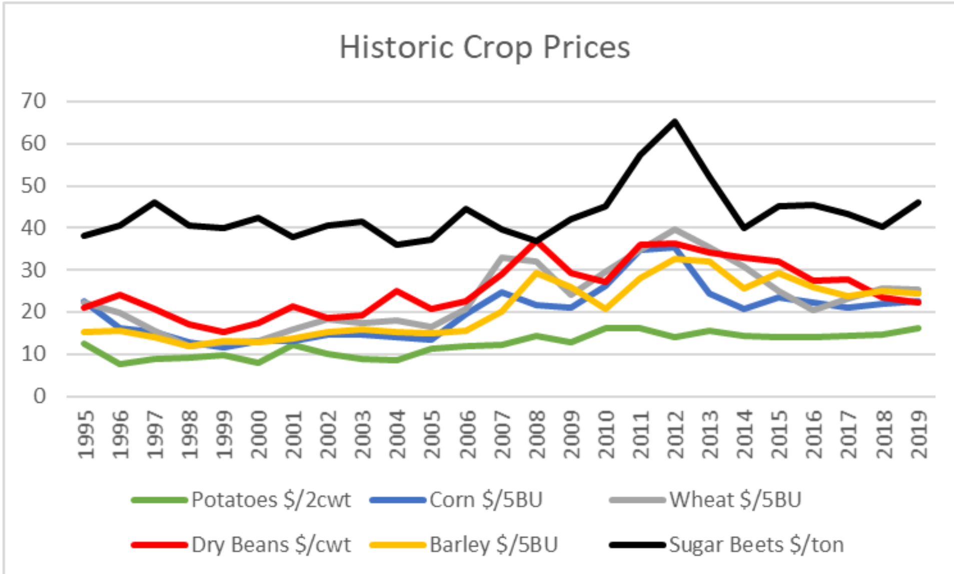
Potato – Potato
Potato – Sugar beet
Sugar beet – Potato
Sugar beet – Sugar beet

The total NPV return is the discounted sum of the five years of crops return taken from the enterprise budgets. We can then sort the list from highest to lowest total return to see the crop rotation options that give the highest total returns. When this is done the crop rotation with the highest total return is going to be the rotation with the top grossing commodity, in this case potatoes, in all five years. This is not actually the ideal crop rotation because one of the main reasons for crop rotations is rotating different crops to maintain soil health. If you were to grow potatoes every year it would not give you the highest total return because the yields would decrease substantially every year due to decreased soil health. With this research we want to take the soil health and change in yields into account. For this reason, we are not going to allow potatoes to be grown in back to back years, sugar beets to be grown in back to back years, or sugar beets and potatoes to be grown back to back. Therefore, the crop options listed in table 2.2 were removed. In future versions of this model, these restrictions can be accounted for by including low values in the yield multiplier, δ_{ij}.

After the crop rotations with the highest NPV are identified, we use a Monte-Carlo simulation to draw possible outcomes from historic distributions of prices to create an NPV distribution for each rotation. The Monte-Carlo simulation allows us to characterize risk by including crop prices as a random distribution, which have inherent uncertainty. Each realization of the draw includes a different set of random prices from the probability distribution (Palisade, 2020).

Price distributions are created from historic crop prices. Using the historic prices from the previous 25 years taken from NASS, shown in Figure 2.3, we discretized price distributions for each crop by creating five bins with corresponding probabilities for each price to happen.

Figure 2.4: Historic crop prices



We create these price bins by finding the standard deviation of the past 25 years of crop prices for each crop and assigning the price that is associated with a 17%, 33%, 50%, 67%, and 83% probability of an approximately normal distribution. This is done by calculating the mean and standard deviation for each of these crop prices over the last 25 years. These are shown in Table 2.3

Table 2.3: Mean and standard deviation of historic crop prices

	Potatoes	Corn	Wheat	Dry Beans	Barley	Sugar Beets
Average	$6.16	$4.01	$4.65	$25.52	$4.13	$43.32
SD	$1.36	$1.25	$1.51	$6.36	$1.32	$6.50

From these normal distribution means and the standard deviation, we calculated the prices that line up with each probability bin. For example, for potatoes we found that there is a 17 % chance that the price will be $4.85 or lower so every random draw from 0 to 0.17 will give a price of $4.85, then there is a 33% chance that the price will be lower than $5.64, so any random draw from 0.18 to 0.33 will give a price of $5.64, and so on. With these bins we ran a random pull between zero and one for each year of the rotation to pull the historic price from one of the probability bins. This draw will be done 10,000 times to get a distribution of possible net returns representing the changing historical prices to show the risk associated with price for each top crop rotation.

Then we look at the average and range of net revenues for each crop rotation. We are holding all costs constant through this simulation. This means that we are assuming output price is independent from input price which may or may not be true. We are also holding yields and interest rate constant which are not things that are normally a constant and which both also hold different levels of risk that are not taken into consideration.

2.3 Objective 3: Creating a Dynamic Tool

Objective three is to take what is done in the other objectives and turn them into a useable tool within excel to easily find optimal crop rotations in the future. Farmers are often looking for support tool to help make decision making easier. This is something that can be added to whatever current decision-making tools people already have, such as partial budgets, web-based decision-making systems, and other custom decision tools, as something easy and quick to use. Excel was chosen because it is very common that many people know how to use Excel in some capacity. With instructions provided anyone with even very basic understanding of Excel should be able to use this tool and even modify it to fit their needs. This also allows for anyone to be able to input unique crop options along with prices, yields, acres, and interest rates to find optimal crop rotations. With the setup of the use of price and yield multipliers, once the effect that crops have on different crops yields are found these can be included to find more accurate crop rotations.

These multipliers will be set up on a matrix within the tool so every crop option can have an impact on whichever crop is grown after it. For example, if it is found that when wheat is grown the year before potatoes the yield of potatoes goes up by five percent this can be put into the matrix so anytime a crop rotation has alfalfa the year before potatoes the yield pulled from the enterprise budget is increased by five percent. This will allow every crop option to have an impact on every crop option that is grown the year after it whether that impact is positive or negative. If there is no impact found between certain crops the multiplier can be left at one and there will be no change from what is pulled from the enterprise budget. This multiplier was also used to take out rotation options that are infeasible as highlighted in table 2.2 by setting those crop pairings multipliers to zero. This also permits farmers to take out options that they know they will never do. If they know that they will never grow corn right after growing potatoes, then they can set that multiplier to zero so no crop rotations given by the tool will have corn right after potatoes. With these multipliers there will be more useful results from the looping in the excel sheet as well as in the linear programming.

The usable dynamic tool is created from the linear programming from objective one instead of the looping done in objective two. Although the looping gives more crop rotation options than the linear programming, most farmers will not be able to use that excel file with ease. It would be easy for them to set up and run, but the computational requirements are higher which makes it more difficicult for most people to run. Even if a computer could run the looping it takes a substantial amount of time to do so. It is unrealistic to think that most farmers will want to use this tool when it is that much of a burden to get it to work. Therefore, we shifted to a linear programming model for the usable dynamic tool. Using linear programming we can get similar results but excel is able to run it in much faster.

3. Results

3.1 Objective 1: Optimal Crop Rotations

We were able to find an optimal crop rotation for our given prices, yields, and crop options. Using the linear programming problem, we set up the crop rotation that gives the optimal net revenue is potato-barley-potato-barley-potato. Table 3.1 shows this optimal rotation with its annual revenue and NPV for 1,000 acres. In this problem the first year, which is year 0, is a given and not solved for. We chose to have potatoes be our first year because that is the crop we are most focused on and has the highest annual returns. This could be changed though to have any crop inputted as the first-year crop choice, and this will affect the solution for the crop rotation with the maximum NPV.

Table 3.1: Linear programming model optimal crop rotation (1000 acres, 5% discount rate)

Year	Crop	Annual Revenue	NPV
0	Potato	$1,281,048.00	$1,281,048.00
1	Barley	$211,487.00	$203,352.88
2	Potato	$1,281,048.00	$1,184,400.89
3	Barley	$211,487.00	$188,011.17
4	Potato	$1,281,048.00	$1,095,045.20
Total		$4,266,118.00	$3,951,858.14

These rotations don't yet have multipliers other than one attached effecting the yields and price based on what was grown the year before so the top rotation is potato-barley-potato-barley-potato just because barley has the highest annual net revenue that isn't sugar beets and potatoes. The total NPV on table 3.1 is the number that is being solved for within this linear programming problem. This rotation shown is the one that gives the maximum total NPV at $776,441.92 within our constraints. It is possible that wheat increases the yields of potatoes more by being grown the year before than barley does which would possibly change the top crop rotation to potato-wheat-potato-wheat-potato. With our current input variables if we were to assume that wheat has just a 1% increase on the yield and quality of potatoes by setting the multipliers to compared to barley by setting the wheat multipliers to 1.01 the optimal crop rotation would then be potato-wheat-potato-wheat-potato. Similarly, if dry beans had a 14% increase on the yield and quality of potatoes compared to all other crops by setting the multipliers to 1.14 the top crop rotation would then be potato-dry beans-potato-dry beans-potato. This shows the impact that these multipliers can have on choosing an optimal rotation. If a crop like wheat has an 8% increase on the yield and quality of potatoes or multipliers of 1.08 the increase of net revenue of potatoes in the following year is larger than the net revenue of the wheat itself. This highlights the importance of including these multipliers and knowing the one-year dependence among crops as it is possible that this impact is more important when choosing a crop rotation than the individual net revenue of each crop.

3.2 Objective 2: Identifying Risk

We were able to run the excel file to get every permutation and get all 7,776 crop rotations along with their net revenue. These rotations are in order from highest to lowest net revenue as shown in table 3.2.

Table 3.2: Top ten crop rotations

	Year 1	Year 2	Year 3	Year 4	Year 5	NPV
Rotation 1	Potato	Barley	Potato	Barley	Potato	$ 3,951,858.14
Rotation 2	Potato	Barley	Potato	Wheat	Potato	$ 3,949,049.36
Rotation 3	Potato	Wheat	Potato	Barley	Potato	$ 3,948,820.16
Rotation 4	Potato	Wheat	Potato	Wheat	Potato	$ 3,946,011.38
Rotation 5	Potato	Barley	Potato	Dry Beans	Potato	$ 3,910,527.81
Rotation 6	Potato	Wheat	Potato	Dry Beans	Potato	$ 3,907,489.83
Rotation 7	Potato	Dry Beans	Potato	Barley	Potato	$ 3,907,155.26
Rotation 8	Potato	Dry Beans	Potato	Wheat	Potato	$ 3,904,346.48
Rotation 9	Potato	Dry Beans	Potato	Dry Beans	Potato	$ 3,865,824.93
Rotation 10	Potato	Barley	Potato	Corn	Potato	$ 3,846,524.52

Not surprisingly, the top sixteen crop rotations are all potato-crop-potato-crop-potato. There is only a five percent difference between the top rotation and the sixteenth, so any of these rotations with potatoes in the first, third, and fifth years give high net returns and someone could reasonably choose any of these options to help maximize profits. Since potatoes are by far the crop with the highest NPV return, as long as potatoes are being grown for three out of the five years there will be little difference in the total NPV of the rotation choices. These results are what we would expect as potatoes are the highest profit crop and the top rotations should be ones that are growing potatoes as frequent as possible. The only crop option not included in the top rotations is sugar beets. This is because we had a constraint to stop sugar beets and potatoes being grown in back to back years so with potatoes being the crop with the highest net revenue this means that sugar beets would not be in a rotation until every rotation with potatoes in the first, third, and fifth years with some combination of wheat, barley, dry beans, and corn grown in the second and fourth years has been used. We used these top rotations to run the Monte-Carlo simulation to see the distribution of NPV of these top crop rotations when taking the risk of price into account. We plugged all ten of these crop rotations into the Monte-Carlo simulation with the price bins from the probabilities found from the historic crop prices. Results are presented in table 3.3.

Table 3.3: Monte-Carlo simulation

Probability Bin		Potatoes	Barley	Potatoes	Barley	Potatoes
0.167	Price 1	$679.00	$27.16	$679.00	$27.16	$679.00
0.333	Price 2	$1,042.40	$128.66	$1,042.40	$128.66	$1,042.40
0.5	Price 3	$1,281.60	$211.31	$1,281.60	$211.31	$1,281.60
0.667	Price 4	$1,548.40	$293.96	$1,548.40	$293.96	$1,548.40
0.833	Price 5	$1,884.20	$396.91	$1,884.20	$396.91	$1,884.20

The leftmost column shows the probability bins that are being drawn from. To the right of that you will see each of the five crops within one particular rotation and the annual revenue of that crop that corresponds with the probability bin it is lines up with. The random draw pulls a new random number between zero and one each time the simulation is run this will then line up with one of the five probability bins and then pull the annual revenue of the crop in that column that is within that particular bin. This number will then be the realized return for that year and calculated into the NPV. Then the NPV for each year will be summed up to give a total NPV per acre for the entire five-year rotation. This is done 10,000 times to get 10,000 different total NPV for each individual rotation. These distributions may not sufficiently account for the tails of the distribution. Since we are only using the five bins with similar probabilies we don't have the possiblity of getting an extreme high or an extreme low price. Having the simulation draw randomly straight from the normal distribution may give a more accurate representation of the real distribution of prices, but for this simulation the five bins will work sufficiently.

We see how taking risk into account can potentially change what the optimal crop rotation is. For example, if we take the average net revenue of each crop rotation from the 10,000 random pulls it is possible that the order of the top crop rotations by net revenue changes. The new order of our top ten rotations based on average NPV per acre over the 10,000 random draws are as follows in table 3.4. The average NPV column shows the average NPV per acre for the entirety of the rotation, not just one single year.

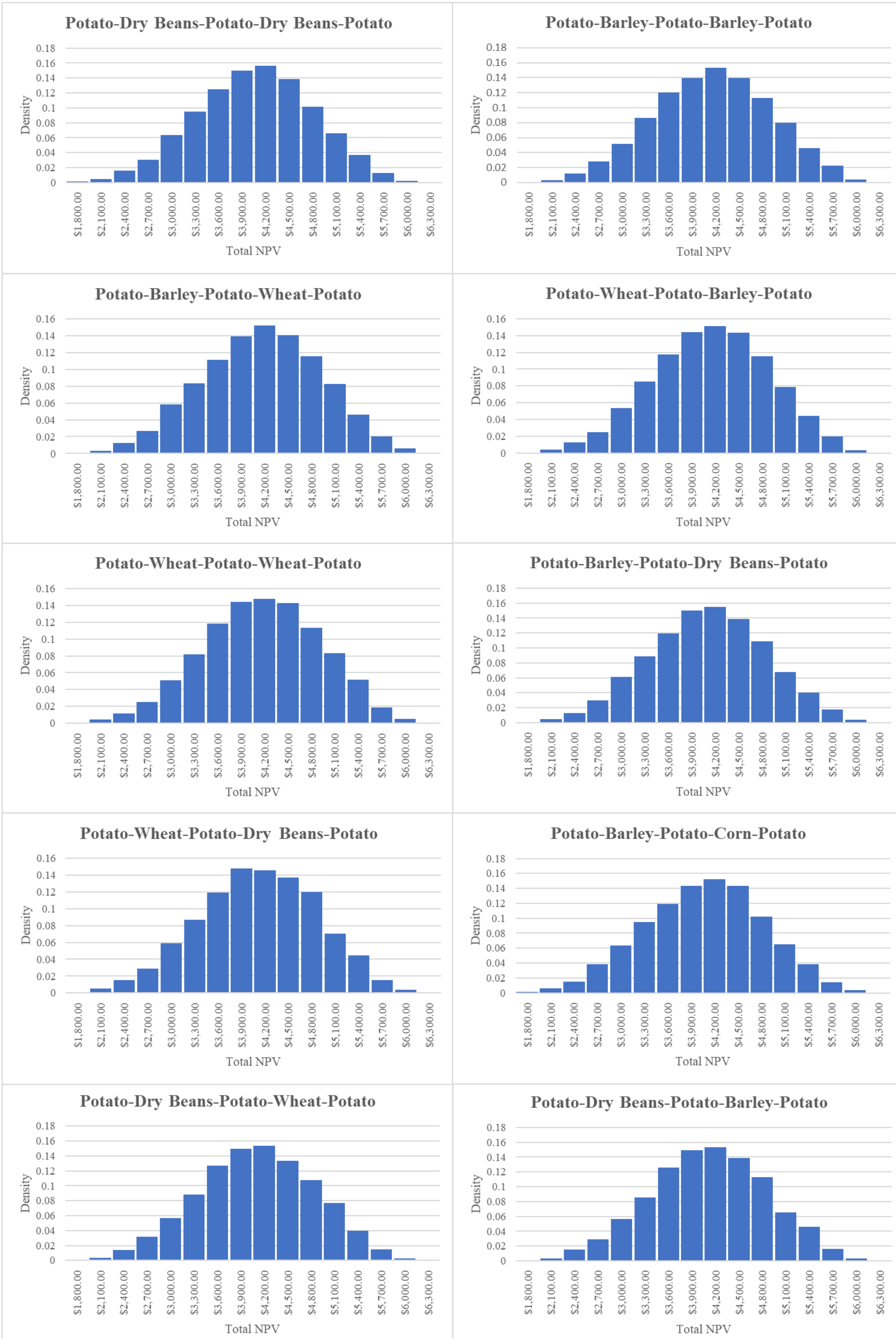
Table 3.4: Top ten crop rotations after Monte-Carlo simulation

	Year 1	Year 2	Year 3	Year 4	Year 5	Average NPV
Rotation 1	Potato	Wheat	Potato	Wheat	Potato	$ 4,315.91
Rotation 2	Potato	Barley	Potato	Wheat	Potato	$ 4,307.10
Rotation 3	Potato	Barley	Potato	Barley	Potato	$ 4,299.81
Rotation 4	Potato	Wheat	Potato	Barley	Potato	$ 4,298.16
Rotation 5	Potato	Wheat	Potato	Dry Beans	Potato	$ 4,262.98
Rotation 6	Potato	Dry Beans	Potato	Barley	Potato	$ 4,259.45
Rotation 7	Potato	Barley	Potato	Dry Beans	Potato	$ 4,249.46
Rotation 8	Potato	Dry Beans	Potato	Wheat	Potato	$ 4,248.93
Rotation 9	Potato	Dry Beans	Potato	Dry Beans	Potato	$ 4,210.38
Rotation 10	Potato	Barley	Potato	Corn	Potato	$ 4,209.79

As we see here the top rotation changed to potato-wheat-potato-wheat-potato from potato-barley-potato-barley-potato. Although we see that the difference in our top ten crop rotations, even when taking the risk of price difference into account, is very minimal. In fact, most of the time when running the simulation, the order of the top ten rotations should not change. If we were to increase the amount of draws from 10,000 to a much larger number, the average NPV would continue to normalize more and the order would eventually remain unchanged. Due to the fact that the difference in NPV for each rotation is so small, with potatoes driving a majority of the NPV and being unchanged in each rotation, the change in order we see here is mostly due to luck and the fact that there is such a small difference in the NPV of each rotation.

The range of the average net revenue for all ten rotations is only $106 per acre, the difference between the minimum possible NPV and the maximum possible NPV for each rotation is also less than $200 per acre. This means that there is not much difference in the risk of any of these ten rotations because there is no rotation that with the right luck could give you a much higher NPV, and there also are not any rotations that are higher risk and with poor luck could possibly give you a much lower NPV than any others. Each of the crop rotations only have less than $2,700 in NPV around 2% of the time, with Potato-Barley-Potato-Corn-Potato returning it the most at 2.28% of the time, and Potato-Barley-Potato-Wheat-Barley doing it the least with only returning less than $2,700 1.61% of the time. Also, on average any of these ten crop rotations will give you the same NPV within $106 per acre. We see the distribution of the 10,000 different NPV for each of the ten rotations in Figure 3.1

Figure 3.1: Top ten crop rotations Monte-Carlo risk histograms



This shows that there is very little difference in the risk from price in these ten different rotations and the distribution for all of them is very normal. Perhaps because the discretized bins do not properly account for extreme price values the difference in risk is relatively small the correct choice for which crop rotation someone would want to incorporate would most likely be whatever crop in the second and fourth years has the biggest impact on the yield of potatoes in the third and fifth years. If one of the crop options gives a boost in potato yield, then it is most likely that that added revenue would outweigh any risk or difference in revenue from the non-potato crops in the rotation.

For this simulation we are assuming that prices are independent of each other. We are assuming that if the price of one crop goes up in one year that this has no effect on the probability of the price of a different crop going up or down in the same or next year. This is not true in practice as these prices do all have some degree of positive correlation to each other. Potatoes and sugar beets have the lowest correlation at 0.43, but this is still a relatively high correlation among prices. All other crops have a correlation of 0.50 or higher over the 25 years of crop prices with the highest being between corn and wheat with a 0.90 correlation. This means that even though we considered them independent and having no effect on each other, in reality a price increase of any of these crops is actually a good indicator that all of the other crop prices will also increase.

There is more risk in these crop rotations then is shown here because this is only looking at the risk of price. There is also risk associated with yields and interest rates. If we were to also create bins with probabilities for different yields and interest rates the effect of the risk within the simulation would be much greater. Although they are not included here the risk of change in yields from factors such as weather and disease should also be considered when choosing a crop rotation in practical use.

3.3 Objective 3: Creating a Dynamic Tool

Using the findings and work put into the first two objectives of this thesis we were able to create an easy to use excel file that can be modified to find optimal crop rotations. This will allow anyone to be able to take the research that was done in this thesis to help find optimal crop rotations in the future. Where this thesis just focused on six crops in Idaho this tool will allow anyone to be able to take their own crops and data and plug them into this tool to be able to see the optimal crop rotations for their particular region and data. This tool includes instructions on how to enter the crop information and run the model to get the optimal crop rotation for maximizing net revenue. The two sheets of this dynamic tool are shown in figures 3.2 and 3.3.

Figure 3.2: Dynamic tool linear programming setup

	Potatoes	Corn	Wheat	Dry Beans	Barley	Sugarbeets
Price	$6.16	$4.01	$4.65	$25.52	$4.13	$43.32
Yeild	460.00	175.00	125.00	26.00	145.00	41.00
Operating Costs	$1,552	$610	$373	$499	$388	$880
Net Revenue	$1,281	$93	$208	$165	$211	$896

Land (Acres)	200
Interest rate	5.00%

	Annual	NPV
PROFIT	$853,223.60	$776,204.85

YEAR	FROM	TO P	C	W	Z	B	S	Planting	Constraint	Rotation	
0		200	0	0	0	0	0	200	200	0	0
1	P	0	0	0	0	200	0	200	200	0	0
1	C	0	0	0	0	0	0	0	0	0	0
1	W	0	0	0	0	0	0	0	0	0	0
1	F	0	0	0	0	0	0	0	0	0	0
1	B	0	0	0	0	0	0	0	0	0	0
1	S	0	0	0	0	0	0	0	0	0	0
2	P	0	0	0	0	0	0	0	0	0	0
2	C	0	0	0	0	0	0	0	0	0	0
2	W	0	0	0	0	0	0	0	0	0	0
2	F	0	0	0	0	0	0	0	0	0	0
2	B	200	0	0	0	0	0	200	200	0	0
2	S	0	0	0	0	0	0	0	0	0	0
3	P	0	0	0	0	200	0	200	200	0	0
3	C	0	0	0	0	0	0	0	0	0	0
3	W	0	0	0	0	0	0	0	0	0	0
3	F	0	0	0	0	0	0	0	0	0	0
3	B	0	0	0	0	0	0	0	0	0	0
3	S	0	0	0	0	0	0	0	0	0	0
4	P	0	0	0	0	0	0	0	0	0	0
4	C	0	0	0	0	0	0	0	0	0	0
4	W	0	0	0	0	0	0	0	0	0	0
4	F	0	0	0	0	0	0	0	0	0	0
4	B	200	0	0	0	0	0	200	200	0	0
4	S	0	0	0	0	0	0	0	0	0	0

		Total Planted
YEAR 0	Potatoes	200
	Corn	0
	Wheat	0
	Dry Beans	0
	Barley	0
	Sugarbeets	0
YEAR 1	Potatoes	0
	Corn	0
	Wheat	0
	Dry Beans	0
	Barley	200
	Sugarbeets	0
YEAR 2	Potatoes	200
	Corn	0
	Wheat	0
	Dry Beans	0
	Barley	0
	Sugarbeets	0
YEAR 3	Potatoes	0
	Corn	0
	Wheat	0
	Dry Beans	0
	Barley	200
	Sugarbeets	0
YEAR 4	Potatoes	200
	Corn	0
	Wheat	0
	Dry Beans	0
	Barley	0
	Sugarbeets	0

	Annual	NPV
Annual Revenue	$256,209.60	$256,209.60
Annual Revenue	$42,297.40	$40,283.24
Annual Revenue	$256,209.60	$232,389.66
Annual Revenue	$42,297.40	$36,538.08
Annual Revenue	$256,209.60	$210,784.27

Potatoes	Barley	Potatoes	Barley	Potatoes

Yield FROM	P	C	W	D	B	S
P	0	1	1	1	1	0
C	1	1	1	1	1	1
W	1	1	1	1	1	1
Z	1	1	1	1	1	1
B	1	1	1	1	1	1
S	0	1	1	1	1	0

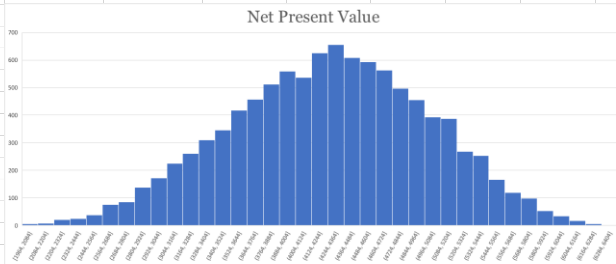
Price FROM	P	C	W	D	B	S
P	0	1	1	1	1	0
C	1	1	1	1	1	1
W	1	1	1	1	1	1
Z	1	1	1	1	1	1
B	1	1	1	1	1	1
S	0	1	1	1	1	0

Figure 3.3: Dynamic tool Monte-Carlo setup

Prob		Potatoes	Barley	Potatoes	Barley	Potatoes
0.166666667	P1	$679.00	$27.16	$679.00	$27.16	$679.00
0.333333333	P2	$1,042.40	$128.66	$1,042.40	$128.66	$1,042.40
0.5	P3	$1,281.60	$211.31	$1,281.60	$211.31	$1,281.60
0.666666667	P4	$1,548.40	$293.96	$1,548.40	$293.96	$1,548.40
0.833333333	P5	$1,884.20	$396.91	$1,884.20	$396.91	$1,884.20
	random draw	0.110932656	0.210376583	0.166840563	0.740900307	0.872825328
	Realized Return	679	128.66	1042.4	396.91	1884.2
	interest rate	0.04				
	NPV	$679	$124	$964	$353	$1,611
	year	0	1	2	3	4

RUN SIMULATION

	PDPDP
	$3,729.94
	NPV draw
1	4936
2	3825
3	4351
4	5499
5	3929
6	4661
7	4803
8	2691
9	4547
10	4368
11	5233
12	3935
13	3799



The Instructions for using this tool are laid out here:

Dynamic Linear Programming Instructions

This Excel file can easily be adjusted to solve for the crop rotation that will return the highest net present value (NPV). There is a limit to only six crops so you will not be able to solve for more than six crop options at a time. In order to solve for the optimal crop rotation, you only need to be able to input the following things for each crop:

Price

Yield

Operation Costs

Net Revenue

Optional: (If you do not have these this can be left at the base numbers for the problem which are 200 acres and a 5% interest rate)

Land (Acres)

Interest Rate

These inputs are to be inputted in two places. The price, yield, operation costs, and net revenue can be put straight into the enterprise budgets within the excel file. Once everything is put into those enterprise budgets they will automatically be put in to the top left of the excel in cell range A1:K5. The acres and interest rate can then be modified directly in that top left block of cells. If you are using less than six crops just input zeros for all of the numbers for that crop column.

After these inputs are put in you can solve for the optimal crop rotations. To do this you will click on the data tab in excel and then click on solver. In the pop up you will click on Solve, then make sure keep solver solution is selected and then click OK. This will solve for your crop rotation with the maximum NPV.

Then you can run the Monte-Carlo Simulation in the next tab. After running the Solver, the MC Simulation tab will automatically update with the optimal crop rotation and their prices. You can then just hit the Run Simulation button to run the 10,000 draws (this will take a few minutes to run). After this is run the NPV histogram and the average, max, min, and range of NPVs will all update.

This tool can be used by both producers using it as a decision tool or future researchers to further the work done in this thesis. By being done in Excel it can be left simple and just used as the instructions say or it can be modified however someone would want to make it fit their specific needs.

4. Conclusion

4.1 General Conclusions

We found the optimal crop rotations for Idaho potato farmers from the enterprise budgets gathered from the University of Idaho through linear programming. We found that the top crop rotations were all had potatoes grown in the first, third, and fifth years. These rotations affirmed previous work that suggests short rotations of potatoes and wheat or potatoes and barely are optimal, although this result may change when we include multipliers. Since potatoes make the majority of the NPV in all of the rotations we found very little difference in the NPV of the top rotations. These results show that there is more importance in the crops grown in between potatoes being beneficial to the quality and yield of the potato years than the amount of NPV that those crops are making. This highlights why knowing the impact that other crops have on the yield and quality of potatoes and being able to quantify that within the multipliers could greatly change the results of the optimal crop rotations, and more accurately predict the NPV of rotations.

We used a loop and find the NPV for all feasible crop rotations. We then took the rotations with the ten highest NPV and ran a Monte-Carlo simulation using historical crop prices to identify the risk associated with each of the rotations. We found that when taking the price risk into account it slightly changed the order of these top ten rotations but only because the difference in NPV for each of these rotations is so small. We found that none of the rotations have much higher risk than the others. We learned that there is not a significant amount of price risk difference among these rotations because potatoes themselves drive so much of the NPV within each rotation.

We then took the linear programming and Monte-Carlo simulation and created a usable dynamic enterprise budget that allows for individualization. This tool can be used to help farmers but in unique enterprise budgets and see what crop rotations would be optimal for maximizing NPV. This tool can also be used to add future work and findings to continue to become more accurate in finding the optimal crop rotations for any given crops.

4.2 Weaknesses

This thesis does have some general weaknesses. When solving for the crop rotation with the maximum NPV we make several assumptions that are not always true and if not assumed could cause differences in the results. Our first assumption when looking at crop rotations is that we are assuming that only one crop is grown per acre per year. This means that there are some rotation practices that aren't able to be included such as intercropping, biannual planting, and other non-traditional planting methods. This takes away some alternatives that could be optimal compared to the found crop rotations within this thesis. Another assumption we make is that land is the only constraint. This is not usually the case when it comes to looking at different crops. For each crop there are different amounts of labor, water, machinery, and other factors that go into producing them. We assume that we have sufficient amounts of each of these other constraints no matter what is grown, but in reality these are factors that may come into play when making these decisions. These different factors could be added to the problems within this thesis, and a new constraint would just need to be added for each additional factor that is to be accounted for. One more assumption we have is that there are constant returns. While some evidence has been shown of farmers having diminishing returns to scale, for most crops constant returns to scale seems to prevail (Bardhan, 1973).

Another weakness is that we do not yet know the impact that each crop has on the yields of other crops grown after them. We have set up multipliers within the model to take these into account, but for now all that these have been used for is to remove impractical rotations such as back to back years of potatoes. Having what the impact the crops have on each other years will give more accurate returns especially when dealing with potatoes.

When looking at risk within the Monte-Carlo simulation we only look at the risk of price fluctuation through historic prices. There is also risk involved in other factors of production such as yields and interest rates. It is possible that the higher risk comes in the form of yield fluctuation because this is impacted by many different sources such as weather, machinery, and labor. We did not identify large differences in risk among the different identified crop rotations. However, if these different factors of risk were to be looked at it is possible that some crops have much higher risk and reward than what we identified from just looking at the risk of price. We also assumed that all prices are independent of each other and that the output prices are independent of input prices. There is a correlation between all of the crops output prices so we know that they are not completely independent, and if this was taken into consideration would have an impact on the way we are characterizing the risk. There is also probably some correlation between the input and output prices meaning that when the output price of a crop increases the input prices or costs of that crop also increase so the increase of net revenue when a price increases would be smaller than we are assuming.

4.3 Future Work

There is other work that is being done to further progress this research. There is currently a survey in progress to help identify what potato farmers are currently doing in terms of soil health conservation, as well as what their preferences are for willingness to change practices in favor of greater soil health conservation.

The future work that will benefit this research the most is finding the impact that crops have on yields of crops grown after them. Knowing this and being able to take advantage of the multipliers built into our modeling this information would highly increase the accuracy of the projected rotations. Especially when it comes to growing potatoes, knowing what crops have the potential of increasing your yields for the years you grow potatoes could greatly influence the potential NPV for those crop rotations. Through the field experiments currently underway we can parameterize the multipliers and have them impact our rotations beyond just taking out infeasible rotations. These multipliers will then be able to also account for yield and price changes through the improved yield and quality from the interannual dependence of crops. This dependence may also last more than one year which then would allow for the multipliers to be expanded to include the impact of crops grown for multiple previous years on the yield and price of a crop.

The model could also be expanded on to be more accurate by containing more constraints such as labor, water, machinery, and other factors. With the addition of these constraints there would be more accurate change of NPV from rotation to rotation by accounting for different costs and variables that we have ommitted. These would also give more accurate NPV as currently the NPV that is given for each rotation is relatively high compared to what farmers are normally actually receiving. All of these additions will help this research and the tool created to continue to be more useful and relevant for the future.

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