Economics of Plant and Soil Health on Potatoes

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Abstract

This research study explores the economics of plant and soil health in potato cultivation, with a specific focus on two key aspects: the economic impact of *Pectobacterium* and *Dickeya* on potato crops in the first chapter and the impact of soil management practices on net returns in the second chapter. The first chapter examines the economic consequences of *Pectobacterium* and *Dickeya*, two pathogens affecting potato crops. By assessing the change in total revenue resulting from percentage of infection at planting, this study provides insights into the financial implications associated with these pathogens. The second chapter evaluates the impact of soil management practices on net returns in potato cultivation. By analyzing the economic outcomes of various soil management techniques, such as crop rotation, fumigation and manure application this study assesses their effects on potato yields and overall net returns. Understanding the economic implications of different soil management practices enables informed decision-making for farmers and policymakers, aiming to enhance the profitability and sustainability of potato production. By exploring the economic dimensions of *Pectobacterium* and *Dickeya* on potato crops and the impact of soil management practices on net returns, this research provides valuable insights for improving the economic viability of potato cultivation. These findings can inform farmers, researchers, and policymakers seeking to optimize their net returns while ensuring plant and soil health.

Keywords: economics, potato, disease management, crop rotation, net returns.

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Dedication

To my loving family,
This thesis is dedicated to the pillars of my life – my incredible parents, Dipendra Adhikari and Apsara Adhikari, and my wonderful brother, Ajay Adhikari.

Your constant love, encouragement, and belief in me have been the foundation of my success. Thank you for standing by me through every challenge and celebrating every triumph. Your unwavering support and guidance have been the wind beneath my wings.

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Chapter 1: Economic Impact of Pectobacterium and Dickeya on Potato

1.1 Abstract

This study investigates the relationship between total revenue and the percentage of infection caused by four different bacteria (*P. carotovorum, D. chrysanthemii, P. parmentieri,* and *P. atrosepticum*) in the Burbank potato variety. Linear regression analysis was conducted to examine the association between these variables. While positive associations were observed for *P. carotovorum*, *D. chrysanthemii*, and *P. atrosepticum*, none of the pathogens showed a statistically significant relationship with total revenue. *P. parmentieri* exhibited a negative association, but it lacked statistical significance. The Wilcoxon signed-rank test indicated no significant median differences between paired observations, except for specific comparisons involving *D. chrysanthemii* and *P. parmentieri*. Further research and consideration of confounding factors are crucial when examining the impact of bacterial infections on total revenue in potato production.

Keywords: Burbank potato, bacterial infections, total revenue, linear regression, Wilcox signed-rank test

1.2 Introduction

The disease known as "potato blackleg" affects potatoes on a large scale and is brought on by plant pathogenic pectolytic bacteria of the genera *Pectobacterium* and *Dickeya* (Czajkowski et al., 2015). Inoculum concentration in seed tubers, potato cultivar susceptibility, environmental factors, and soil moisture level play a great role in the establishment of potato blackleg disease (Markovic et al., 2021). The year 2015 witnessed a devastating blackleg outbreak in the potato industry, primarily impacting the Eastern USA. Referred to as the "North American *Dickeya* Outbreak," this outbreak led to substantial losses in potato crops (Perry, 2011). Perry's research suggests that *Dickeya sp*. bacteria were already present in potatoes before the outbreak occurred. However, specific environmental conditions played a crucial role in the outbreak's progression. The cool climate and abundant rainfall experienced in 2013 and 2014 created an environment conducive to latency, allowing the bacteria to remain dormant within the potato plants. Ultimately, in 2015, the outbreak emerged as favorable conditions for *Dickeya sp*. prevailed. Notably, the disease was not a significant concern in the USA before the outbreak; however, Maine is a major supplier of seed potatoes to other northeastern and mid-Atlantic states. Accordingly, the Maine outbreak in the summer of 2015, spread across multiple states (Jiang et al., 2016).

Blackleg, soft rot, and aerial stem rot are caused by the commercially significant potato seed-borne bacteria *Dickeya* and *Pectobacterium* species (Potrykus et al., 2014). Tuber soft rot in potatoes shows small water-soaked spots on the surface that quickly spread and cause mushy, slimy tissue. Soft rot affects seed pieces, causing poor emergence and wilt-like symptoms in plants. The bacteria block the plant’s vascular system, leading to yellowing, wilting, and potential rot in stems and roots (Noah et al., 2016). The typical blackleg signs on potato plants include wilting canopy, darkened and necrotic basal stems, and non-emergence due to rotten tuber (Jiang et al., 2016). The disease can be identified by the inky-black color of the weakening sprout or vine that starts below the soil level and spreads upward. No currently existing potato variety is resistant to blackleg, and no treatment can stop the disease from spreading in an infected potato plant (MacNeil, 2022). *Pectobacterium atrosepticum* is commonly associated with blackleg and soft rot during storage, while *P. carotovorum* is linked to aerial stem rot, lenticel rot and soft rot. Blackleg thrives in cool, moist conditions below 70°F, whereas soft rot prefers warmer temperatures ranging from 70°F to 80°F. Additionally, soft rot can also be caused by *P. parmentieri* and *P.carotovorum* in the Pacific Northwest Region(PNW), although their prevalence and economic importance are currently unknown. Blackleg in potato plants on the East coast is associated with the bacterium *Dickeya dianthicola*, and it causes the reduced emergence of potato plants under warmer temperatures and leads to decayed daughter tubers in affected fields. In PNW, diseased potatoes have occasionally shown the presence of a *Dickeya* species, likely *D.dianthicola* (Frost and Ocamb, 2023).

Economic loss from *Dickeya* and *Pectobacterium* can occur due to delayed emergence, weak stands, and in extreme situations, due to non-harvestable fields (Rosenzweig et al., 2016). These losses have significant financial implications, with annual estimates reaching approximately $53.82 million, subject to variations from year to year (Dupuis et al., 2021). Moreover, these losses are distributed among different sectors within the potato industry, with seed potatoes accounting for 32%, table potatoes for 43%, and processing potatoes for 25% of the total economic impact (Dupuis et al., 2021). In Switzerland, the cost of roguing, which involves removing diseased plants, amounts to around $287.67 per hectare (Dupuis et al., 2021). Furthermore, in the Netherlands, the bacteria-caused disease causes direct losses of up to $35.1 million annually due to the downgrading and rejection of seed tuber stocks (Prins and Breukers, 2008). In Finland, the presence of *Dickeya*, particularly *Dickeya dianthicola*, leads to a higher percentage of stem rot than tuber rot (73% vs. 20%) and the rejection of potatoes during seed tuber certification, resulting in significant direct losses to potato production (Laurila et al., 2008). Additionally, weather conditions during the early part of the season significantly influence symptom occurrence during seed tuber certification and crop inspections, with varying economic impacts across European countries due to differences in national certification standards (Toth et al., 2011).

The research on *Pectobacterium* and *Dickeya* in potato production has predominantly focused on their description, breeding, and management, leaving a significant research gap concerning their economic implications. While studies have explored the relationship between bacterial infections and yield loss, the broader impact on total revenue within the potato industry remains understudied. Specifically, the relationship between the percentage of infection at planting and its effects on overall revenue remains insufficiently examined. Thus, our research aims to fill this critical research gap by investigating the impact of percentage infection at planting in total revenue due to *Pectobacterium* and *Dickeya* by utilizing advanced statistical methods such as linear regression.

This research aims to examine how *Pectobacterium* and *Dickeya* infections impact the predictability of total revenue in potato production. Specifically, the main research question revolves around whether the presence of these bacterial infections affects the reliability of forecasting changes in total revenue within the potato industry. The study will investigate if the occurrence of *Pectobacterium* and *Dickeya* infections can serve as a strong indicator of potential fluctuations in revenue generation. Moreover, the research aims to determine if there exists a statistically significant relationship between the percentage of infection and total revenue through the application of linear regression analysis. Thus, by employing this analytical approach, the study seeks to provide essential insights into the economic consequences of percentage of bacterial infection at planting in potato production.

1.3 Data and Methods

1.3.1 Yield data

For our analysis, we used the data collected in the year 2018 and 2019 from Hermiston Ag. Research and Extension Center in Hermiston, Oregon (OR) for Burbank potatoes for bacteria *P. carotovorum, D. chrysanthemii, P. parmentieri, P. atrosepticum*. There was data for percentage clean at planting from which the percentage of infection was calculated.
i.e. Percentage infection at planting = 100 – percentage clean at planting

1.3.2 Inoculum preparation

In 2018, *P. carotovorum and D. chrysanthemii* were used for inoculation. In 2019, the inoculum was prepared from the culture of *P. atrosepticum* and *P. Parmentieri* isolated from diseased potatoes from the Columbia Basin. In both years, axenic cultures of each bacterium were grown on nutrient agar for 48 hours at 28, collected from plates, and diluted with ¼ strength Ringer's solution to an optical density at 600nm of 0.1 OD (c.10^8 cells mL^{-1}). Bacterial suspensions were used to inoculate seed potatoes and, in 2019, 2 ul/l Tween was added to the bacterial suspension before inoculation by vacuum infiltration.

1.3.3 Tuber inoculation and seed tuber mixing

In 2018, potatoes of varieties Russet Burbank were cut before inoculation and, in 2019, whole potatoes were inoculated before cutting. In both years, potatoes of each variety were placed in a vacuum desiccator, completely submersed in a bacterial suspension, and placed under a vacuum of 0.7 bars for 15 minutes. The vacuum was released, and the potatoes remained in the bacterial suspension for an additional 10 minutes.

In 2018, the inoculated potatoes were mixed with non-inoculated potatoes to establish planting stocks differing in the prevalence of inoculated tubers. Treatments were established for each cultivar with the prevalence of 0%, 5%, 10%, 20%, and 30% inoculated tubers based on fresh weight. In 2018 there were a total of 20 treatments (2 cultivars x 2 strains x 5 levels of initial inoculum). In 2019, inoculated potatoes were stored in a cold room for one week and were then cut and mixed with non-inoculated potatoes to establish planting stocks made up of 0%, 5%, 10%, 20%, and 30% inoculated tubers to create 20 treatments. In 2019, the prevalence was established based on the number of potato seed pieces required to plant each plot.

1.3.4 Market data

The market data was collected from the U.S. Department of Agriculture's (USDA) Agricultural Marketing Service (AMS) for Columbia Basin Washington and Umatilla Basin Oregon (AMS, 2023). The obtained market data was categorized according to the item size, i.e. 40s, 50s, 60s, 70s, 80s, 90s, 100s, 10 oz min, and non-size A. Then, the average price data for all size categories was obtained and it was converted into dollars per hundredweight. The data categorization was done in the following way:

Table 1 Data categorization according to item size and market price

Item size	Size in ounce(oz)	Size in gram (gm)	Market price($/cwt)
	< 4 and culls	< 113.39	3
90s, 100s, 10 oz min, non-size A	4-8	113.39 – 226.79	15.01
70 s, 80s, 90s	8-12	226.79 – 340.19	21
40s, 50s, 60s	>12	> 340.19	24.6

Then, using the information in Table 1, revenue for each item size was calculated, and they were summed to calculate the total revenue.

Here, Revenue for each item size = Yield x Price

Total revenue ($/ha) = Sum of revenue for each item size

Then, the total revenue was regressed on the percentage of infection at planting. Separate regressions were run for Burbank and *P. carotovorum*, Burbank and *D. chrysanthemii*, Burbank and *P. parmentieri*, Burbank and *P. atrosepticum*.

The regression model is as follows:

$$Y = \beta_0 + \beta_1 X + \in$$

Where Y = total revenue

X = percentage of infection at the time of planting

$\in$ = Error

1.4 Results and Discussion

1.4.1 Overview of Variable Summary Statistics

Table 2 Summary statistics of variable in use

Bacterium	Metric	Mean	Median	Std. dev	Min	Max
P. carotovorum	Total yield	102394	107608	17972.18	60353	123311
	Total revenue	1751436	1812264	412952.7	824141	2355830
D. chrysanthemii	Total yield	100395	101143	16904.96	64405	130740
	Total revenue	1735109	1803368	339551	104792	2214654
P. parmentieri	Total yield	69022	67782	10505.84	52200	90457
	Total revenue	918661	909792	205597.4	526307	1282030
P. atrosepticum	Total yield	70125	71618	8444.87	43226	80326
	Total revenue	948214	958452	158426	589501	1210005
No of observation for each category				20		

Table 2 presents a summary table presenting key metrics for different bacteria types. The metrics considered are total yield and total revenue. The mean and median values for total yield range from 69,022 to 102,394, while for total revenue, they vary from 918,661 to 1,751,436. Standard deviations for both metrics are in the range of 8,444.87 to 41,295.2. The minimum values for total yield and total revenue are 43,226 and 526,307, respectively, while the maximum values are 123,311 and 2,355,830. Each category comprises 20 observations. This table allows for a quick comparison of these metrics across the bacteria types, highlighting variations in yield and revenue within the dataset.

1.4.2 Regression Analysis: Total Revenue ($/ha) on Percentage Infection in Burbank

Table 3 Regression of total revenue($/ha) on percentage infection in Burbank

	Estimate	Std.error
P. carotovorum	7614	8624^{ns}
D. chrysanthemii	4742	715^{ns}
P. parmentieri	-1526	4371^{ns}
P. atrosepticum	2103	334^{ns}

Ns: Indicates not significant

Table 3 represents the results of a linear regression analysis that examines the relationship between total revenue and the percentage of infection in the Burbank potato variety by four different types of bacteria: *P. carotovorum, D. chrysanthemii, P. parmentieri.* The results reveal that none of the pathogens demonstrated a statistically significant relationship with total revenue. *P. carotovorum*, *D. chrysanthemii* and *P. atrosepticum* exhibited a positive coefficient estimate, indicating a potential positive association with total revenue, but it was not statistically significant. Even though not significant, a positive economic response is counter to the existing literature that economic loss occurs due to bacterial infection (Dupuis et al., 2021). Conversely, *P. parmentieri* displayed a negative coefficient estimate, which means that for each percentage point increase in infection due to this pathogen, the total revenue decreases by $1526/ha, but it lacked statistical significance. This result could be due to small sample size or other factors that affect the precision of the estimate. Also, since blackleg was not observed in the plots in OR (according to plant scientists), the effect may have been insignificant. These findings suggest that bacterial infections may not have a substantial impact on total revenue in the Burbank variety. However, it is important to acknowledge the limitations of the study and the potential influence of unaccounted factors.

1.4.3 Wilcoxon signed rank test

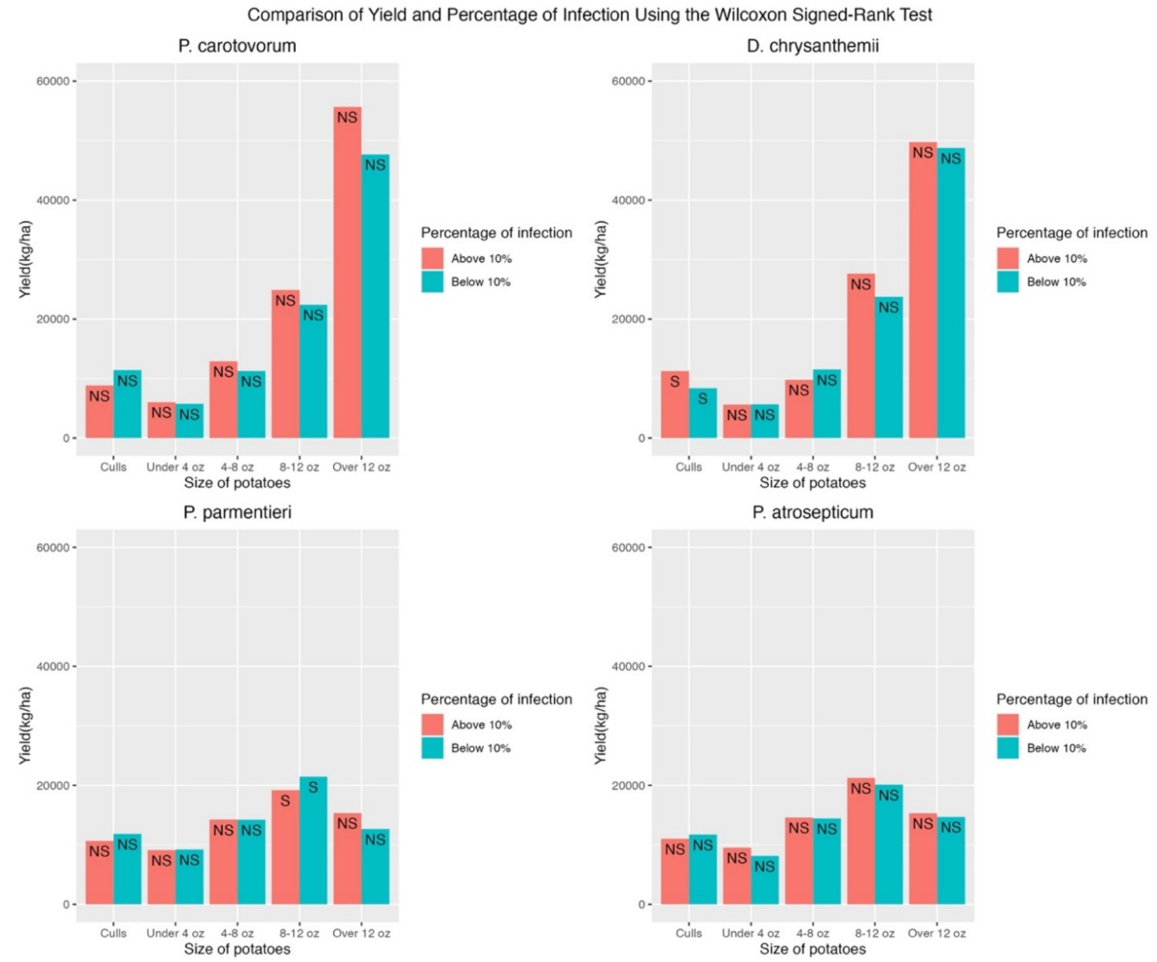

Figure 1 Wilcoxon signed rank test

Caption: This bar graph illustrates the comparison between yield and percentage of infection in a dataset using the Wilcoxon Signed Rank Test. The presence of S (significant) and NS (non-significant) labels indicates the statistical significance of the differences observed.

The Wilcox signed-rank test was conducted to compare two related samples, total yield with different size categories (Under 4 oz, culls, 4-8 oz, 8-12 oz, and Over 12 oz) of Burbank with the bacteria (*P. carotovorum, D. chrysanthemii, P. parmentieri, and P. atrosepticum).* This non-parametric test was chosen due to the data's non-normal distribution and small sample size. The null hypothesis for the test stated no statistically significant difference between the percentage of infection at planting and total yield, while the alternative hypothesis suggested otherwise.

Most p-values were greater than 0.05, indicating no significant median differences between the paired observations. Thus, the null hypothesis of a median difference of zero could not be rejected, implying that observed differences might be due to chance rather than a genuine relationship. An exception was found in comparisons between D.*chrysanthemii and P. parmentieri* for "culls," and “8-12 oz” size categories, where the p-value was 0.01, suggesting a meaningful relationship for those specific comparisons.

1.5 Conclusion

Based on our data, we did not find a statistically significant relationship between percentage of infection at the time of planting and total revenue. This suggests that the presence of *Pectobacterium* and *Dickeya* infection alone may not reliably indicate potential changes in total revenue. Other factors might influence the relationship between infection and revenue, and additional research is necessary to identify and understand these contributing factors. In the future, it would be beneficial to focus on developing a predictive model that considers multiple variables to accurately forecast revenue changes in the presence of *Pectobacterium* and *Dickeya* infection. This predictive model could potentially offer more comprehensive insights and enhance decision-making in managing bacterial infections and optimizing revenue generation in potato production.

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Chapter 2: Impact of Soil Health Management Practices in Net Returns in Potato

2.1 Abstract

This study explores the influence of crop rotations and soil health management practices on potato yields and net returns across four states: Idaho, North Dakota, Minnesota, and Oregon during the year 2017-2021. The impact of soil health management practices, such as fumigation, manure application, and mustard bio fumigation, on overall net returns is also evaluated. Though not significant, the study highlights the significance of adopting a three-year crop rotation strategy to maximize yields of larger-sized potatoes across the four states. Furthermore, the analysis of various treatments within two and three-year crop rotations showed that fumigation had a positive impact on net returns in Idaho and Oregon. Overall, the study suggests that implementing a three-year crop rotation strategy may be beneficial for maximizing yields of larger-sized potatoes across the studied regions. However, further research and consideration of specific factors are necessary to draw more conclusive findings and make specific recommendations for potato production optimization.

Keywords: Crop rotations, soil health management practices, potato yields, net returns, fumigation

2.2 Introduction

The potato is one of the most significant crops in the world and can be grown in a number of agro-ecological systems. Potatoes are the most popular vegetable crop in the United States, cultivated commercially in 30 states (AgMRC, 2023). Potato production in the United States stands at 392 million hundredweight (cwt) in 2022, reflecting a slight decline of 4 percent compared to the previous year (USDA NASS, 2023). Idaho is the top potato producing state contributing nearly one-third of all potatoes grown in the United States, with over 300,000 acres, over 100 million hundredweight of potatoes are produced annually (ISDA, 2023). The retail and food service sales of potatoes in the Idaho in 2019/2020 were 47% (15,958 lbs.) and 53% (17,873 lbs.), respectively (ISDA, 2023). Some notable states in potato production include Washington, North Dakota, Wisconsin, and Colorado (AgMRC, 2023). Approximately 63% of potato sales go to processors for making products like french fries and chips, and the rest is divided between the fresh market, farm animal feed, and seed tubers (AgMRC, 2023).

In the U.S. Pacific Northwest and beyond, there is a growing interest in enhancing soil health within potato production systems driven by the desire for sustainability, economic viability, and meeting consumer preferences. However, the intensive tillage, limited residue on fields, short rotations, and the necessity to manage soilborne pathogens pose significant challenges to this objective. To address these issues, farmers are increasingly adopting practices such as reduced tillage, modified crop rotations, decreased fumigation, and the incorporation of cover crops, green manures, and organic amendments (Hills et al., 2020).

Soil health refers to the ongoing capacity of soil to function as a vibrant living system within the boundaries of ecosystems and land use (Doran, 1996). It encompasses sustaining biological productivity, preserving air and water quality, and promoting the well-being of plants, animals, and humans. Soil health is affected by three main factors: initial soil conditions, agricultural management practices, and environmental conditions, which all interact to determine its overall state. Farmers have direct control over agricultural management practices, and the adoption of specific practices depends on the economic costs and benefits associated with them (Rejesus et al., 2021). Thus, the most significant challenge in formulating effective soil health policies is the insufficient data that explains the dynamic relationships between soil health indicators, agricultural practices, and agricultural production in diverse settings (Stevens, 2018). The adoption of soil health management practices affects the economics of soil health by generating dynamic economic outcomes that extend beyond the adoption period. These outcomes are influenced by evolving environmental and soil conditions. Understanding this dynamic nature is crucial in evaluating the long-term economic benefits of soil health practices, including their potential to reduce yield variability over time (Rejesus et al., 2021).

Several approaches can be employed to enhance soil health in potato systems, including crop rotation, manure application, and bio fumigation. Crop rotation plays a crucial role in potato production, serving multiple purposes, including disease and pest management, improving soil fertility, and enhancing overall soil health (Boiteau et al., 2014). Longer rotation cycles bring greater benefits to the subsequent potato crop, as shorter intervals between potato years can have significant negative impacts on soil biological and physical properties (Nelson et al., 2009). Research in Eastern Idaho demonstrated higher average yields in three-year rotation compared to two-year rotation (Stark, 2003). Thus, implementing effective crop rotation strategies is vital for maintaining a healthy and sustainable potato production system.

A "cover crop" is a secondary rotation crop grown to provide benefits like erosion prevention, organic matter addition, or nitrogen contribution, while a "green manure" is a cover crop specifically incorporated into the soil before maturity (Hills et al., 2020). Sodium N-methyldithiocarbamate (metam sodium) is widely used in potato production to control potato early dying caused by Verticillium dahlia (Ingham et al., 2019). Interest in alternatives to chemical fumigation due to cost, consumer/regulatory pressure, and impacts on non-target soil organisms (Collins et al., 2006). Sudan grass incorporation in southeastern Idaho reduced Verticillium wilt and increased potato yields compared to no green manure and no fumigation (Davis et al., 1996). McGuire (2003) estimated potential cost savings of $163/ha by using mustard green manures instead of metam sodium.

The existing literature focuses on the need for soil health indicators that are responsive to changes in crop management (Awale et al., 2017). However, there is limited research exploring the relationship between soil health management practices and net returns in potato production. Additionally, further investigation is needed to understand the impact of crop rotation duration on potato yields. The interconnections between soil health management practices, net returns, crop rotation duration, and potato yields remain inadequately understood. To bridge this research gap, our study aims to investigate the relationship between soil health management practices and net returns in potato production, while also assessing the yield and overall average net return profile for two and three-year crop rotations.

Our research seeks to address three key questions related to potato production in two and three-year crop rotation systems. Firstly, we aim to examine how potato yield varies across different size categories in these rotation systems. Secondly, we will investigate the differences in average net returns for potato crops under various soil management practices, encompassing fumigation, manure application, and mustard bio fumigation. Lastly, we will determine the overall net return of potato cultivation concerning other crops in two and three-year crop rotation systems. By answering these questions, we anticipate gaining valuable insights into the relationship between soil health practices, potato yield, and net returns, thereby contributing to a deeper understanding of sustainable potato production.

2.3 Data and Methods

2.3.1 Market Data

The market data i.e. the custom average price for shipping point was collected from U.S. Department of Agriculture’s (USDA) Agricultural Marketing Service (AMS) website from year 2017- 2021 for variety Russet and sub-variety Burbank and Norkotah for upper valley, Idaho (USDA AMS, 2023). Then, the five-year average price data was obtained for each sub-variety and their respective item size. In our study, we utilized market data from Idaho for all four states since only Idaho provided comprehensive market data for the Russet variety. And, the prices for each item size of Burbank were applied to Bannock potatoes, because the market data was unavailable.

To convert the market data into respective counts, the following price conversions were applied:

Table 4 Data categorization according to item size and market price

Item size (oz)	Number of counts	Average market prices ($/cwt)	
		Burbank	Norkotah
0-4		3.50	3.50
4-6	non-size A	5.90	6.26
6-10	100	8.97	8.75
10-14	60	12.34	11.37
14	40	12.03	11.22

By applying these conversion factors to the five-year average price data, the collected information enabled the determination of respective counts and prices for the different item sizes within each sub-variety. The market data used was the nominal price, not adjusted for inflation.

2.3.2 Field Data

The field data on potato and rotation crop yields were collected by researchers in four states: Idaho, Oregon, North Dakota, and Minnesota. The plot size for different states is as follows:

ID: 11.33 feet (4 rows) wide x 34 feet long
MN: 20 feet (6 rows) wide x 30 feet long
ND: 12 feet (4 rows) wide x 40 feet long
OR: 24 feet wide by 50 feet long.

A total of 12 treatments were utilized in each state, with treatments 1-6 representing three-year crop rotations and treatments 6-12 representing two-year crop rotations. Each state had its unique set of treatments, including different rotation crops. The specific treatments used in each state are as follows:

Table 5 Description of crop rotation and treatments in Idaho

Treatment	2019 Crop	2020 Crop	2021 Crop	2022 Crop
	Three-year crop rotation			
1	Burbank	Sileage corn	Spring wheat	Burbank
2	Norkotah	Sileage corn	Spring wheat	Norkotah
3	Norkotah	Sileage corn	Spring wheat	Norkotah
4	Norkotah	Sileage corn	Summer GM	Norkotah
5	Norkotah	Sileage corn	Spring wheat	Norkotah
6	Norkotah	Sileage corn	Summer GM	Norkotah
	Two-year crop rotation			
7	Spring wheat	Burbank	Spring wheat	Burbank
8	Spring wheat	Norkotah	Spring wheat	Norkotah
9	Spring wheat	Norkotah	Spring wheat	Norkotah
10	Summer GM	Norkotah	Summer GM	Norkotah
11	Spring wheat	Norkotah	Spring wheat	Norkotah
12	Summer GM	Norkotah	Summer GM	Norkotah

In Idaho, treatments 6, 11, and 12 were manure, while treatments 1, 2, 4, 5, 7, 8, 10, and 11 were chemically fumigated. However, no mustard bio fumigation was applied in any of the treatments.

Table 6 Description of crop rotation and treatments in Minnesota

Treatment	2019 Crop	2020 Crop	2021 Crop	2022 Crop
	Three-year crop rotation			
1	Burbank	Field corn	Soybean	Burbank
2	Norkotah	Field corn	Soybean	Burbank
3	Bannock	Field corn	Soybean	Bannock
4	Burbank	Field corn	Field Pea	Burbank
5	Norkotah	Field corn	Field Pea	Norkotah
6	Burbank	Field corn	Soybean	Burbank

Table 6 continued

	Two-year crop rotation			
7	Soybean	Burbank	Soybean	Burbank
8	Soybean	Norkotah	Soybean	Norkotah
9	Soybean	Bannock	Soybean	Bannock
10	Soybean	Burbank	Field Pea	Burbank
11	Soybean	Norkotah	Field Pea	Norkotah
12	Soybean	Burbank	Soybean	Burbank

In Minnesota, treatments 4, 5, 10, and 11 received manure, while treatments 1, 2, 4, 5, 7, 8, 10, and 11 were chemically fumigated. Additionally, treatments 4, 6, 10, and 12 were subjected to mustard bio fumigation

Table 7 Description of crop rotation and treatments in North Dakota

Treatment	2019 Crop	2020 Crop	2021 Crop	2022 Crop
	Three-year crop rotation			
1	Burbank	Maize	Wheat	Burbank
2	Burbank	Maize	Wheat	Burbank
3	Burbank	Maize	Wheat	Burbank
4	Burbank	Maize	Wheat	Burbank
5	Burbank	Maize	Wheat	Burbank
6	Bannock	Maize	Wheat	Bannock
	Two-year crop rotation			
7	Field Pea	Burbank	Wheat	Burbank
8	Field Pea	Burbank	Corn	Burbank
9	Field Pea	Burbank	Wheat	Burbank
10	Field Pea	Burbank	Corn	Burbank
11	Field Pea	Burbank	Wheat	Burbank
12	Field Pea	Bannock	Wheat	Bannock

In North Dakota, the treatments were distributed as follows. Treatments 4, 5, 10, and 11 received manure, while treatments 1, 2, 4, 5, 7, 8, 10, and 11 were chemically fumigated. Furthermore, treatments 3, 5, 9, and 11 received mustard bio fumigation.

Table 8 Description of crop rotation and treatments in Oregon

Treatment	2019 Crop	2020 Crop	2021 Crop	2022 Crop
	Three-year crop rotation			
1	Norkotah	Sileage corn	Winter wheat	Burbank
2	Burbank	Sileage corn	Winter wheat	Norkotah
3	Norkotah	Sileage corn	Winter wheat	Norkotah
4	Norkotah	Sileage corn	Winter wheat	Norkotah
5	Norkotah	Sileage corn	Winter wheat	Norkotah
6	Norkotah	Sileage corn	Winter wheat	Norkotah
	Two-year crop rotation			
7	Winter wheat	Norkotah	Winter wheat	Burbank
8	Winter wheat	Burbank	Winter wheat	Norkotah
9	Winter wheat	Norkotah	Winter wheat	Norkotah
10	Winter wheat	Norkotah	Winter wheat	Norkotah
11	Winter wheat	Norkotah	Winter wheat	Norkotah
12	Winter wheat	Norkotah	Winter wheat	Norkotah

In Oregon, the treatments were allocated as follows. Treatments 5, 6, 11, and 12 received manure, treatments 3 and 9 were chemically fumigated, and treatments 4, 6, 10, and 12 were subjected to mustard bio fumigation.

In summary, the two-year crop rotation, the sequence followed was Other Crop - Potato - Other Crop - Potato for the years 2019, 2020, 2021, and 2022. In the three-year crop rotation, the sequence was Potato - Other Crop - Other Crop – Potato for the respective years. This comprehensive data collection approach allowed for the analysis of potato yields and crop rotations across different states and treatment combinations.

2.3.3 Total revenue, total cost and net return calculation

To calculate the total revenue for potatoes, the yields for each item size collected by researchers in each of the four states were multiplied by the respective market prices obtained from USDA AMS. This computation resulted in the total revenue per acre for potatoes,

i.e. Total revenue (($/acre) for potato = Yield for each item size x five-year average market price

For other crops: Total revenue (($/acre) for other crop = Yield information collected by researchers in each state x five-year average price from USDA NASS (2017-2021), and average net return was also calculated by researchers from respective states.

The base cost represents the cost of production without any treatments. Here, a total base cost of $1627 was used in the calculation from Idaho's cost of production budget (IdahoAgBiz, 2023). Next, treatment costs were estimated for each state. Using available cost and returns budgets from several states and conversations with the researchers who administered the trials in each state, we estimated costs of manure application, fumigation, and mustard bio fumigation. The cost of fumigation was estimated to be $328/acre based on the difference in fumigated versus non-fumigated potato budgets for Idaho (IdahoAgBiz, 2023). We estimated the cost of manure application to be $90/acre, based on reports from researchers in Minnesota. Minnesota researchers applied turkey manure at a rate of 3 tons/acre at $30/ton. and the cost of mustard bio fumigation was $247/acre. The total cost for each treatment was calculated as the sum of the base cost and the treatment costs of the associated treatment. We assumed the same costs for all states for each treatment for simplicity, although in reality costs would vary by location.

Therefore, average net return was calculated for potato years for two and three-year crop rotation and net returns were determined by subtracting the total cost from the total revenue, i.e.

Net return ($/acre) = Total revenue - Total cost

2.3.4 Data adjustments

The adjustment of yields for other crops was implemented as follows:

- In the case of Oregon, the wheat yield data was missing for the year 2019. To compensate for this, the wheat yield data for 2021 for the same treatments was utilized as a substitute.
- In Minnesota, there was no available data for soybean yield. Therefore, the soybean yield data from 2021 was used for the treatments where it was available. For treatments where soybeans were not planted in 2021 (field pea was planted instead), the average soybean yield from 2021 was used.
- For North Dakota, 2019 field pea yield data was not collected. To estimate the net return, an approximation was made using the yield provided in the North Dakota field pea enterprise budget (NDSU, 2023) and the five-year average price from USDA NASS. The average field pea price over five years was $7.41 per bushel, and the NDSU budget indicated a yield of 33 bushels per acre.

These adjustments ensured that the net returns accurately reflected the variations in yields for the respective crops in each state, and they were also made to make rotations comparable using the best available information.

2.4 Results and Discussion

2.4.1 Total yield by size category of Russet Potato

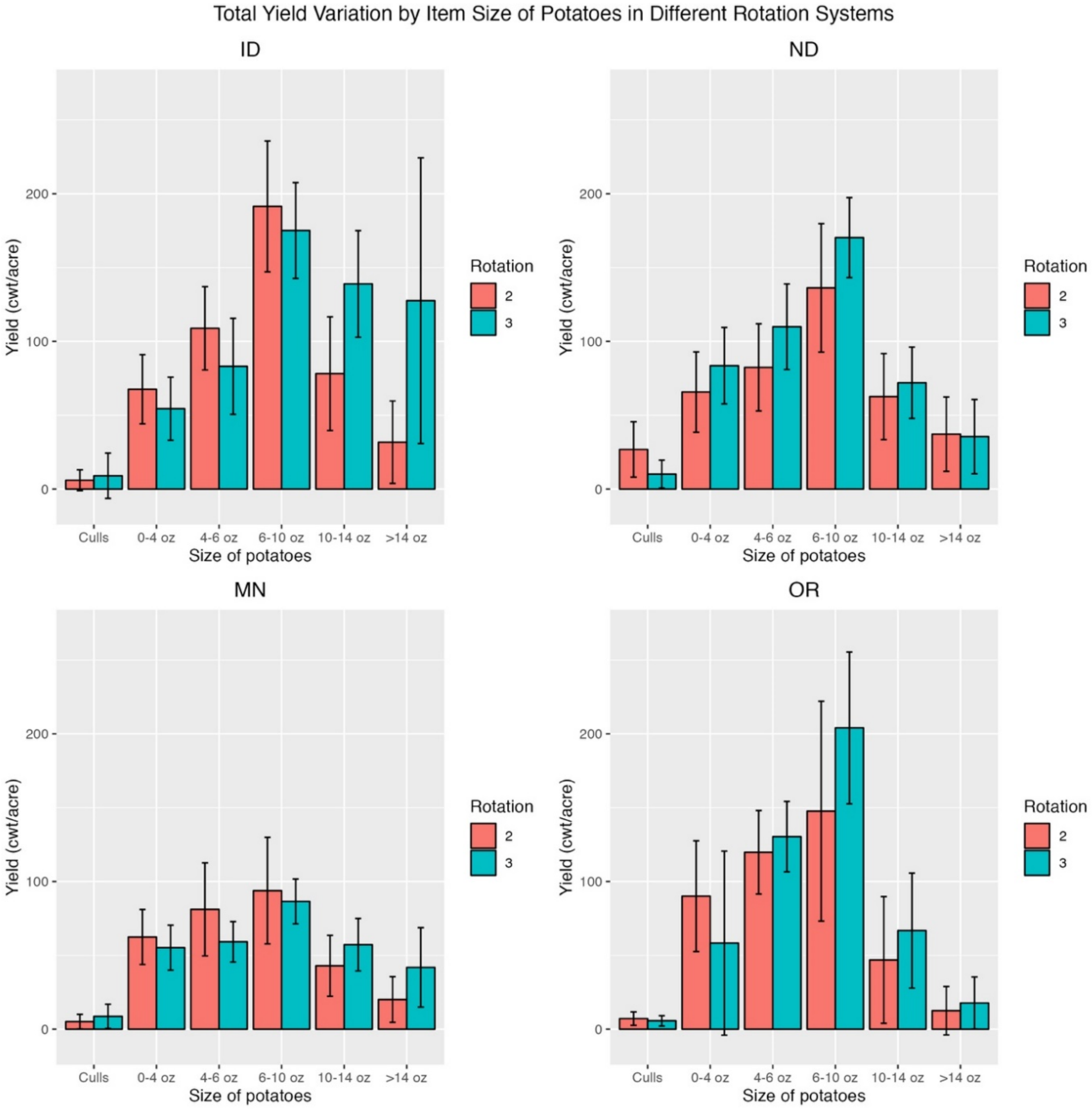

Figure 2 Variation in total yield of Russet by state and treatment

Caption: This figure presents the total yield (cwt/acre) of potatoes categorized by item size in two and three-year crop rotation systems abbreviated as Rotation-2 and Rotation-3 in four different states. The item size categories considered are represented on the x-axis, while the total yield is shown on the y-axis. The bars represent the average yield for each item size category. The comparison between two and three-year crop rotations provides insights into the impact of rotation length on total potato yield.

The comparison of potato yields in different size categories across Idaho, North Dakota, Minnesota, and Oregon revealed the following results:

The two-year crop rotation in Idaho yielded the highest results for smaller potato sizes (0-4 oz, 4-6 oz, and 6-10 oz), while the three-year rotation performed better for larger sizes (culls, 10-14 oz, and sizes above 14 oz). In North Dakota, the three-year rotation yielded the best results for most sizes, except for culls, where the two-year rotation was more favorable. Minnesota showed the lowest yields overall. It is important to note that since there were numerous instances of zero yields, the mean yield values were relatively low. However, the standard deviation was high for various size categories, as observed in the figure. Though not significant, the analysis consistently indicated that the three-year rotation produced the highest yields for larger potato sizes. This finding suggests that implementing a three-year crop rotation strategy is advantageous for maximizing yields of larger-sized potatoes across the studied regions.

2.4.2 Comparative Analysis of Average Net Return across Different Soil Management Practices and Crop rotation

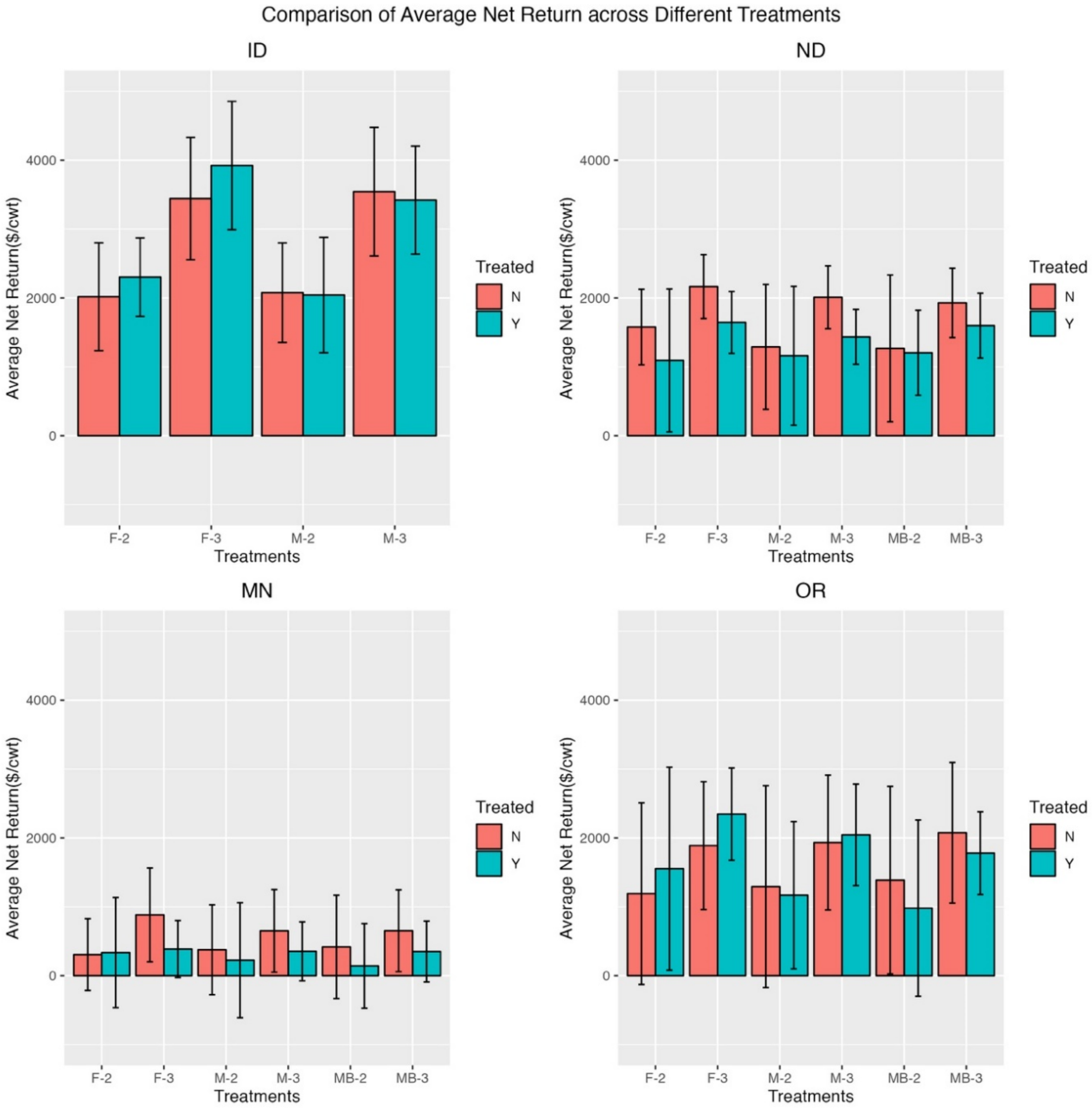

Figure 3 Comparison of average net return by state and treatment

Caption: This figure compares the average net return across various treatments and rotation systems. The treatments are labeled as Treated N (No) and Treated Y (Yes), indicating the presence or absence of treatment. The abbreviations F-2 and F-3 represent fumigation, M-2 and M-3 denote manured, and MB-2 and MB-3 indicate mustard bio-fumigation. The numerical values 2 and 3 in the treatment labels signify the two-year and three-year rotation systems, respectively. The bars represent the average net return for each treatment, providing insights into the economic impact of different treatment methods.

Figure 3 illustrates the average net return ($/acre) for various treatments in two- and three-year crop rotations. There wasn’t significant difference but the comparison in Idaho, three-year rotation with fumigation showed the highest net return, while manure application had a comparable impact on net return to non-manured fields. Mustard bio fumigation was not used in Idaho. For North Dakota, three-year rotation with fumigation had the highest net return, but the greatest net return overall came from fields with no fumigation treatment. Minnesota had the lowest average net return, with the highest return observed in fields without any treatments. In Oregon, fumigated fields, particularly in rotation 3, had the highest net return. Although insignificant, three-year rotation consistently yielded the highest average net return across the four states.

2.4.3 Overall average net return across two- and three-year crop rotation for all crops

Figure 4 Overall average net return profile for two- and three-year crop rotation

Caption: R2 and R3 is the two- and three-year crop rotation. The sequence of the crop rotations in different states is shown in detail in Table 5-8.

In Figure 4, the specific crop rotation and their average net return varied across states. In Idaho, two-year rotation had the highest average net return for potatoes in 2022. In North Dakota, three-year rotation had the highest overall net return, but two-year rotation had the highest average net return for potatoes in 2022. In Minnesota, three-year rotation had the highest overall net return. In Oregon, there wasn't a significant difference in the overall average net return between two- and three-year rotation. Thus, these crop rotations varied in their composition across the states, and the specific crops chosen for each rotation had an impact on the net returns achieved.

2.5 Conclusion

In conclusion, the comparison of crop rotations, potato yields, and net returns in Idaho, North Dakota, Minnesota, and Oregon offers valuable insights for optimizing potato production. In the data we analyzed, yield of large-sized potatoes from most of three-year rotations were higher than that of two-year rotation. Based on our comparison, three-year rotation in Idaho, North Dakota and Minnesota resulted in higher average net returns for potato and other crops. Based on our data, Minnesota had the lowest average net return owing to its lower yield compared to other states. In Oregon, fumigated plots had higher average net returns than plots that were not fumigated. Given the mixed results and regional variability observed, cautious consideration is required in making specific recommendations for potato production optimization. Further research should focus on employing precision farming technologies, addressing sustainability concerns, and evaluating market demand for different potato sizes to improve production systems, increase profitability, and support sustainable practices within crop rotations.

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