Potato Yields, Beet Leaf Hoppers and Green Peach Aphids: Empirical Examination in the Columbia Basin

A Thesis

Presented in Partial Fulfillment of the Requirement for the

Degree of Master of Science

with a

Major in Applied Economics

in the

College of Graduate Studies

University of Idaho

by

Juan Luo

August 2014

Major Professor: Dr. Levan Elbakidze

Authorization to Submit Thesis

This thesis of Juan Luo, submitted for the degree of Master of Science with a major in Agriculture Economics and titled “Potato Yields, Beet Leaf Hoppers and Green Peach Aphids: Empirical Examination in the Columbia Basin” has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the college of Graduate Studies for approval.

Major Professor: ________________________________Date:_______________
Dr. Levan Elbakidze

Committee
Members: ________________________________Date:_______________
Dr. Christopher McIntosh

________________________________Date:_______________
Dr. Carrie Huffman Wohleb

Department
Administrator: ________________________________Date:_______________
Dr. Christopher McIntosh

Discipline’s
College Dean: ________________________________Date:_______________
Dr. Larry Makus

Final Approval and Acceptance

Dean of the College
of Graduate Studies: ________________________________Date:_______________
Dr. Jie Chen

Abstract

The potato industry in Washington State, which generates $4.6 billion in economic impact and 23,500 jobs, is susceptible to outbreaks of numerous pests. Two such pests are Beet leafhopper (BLH), which causes a disease called “purple top” caused by the Beet Leafhopper Transmitted Virescence Agent (BLTVA), and Green peach aphid (GPA) which vectors Potato leaf roll virus (PLRV). This thesis examines how BLH and GPA populations affect potato yields in the Columbia Basin of Washington. In addition, this thesis also examines how pest populations are correlated with weather conditions and planted potato acreages. Endogeneity of pest populations is examined using two and three stage least squares regression analyses (2SLS and 3SLS) and the Hausman Test.

The regression results from Seemingly Unrelated Regression (SUR) and Ordinary Least Squares (OLS) show that an increase in the peak of BLH population by 1 per trap, decreases potato yield by 9.26 cwt/acre. Peak GPA population displays a positive but statistically not as significant correlation with yields as BLH perhaps due to a common correlate like weather. Acreage has a significant effect on BLH population but not on GPA population. Although acreage does not have a direct effect on yields, it appears to have an indirect effect on yields because increased acreage increases BLH population which in turn reduces yields. The effects of temperature and precipitation on the populations of BLH and GPA vary throughout the growing season. Finally, no direct evidence of pest population endogeneity is detected, although system estimation of SUR produces more significant coefficients than equation by equation OLS estimation.

Acknowledgements

I cannot image that I have been in Moscow for two years, and I am extremely excited to finish my Master program soon. During these two years of life, I received a lot of guidance and encouragement from professors, staff and students of University of Idaho and Washington State University. First, I would like to thank my major professor, Dr. Levan Elbakidze. He is very patient, motivated and, more importantly, he encouraged me to try some assumptions and be optimistic when there were difficulties. I really enjoy working with him and learning a lot from him. Meanwhile, I would like to thank the other two committee members: Dr. Christopher S. McIntosh, for providing some suggestions about the model, and Dr. Carrie Huffman Wohleb, for sharing observational data. In addition, I really appreciate the time with my lovely classmates, Mahalingam Dhamodharan, Tayebeh Soltaninejad, Steven Turi and Elijah Kosse. They are so brilliant and nice.

Most of all, I would like to thank my parents and my elder sister who encourage me to do what I like, and they always support me.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

This thesis examines some factors that affect potato yields in the Columbia Basin of Washington. These factors include acreage, temperature, precipitation, and two different pests: the Beet leafhopper (Hemiptera: Cicadellidae, BLH) and the Green peach aphid (Homoptera: Aphididae, GPA). In addition, empirical analysis also examines the effects of weather and planted potato acreage on the population of BLH and GPA in Adams, Benton, Franklin, and Grant counties in Washington State.

Suitable climatic conditions, rich volcanic soil, water accessibility and long growing season allow Washington State to achieve the world's highest potato yield per acre (Washington State Potato Commission (WSPC), 2014). Although the number of commercial growers is approximately 300, together they plant more than 160,000 acres annually, and harvest an average of 30 tons per acre. This yield is twice as much as the average yield in the United States. Washington State produces 20 percent of all U.S. potatoes (WSPC, 2014). The potato industry accounts for a $4.6 billion economic impact and is responsible for 23,500 jobs in Washington State (WSPC, 2014).

Figure 1.1 shows the geographic location of Adams, Benton, Franklin and Grant Counties. Growers plant russets, red and white potatoes (along with other varieties). The planting months are usually from March to May while the harvest time is from July to November. The Columbia Basin Irrigation Project provides cheap and dependable hydroelectric power and irrigation water for growers. Because of the availability of ground and surface water, the dependence on precipitation in this region has not been critical (WSPC, 2014).

Figure 1. 1 Washington Growing Area Map (source: WSPC, 2014)

This thesis examines how two types of pests, BLH and GPA, based on their peak observed counts and variance of observed counts during the growing season, affect potato yields. In addition, the empirical analysis also investigates how these pests are affected by temperature and precipitation. Unfortunately, no data could be obtained for pesticide application. Therefore, the results in the study should be interpreted with care. Specifically, the estimated statistical relationships implicitly incorporate the effects of pesticide applications, especially for GPA which are typically managed in this region with systemic insecticides applied at the time of planting. Hence, estimated coefficients cannot be interpreted as direct relationships between pests and yield, or between pest populations and temperature. Instead, the coefficients correspond to the relationship between pesticide adjusted pests and yields, and pesticide adjusted pests and temperature (Elbakidze et al. 2011).

Another objective of this study is to see whether simultaneous system equation estimation proves to be superior relative to equation by equation OLS estimation in this context. Potential cross equation error correlation, which is ignored by equation by equation OLS estimation, may improve efficiency (confidence intervals) of estimated coefficients. This study also examines whether potential endogeneity of some of the variables of interest may be a problem. In theory, pest population maybe endogenously determined as a function of planted acreage as well as weather conditions, and thus may be correlated with the error terms. If so, potential endogeneity may lead to biased estimates (Green, 2007, Wooldridge, 2002).

BLH is common throughout the western United States. It feeds on more than 300 plant species such as beans, sugar beets and several ornamental species. It develops rapidly and disperses readily to find new food sources (Munyaneza et al., 2005). In the Columbia Basin of Washington BLHs usually move into potato fields from mid-April to mid-October and have at least three generations per year (Munyaneza, et al., 2005).

According to Schreiber et al., (2010), a serious epidemic of the "potato yellows" disease, also called purple top, occurred in many potato fields throughout the Columbia Basin from 2002 to 2004 (Munyaneza et al., 2005). The disease reduced yields, and decreased the quality of potato tubers (Munyaneza et al., 2007). Symptoms in affected potato plants include a rolling upward of the top leaves with reddish or purplish discoloration, moderated proliferation of buds, shortened internodes, swollen nodes, aerial tubers, and early plant decline (Munyaneza et al., 2005).

This disease is caused by Beet Leafhopper Transmitted Virescence Agent (BLTVA), a bacteria-like organism, whose only known vector (source) in the Columbia Basin of Washington and Oregon is beet leafhopper (BLH) (Schreiber et al., 2010, Munyaneza et al., 2005, 2006, 2007, 2008). BLTVA is transmitted to potatoes every year and is more severe in the years when BLH numbers are highest. Thus it is very important to watch for BLH. Research shows that potatoes are more susceptible to BLTVA when plants are in the early growth stage, which is May to June for most of the potato crop in the Columbia Basin.

Data on Beet leafhoppers' population in potato fields for this study were obtained from a regional survey of insect potato pests in the Columbia Basin of Washington. BLH population numbers were monitored using yellow sticky cards (5.25 x 3.75 inches) mounted on small stakes about 3 inches above the soil surface, located adjacent to potato fields. Aphid counts were recorded on a per-trap basis. **Figure 1.2** shows the weekly BLH trap counts in 2007-2012 and the six-year average for each trapping date (Wohleb, et al., 2012).

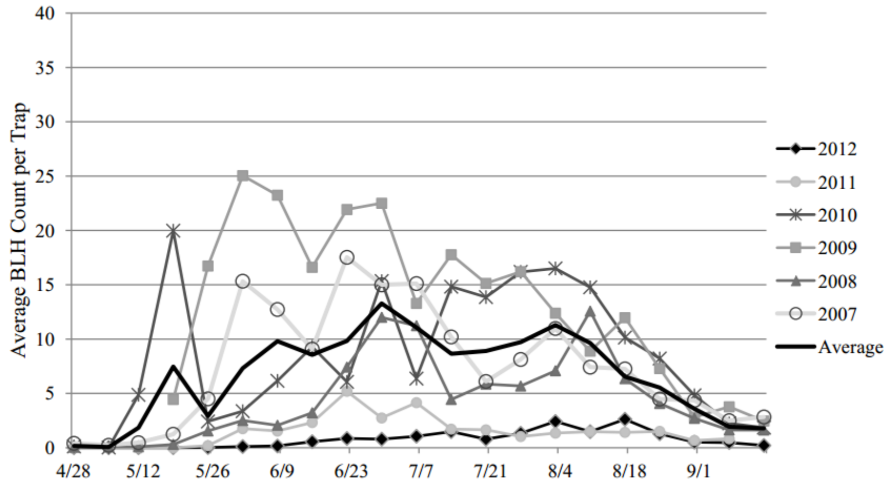


Figure 1. 2 Beet Leafhopper Population Trends from 2007 to 2012 vs. 6-Year Average (Wohleb, et al., 2012)

Potato leaf roll virus (PLRV) causes a viral disease, which can reduce yields by 90% (Jayasinghe, 1988). One estimate suggests that PLRV is responsible for an annual global yield loss of 20 million tons of potatoes (Whalon and Smilowitz, 1979). PLRV affects foliage and sometimes tubers. The virus causes net necrosis in some potato cultivars, a tuber defect which reduces the value of processing potatoes in the Columbia Basin (Carrie, 2011). The virus also causes the abnormal formation of a carbohydrate called callose which blocks starch transport from leaves to tubers. The severity of symptoms depends on environmental conditions (Jayasinghe, 1998). Green peach aphid (GPA) is the most significant vector of PLRV.

The spread of PLRV depends on environmental conditions. Any condition that affects the aphid population, such as rainy and cool weather, influences PLRV dissemination. Although temperatures above 26 ℃ (78.80 F) reduce dissemination, aphid populations in the tropics are usually high throughout the year (Jayasinghe, 1998).

Figure 1. 3 shows the weekly GPA trap counts in 2004-2006 and 2009-2012 and the seven-year average for each trapping date in the Columbia Basin (Wohleb, et al., 2012).

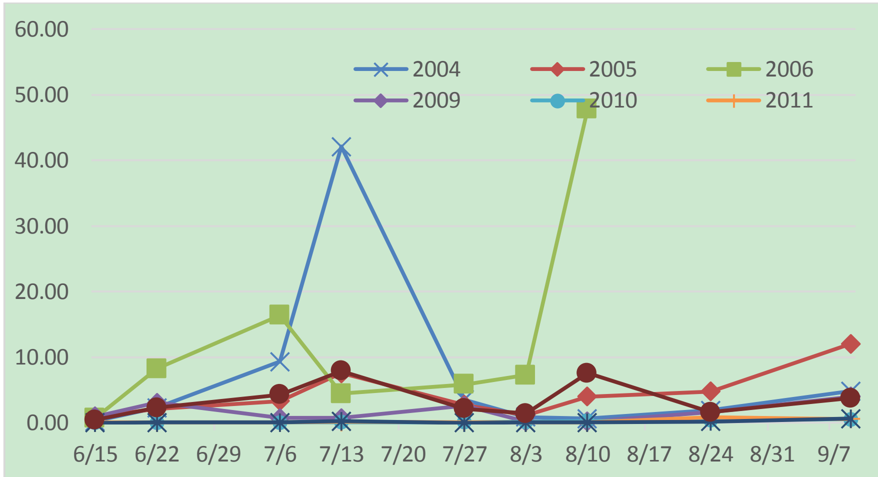


Figure 1. 3 GPA Population Trends vs. 7-Year Average

In order to maximize profit in potato production, growers need to have sufficient information about these pests to increase yields and/or reduce pest management costs. This applies particularly to growers in the Columbia Basin of Washington where potatoes account for a large proportion of the economic income (Schreiber, et al., 2010). A critical piece of information is how BLH and GPA affect the potato yields.

Chapter 2: Literature Review

Beet leafhoppers transmit BLTVA to potato cultivars as well as beets and several weeds (Munyaneza, et al., 2006). Experiments were conducted to determine the settling behavior, survival, and reproduction of the beet leafhopper on different crops. The results showed that leafhopper mortality was high on bean and tomatoes while 80% of leafhoppers survived on potatoes, sugar beets and radishes (the experiments were conducted in both greenhouse and controlled experimental rooms). Beet leafhopper reproduction was lower on potato plants than on other plants (Munyaneza and Upton, 2005). The overwintering BLH data collected in the Columbia Basin and Yakima Valley showed that overwintering leafhoppers near potato fields carried the phytoplasma (Munyaneza et al., 2010).

Several environmental factors significantly affect the BLH populations. These include temperatures of the preceding fall and winter, elevation, and precipitation. In addition, BLH populations increase as moisture increases at lower elevations (Murphy, et al., 2012).

Researchers have examined the relationship between GPA and PLRV presence. Teulon and Stufkens (2001) detected no evidence of a strong linear relationship between aphid flight activity and virus incidence. There may be several explanations for this. The relationship between PLRV incidence and aphid vectors is more complex than simple linear correlation would imply. The relationship may be affected by the amount of PLRV carried-over in seed potatoes. The relationship may also be affected by pest management. However, Mowry (2001) showed that there appears to be significant linear relationships between GPA numbers and PLRV incidence. Furthermore, when GPA density was low, its population was affected dramatically by fungal pathogens. The experiments demonstrate that GPA population is affected by fungi more than generally recognized (Lagnaoui and Edward, 1998).

Some studies compared several similar pests. A survey of psyllids, leafhoppers and sharpshooters in commercial potatoes near McAllen, TX was conducted. This study shows that psyllids are the most common species in the study area, causing 87% of the zebra chip disorder in potatoes. Leafhoppers are less common and their role in zebra chip disorder is unknown. Sharpshooters are rare and do not appear to play a role in the zebra chip disorder (Goolsby, 2007).

In past decades, many studies assumed various forms of production functions to examine the pest influence on yields. The researchers separated the contribution to production into two parts. One is the maximum quantity of the product, assuming optimal inputs, when pests do not exist. Another one is the proportional yield loss caused by pests (Lichtenberg and Zilberman, 1986). Later, the functional form was extended by examining the interaction between direct production inputs and damage control inputs within the abatement function (Saha et al., 1997). Then, a functional form which provides symmetric treatment of damage control and direct inputs was presented (Carpentier and Weaver, 1997). Two stage semi-parametric approach was later developed (Simar and Wilson 2003, Kuosmanen ect. 2006), which combines attractive features of both the nonparametric and parametric techniques: the minimal assumptions of the nonparametric techniques and the specificity of the parametric techniques. They found that this approach avoids the problems of misspecification of the production function, small sample bias and correlated error terms.

However, a single equation estimation may encounter endogeneity bias. The problem is that independent variables in the yield function, like the aphid population, can also be affected by the weather and planted acreage. The effect of the pests on the potato yield is probably influenced by weather conditions like temperature and precipitation. Favorable weather conditions provide a better environment for pests to grow, resulting in an increase in pest population. In addition, the dissemination rate can be affected by the plant acreage in terms of habitat. A crop with limited acreage may not provide needed space for dissemination of the virus. With limited acreage, spread of the virus may decrease. To account for these types of possibilities, endogeneity tests and a three stage least squares regression technique involving simultaneous estimation of a system of equations can be used. Simultaneous equations estimation has been used in previous literatures on pests in crop production (Babcock, et al., 1992; Elbakidze et al., 2011).

Considering the close relationship between the virus and its vector, controlling the vector population has been a critical way to control the virus. This relationship is apparent in many plant virus-vector systems (Mowry, 2001; Elbakidze et al. 2011; Marsh et al. 2000). Unfortunately, our data does not include information on PLRV and BLTVA. The analysis in this study is limited to examination between vectors and yields.

This thesis attempts to capture the changes in pest population and potato yield as influenced by climate parameters and planted acreage. Data on yields, acreage, temperature, and precipitation combined with historical data on BLH and GPA population is used.

Chapter 3: Data Collection and Simulation

Following Burrows (1983) and Elbakidze, et al., (2011) we empirically examine 5 equations. However, unlike Burrows (1983) and similar to Elbakidze (2011), data about pesticide use in the Columbia Basin is not available. Temperature and precipitation are considered along with acreage. These considerations capture the relationship between pesticide-use adjusted pest populations and potato yield that are influenced by climate parameters and planted acreage. Planted acreage is utilized to determine whether the relationship between the potato yield and the amount of aphids changes due to the acreage and how the weather affects aphids.

Time series cross-sectional (panel) data are divided into three parts. The data for BLH and GPA are provided weekly by the annual survey conducted by Washington State University (Wohleb, et al., 2010) in the North Columbia Basin Route, West Columbia Basin Route and South Columbia Basin Route. The weather data, including temperature and precipitation, are from Western Regional Climate Center. The U.S. Department of Agriculture (USDA) is the source of potato yields and planted acreage data per county.

3.1 Weather Variables

The weather data are collected from Western Regional Climate Center, including minimum Daily Air Temperature (MN, F), maximum Daily Air Temperature (MX, F), mean Daily Air Temperature (MM, F) and Daily (24hours) Precipitation (PP, in).

Degree days (DD) for GPA are defined as the difference between arithmetic mean air temperature and the base (threshold) temperature (Ro and Long, 1999):

$$Degreeday = \left[(T_{\max} + T_{\min}) / 2 - T_b \right] \tag{3.1}$$

$T_{\max}$ is daily maximum air temperature (F), $T_{\min}$ is daily minimum air temperature (F), and T_b is the base temperature for GPA development (39.2 F). The accumulated degree days above the 39.2 F threshold is for GPA at Columbia Area, Washington. Accumulated DD were calculated by summation of degree days beginning 1 January of each year. The Western Regional Climate Center recorded daily maximum and minimum temperatures.

Degree day models have been applied to predict the development of many insects including BLH and GPA (Anderson 2006, Archer 2004). The same formula (3.2) is used for both GPA and BLH. Furthermore, the same base temperature (T_b) is used for both insects because a corresponding parameter for BLH could not be obtained from literature. In this study, accumulated DDs for BLH and GPA are used as explanatory variables.

The growing season is also divided into 10 day periods. Average temperature values during the 10 day intervals are also used in the regression analysis. Similarly, precipitation is measured as cumulative precipitation during the ten day intervals.

3.2 BLH and GPA Population Data

BLH and GPA population data are provided weekly by the annual survey (Wohleb et al., 2011) from 2004 to 2012. However, GPA population data in 2007 and 2008 are not available. There are several observations in one county in specific weeks. Therefore, an average is taken. Aphid counts were recorded on a per trap basis. The default value is zero when there are no observations in a given week. There are several observations in different counties per week, and the numbers of observations per week differ across counties and different years. Therefore, I use an average and produce one estimate per county per week per year.

For BLH, there are no observations in some counties in some years. Data in Benton County in the years 2005, 2006 and 2010 are not available. Since four counties are near to each other, it is reasonable to utilize data from nearby counties to simulate the data for Benton County in those years. The data for the missing years are approximated as follows:

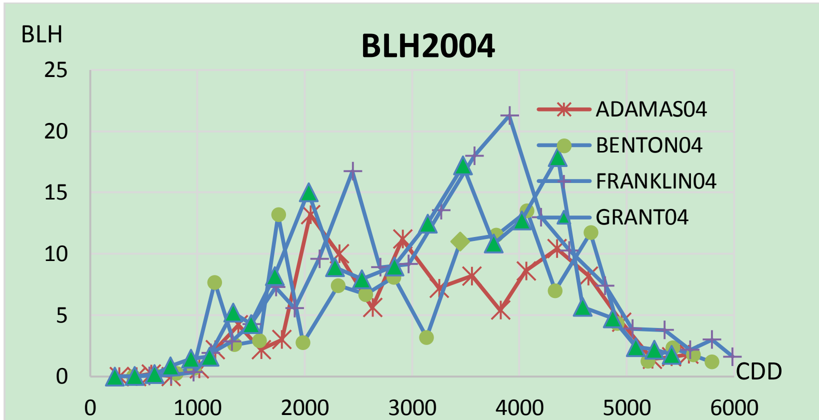
1) The BLH population data for each county is divided by the total in four counties to obtain ratios in the years 2004, 2007 to 2009, 2011 and 2012. **Table 3. 1** shows the ratios. The average ratio for Benton County is 0.09. The ratio is calculated by dividing the BLH population by the total amount in four counties.

Table 3. 1 Ratios of BLH population for each county in the years from 2004 to 2012

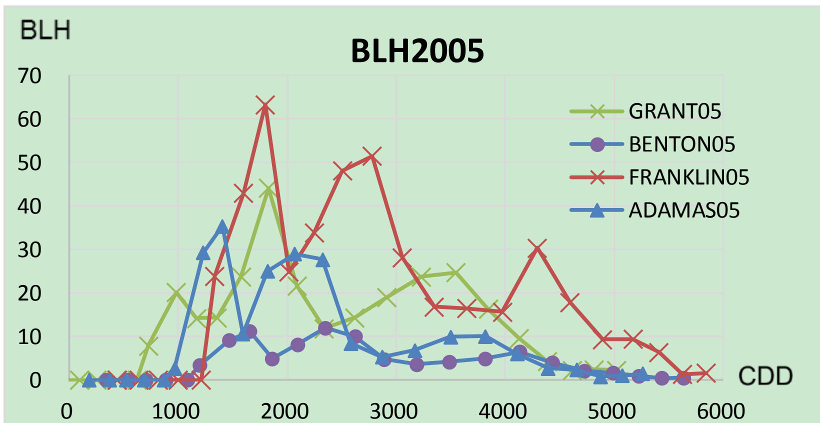
COUNTIES	*2004*	*2007*	*2008*	*2009*	*2011*	*2012*	Average(04-12)
ADAMS	0.23	0.25	0.23	0.04	0.2	0.35	
BENTON	0.25	0.08	0.09	0.15	0.02	0.11	0.09
FRANKLIN	0.28	0.39	0.18	0.47	0.34	0.21	
GRANT	0.25	0.29	0.50	0.34	0.43	0.33	

2) Since BLH population data in other counties except for Benton County in the years 2005, 2006 and 2010 are available, the data for the three missing years in Benton County are obtained using the average ratio for Benton County, which is 0.09.

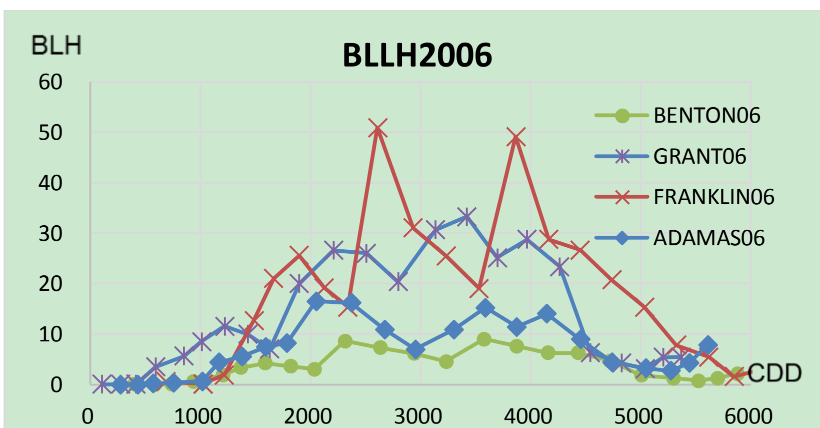
Figure 3. 1 shows the amount of BLH over time for each county in each year. The term on the horizontal axis is cumulative degree day. The vertical axis is BLH per trap.


BLH
BLH2004
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
CDD
ADAMAS04
BENTON04
FRANKLIN04
GRANT04

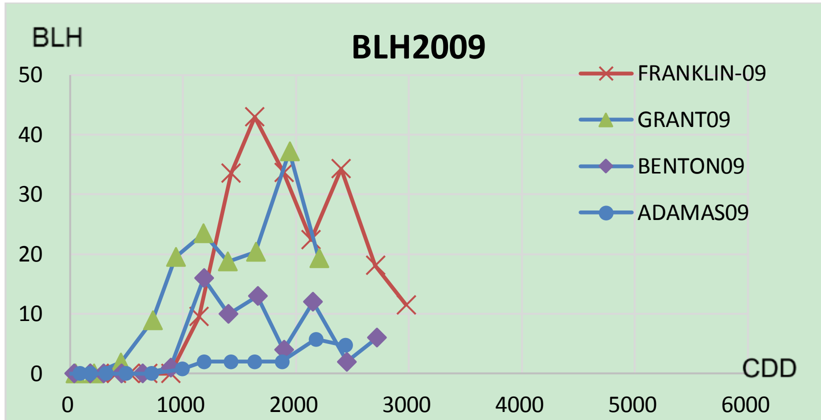
(a)


BLH
BLH2005
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
CDD
GRANT05
BENTON05
FRANKLIN05
ADAMAS05

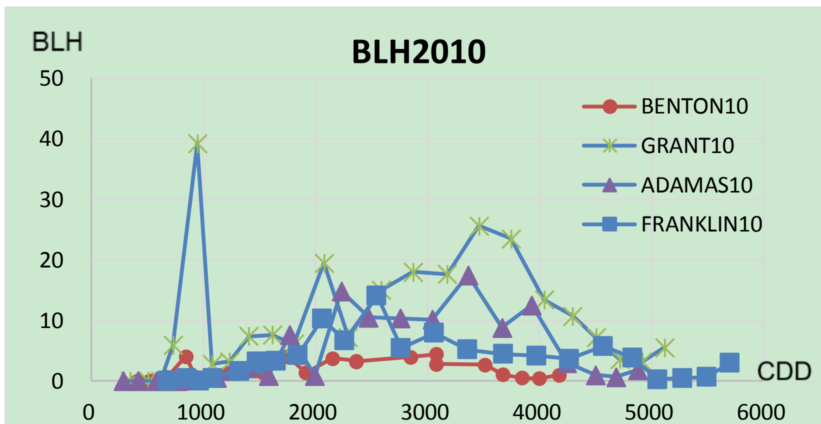
(b)


BLH
BLLH2006
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
CDD
BENTON06
GRANT06
FRANKLIN06
ADAMAS06

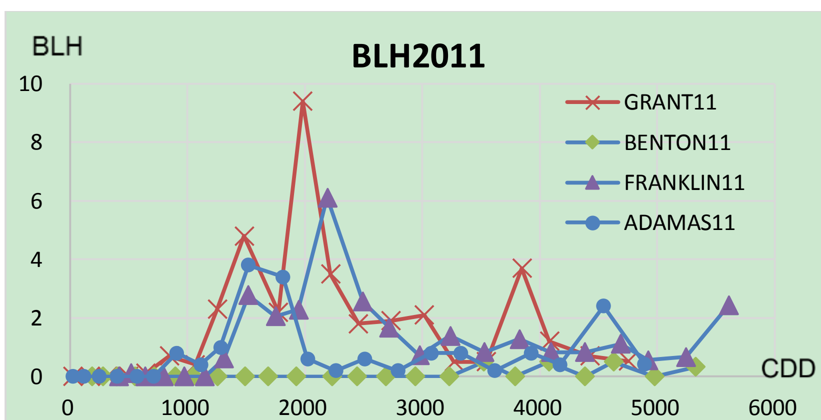
(c)


BLH
BLH2009
FRANKLIN-09
GRANT09
BENTON09
ADAMAS09
CDD
0
10
20
30
40
50
1000
2000
3000
4000
5000
6000

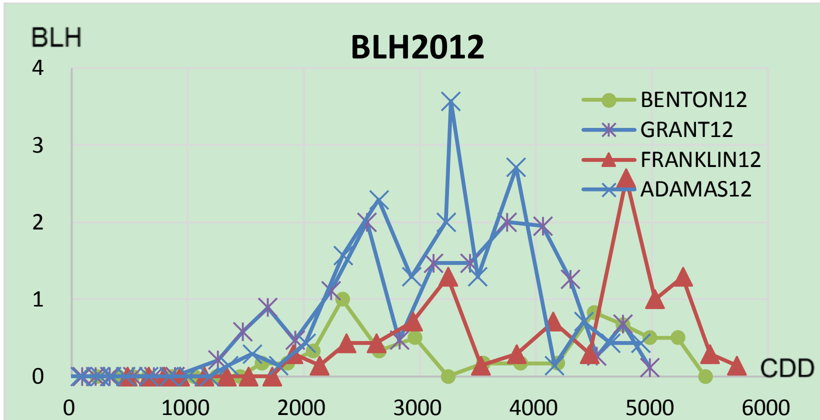
(d)


BLH
BLH2010
BENTON10
GRANT10
ADAMAS10
FRANKLIN10
CDD
0
10
20
30
40
50
1000
2000
3000
4000
5000
6000

(e)


BLH
BLH2011
GRANT11
BENTON11
FRANKLIN11
ADAMAS11
CDD
0
2
4
6
8
10
1000
2000
3000
4000
5000
6000

(f)



(g)

Figure 3. 1 The amount of BLH over time for four counties

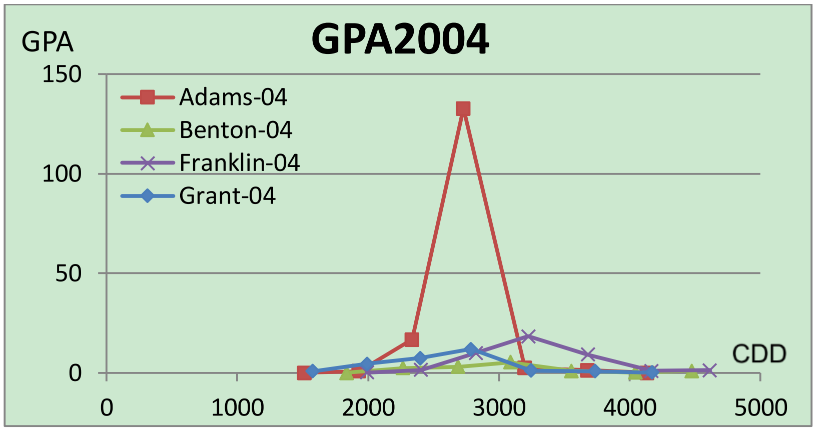
Figure 3. 1 shows that the amount of BLH decreases, and then increases over the growing season. The trend follows a cubic polynomial shape, which can be used to simulate the trend of BLH population over time during a growing season.

Since the trend follows the cubic polynomial, peaks exist for each county in each year. The peak of BLH may be a critical independent variable for explaining yield variability. The variance of BLH population is calculated from the data for each year and county.

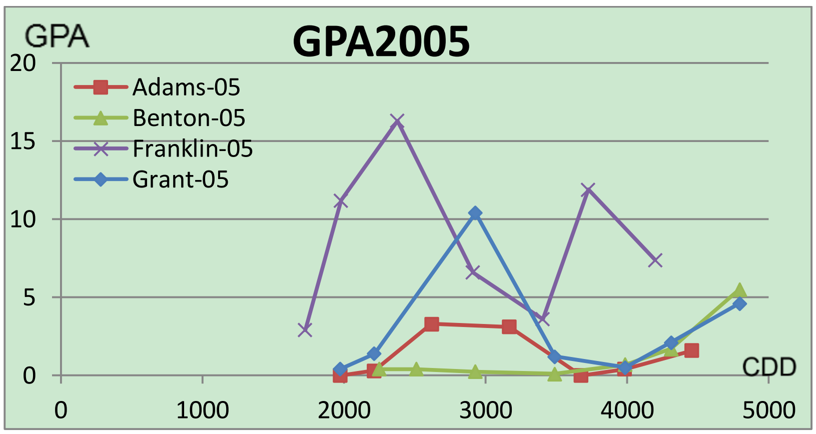
For GPA, the data cover areas in the north, west and south Columbia Basin. However, some data in some years are missing. For example, the data in Benton County in the year 2010 are missing. In order to make the data more complete, the average of years 2009 and 2011 is used.

Data on certain observed days have been dropped to construct a balanced dataset. In the final dataset, there are seven observation periods for BLH and GPA, middle June, late June, early July, middle July, late July, early August, and middle August.

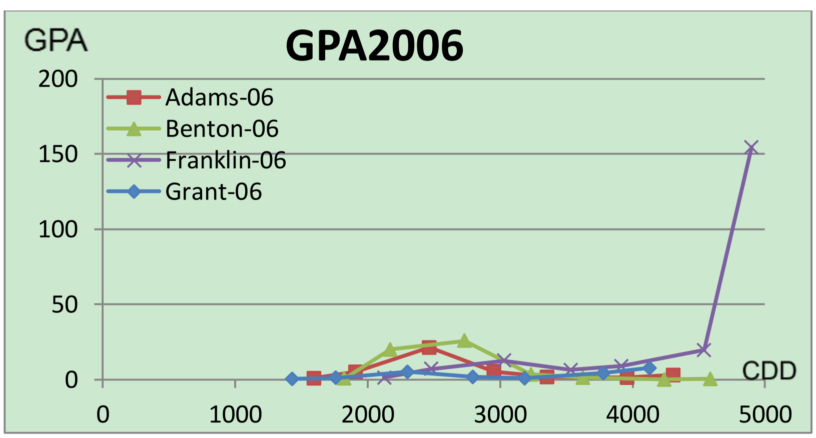
The following figures describe the relationship between the amount of GPA and temperature. The term on the horizontal axis is cumulative degree day (CDD).


GPA
GPA2004
150
100
50
0
Adams-04
Benton-04
Franklin-04
Grant-04
CDD
0
1000
2000
3000
4000
5000

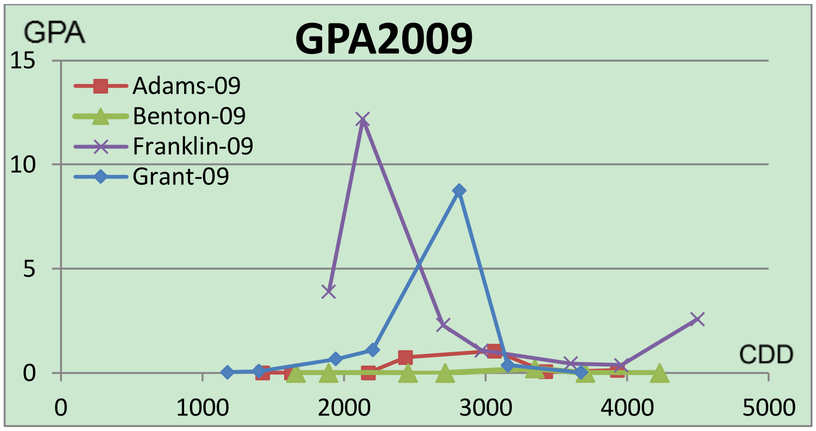
(a)


GPA
GPA2005
20
15
10
5
0
Adams-05
Benton-05
Franklin-05
Grant-05
CDD
0
1000
2000
3000
4000
5000

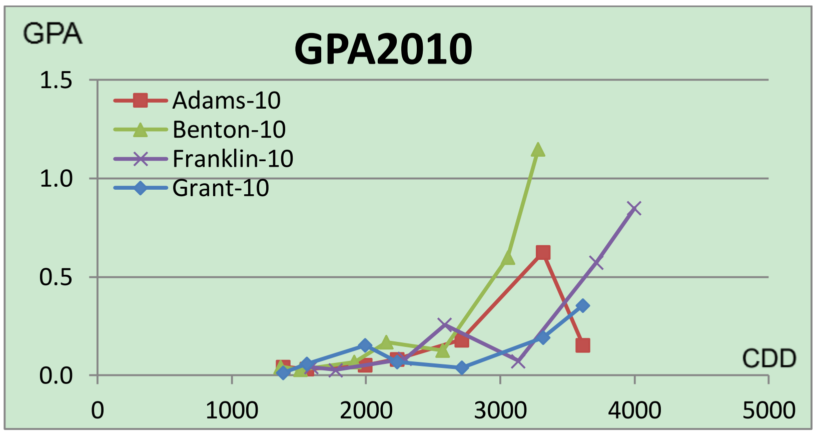
(b)


GPA
GPA2006
200
150
100
50
0
Adams-06
Benton-06
Franklin-06
Grant-06
CDD
0
1000
2000
3000
4000
5000

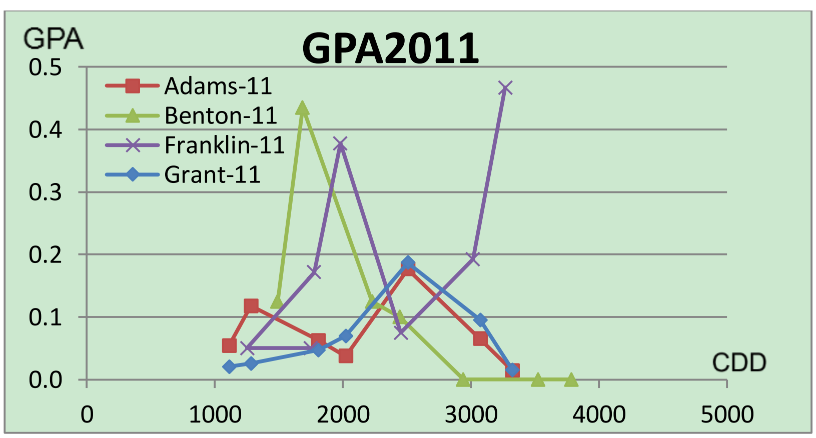
(c)


GPA
GPA2009
15
10
5
0
Adams-09
Benton-09
Franklin-09
Grant-09
CDD
0
1000
2000
3000
4000
5000

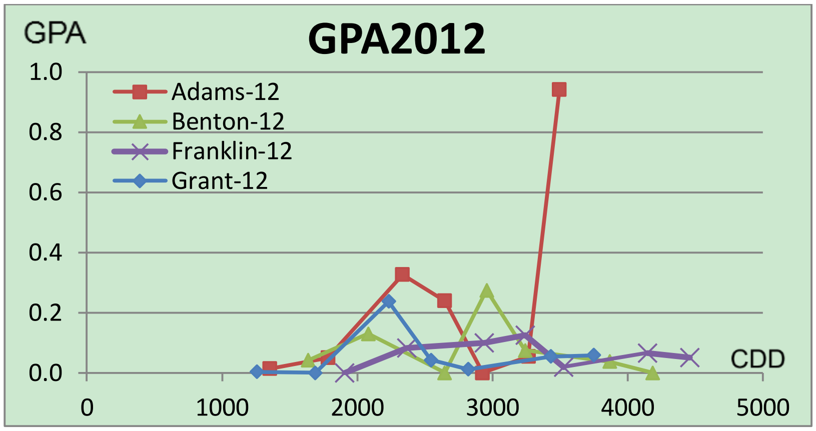
(d)


GPA
GPA2010
1.5
1.0
0.5
0.0
Adams-10
Benton-10
Franklin-10
Grant-10
CDD
0
1000
2000
3000
4000
5000

(e)


GPA
GPA2011
0.5
0.4
0.3
0.2
0.1
0.0
Adams-11
Benton-11
Franklin-11
Grant-11
CDD
0
1000
2000
3000
4000
5000

(f)



(g)

Figure 3. 2 The amount of GPA and accumulated degree day

Figure 3.2 shows that there are no obvious patterns in the fluctuation of GPA population. Therefore, the maximum observed count of GPA and corresponding cumulative degree day are used in the analysis.

As with BLH, the variance of GPA is calculated per county and per year. Since the data of GPA in the year 2007 and 2008 are not available for any counties, the analysis is performed without 2007 and 2008.

3.3 Potato Yield

Potato yields data come from the USDA. The data for four counties is from the years 2004 to 2012, some of which are missing, as shown by **Table 3. 2**.

Table 3. 2 The missing data in potato yield data

Year	Counties
2010	Benton, Grant
2011	Adams, Benton, Franklin
2012	Adams, Benton, Franklin

The missing data are simulated for empirical analysis. Grant County is in the middle of Washington State and close to Adams County and Franklin County. Adams County and Franklin County are in the East Central Area of Washington State (All counties in Washington State are divided into four regions (USDA): East Central, Central, East and West). The potato yield data in Adams County and Franklin County are available, as is the average potato yield data in East Central region. The ratios are calculated by dividing the yield in a given county by the yield in East Central region. **Table 3. 3** shows the ratios for Adams County, Franklin County and Grant County. In general, the ratios remain stable. The average ratios represent the percentage of the yield in a given county relative to East central region.

Table 3. 3 Ratios in the central Washington States (Yield, Measured in cwt/Acre)

	2006	Ratio	2007	Ratio	2008	Ratio	2009	Ratio	2010	2011	2012	average Ratio(06-09)
EAST CENTRAL	589		624		628		638		675	601	587	
ADAMS	625	1.06	641	1.03	665	1.06	668	1.05	712	630*	616*	**1.05**
FRANKLIN	576	0.98	620	0.99	615	0.98	630	0.99	690	592*	578*	**0.98**
GRANT	565	0.96	616	0.99	606	0.96	625	0.98	657*	580	612	**0.97**

* Data is simulated. Ratio is calculated by dividing potatoes yield in the counties by the yield in East Central.

The above table shows that the ratio of Adams is 1.05, Franklin is 0.98 and Grant is 0.97. Since yield data in the East Central region is available from USDA, yield in missing counties in 2011 and 2012 can be estimated.

The record of potato yields in Benton County is not available from 2010 to 2012. However, data from 2004 to 2009 is available. So, the ratios of yield in Benton County relative to central region are provided in **Table 3.4**.

Table 3. 4 Ratios of Benton County in Central Area

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012
Ratio	0.56	0.51	0.57	0.56	0.47	0.45	0.45*	0.43*	0.41*

* Represents data is simulated. Ratio is calculated dividing the yield in Bento County by the yield in Central Region.

A regression analysis is used to estimate the ratio of Benton county yield and Central Region yield in the missing years. After comparing R squares of linear, quadratic and cubic equations, and double log functions, the double log function is chosen to estimate the missing ratio. The result is provided in equation 3.1:

$$\ln(\text{Ratio}) = -0.52 - 0.04 * \ln(t) \qquad (3.2)$$

The ratios for 2010, 2011 and 2012 are 0.45, 0.43 and 0.41, respectively. The yield data in the Central Area for 2010 to 2012 are not available. However, the Central Area of Washington State is located near to Morrow County and Umatilla County of Oregon State, where the data are available. The average of yield in Morrow and Umatilla counties of Oregon is used as the value of yield in the Central Area of Washington State. Using the yield data for Central Area and ratio of Benton County in Central Area, the yield data for Benton County is simulated.

3.4 Planted Acreage

Potato planted acreage data is from the USDA. The data for four counties are from 2004 to 2012, some of which are missing as shown in **table 3. 5**:

Table 3. 5 Missing data in planted acreage

Year	Counties
2010	Adams, Benton
2011	Adams, Benton, Franklin
2012	Adams, Benton, Franklin

Adams and Franklin counties are in the East Central region of Washington State. Planted acreage of potatoes in the East Central Region of Washington State is available from the USDA. The ratios of Adams County and Franklin County in the East Central region are used to simulate the missing data.

After comparing several methods including linear, quadratic, and cubic equations, the linear one is selected for Adams County based on R square:

$$y = -0.0084x + 0.3261 \tag{3.3}$$

Where x is the year and y is the ratio of acreage in Adams county and acreage in the East Central region of Washington State. Using data from 2004 to 2009, the predicted ratios in 2010, 2011 and 2012 are 0.2673, 0.2589 and 0.2505 respectively. The estimated acreages in Adams County in those years are 24,538.14, 27,313.95 and 27,655.20.

Similarly, for Franklin County, the linear model is the best in comparison to the quadratic equation and cubic equation. The linear function is

$$y = -631.43x + 32827 \tag{3.4}$$

Where x is the year and y is the ratio of acreage in Franklin County relative to East Central region. The ratios in 2011 and 2012 are 0.3543 and 0.3643, respectively. The acreages in 2011 and 2012 are 37,378.65 and 40,218.72, respectively.

Benton County is in the Central region of Washington State and planted acreage data in the Central region are not available. Therefore, the historical data in planted acreage are used to simulate the missing data. The linear model is built by using the previous acreage data:

$$y = 0.01x + 0.2843 \tag{3.5}$$

Where x is the year and y is the acreage. The acreages in Benton County in 2010, 2011 and 2012 are 28,407, 27,776 and 27,144, respectively.

3.5 Data Summary

Table 3. 6 Summary Statistics

Variables	Description(Unit)	Obs	Means	Std. Dev.	Min	Max
Yield	Potato yield (CWT/ACRE)	28	619.11	1928.95	521.00	712.00
Acreage	Acres Harvested of Potatoes (ACRE)	28	31379.69	22508669.89	22500.00	43000.00
PEAK(AD)_B	Peak of Accumulated Degree Day for BLH (F)	28	2969.52	635135.08	0.07	15.80
PEAK(BLH)_B	Peak of Amount of BLH (/TRAP)	28	10.24	98.01	0.36	35.47
Variance_BLH	Variance of amount of BLH	28	57.00	6263.09	1737.10	4468.10
PEAK(AD)_G	Peak of Accumulated Degree Day for GPA (F)	28	4023.72	1183220.65	0.36	35.47
PEAK(GPA)_G	Peak of Amount of GPA (/TRAP)	28	21.31	1776.88	0.03	297.57
Variance_GPA	Variance of amount of BLH	28	218.29	511199.12	0.00	0.01
June5_P	Total Precipitation from Jun 5 to Jun 14 (in)	28	0.34	0.10	0.01	1.24
June15_P	Total Precipitation from Jun 15 to Jun 24 (in)	28	0.10	0.04	0.00	1.00
June25_P	Total Precipitation from Jun 25 to Jul 4 (in)	28	0.11	0.08	0.00	1.18
July5_P	Total precipitation from Jul 5 to Jul 14 (in)	28	0.08	0.01	0.00	0.35
July15_P	Total Precipitation from Jul 15 to Jul 24 (in)	28	0.08	0.03	0.00	0.57
July25_P	Total Precipitation from Jul 25 to Aug 4 (in)	28	0.07	0.02	0.00	0.53
August5_P	Total Precipitation from Aug 5 to Aug 14 (in)	28	0.04	0.01	0.00	0.27
August15_P	Total Precipitation from Aug 14 to Aug 24 (in)	28	0.07	0.02	0.00	0.51
August25_P	Total Precipitation from Aug 25 to Sep 4 (in)	28	0.03	0.01	0.00	0.28
June5_T	Average Temperature from Jun 5 to Jun 14 (F)	28	61.94	9.08	56.90	68.37
June15_T	Average Temperature from Jun 15 to Jun 24 (F)	28	64.86	9.23	60.17	72.22
June25_T	Average Temperature from Jun 25 to Jul 4 (F)	28	70.00	19.12	63.69	79.05
July5_T	Average Temperature from Jul 5 to Jul 14 (F)	28	71.58	8.63	67.21	78.69
July15_T	Average Temperature from Jul 15 to Jul 24 (F)	28	73.63	12.30	65.91	79.05
July25_T	Average Temperature from Jul 25 to Aug 4 (F)	28	74.86	9.91	69.74	81.94
August5_T	Average Temperature from Aug 5 to Aug 14 (F)	28	73.00	7.19	68.39	79.09
August15_T	Average Temperature from Aug 14 to Aug 24 (F)	28	71.94	3.67	68.67	76.76
August25_T	Average Temperature from Aug 25 to Sep 4 (F)	28	67.34	6.80	62.43	72.65

Table 3. 6 provides summary statistics for the data. The average per acre yield for potatoes is 619.11 CWT. The average of peaks of accumulated degree day for BLH and GPA are 2, 969.52 F and 4, 023.72 F, respectively. The population of BLH reaches the peak earlier than that of GPA in terms of accumulated degree day. Based on the calculation results, the averages of peaks of the amount of BLH and GPA are 10.24 and 21.31, respectively. The variances of BLH and GPA counts are 57.00 and 218.29, respectively. The table provides temperature and precipitation by periods from June 5 to Sep 4. This period is chosen because the potatoes are affected by GPH and BLH in mid-summer (Alvarez et al. 2003).

Chapter 4: Methods

In our model, there are data about potato yields, BLH, GPA and weather, including temperature and precipitation from the years 2004 to 2012, except for 2007 and 2008, since GPA population data in 2007 and 2008 are not available. A system of five equations is used in this study, including yield equation, PeakBLH_B equation, PeakGPA_G equation, Variance_B equation and Variance_G equation.

Two alternative approaches can be used for estimation: single equation estimation and system estimation. Single equation estimation involves estimating either one equation in the model, or two or more equations in the model separately. Ordinary least squares (OLS) and two stage least squares (2SLS) estimators are examples of single equation estimator, and they are used in this study. System estimation involves estimating two or more equations in the model jointly. Three-stage least squares (3SLS) and Seeming Unrelated Regression (SUR) are two system estimators.

The major advantage of system estimation is that it uses more information, and therefore it can produce more precise parameter estimates.

4.1 Ordinary Least Squares (OLS)

Standard multivariate regression requires that each dependent variable has exactly the same matrix such that:

$$Y_{(N\times p)} = X_{(N\times k)} B_{(k\times p)} + \varepsilon_{(N\times p)} \tag{4.1}$$

Where Y is a matrix of dependent variables, X is a k-dimensional deign matrix, and is assumed to be distributed as $\mathbb{N}_{(\mathrm{N}\times p)}(0, \sum \otimes I_N)$. Multivariate regression theory using ordinary least square (OLS) assumes that all of the B coefficients in the model are unknown and can be estimated from the data as:

$$B = (X'X)^{-1}(X'Y) \tag{4.2}$$

4.2 Seeming Unrelated Regression (SUR)

Zellner (1962) formulated the Seemingly Unrelated Regression (SUR) model as p correlated regression equations. The p regression equations can be assumed as “seemingly unrelated” when they are taken separately consistent with standard linear OLS model form.

However, there may be “contemporaneous” correlation among error terms across the p equations. Thus, SUR model is applied when there are several equations where disturbances may be correlated across equations.

4.3 Three-stage least squares (3SLS)

3SLS is a combination of 2SLS and SUR. It is used in a system of equations where endogeneity may be a problem. In each equation there are endogenous variables on both the left and right hand sides of the equation. In the study, pest populations can be endogenous in the system as planted acreage or weather data can affect pest population. The most often used test of endogeneity is the Hausman test.

Furthermore, in a multi-equation estimation error terms can be correlated across equations. If the error terms are correlated, then 3SLS can be used. It is consistent and asymptotically more efficient than single equation estimators.

4.4 Hausman Test

The Hausman test is the most often used test of endogeneity. The Hausman Test is a general test that allows us to compare two estimation methods. Here, it is used to compare 2SLS with OLS, and 3SLS with OLS. (White, 1982, Cameron and Trivedi, 2005).

Chapter 5: Empirical Estimation and Results

The result from the comparison between OLS and 2SLS is as follows:

Table 5. 1 Hausman test for OLS and 2SLS

	Coefficients (b) EQN2sls	(B) EQNols	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
Yield_1	10.08489	10.53291	-.448019	2.584813
Yield_1_2	-.0072478	-.0076007	.0003529	.0020195
Acreage	.000014	.000091	-.000077	.0003603
PEAKBLH_B	-6.935704	-7.843618	.9079144	4.002478
PEAKGPA_G	.7127473	.6519968	.0607505	.5204651
Variance_BLH	.8060796	.9018081	-.0957286	.3981821
Variance_GPA	-.0594416	-.0572807	-.0021609	.0280748
June15_T	-7.544723	-7.965223	.4204999	2.103944
June25_T	7.14346	7.830955	-.6874946	2.261766
July5_T	-7.159844	-7.569546	.4097018	1.387912
July25_T	13.42336	14.11517	-.6918056	2.745787
August5_T	11.32035	11.78128	-.4609275	1.830622
August15_T	-8.677818	-9.718869	1.041051	4.280564
August25_T	-10.42421	-10.87916	.4549488	1.435852

```
                  b = consistent under Ho and Ha; obtained from reg3
   B = inconsistent under Ha, efficient under Ho; obtained from reg3

Test:  Ho:  difference in coefficients not systematic

             chi2(12) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                      =        0.26
           Prob>chi2 =      1.0000
```

The Hausman test statistic is 0.26, and the significance level is 1.00. It is clearly far from being significant at the 10% level. So, it appears that coefficients from the two regressions are not significantly different. Hence, endogeneity does not seem to be a problem in this case, based on this specification.

In the same way, **Table 5. 2** reports the results of Hausman test comparing OLS and 3SLS results:

Table 5. 2 Hausman test for OLS and 3SLS

	Coefficients (b) EQNols	(B) EQN3sls	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
Yield_1	10.53291	9.588877	.944035	4.032048
Yield_1_2	-.0076007	-.0068102	-.0007905	.0031917
Acreage	.000091	.0002068	-.0001158	.0011831
PEAKBLH_B	-7.843618	-7.784338	-.0592803	1.90109
PEAKGPA_G	.6519968	.8379987	-.1860019	.3681686
Variance_BLH	.9018081	.9098721	-.008064	.2506545
Variance_GPA	-.0572807	-.0657991	.0085184	.0222364
June15_T	-7.965223	-7.485327	-.4798957	2.412825
June25_T	7.830955	7.200596	.6303586	1.979855
July5_T	-7.569546	-7.226236	-.3433099	2.527558
July25_T	14.11517	13.91281	.2023572	2.542444
August5_T	11.78128	11.17315	.6081233	3.791313
August15_T	-9.718869	-8.43466	-1.284209	4.071917
August25_T	-10.87916	-10.90879	.0296269	2.582026

```
                           b = consistent under Ho and Ha; obtained from reg3
            B = inconsistent under Ha, efficient under Ho; obtained from reg3

    Test:  Ho:  difference in coefficients not systematic

                  chi2(13) = (b-B)'[(V_b-V_B)^(-1)](b-B)
                           =        0.63
                Prob>chi2 =      1.0000
```

The Hausman test statistic is 0.63, and the significance level is 1.00. It is clearly far from being significant at the 10% level. So, it appears that the coefficients from the two regressions are not significantly different. Hence, endogeneity does not seem to be a problem in this case, based on this specification.

As discussed above, since there is no endogeneity, SUR and OLS can be used to examine the relationships between weather and potatoes yields, weather and pests, and potato yields and aphids taking into account potential cross equation error correlation. The results are provided in **Table 5.3** and **Table 5.4**. **Table 5.3** reports the results using full data which includes original as well as simulated data. **Table 5.4** reports results from analysis of only the original data. In both tables, for each of the five estimated equations, OLS and SUR results are presented.

Table 5. 3 Regression result for all equations by full data

	Yield		**PEAKBLH_B**		**PEAKGPA_G**		**Variance_BLH**		**Variance_GPA**	
	SUR	OLS	SUR	OLS	SUR	OLS	SUR	OLS	SUR	OLS
Yield_1	9.9305**	10.5329*								
	(3.9869)	(5.9490)								
Yield_1_2	-0.071**	-0.0076								
	(0.0031)	(0.0046)								
Acreage	0.0003	0.0001	0.0003*							
	(0.0011)	(0.0016)	(0.0001)							
PEAKBLH_B	-9.2611***	-7.8436*								
	(3.007)	(4.4879)								
PEAKGPA_G	0.7714*	0.6520								
	(0.4624)	(0.6989)								
Variance_BLH	1.0623***	0.9018*								
	(0.3351)	(0.582)								
Variance_GPA	-0.0624**	-0.0573								
	(0.0265)	(0.0495)								
PEAKAD_B			-0.0053***	-0.0087***						
			(0.0014)	(0.0027)						
PEAKAD_G					-0.006***	-0.0133**				
					(0.0031)	(0.0059)				
June5_P			16.9383***	19.4620***	97.4814***	98.4117***			2003.9890***	1841.9600***
			(3.7202)	(6.2661)	(13.9647)	(20.9804)			(207.4050)	(330.6842)
June15_P					-201.0927***	-204.3642***			-2701.4300***	-2854.7120***
					(35.6528)	(55.4595)			(442.9268)	(673.2989)
June25_P			16.8680***	15.0492*	110.1918***	105.6494***	132.1619***	152.4082**	2005.1530***	2126.4860***
			(5.9509)	(8.2555)	(24.7164)	(38.6496)	(50.2196)	(75.8722)	(307.7333)	(470.1383)
July5_P			34.0169***	34.1243*	-208.8309***	-208.2219**	366.6451***	392.3296**	-3165.2750***	-3463.5980***
			(12.0270)	(17.9086)	(35.8041)	(54.7071)	(113.5866)	(169.0751)	(476.2941)	(740.3681)

July15_P			-30.3230***	-29.3384***	-119.8423***	-119.9803**	-177.4672***	-173.4494*	-2500.0990***	-2967.1210***
			(6.8442)	(10.5695)	(30.2635)	(45.9210)	(58.7115)	(88.3861)	(437.6023)	(698.8596)
July25_P					-108.1552***	-120.9113**				
					(27.6283)	(50.5517)				
August5_P			69.9987***	70.2085***	-240.1688***	-244.9603**			-3680.4290***	-3370.3200**
			(16.1001)	(26.5222)	(72.4229)	(110.4101)			(920.4615)	(1384.9420)
August15_P			28.8694***	26.2714*	-114.6780***	-109.6416***	250.0777***	240.6079**	-1496.3940***	-1210.3640*
			(8.0173)	(11.9782)	(30.9287)	(47.4584)	(71.6299)	(104.3569)	(404.8501)	(616.8984)
August25_P			-61.8390***	-53.1460*	-531.0728***	-537.8907**	-633.1992***	-658.7969***	-8568.4840***	-9357.9400***
			(16.1868)	(25.5806)	(63.3351)	(94.4138)	(135.8442)	(205.5976)	(910.6520)	(1432.4360)
June5_T			4.2640***	4.3049**			21.3128***	20.9571***		
			(0.6531)	(0.9310)			(4.9711)	(7.3140)		
June15_T	-8.0964***	-7.9752**							76.7620***	78.6794**
	(2.5765)	(3.8158)							(16.3098)	(30.0893)
June25_T	8.1336***	7.8309**			5.4154***	5.2034**	12.4356***	15.2460***	79.9267***	76.1301***
	(2.989)	(3.4034)			(1.6448)	(2.5249)	(2.9821)	(4.6886)	(22.2599)	(34.4223)
July5_T	-7.853***	-7.5751**	-3.54311***			-2.9712**	-24.0945***	-25.4494***		
	(2.4693)	(3.6679)	(0.7930)			(1.1396)	(6.3514)	(9.59)		
July15_T					-4.8525***		-15.4986***	-17.7327***	-86.0120***	-100.2485***
					(1.6770)		(3.3515)	(5.5810)	(22.7390)	(34.5169)
July25_T	15.00***	14.1212**	-1.0580**		9.1756***	-1.300***	10.4469***	11.7158**	84.6277***	90.8890**
	(2.8868)	(4.2834)	(0.4562)		(1.7126)	(0.6636)	(3.1514)	(4.7843)	(24.2456)	(37.5463)
August5_T	11.8259***	11.7888***	4.5806***	4.2598***			18.1188***	17.9033**		
	(3.6398)	(5.4158)	(0.7645)	(1.1280)			(5.8482)	(8.3632)		
August15_T	-10.1821**	-7.1791**					21.8454***	21.6744**	66.2854**	144.1596***
	(4.689)	(6.800)					(6.0927)	(10.3975)	(31.7737)	(62.1855)
August25_T	-11.514***	-10.8890***	-1.7294***	-1.9494*	-16.6080***	-17.17*23**	-18.8996***	-21.2744***	-144.5589***	-148.8100**
	(2.5514)	(3.7680)	(0.5497)	(0.8051)	(2.1426)	(3.2836)	(5.0525)	(7.4095)	(28.2610)	(43.3675)
_cons	-2750.2800**	-2928.78	-125.4075	-112.1079	516.4225***	569.5523**	-1696.8970***	-1520.8540	-5071.1767***	-9555.6050***

	(1284.0210)	(1910.2411)	(78.6217)	(116.7360)	(172.9934)	(270.7705)	(720.9726)	(1077.8220)	(2827.6923)	(4851.1210)
R^2	0.703***	0.7098**	0.7692***	0.7772***	0.8677***	0.8692***	0.7668***	0.7736***	0.9072***	0.9182***

Notes: Numbers in parentheses are standard errors. Single, double, and triple asterisks (, **, ***) represent significance at the 10%, 5% and 1% level. Bold variables exhibit statically significant patterns illustrated in the analytical model.*

1. Coefficient estimates across the two estimation methods (OLS and SUR) are quite similar in **Table 5. 3** and in **Table 5. 4** when coefficients are significant. For example, in the yield equation, for the full data in **Table 5.3**, the value of coefficient for August15_T is -10.18 in SUR, and -7.17 in OLS. For the original data in **Table 5. 4**, the value of coefficient for Augut15_T is 12.61 in SUR model and 16.83 in OLS. However, some coefficients are significant in the SUR while not significant in OLS. For instance, in **Table 5. 3,** the coefficients for August15_P and August25_P are significant in SUR but not in OLS. Therefore, the rest of the discussion is based on the results by SUR using full data.
2. Note that precipitation is not in the yield equation. This variable was found to be statistically insignificant in all trials and was removed from the list of independent variables for this equation. The Columbia Basin Irrigation Projects provide water to irrigate. Therefore natural precipitation does not play an important role in potato yield.
3. Potato yield is affected by previous yields. The results show that current yield is a quadratic function of yield in the last year. The quadratic coefficient is -0.0071, and the linear coefficient is 9.9304, the peak of yield is:

$$-\frac{\beta}{2\alpha} = 699.: \qquad (5.1)$$

This implies that, all else constant, the yield reaches peak at 699.32 unit cwt per acre considering it is the function of the previous yield.

Taking a derivative with respect to yield in the previous year:

$$\frac{\partial Yield_t}{\partial Yield_{t-1}} = 2\alpha \times Yield_{t-1} + \beta \qquad (5.2)$$

$Yield_t$ is the yield in the year t and $Yield_{t-1}$ is potato yield in the year $t-1$. α represents the quadratic coefficient and β represents linear coefficient in the quadratic equation. According to the regression result (**Table 5.3**), $\alpha = -0.0071$ and $\beta = 9.9304$. Since the average of yield over seven years is 619.11 cwt/acre (**Table 3.6**),

$$2\alpha \times Yield_{t-1} + \beta = 1.14 \qquad (5.3)$$

In other words, the yield increase in 1 cwt/acre in one year will increase yield in the next year by 1.14 cwt/acre, given that current average yield is 619.11 cwt/acre.

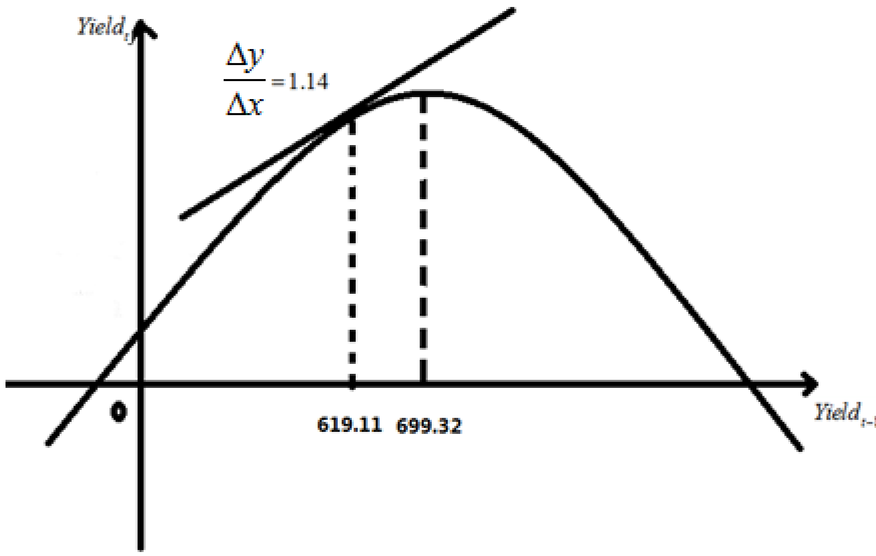


Figure 5. 1 The yield function

4. The coefficient for acreage in the yield equation is not significant. **Figure 5. 2** shows that variance of acreage is small, which may explain why acreage variables are statistically insignificant.

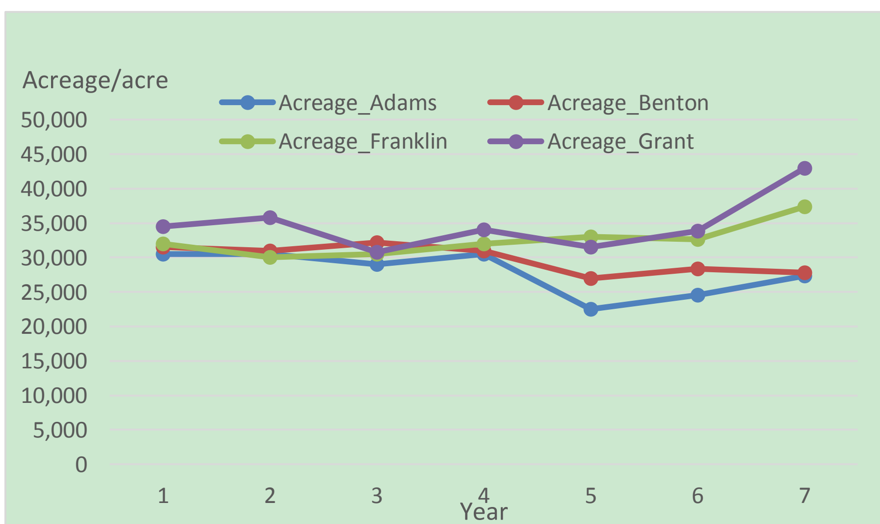


Figure 5. 2 Changes in acreage in four counties over seven years

5. In the yield equation for full data (**Table 5. 3**), the value of the coefficient for peak of BLH

is -9.26 and is statistically significant at the 1% level. It suggests that if the value of peak of BLH increases by 1/trap, the potato yield will decrease by 9.26 cwt/acre. On the other hand, the value of coefficient for peak of GPA is 0.77, and is not statistically significant.

6. The value of the coefficient for variance of BLH is 1.06 and is statistically significant at the level of 1%. When the variance increases by 1 unit, the potato yield increases by 1.06 cwt/acre. In other words, the more the amount of BLH fluctuates, the greater the yield.
7. The value of the coefficient for variance of GPA is -0.06 and is statistically significant at the level of 5%. This relationship may be due to pesticide application strategy. During GPA outbreaks the use of pesticides may be contributing to greater swings in GPA population. GPA outbreaks may also be negatively correlated with yields (although not confirmed in this study perhaps due to pesticide use or low levels of PLRV infected GPA). Therefore, the results may show negative correlation between variance of GPA population and yield.
8. In the yield equation, the coefficient for the average temperature from June, 15^{th} to June, 24^{th} is 8.086. When temperature increases by 1F, the potato yield increases by 8.086 cwt/acre. The coefficient for average temperature from Aug, 15^{th} to Aug, 24^{th} is -10.18, If temperature increases by 1F, the potato yield decreases by 10.18 cwt/acre.
9. In the PeakBLH_B equation (**Table 5. 3**), the coefficient for acreage is 0.0003. The coefficient is statistically significant at the level of 10%. When acreage increases by 1 acre, the peak of BLH increases by 0.0003. In all other equations, the coefficient for acreage is not significant. In the yield equation, the coefficient for acreage is not significant, showing that acreage has no direct influence on potato yield. However, it appear to have indirect influence on potato yield from PeakBLH_B equation.
10. In two peak equations, accumulated degree days at the peak populations has negative impact on the peak. The higher the temperature, the lower the peak of pest populations. Coefficients from SUR and OLS are around -0.01 and -0.02, respectively and are

significant at the level of 5%. SUR estimation produces more statistically significant variables than OLS estimation. This is true for the full data regression as well as the original data regression.

Table 5. 4 Regression result for all equations by original data

	Yield		**PEAKBLH_B**		**PEAKGPA_G**		**Variance_BLH**		**Variance_GPA**	
	SUR	OLS	SUR	OLS	SUR	OLS	SUR	OLS	SUR	OLS
Yield_1	23.2536***	31.1517***								
	(5.3545)	(10.1577)								
Yield_1_2	-0.0283***	-0.0244***								
	(0.0042)	(0.0008)								
Acreage	0.0002	0.0008								
	(0.0012)	(0.0022)								
PEAKBLH_B	4.3159*	7.6530								
	(2.2941)	(4.8802)								
PEAKGPA_G	0.8587*	1.3922								
	(0.4358)	(0.8595)								
Variance_BLH	-0.5306*	-0.9638								
	(0.2940)	(0.5953)								
Variance_GPA	-0.0612***	-0.0844*								
	(0.0225)	(0.0432)								
PEAKAD_B			-0.0132***	-0.0181***						
			(0.0023)	(0.0051)						
PEAKAD_G					-0.0207***	-0.0261***				
					(0.0025)	(0.0081)				
June5_P			24.2064***	22.5805**	96.3181***	85.5549**			2729.2490***	2505.3410
			(3.9777)	(9.4433)	(13.2531)	(35.0171)			(146.4163)	(350.1548)
June15_P					-424.7738***	-518.9128***			-464.3090***	
					(50.5502)	(154.4044)			(138.8923)	
June25_P					293.474686***	367.9244***	-131.1065***	-127.8067***		
					(42.3324)	(127.6811)	(20.8674)	(35.4103)		

July5_P			42.1413***	68.3379***	-229.1135***	-244.8250***	581.3299***	603.3693***	-5158.5640***	-6381.3380
			(9.5481)	(24.4007)	(26.2896)	(68.4299)	(66.6455)	(114.3920)	(440.7747)	(951.5610)
July15_P			-77.6037***	-54.594**			-152.1360***	-144.5867**	-2960.3900***	-2320.00
			(9.0122)	(22.0492)			(35.2217)	(59.6019)	(337.4186)	(770.7185)
July25_P					-432.4847***	-464.1525***				
					(50.9403)	(134.4598)				
August5_P			141.1509***	137.7652***	-340.8111***	-315.0154***			-5816.0550***	-7094.5740
			(17.8681)	(46.7262)	(37.2004)	(106.2122)			(560.7594)	(1315.1550)
August15_P			27.9867***		-133.3019***	-133.2715**			-868.6553***	
			(8.0114)		(19.4117)	(50.3963)			(311.75469)	
August25_P			-72.6161***		-651.0538***	-676.8208***	-480.2721***	-469.4504***	-11796.9200***	-12620.7300
			(13.5020)		(38.0834)	(100.5603)	(59.9936)	(101.9298)	(583.8210)	(1195.2880)
June5_T			4.8162***	4.1030***			14.2621***	15.2900***	58.0952***	
			(0.3976)	(0.9742)			(1.9712)	(3.5329)	(14.5186)	
June15_T										
June25_T					7.1255***	7.2909**	17.5052***	17.4896***		
					(1.32883)	(3.4873)	(2.0767)	(3.5282)		
July5_T			-1.7944***							
			(0.5859)							
July15_T	-2.0358	-4.5821			-7.4763***	-8.7106***	-17.2124***	-16.7765***	-54.7182***	-72.2541
	(1.8003)	(3.1651)			(1.1328)	(3.1090)	(1.9439)	(3.308)	(11.6361)	(25.4997)
July25_T			-1.6743***	-2.4628***	13.2285***	13.7711***	9.9930***	9.5526***	112.2101***	165.0402
			(0.3453)	(0.8232)	(0.9889)	(2.5437)	(1.8452)	(3.1357)	(15.1837)	(26.9240)
August5_T			4.8925***	2.4822*			12.2426***	11.5514**		
			(0.5859)	(1.2598)			(2.8648)	(4.9730)		
August15_T	12.6051***	16.8279**							203.5695***	263.7917

	(4.1330)	(7.6017)							(27.2248)	(60.6934)
August25_T			-4.3938***	-4.751***	-21.6688***	-22.9331***	-33.3966***	-34.366***	-120.5556***	-112.7837
			(0.5651)	(1.5493)	(1.4978)	(3.7992)	(3.3553)	(5.7874)	(16.3517)	(32.7977)
_cons	-7512.9730***	-10260.0700***	-69.3199	116.8739	679.5141***	831.0289***	-156.9848	-98.0222	-13967.5757***	-17552.5300
	(1840.4860)	(3570.1720)	(64.3446)	(154.8813)	(104.4657)	(282.6609)	(341.0115)	(588.2224)	(2102.1040)	(4377.5250)
R^2	0.6555***	0.6988***	0.9211***	0.8031	0.9730***	0.9776***	0.9642***	0.9636***	0.9811***	0.9660***

Notes: Numbers in parentheses are standard errors. Single, double, and triple asterisks (, **, ***) represent significance at the 10%, 5% and 1% level.*

Bold variables exhibit statically significant patterns illustrated in the analytical model.

Chapter 6: Concluding Remarks

This study is the first of its kind to simultaneously examine the effects of BLH and GPA on potato yields. Furthermore, the study explicitly considers possible endogeneity of both pest populations in the system of equations. The results show that yield in the current period is a quadratic function of yield in the preceding year. When the yield increases by 1cwt/acre, the yield next year should increase by 1.14 cwt/acre given that current yield is 619 cwt per acre. The coefficient for acreage is not statistically significant in the yield equation. Hence, acreage does not have a direct influence on the average potato yield. However, acreage appears to have an indirect effect on yield via BLH. Greater acreage increases BLH population. In turn, higher BLH population decreases yields, based on the sign and statistical significance of corresponding coefficients in the yield equation. The peak of BLH increase by 1/trap corresponds to a decrease in potato yield by 9.26 cwt/acre. This result suggests that potato producers should treat BLH as a pest with significant implications for production.

The coefficient for the peak of GPA population is not significant. For BLH and GPA, weather coefficients do not show obvious common characters, and no regular pattern about the direction of the effect of weather variable can be detected. Regression results from SUR and OLS show that SUR is a more suitable method to estimate the system of equations.

There are several limitations that should be taken into account. The primary limitation of this research is poor data availability. First, there are several missing observations for pest populations, as well as in yield and acreage. This required the use of simulated data. The results using original data, as well as data including simulated missing observations, are reported. Second, data on pesticide use is not available. Therefore, estimated coefficients correspond to pesticide-use-adjusted pest populations and yields. Lack of ability to control for the influence of pesticide use precludes us from estimating the effect of pests (BLH and GPA) on yields without pesticide use. It is also not possible to estimate how weather variables affect pest populations when pesticides are not used. Third, the data do not include information about phytoplasma and virus vectored by BLH and GPA. As a result, nothing can be said about whether the estimated coefficients for the yield equation correspond to pests directly or viruses and phytoplasma vectored by the pests. Some researchers have studied vector-virus-yield systems (Thomas, et al., 2000, Elbakidze et al., 2011). Fourth, the possible presence of other pests was not considered because no such data are available for these plots. Fifth, the quality of the potatoes was not considered as a variable in this study. In practice, pests like GPA affect not only the amount of output but also quality. This can have a significant impact on industry profits. Unfortunately, data on quality distribution of total production are not available.

Future research should address the limitations of this study subject to data availability. The negative effect of BLH on yields, as detected in this study, merits further examination to design appropriate prevention and response strategies for mitigating the negative effect of BLH in potato production.

References

Alvarez, J. M., Stoltz, R. L., Baird, C. R., Sandvol, L. E., “Potato insects and their management.” *Potato production systems*, 12 (2003): 204-239.

Anderson, B., Lawson, W., Owens, I., "Response of Franz Jos*ef* Glacier Ka Roimata o Hine Hukatere to climate change." *Global and Planetary Change*, 63.1 (2008): 23-30.

Archer, M. S., “Annual variation in arrival and departure times of carrion insects at carcasses: implications for succession studies in forensic entomology.” *Australian Journal of Zoology*, 51.6 (2004): 569-576.

Babcock, B. A., Lichtenberg E., Zilberman D., “Impact of Damage Control and Quality of Output: Estimating Pest Control Effectiveness.” *American Journal of Agricultural Economics*, 74 (1992): 163-172.

Beasley, T. M., "Seemingly unrelated regression (SUR) models as a solution to path analytic models with correlated errors." *Multiple linear regression viewpoints*, 34.1 (2008): 1-7.

Bhagat, S., Brian B., "Corporate governance and firm performance." *Journal of Corporate Finance*, 14.3 (2008): 257-273.

Blackwell, M., Pagoulatos A., “The Econometrics of Damage Control.” *American Journal of Agricultural Economics*, 74 (1992): 1040-44.

Cameron, A. C., & Trivedi, P. K. *Microeconometrics: methods and applications*. Cambridge university press, 2005.

Carpentier, A., Weaver R. D., “Damage, Control Productivity: Why Econometrics Matters.” *American Journal of Agricultural Economics*, 79 (1997): 47–61.

Crosslin, J. M., Munyaneza, J. E., Jensen, A., Hamm, P. B. "Association of beet leafhopper (Hemiptera: Cicadellidae) with a clover proliferation group phytoplasma in Columbia Basin of Washington and Oregon." *Journal of Economic Entomology*, 98.2 (2005): 279-283.

Elbakidze, L., Lu, L., Eigenbrode, S., "Evaluating vector-virus-yield interactions for peas and lentils under climatic variability: a limited dependent variable analysis." *Journal of Agricultural and Resource Economics*, 36.3 (2011): 504-520.

Fox, G., Weersink A., "Damage Control and Increasing Returns." *American Journal of Agricultural Economics*, 77 (1995): 33–39.

Goolsby, J. A., Bextine, B., Munyaneza, J. E., Setamou, M., Adamczyk, J., Bester, G. "Seasonal abundance of sharpshooters, leafhoppers, and psyllids associated with potatoes affected by zebra chip disorder." *Subtropical Plant Science*, 59 (2007): 15-23.

Green, W.H., "Econometric Analysis (7 th)." Upper Saddle River, NJ: Prentice Hall, 2007.

Jayasinghe, U., "Potato leaf roll virus." *Technical Information Bulletin*, 22 (1988).

Koss, A. M., Chang, G. C., Snyder, W. E., "Predation of green peach aphids by generalist predators in the presence of alternative, Colorado potato beetle egg prey." *Biological control*, 31.2 (2004): 237-244.

Kuosmanen, T., Pemsl, D., Wesseler, J., "Spefication and Estimation of Production Functions Involving Damage Control Inputs: A Two-Stage, Semiparametric Approach." *American Journal of Agricultural Economics*, 88 (2006): 499-511.

Lagnaoui, A., Radcliffe, E. B. "Potato fungicides interfere with entomopathogenic fungi impacting population dynamics of green peach aphid." *American Journal of Potato Research*, 75.1 (1998): 19-25.

Lichtenberg, E., Zilberman, D. “The Econometrics of Damage Control: Why Specification Matters.” *American Journal of Agricultural Economics*, 68 (1986): 261–273.

Marsh, T. L., Huffaker, R. G., Long, G. E., “Long Optimal Control of Vector-Virus-Plant Interactions: The Case of Potato Leafroll Virus Net Necrosis” *American Journal of Agricultural Economics*, 82 (2000): 556-569

Mowry, T. M., "Green peach aphid (Homoptera: Aphididae) action thresholds for controlling the spread of potato leafroll virus in Idaho." *Journal of Economic Entomology*, 94.6 (2001): 1332-1339.

Munyaneza, J. E., Upton, J. E., "Beet leafhopper (Hemiptera: Cicadellidae) settling behavior, survival, and reproduction on selected host plants." *Journal of Economic Entomology*, 98.6 (2005): 1824-1830.

Munyaneza, J. E., Crosslin, J. M., Jensen A. S., Hamm P.B., Thomas P.E., Pappu H.R., Schreiber, A., “Update on the potato purple top disease in the Columbia Basin.” In: Proceedings, *44th Annual Washington State Potato Conference,* 1-3 February 2005, Moses Lake, WA.

Munyaneza, J. E., Crosslin, J. M., Upton J. E., "Beet leafhopper (Hemiptera: Cicadellidae) transmits the Columbia Basin potato purple top phytoplasma to potatoes, beets, and weeds." *Journal of Economic Entomology,* 99.2 (2006): 268-272.

Munyaneza, J. E., Crosslin, J. M., Lee, I., "Phytoplasma diseases and insect vectors in potatoes of the Pacific Northwest of the United States." *Bulletin of Insectology*, 60.2 (2007): 181.

Munyaneza, J. E., Jensen, A. S., Hamm, P. B., Upton, J. E. "Seasonal occurrence and abundance of beet leafhopper in the potato growing region of Washington and Oregon Columbia Basin and Yakima Valley." *American Journal of Potato Research,* 85.1 (2008): 77-84.

Munyaneza, J. E., Crosslin, J. M., Upton, J. E., Buchman, J. L., "Incidence of the beet leafhopper-transmitted virescence agent phytoplasma in local populations of the beet leafhopper, Circulifer tenellus, in Washington State." *Journal of insect science*, 10 (2010).

Murphy, A. F., Rondon, S. I., Jensen, A. S., "Population dynamics of the beet leafhopper (Hemiptera: Cicadellidae) in the Columbia Basin as influenced by abiotic variables." *Environmental Entomology*, 41.4 (2012): 768-775.

Ro, T. H., Long, G. E., "GPA-Phenodynamics, a simulation model for the population dynamics and phenology of green peach aphid in potato: formulation, validation, and analysis." *Ecological modelling*, 119.2 (1999): 197-209.

Saha, A., Shumway, C. R., Havenner, A., "The Economics and Econometrics of Damage Control." *American Journal of Agricultural Economics*, 79 (1997):773–785.

Schreiber, A., Jensen, A., Pike, K., Alvarez, J., & Rondon, S. I., "Integrated Pest Management guidelines for insects and mites in Idaho." *Oregon, and Washington Potatoes*. (2010).

Simar, L., Wilson P., "Estimation and Inference in Two-Stage, Semi-Parametric Models of Production Processes." *Journal of Econometrics*, 136 (2007): 31–64.

STATA, http://www.stata.com/manuals13/rhausman.pdf, 07/25/2014

Teulon, D. A. J., Stufkens, M. A. W., "Lack of relationship between aphid virus vector activity and potato leaf roll virus incidence." *Proceeding of the New Zealand Plant Protection Conference*. 2001.

Washington State Potato Commission (WSPC), History of Potatoes, http://www.potatoes.com/our-industry/history/, Last accessed 07/29/2014

Whalon, M. E., Smilowitz, Z., "Temperature-dependent model for predicting field populations of green peach aphid, Myzus persicae (Homoptera: Aphididae)." *The Canadian Entomologist*, 111.09 (1979): 1025-1032.

White, H., “Instrumental variables regression with independent observations.” *Econometrica: Journal of the Econometric Society*, (1982): 483-499.

Wohleb, C. H., Jensen W., Waters T., "Sampling network for potato insect pests in the Columbia Basin of Washington." *Poster presented at the Washington State University Academic Showcase*, Pullman, WA (2010).

Wohleb C. H., Jensen A., Waters T., “Regional Survey for Insect Pests of Potato in the Columbia Basin of Washington.” 2011. http://potatoes.wsu.edu/survey/2011/Wohleb_2011_WSPC%20Annual%20Report_Potato%20Insect%20Pest%20Survey%20(2).pdf

Wohleb C. H., Jensen A., Waters T., “Regional Survey for Insect Pests of Potato in the Columbia Basin of Washington.” *Annual Progress Report*, 2012. http://potatoes.wsu.edu/survey/2012/Wohleb_2012_WSPC%20Annual%20Report_Potato%20Insect%20Pest%20Survey.pdf

Wooldridge, J., Econometric Analysis of Cross Sectional and Panel Data, MIT Press, Cambridge, Massachusetts, 2002.

Wossink, G. A. A., Rossing, W. A. H., “On Increasing Returns and Discrete Choice: Integrating Production Ecological Principles in Economic Analysis of Crop Management.” *Journal of Environmental Management*, 54 (19 98):233–247