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RELATIONSHIPS BETWEEN
SELECTED BIOLOGICAL AND MANAGEMENT ATTRIBUTES
OF MICHIGAN POTATO PRODUCTION SYSTEMS

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Rebecca L. Gore

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George W. Bird
Major professor

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RELATIONSHIPS BETWEEN SELECTED BIOLOGICAL AND MANAGEMENT ATTRIBUTES OF MICHIGAN POTATO PRODUCTION SYSTEMS

By

Rebecca L. Gore

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ABSTRACT

RELATIONSHIPS BETWEEN SELECTED BIOLOGICAL AND MANAGEMENT ATTRIBUTES OF MICHIGAN POTATO PRODUCTION SYSTEMS

By

Rebecca L. Gore

Potato early die is an important economic disease of potato in Michigan. Many management decisions impact symptom expression for this disease complex. This study consists of two components. One part involved a survey that generated a series of multiple regression models that demonstrated the relationships between certain management strategies and expected potato yields. It was found that first dividing the state into regions and management systems into rotation, irrigation and chemigation parameters explained more of the variability in expected yields (r^2=0.7986) than any other model tested (other models were based on farm size, nematicide usage and rotation scheme). The objective of the second component was to distinquish responses to potato early die pathogens (Pratylenchus penetrans and Verticillium dahliae) among ten different potato cultivars (Red dale, Kennebec, Superior, Russet burbank, Norkota russett, Hudson, Desiree, Rosa, Snowden and Atlantic). Several types of analyses were used in the study including ANOVA, linear regression, rankings and relative yields. Summarizing the data, it was found that Hudson, Russet burbank, Snowden and Superior were most susceptible to potato early die, while Atlantic, Norkota russet and Desiree were most resistant.

DEDICATION

With deepest admiration and respect

I would like to dedicate

my thesis

to my mentor and teacher

Dr. George W. Bird

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I want to express my sincere gratitude to all of the members of my guidance committee. Before I began my study in Nematology I listened to Jim Miller give a talk at a regional entomology meeting about ethics in science, and it was for that reason I wanted him on my graduate guidance committee and now is the time to thank him for his earlier advice and his contribution to my graduate study.

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LITERATURE REVIEW

INTRODUCTION

The potato early-die disease complex is an important aspect of potato production in many geographical locations. Understanding the nature of this disease complex is essential for development of future management strategies and tactics, and a thorough understanding of the potato plant and the production system is requisite to understanding the disease complex. The literature review, therefore, is divided into sections on the potato production system and the potato early-die causal components.

THE POTATO SYSTEM

Introduction

In 1980, it was estimated that potatoes were cultivated on 18,026,000 ha, yielding 225,676,000 tons of food and feed. Approximately 40% of the production was used for human consumption and 31% for livestock (Burton 1989). The most common cultivated potato in the United States is classified in the plant family Solanaceae as Solanum tuberosum (Hooker 1990). Propagation can be either from true seed or tubers with tubers being the most common in the U.S. (Burton 1989).

The potato plant is a herbaceous dicot, with a C_3 pathway (Dwelle 1985). It is composed of flowers, fruit, leaves, above-ground stems, below-ground stems, stolons, four types of roots (basal, nodal, stolon and tuber) and tubers. If the potato is grown from seed it has a primary tap root, hypocotyl, cotyledons, and epicotyle (Hooker 1990). Potatoes grown from tubers have adventitious root systems.

The Origin of the Potato

Tom Dillehay, an anthropologist at the University of Kentucky, discovered peelings from cultivated potatoes in a swamp in Chile. He had them carbon-dated and found that they were 10,000 years old (Hughes 1991). It is believed the potato originated near Peru, and was an important source of food for the Incas. In the early 1570s, Spanish explorers brought the potato plant to Spain to use as food for prisoners and slaves. From Spain it was transported to Italy. Europeans, at this time, considered the plant more of a curiosity than a food. Gradually, during the 17th Century, the potato plant spread to China, Japan, Africa, India and Southeast Asia. New Zealand obtained it in the 1700s. The first records of the potato in the U.S. indicated that it came with John Smith in 1620 (Salaman 1989). The most tragic demonstration of its growing dominance was, of course, the Irish Potato Famine of 1845 caused by Phytophythora infestans (late blight) (Salaman 1989).

Morphology, Growth and Development of the Potato Plant

The above ground potato plant consists of stems, leaves, flowers and fruit. The below ground part of the plant consists of roots, stolons, and tubers. Each part of the plant has specific functions as well as functions connecting it to whole-plant processes.

Flowering and Fruit Set. The flowering and fruit set include the structure of the flower, the development of the flower, plant growth regulators and external factors.

<u>Structure</u>. The potato flower can be white, yellow, purple or blue. It is complete, having sepals, petals, stamens and carpels (Hayward 1938). The pollen is wind-borne. Self-fertilization is the norm (Hayward 1938).

<u>Development</u>. Development begins with primordia aligned to the stem that looks like a dome-shaped enlargement. From this, the pedicel of the flower is formed which is composed of primarily vascular tissue. The strands divide into five parts to form the sepals, then five petals are formed, then the corolla, stamen, and carpels. Finally, the vascular bundles form the ovaries.

<u>Plant growth regulators</u>. It is hypothesized that gibberellins are responsible for initiating the flowering process in the potato species *Solanum andigena* (Burton 1989).

<u>External factors</u>. It is believed that flowering is also induced by a number of factors including: light, temperature, water supply, humidity, nutrition, and seed tuber condition. These factors vary from cultivar to cultivar. Burton (1989) showed that the same variety can respond to light differently if environmental conditions are changed. He concludes that most species will flower at 15-16 hours of light, which is the typical schedule used by plant breeders (Burton 1989).

<u>Fruit and Seed</u>. The fruit is brown or purplish-green, measuring about one-half inch in diameter, and containing 200 to 300 seeds (Haywood 1938). The seeds are yellowish brown, small, flat and oval or kidney-shaped. The fruit contains a single, massive integument and a long micropyle. The mature integument has three layers: an external layer of epidermal cells, and intermediate zone, and a digestive zone covering the endosperm (Haywood 1938). This digestive layer disappears as the seed mature (Haywood 1938).

Leaf Canopy. The leaf canopy includes the structure of the leaf, its development, and the growth process.

Leaf Structure. Potato leaves are arranged spirally, usually counter-clockwise in orientation, with the petiole ensheathed about one-third of the circumference of the stem at the node (Haywood 1938). The first leaves of a plant originating from seed are simple with later leaves compound (Haywood 1938). The leaflets are typical dicots, with netted venation. Young leaflets are densely pubescent. Leaves originating from seed pieces, can also begin with simple leaves, but many of these plants begin with complex leaves (Haywood 1938).

Leaf Development. Leaves develop at nodes on the stem. The primordia first appear as small leaf buttresses but rapidly change in appearance to a small stalk with a visible blade. The terminal leaflet develops much faster than lateral leaves. Leaf hairs appear dense when the leaf is small, but decrease in density when the leaf enlarges. The number of hairs remain the same; however, since the leaf is increasing in size it is much less dense.

Each leaflet is composed of epidermis (outer edge), the mesophyll, with two types of parenchyma cells, the palisade (just below the epidermis), with the spongy parenchyma beneath it. Chloroplasts are contained in the palisade region (Haywood 1938). As the leaf primordia matures, small groups of procambial cells are formed, these become protoxylem. Then the phloem is differentiated (Haywood 1938).

Development Process. Leaf growth occurs primarily at night, and is negatively correlated to water potential. In fact, the rate of leaf growth stops when the water potential of the plant is greater than -5 bars (Gander and Tanner 1976). Gander and

Tanner (1976) also showed that leaf area never recovers from water shortages, even if only one irrigation period is missed. Total leaf area in a treatment that missed one irrigation period was reduced to as much as 60% of the controlled, unstressed plant.

Root System. The root system includes its structure, both primary and lateral root systems, and adventitious roots.

The structure. There are two types of root systems in potato plants, depending on the origin of the plant. Plants grown from seeds have one taproot and a well developed lateral root system; whereas, plants grown from seed pieces have adventitious roots arising from young sprouts developing from buds of the seed piece. The root system is fairly shallow, if water is plentiful. It tends to go deeper when water is more scarce. The majority of the roots have diameters less than 0.2 mm (64%) (Lesczynski and Tanner 1976). Burton (1989) calculated that the surface area of the root system should be approximately five times the leaf area. Along with water, the roots take up the minerals needed for essential plant functions. These include sulfur, phosphorus, magnesium, calcium, potassium, and nitrogen.

Primary and lateral root system. The vascular system of the potato is protostele in arrangement. The inner most part of the root is the primary xylem, followed by parenchyma, where the cambium is later found, then phloem, pericycle, endodermis with Casparian strips, the cortex and epidermis (Hayward 1938). Later roots appear quickly, originating from pericycle cells, rupturing the endodermis.

Adventitious roots. Adventitious roots develop from the pericycle cells of the stele in close proximity to a nodal plate, generally in groups of three (Haywood 1938). The root growth is similar to that of a primary root, except they are not diarch, but sometimes have three or more separate regions of growth. Artschwager suggested that enzymes secreted by the endodermis help the rootlet push through the cortex (Haywood).

The adventitious roots have secondary growth, although it is not as quick to occur as it is in primary roots. Scondary xylem contains fibers and parenchyma. Secondary phloem consists of sieve tubes, companion cells and parenchyma. The primary phloem is crushed in the growth process (Haywood 1938). The cortex increases in size by cell enlargement of parenchyma. Often the epidermis and cortex break away in the final stages of development, leaving the endodermis exposed.

Potato Stem. The potato plant has both above-ground and below-ground stems called rhizomes or stolons. Many researchers have shown that above-ground stems can produce stolons, and stolons can exhibit apical dominance under the correct environmental conditions or when induced by a plant growth regulator.

Above-ground stem development. The first differentiation of the apical meristem is with cells that form the epidermis and the procambial ring that separates the pith from the cortex. This ring eventually becomes the stele, in the mature stem. In the vascular region, the protoxylem cells differentiate, then the inner phloem and outer phloem. While this is occurring, the epidermis is also developing a cuticle and guard cells. Between the vascular region and the epidermis is the cortex, with an outer layer of collenchyma cells, an inner layer of parenchyma cells, and bordered by the endodermis which has distinct Casparian strips. Pericyclic fibers are just inside the endodermis, and also within the vascular bundles (Haywood 1938).

As the stem matures, the six vascular bundles change in size, with three larger and three smaller, which gives the stem a triangular or rectangular appearance. The bundles appear cylindrical because of the development of the interfascicular cambium.

Stolon development. The stolon develops very much like aerial lateral stems, with the following exceptions. Externally, they have a hooked tip, scaled leaves, and grow diageotropically (Booth 1963). Internally, the cells of the epidermis are single-layered, the cortex has less collenchyma cells than the stem, and there is proportionately more phloem than xylem in the stolon (Haywood 1938). In the region where tuberizaiton occurs, the endodermis with its accompanying Casparian strips is extremely pronounced.

Role of plant growth regulators in stolon development. Kumar and Wareing (1971) have shown that any lateral bud can become either a leafy shoot or stolon depending on the presence or absence of three growth regulators; auxin, gibberellin and cytokinins. They elaborated on earlier experiments by Booth (1963), where he cut off the tops of plants and found stolons grew upward without an application of IAA, and remained lateral, when IAA was applied to the cut surface in an effort to maintain apical dominance. Kumar and Wareing found this was also true when a stem cutting was used instead of a whole plant. In addition, they manipulated stolons that were already developed, by cutting off the plant tops. They found that stolons exhibited apical dominance when the top was cut off, but were unable to grow green leaves without the addition of a kinetin in the presence of light.

In an effort to understand why typical potato plants develop leafy aerial laterals at the top of the plant and stolons at the bottom, Kumar and Wareing initiated a group of experiments where they manipulated the three above mentioned growth regulators and concluded it was the presence or absence of these regulators that controlled the emergence of a stolon or leafy shoot. They concluded with the hypothesis that auxins and gibberellins were produced in the above-ground area, and the cytokinins were produced by the roots. The auxins remained at the top, and reacted in the upper buds, giving them apical dominance, while gibberellins flowed to the darker, moister areas beneath the soil. The cytokinins in the roots were attracted to the parts of the plant that exhibited apical dominance, and travelled upward through the stems, leaving the stolons to develop beneath the soil.

Tubers. Tuber development includes tuber initiation and growth, the development process, and the role of growth regulators in the development process.

Initiation and growth. Tubers form first on the stolon closest to the seed piece (Wurr 1977, Plaisted 1958). These tubers also tend to be the largest (Plaisted 1958). Tuber growth is largely due to cell division, Plaisted (1958) estimated that cell numbers increased 500-fold as tubers enlarged, while cells increased in size only 10-fold. Within the tuber, the pith experienced the faster rate of increase as compared to the cortex (Plaisted 1958). It is unusual that cell division continues for such an extended amount of time.

Development. The tuber is morphologically very similar to a thickened stem. The first sign of tuberization is the enlargement of the stolon tip. The first region to grow is the pith, with other regions attempting to adapt. The cortical cells become filled with starch, the endodermis eventually disappears because it cannot form Casparian strips. The cork cambium is active throughout the growth process. With the formation of the periderm, stomata appear. As the tuber develops, buds are differentiated in the axils of small scale leaves, which establish vascular connections to the stele (Haywood 1938).

Role of plant growth regulators in tuber development. Although the exact growth regulator that induces tuber initiation is unknown, it has been demonstrated that it reacts to short-day cues (Chapman 1958). Chapman showed that potato plants would initiate tuberization after a 14-day interval of a 9 hr light regime, if young leaves were present, but would not if the only available leaves were mature. Hence it was concluded that stimuli were present in active above-ground growing points, but could only be induced when daylight dropped to 9 hr (Chapman 1958).

Whole Plant Physiology

Photosynthesis. Dwelle (1985) states that photosynthesis accounts for more than 90% of potato dry weight. The potato has a C_3 photosynthetic pathway. The most important consequence of the C_3 pathway is a net reduction of effective gross assimilation by about 40% because of the competitive oxidase activity of ribulose 1,5-biphosphate carboxylase during photorespiration (Burton 1989).

Factors that influence the rate of CO_2 assimilation include: leaf and canopy structure, leaf area, chlorophyll content, tuber growth rates (translocation), growth regulators and cultivar differences. Environmental factors such as light and temperature are also key (Dwelle 1985).

In general, light interception increases linearly with the canopy leaf area index (LAI), until LAI reaches about 2.5, then the rate decreases until an LAI of 4.0, at which time about 95% of light is intercepted. This appears to be the maximum allowable (Dwelle 1985). Dwelle cited a study conducted by Bremmer and Taha to illustrate the importance of canopy longevity, stating that these researchers found a "direct linear relationship between tuber yield and number of days that the LAI is maintained at values greater than 3.0." In addition, it has been shown that younger leaves have much greater assimilation rate potential than older ones.

CO_2 is absorbed by the leaf through stomates. Stomatal openings are sensitive to temperature. The warmer it is, the greater the opening. However, greater temperatures also increase water loss through transpiration. Water loss causes the leaf surface to cool, causing stomata openings to decrease. Light also effects the stomata. The maximum amount of light a potato plant is able to synthesis is 1200 uE/m2/s (Dwelle 1985).

Chlorophyll can also be a limiting factor in carbon assimilation. When leaf area is increasing rapidly, its chloroplast development lags behind, and for a period of time photosynthetic activity per leaf area can actually decrease (Dwelle 1985).

Translocation. Translocation is the process of getting the carbon to various sinks (eg. tubers). The pathway is through the phloem. It is believed that sucrose is the main transport sugar (Burton 1989). Translocation rates average about 0.5 g/h for the whole plant during photosynthetic periods, or about 0.05 to 0.1 g/hr/tuber (Burton 1989).

The influence of this demand on the photosynthetic process is illustrated by the fact that photosynthetic rates increase during tuber bulking and that individual leaf rates increase when part of the canopy is either damaged (Colorado potato beetle feedings) or removed mechanically (Dwelle 1985).

Transpiration. Transpiration is the process of water loss by the plant through stomata openings. It is driven by leaf surface temperature. Water vapor exits the plant through the stomata, reducing water in intercellular spaces. This water is replaced by water from interfibrillar spaces in cell walls of leaf tissue, creating a water potential gradient. This forces water up through the xylem, which in turn pushes water up from the roots. Water enters roots through root hairs and mycorrhizal fungi, moves into the roots because of the water potential gradient, through the interfibrillar spaces of the cortex, through the endodermis, and into the vascular system (Burton 1989). The net effect of transpiration is the reduction in leaf temperature. It can be stressful for the plant if there is not enough water in the soil to replace the amount lost by the plant.

Plant growth regulators. For a plant to grow optimally and produce high yields, it has to maintain a relative equilibrium among these physiological processes. Growth regulators are probably responsible for this balance. It is hypothesized that many of these processes are regulated by gibberellin/auxin ratios, as well as cytokinins and ethylene (Dwelle 1985). The exact stimuli are unknown.

Conclusion

The potato plant has several important phases of development. It is necessary to establish a good canopy, adequate stolon production, and successful tuber initiation and development. These processes are well synchronized and overlap. First, the above-ground plant emerges, stolons develop, tubers initiate and bulking occurs. For the plant to produce an adequate yield, these processes have to be well synchronized. For example, it is important that stolons are fairly long before tubers initiate or only a few tubers will form. It is also important to note the shape of the tuber growth curve. It is a sigmoid curve (Milthorpe 1963). However, the shape of the curve is variety dependent; it may also be linear, developing at a constant rate; or discontinuous, developing and stopping, and developing again.

POTATO EARLY-DIE DISEASE COMPLEX

Although many studies site a list of organisms associated with potato early die (Martin et al. 1982, Rowe et al. 1987, Powelson 1985, Wheeler & Riedel 1994, Wheeler el al. 1994), this study is exclusively referring to the presence of two pathogens Verticillium dahliae and Pratylenchus penetrans.

Verticillium dahliae

Verticillium dahliae is a fungal pathogen of potato (Smith, 1968; Davis, 1985; Nicot and Rouse, 1987). There are two species of Verticillium that effect potato production, V. dahliae and V. albo-atrum (Isaac and Harrison, 1968). The species most prevalent in Michigan is V. dahliae due largely to Michigan's climatic conditions. It has been found that even this species, has a great amount of variability in potato yield loss due to differences between pathotypes of V. dahliae (Botseas and Rowe, 1994).

Pratylenchus penetrans

The genus Pratylenchus has at least 15 species that are pathogenic on potato (Brodie 1984). The species, P. penetrans (Cobb, 1917) Filipjev & Schuurmans-Stekhoven, 1941, is one of the most pathogenic (Brodie, 1984). It is also the most prevalent species in Michigan (Bird, 1981). The nematode is a migratory endoparasite that remains vermiform throughout its life cycle. The second-stage juvenile emerges from the egg and moves into a host root. All stages are infective and enter the root behind the root cap by cutting an entrance with the stylet (Thorne, 1961). Once inside of the root, the nematode excretes substances that cause necrosis of cells.

Pathogenicity of potato was first reported in 1938 by Hastings and Bosher. It was later confirmed by Oostenbrink (1954, 1956) and Dickerson et al. (1965). It was found that nematode damages varied among the different cultivars (Burpee and Bloom, 1978; Olthof, 1986).

Modelling the Interaction between Pratylenchus penetrans and Verticillium dahliae

Since the early 1980's it has been a goal of many nematologists and plant pathologists to quantify the relationship between root lesion nematode and V. dahliae on potato. The early work was done primary at Ohio State University, through the use of a multi-year, two-locational, microplot series of experiments.

It was during this time period that the relationship between root lesion nematode and V. dahliae was described as synergistic (Martin et al., 1982). An operative definition of synergism is that the combined effect of two pathogens is greater than the sum of their individual effects. From early potato early die research, it was learned that this effect was most easily demonstrated when the two pathogens were kept well below their individual pathogenicity threshold levels (Martin et al., 1982).

The preliminary early die work at Ohio State consisted on an effort to prove the synergistic relationship of the two pathogens at low inoculum levels on potato (cv. Superior). It consisted of a series of experiments with zero, low, medium, and high nematode and Verticillium inoculations, both alone and in combination. In 1980, analysis of variance and mean separations showed that low levels of nematode and Verticillium tuber yield plots were similar to the control, while low nematode and low Verticillium together in a plot were statistically different from the control (Martin et al., 1982).

These experiments were continued in 1981, 1982 and 1983 at two locations with different soil types (Rowe et al., 1985). The experiments were done in Wooster, Ohio with silt loam soil and in Celeryville, Ohio with rifle peat soil. Mean separations were not presented. Instead, a series of p-values associated with ANOVAs were published for four levels of nematodes and three levels of the fungus. Results varied by both location and year. In silt loam soils, low levels of both pathogens resulted in lower yields than the controls, 50% of the time. However, in rifle peat soils low levels of both pathogens yielded less than the controls all of the time. High levels of both pathogens yielded less than the controls at both sites over all four years.

Even though the ANOVAs and presented data show a trend of lower yields in treated plots versus controlled plots, there was no statistical evidence of synergism presented. For an interaction to be synergistic, it had to be shown that crop loss from low Verticillium alone plus low levels of nematodes alone, were statistically less than crop loss when the two were combined in the same plot at the same levels that were in each pot separately. This statistical test cannot be shown with analysis of variance. ANOVAs can show that low P. penetrans and low Verticillium is different from low P. penetrans and it is different from low Verticillium, but it cannot show that it is different from the sum of the effect of low P. penetrans and low Verticillium, which is the operative definition of synergism.

The next phase of modelling potato crop loss came with regression analysis using the same Ohio State data (Francl et al., 1987 and 1990). Eleven regression models were analyzed for each location and year individually, and then larger data sets were used that analyzed each location across years (Francl et al., 1987). Both transformed natural log and untranformed pre-season pathogen counts were regressed with relative potato yields and the best fit models were presented. Adjusted r^2 were significant eight out of eleven years, ranging from 0.28 to 0.97). In general, the best fit models included the natural log of Verticillium x P. penetrans as one of the parameters, which indicated that their relationship was nonlinear. From a biological perspective, it may be interpreted that the pathogens cause proportionally more damage at lower levels than they do at higher levels.

When Francl et al. combined years, a much smaller adjusted r^2 was reported. One location (silt loam soil type) had an r^2 of 0.12, and the other (rifle peat) had an r^2 of 0.44. When both locations were combined, the adjusted $r^2 = 0.20$. These results indicate that there were considerable variability in yield losses between years indicating that environmental factors might be a major indicator of yield loss.

Further data were analyzed by Francl et al. In 1990. They used the previous Ohio State data plus two years of additional data to find better best fit regression models. Along with pre-season nematode and Verticillium data, they used a canopy parameter that improved the fit of the combined data at both locations. The silt loam location (Wooster, Ohio) increased its r^2 value from 0.12 to 0.28%, for a relative yield model. At the peat soil location, the r^2 improved also. It went from 0.44 to 0.55. When true yields were regressed instead of relative yields, the r^2 were much improved. In Wooster (silt loam site), the r^2 was 0.48, and at Celeryville the r^2 was 0.94. Both best fit regression equations were similar in that they had negative coefficients for the canopy parameter alone (potatoes were planted between microtiles some of the years), with a positive parameter for an interaction parameter between canopy and the natural log of the Verticillium x P. penetrans interaction term. In addition, both equations had a negative coefficient for the natural log of the interaction between the two pathogens separate from the canopy and a negative coefficient for the natural log of Verticillium alone.

Francl et al. (1990) used regression residuals to try to explain inter-season variability with four years of the Ohio State data. They found that for two years the residuals were generally positive (greater than zero) and the other two years the residuals were negative, which could indicate environmental variability. They also correlated temperature and moisture and found that there was a strong negative correlation between late season warm weather and tuber yields.

Wheeler et al. (1991) used the Ohio State data to test another hypothesis of yield loss. Their regression model predicted yield loss on the basis of Verticillium pre-plant densities and used P. penetrans as an indicator parameter. Two nonlinear regression models were fit, one in the presence of the nematode and the second in its absence. A combined regression analysis for this model had an r^2 of 0.52.

In 1994, Wheeler and Riedel published a paper that expanded the interaction study to include P. Scribneri as well as P. penetrans. Microplots at Celeryville (rifle peat soil) were used between 1986-1988. Both ANOVA and regression models were used to analyze the data. Verticillium effected potato yields in all three years. Pratylenchus penetrans caused loss in two of the three years, with an interaction between P. penetrans and V. dahliae in those same years as well. Pratylenchus scribneri showed an effect in one year, but there was no interaction with V. dahliae. However, this paper did not attempt to statistically demonstrate a synergistic interaction.

Chen (1995) attempted to quantify yield loss as either synergistic, additive or antagonistic for treatments that contained root lesion nematode alone, the fungus alone, and the results when both pathogen were introduced in the same treatment. He measured yield loss and added the yield loss in the two individual pathogen treatments to get a predicted value for joint interaction. If the actual joint interaction was statistically greater than this number the interaction was considered synergistic, if it was equal than it was additive, and less it was considered antagonistic. The majority of the treatments (9) were considered additive, with one synergistic and two antagonistic.

ANALYSIS OF AGRONOMIC AND SYSTEM DESIGN PARAMETERS OF MICHIGAN POTATO PRODUCTION UTILIZING LINEAR MODELLING TECHNIQUES

INTRODUCTION

Many factors influence variability in potato tuber yields. The literature documents irrigation, crop rotation, and chemical inputs as potential causes of variability along with pest occurrences. The impact of these management strategies can be analyzed using a series of linear models.

OBJECTIVES

It is the objective of this study to determine the impact that selected agronomic management practices and farming system structure have on potato tuber yields (cwt/A). Several hypotheses were examined which entailed a series of linear regression models that explained the variability in expected tuber yields among growers. The series of hypotheses developed for this project include:

a. Variability in potato production, on a statewide basis, is explained by differences in chemical nutrient inputs, rotation schedule, irrigation, use of Temik 15G or chemigation.

b. Variability in potato production can be stratified by farm size, with rotation schedule, irrigation, use of Temik 15G and chemigation having the largest impact on expected yields.

c. Variability in potato production can be stratified by region, with rotation schedule, irrigation, use of Temik 15G and chemigation having the largest impact on expected yields.

d. Variability in potato production can be stratified by nematicide use, with rotation schedule and irrigation having the largest impact on expected yields.

e. Variability in potato production can be stratified by rotation schedule, with irrigation and pesticide usage having the largest impact on expected yields.

MATERIALS AND METHODS

Forty Michigan potato growers were interviewed in 1988 by a representative of Michigan State University Department of Agricultural Economics and the Department of Entomology Nematology Program. They were surveyed in regards to farming system practices and associated variable costs. They were also asked to estimate potato yields for the 1988 growing season. The growers were selected at random from a list of potato farmers supplied by the Michigan Potato Industry Commission. Twenty-four percent of Michigan's 43,500 acres of potato production were included in the study.

The data from the survey were analyzed using a series of linear regression models to determine the importance of agronomic practices on expected yields. The factors evaluated included nitrogen, phosphorus, potassium and sulfur inputs; nematicide use; irrigation practices and crop rotation schemes. These models were developed using the techniques of linear algebra (Stapleton 1995).

The general linear model formulation is as follows:

$Y = mx + b + e$

In matrix form:

$Y = [X][B] + e$

where

Y = array of Y values

X = linear model

B = array of estimated coefficients

e = array of error terms

The following matrix manipulations were completed to estimate the beta values:

$[B] = [X^T * X]^{-1} * X^T * Y$

This provides an unbiased estimate of the beta parameters (Stapleton 1995).

The models were developed in a stepwise fashion. The data were initially analyzed for the state as a whole. Then separate models were developed based on farm size, potato production region, nematicide use, and rotation schedule. Each factor was analyzed individually, then a multiple regression model was developed. For each model, a series of simple regression models were used to determine the relative importance of each factor.

RESULTS

State analysis. Chemical nutrient inputs included nitrogen, phosphorus, sulfur and potassium applications. Nitrogen inputs ranged from 49.6 to 345.2 lb/A with a mean of 181.9

lb/A for Michigan (Table 1). Nitrogen inputs did not correlate with expected yields. It was found that the amount of nitrogen applied per acre was not a good indicator of potato yield (r^2=0.014, p=0.469, Figure 1).

Phosphorus inputs ranged from 0 to 288 lb/A, with a mean of 136.3 lb/A (Table 1). Phosphorus inputs could only explain 0.2% of the variability in expected potato yields (p=0.775, Figure 2).

Potassium inputs ranged from 0 to 425.6 lb/A, with a mean of 214.9 lb/A (Table 1). Amount of potassium also did not correlate to potato yields (r^2 =0.032, p=0.273, Figure 3).

Sulfur inputs ranged from 0 to 120 lb/A, with a mean of 10.5 lb/A. These inputs accounted for 0.5% of potato yield variability (p=0.661, Figure 4).

Generating a multiple regression model that hypothesized that all four of these chemical inputs influenced expected tuber yield, it was found that together these inputs explained only 5.5% of the variability in potato yields, which was not significant (p=0.731).

$$Y = 212.09 + 0.123*X_N - 0.164*X_P + 0.198*X_K - 0.349*X_S \qquad \text{Equation 1}$$

where:

Y = Expected Potato Yield
N = Nitrogen input
P = Phosphorus input
K = Potassium input
S = Sulfur input

The only factor that was significant at the $p \leq .05$ level was the constant (Table 2).

The farming system practices of irrigation and rotation were also analyzed. It was estimated that approximately 85% of the growers irrigate at least a portion of their potato land, with 82% of total potato acreage irrigated in 1988. An average of 74% of each farm

Table 1. The utilization of chemical nutrients (lb/A) in Michigan potato production in 1988 (n=40).

Chemical input	Minimum	Maximum	Mean	Standard deviation
Nitrogen	49.6	345.2	181.9	71.4
Phorphorus	0.0	288.0	136.3	61.6
Potassium	0.0	425.6	214.9	80.5
Sulfur	0.0	120.0	10.5	28.6

Table 2. A multiple regression model correlating potato yields to the chemical inputs of nitrogen, phosphorus, potassium, and sulfur.

Variable	Coefficient	P-value
Constant	212.091	0.001
Nitrogen (lb/A)	0.123	0.584
Phosphorus (lb/A)	-0.256	0.527
Potassium (lb/A)	0.197	0.323
Sulfur (lb/A)	-0.349	0.526

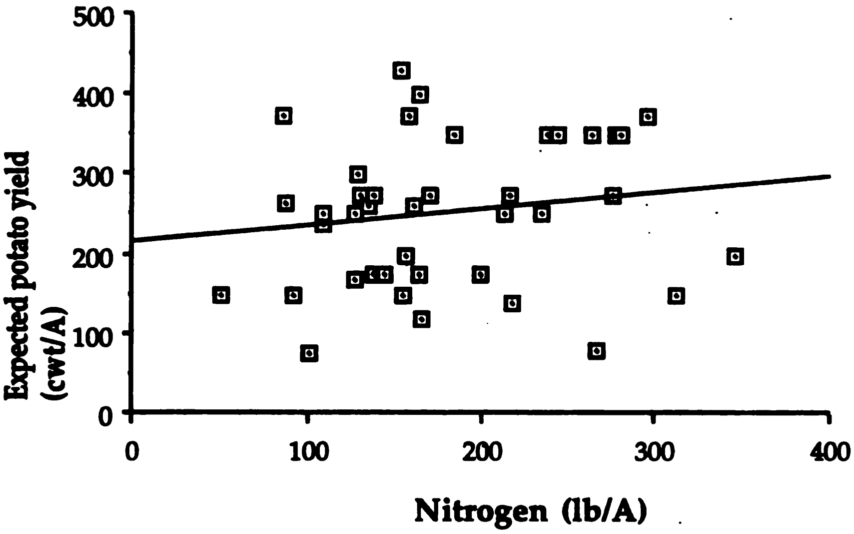


Figure 1. The correlation of nitrogen inputs to expected yields in Michigan potato production in 1988 ($y=223.4+0.15x$, $r^2=0.014$).

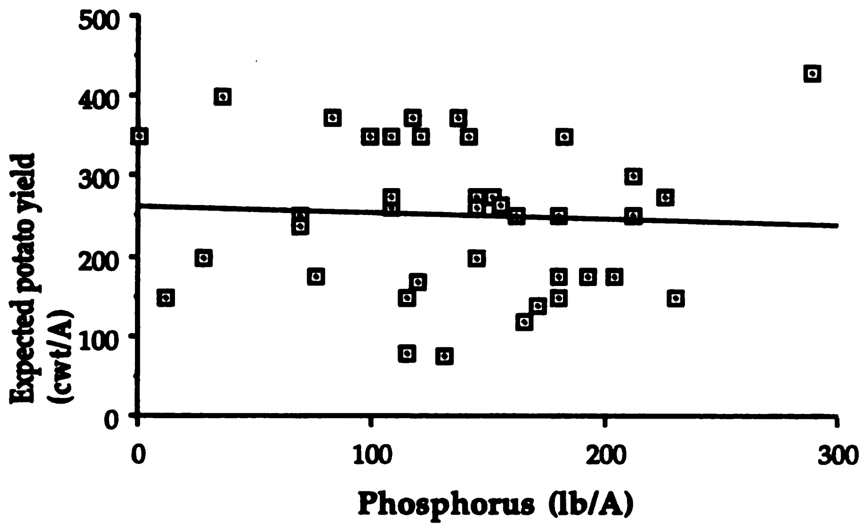


Figure 2. Correlation of phosphorus inputs to expected yields in Michigan potato production in 1988 ($y=260.5-0.07$, $r^2=0.002$).

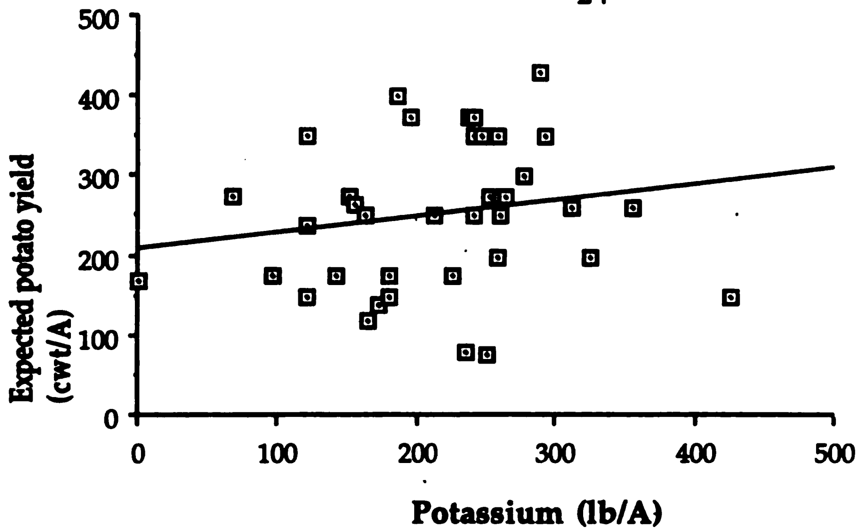


Figure 3. Correlation of potassium inputs to expected yields in Michigan potato production in 1988 ($y=207.5+0.02x$, $r^2=0.032$).

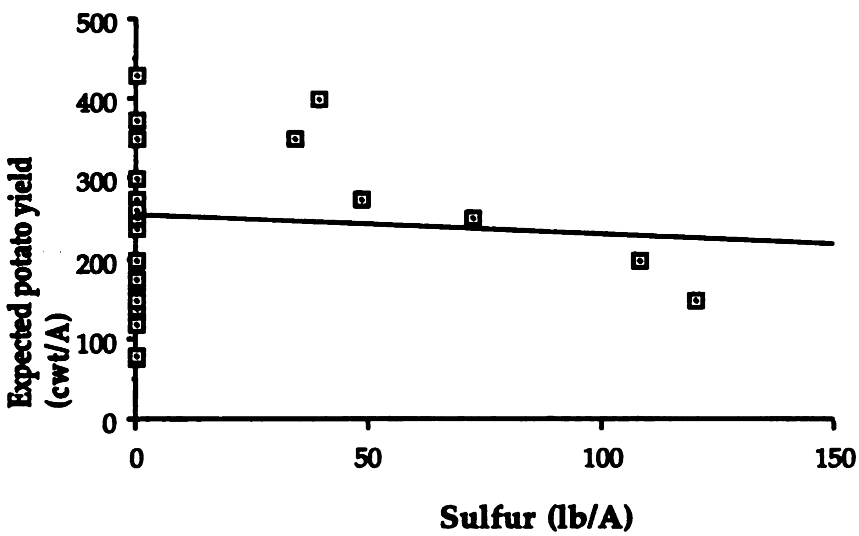


Figure 4. The correlation of sulfur inputs to expected yields in Michigan potato production in 1988 ($y=253.4-0.23x$, $r^2=0.005$).

was irrigated in 1988. The average length of a rotation scheme was 1.5 years out of potato (Table 3).

The portion of irrigated land explained a large portion of the variability in potato yields (r^2=0.437, Figure 5). When the state was taken as a whole, years out of potato had no direct relationship to potato yields (r^2 =0 .007, Figure 6).

Next, two separate multiple regression models were analyzed. One assessed the impact of irrigation and rotation together, and the other included the chemical inputs as well. It was found that irrigation and rotation together explained 45.4% of the variability in potato yields (Equation 2, Table 4). When chemical inputs were included, the model explained 51.9% of the variability in potato yields (Equation 3, Table 5). Both models were statistically significant ($p<.001$).

$$Y = 115.071 + 10.579 * X_R + 162.584 * X_I \qquad \text{Equation 2}$$

where:

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated

When including both chemical inputs and farming system practices, the model is:

$$Y = 71.280 + 0.159 * X_N - 0.213 * X_P + 0.208 * X_K - 0.200 * X_S$$

$$+ 10.579 * X_R + 162.584 * X_I \qquad \text{Equation 3}$$

where:

Y = Expected potato yield
N = Nitrogen input
P = Phosphorus input
K = Potassium input
S = Sulfur input
R = Number of years out of potato
I = Portion of land irrigated

Table 3. Irrigation and rotation schedules in Michigan potato production in 1988 (n=40).

Practice	Minimum	Maximum	Mean	Standard deviation
Irrigation (portion of farms irrigated)	0.0	1.0	0.74	0.379
Rotation (years out of potato)	0.0	5.0	1.50	1.109

Table 4. A multiple regression model correlating potato yields to irrigation and rotation.

Variable	Coefficient	P-value
Constant	115.071	0.000
Rotation (years out of potato)	10.579	0.302
Irrigation (portion of farms irrigated)	29.576	0.000

Table 5. A multiple regression model correlating potato yields to chemical inputs and management practices.

Variable	Coefficient	P-value
Constant	71.280	0.163
Nitrogen	0.159	0.345
Phosphorus	-0.213	0.266
Potassium	0.208	0.162
Sulfur	-0.200	0.622
Irrigation (portion of farms irrigated)	165.590	0.000
Rotation (years out of potato)	10.025	0.334

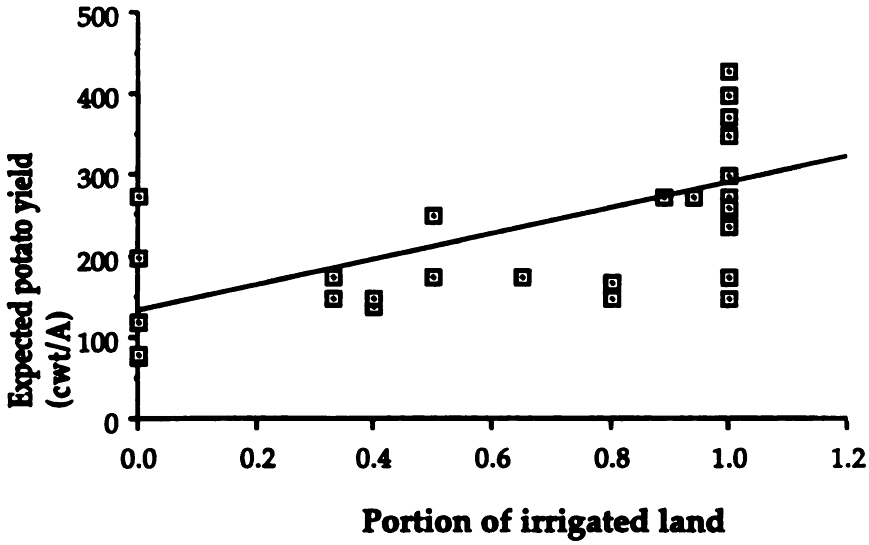


Figure 5. Correlation of portion of irrigated land to expected yields in Michigan potato production in 1988 ($y=132.4+160.6x$, $r^2=0.437$).

Figure 6. Correlation of rotation (years out of potato) to expected yields in Michigan potato production in 1988 ($y=240.4+7.08x$, $r^2=0.007$).

Although both models were statistically significant, the only individual factor that was significant was the portion of land irrigated (Table 5).

Evaluation of nematicide usage was an important component of the survey. Fifty percent of the growers used no nematicide. Thirty-seven percent used an at-plant nematicide and 25% used either a fumigant or a chemigant (Table 6). Of the growers that used at-plant nematicides, Temik 15G was utilized the most (Table 7). Since four or less growers used Mocap 10G, Furadan or a fumigant, these chemicals were not utilized for the regression models.

Temik 15G explained 17.2% of the variability in potato yields ($p=0.008$, Figure 7). Chemigation explained 31.1% of the variability in yield ($p<0.001$, Figure 8). Then a ranking was developed that gave numerical value to different types of nematicide inputs, ranging from 0 for no inputs to 9 for at-plant nematicide, fumigant and chemigant. It was found that this ranking did not correlate with expected yields, for the state as a whole (Figure 9, $r^2=0.000$).

A multiple regression model, correlating potato yields to both Temik 15G and chemigation increased the r^2 to 0.365 (Table 8). The equation is as follows:

$$Y = 207.085 + 17.238 * X_T + 119.591 * X_C \qquad \text{Equation 4}$$

where:

Y = Expected potato yield
T = Amount of Temik applied at-plant
C = 1 if chemigant applied; 0 otherwise

Table 6. Portion of Michigan potato growers utilizing at-plant insecticides and nematicides in 1988.

Chemical input	Mean	Standard deviation
At-plant insecticide	0.825	0.385
At-plant nematicide	0.375	0.490
Fumigant	0.100	0.304
Chemigant	0.150	0.362
No nematicide	0.500	0.506

Table 7. The utilization of at-plant nematicides for Michigan potato production in 1988 (n=40).

Chemical input	Min	Max	Mean	Standard deviation
Temik 15G	0.0	3.0	1.5	1.3
Mocap 10G	0.0	2.7	0.1	0.5
Furadan	0.0	3.0	0.1	0.5

Table 8. A multiple regression model correlating potato yields to Temik and chemigation.

Variable	Coefficient	P-value
Constant	207.09	0.000
Temik 15G	17.24	0.085
Chemigation	119.59	0.002

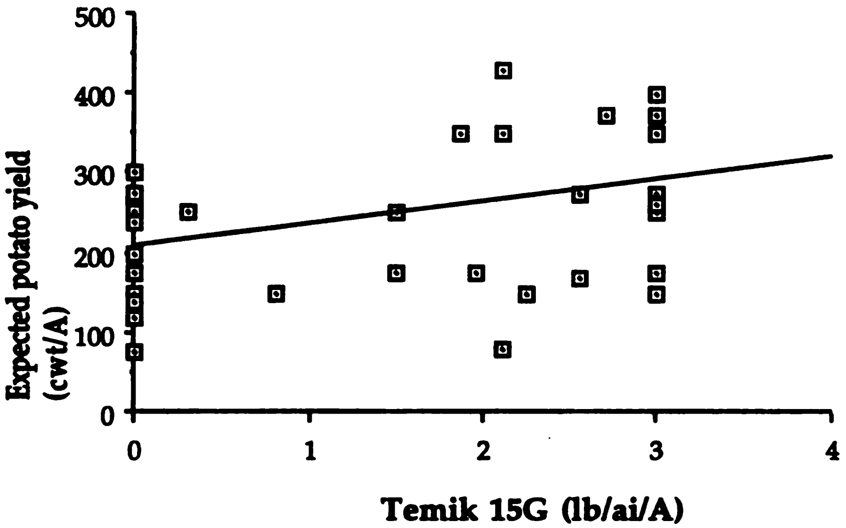


Figure 7. Correlation of Temik 15G inputs to expected yields in Michigan potato production in 1988 ($y=207.6+28.82x$, $r^2=0.172$).

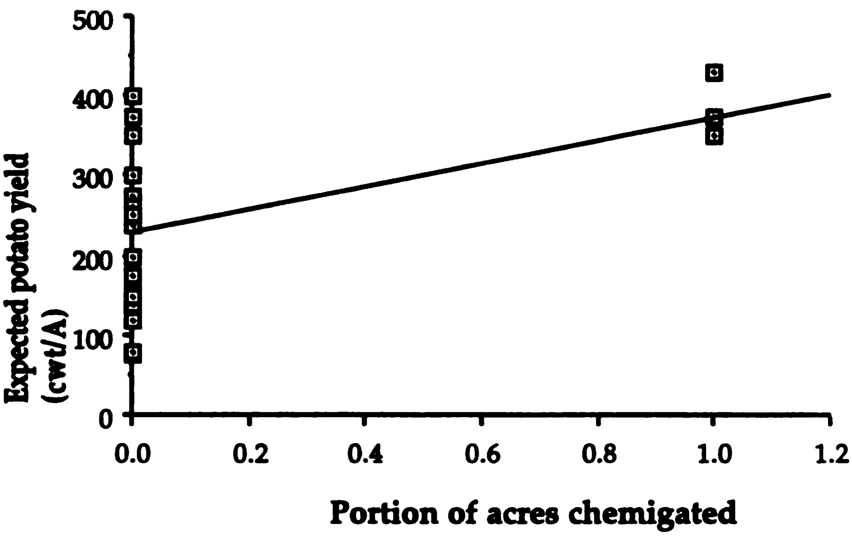
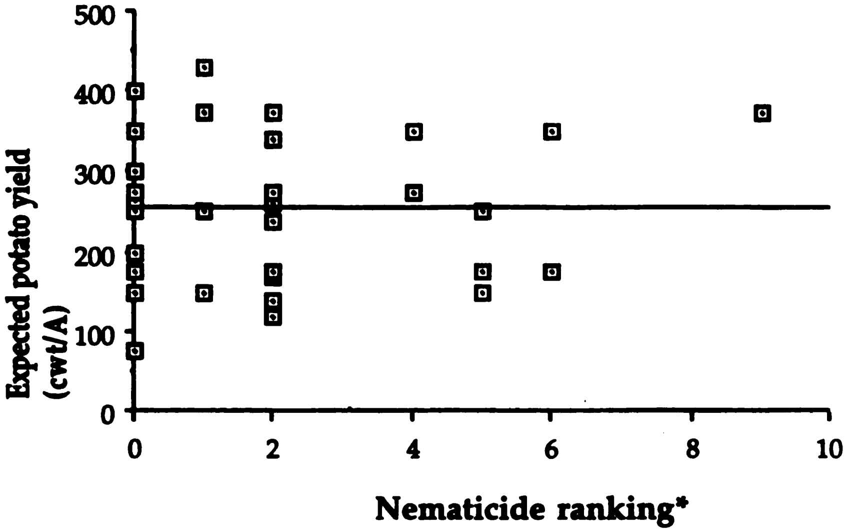


Figure 8. Correlation of portion of acres chemigated to expected yields in Michigan potato production in 1988 ($y=229.7+141.96x$, $r^2=0.311$).



*0 = no nematicide or at-plant insecticide, 1 = at-planting insecticide, 2=at-plant nematicide, 3=fumigant, 4=chemigant. Total sum ranges from 0 to 9, with 9 being the application of at-plant nematicide, fumigant, and chemigant.

Figure 9. Correlation of nematicide ranking with expected potato yields in Michigan potato production in 1988 ($y=255.9-0.2x$, $r^2=0.000$).

Then Temik 15G and chemigation variables were added to the larger model. This model included chemical inputs, management practices and nematicide inputs.

$$Y = 89.755 + 0.038*X_N - 0.154*X_P + 0.179*X_K - 0.054*X_S + 14.722*X_R + 147.663*X_I + 17.238*X_T + 119.591*X_C \qquad \text{Equation 5}$$

where:

Y = Expected potato yield
N = Nitrogen input
P = Phosphorus input
K = Potassium input
S = Sulfur input
R = Number of years out of potato
I = Portion of land irrigated
T = Amount of Temik applied at-plant
C = 1 if chemigant applied; 0 otherwise

This full model for the state of Michigan explained 63.9% of the variability in potato yields ($p<0.001$). The two most important components of this model were portion of land irrigated and use of chemigation (Table 9).

Since it is difficult to quantify every aspect of potato production, the parameter of expenses was chosen as an indirect indicator of collective inputs. Expenses included all costs that were directly related to planting. For the state of Michigan expenses ranged from $317.01 per acre to $965.29 per acre with a mean of $557.93 (Table 10). It was found that expenses explained 14.7% of the variability in yields ($p=0.014$, Figure 10). Along with expenses, return over direct costs were considered. A major component of this includes both potato yields and selling price. Expected yields ranged from 75 to 430 cwt/A with an average

Table 9. A multiple regression model correlating expected yields to chemical inputs, management practices, and nematicide use in 1988 Michigan potato production.

Variable	Coefficient	P-value
Constant	89.75	0.057
Nitrogen	0.04	0.816
Phosphorus	-0.15	0.373
Potassium	0.18	0.185
Sulfur	-0.05	0.882
Irrigation (portion of farms irrigated)	147.66	0.000
Rotation (years out of potato)	14.72	0.145
Temik 15G	-5.84	0.575
Chemigation	100.13	0.003

Table 10. The economics of Michigan potato production in 1988.

Economic indicator	Min	Max	Mean	Standard deviation
Expected yield	75.00	430.00	251.00	92.03
Expected selling price	4.00	11.00	6.23	1.79
Expenses	317.01	965.29	557.93	174.74
Expected profit	-84.50	2927.88	969.81	632.80

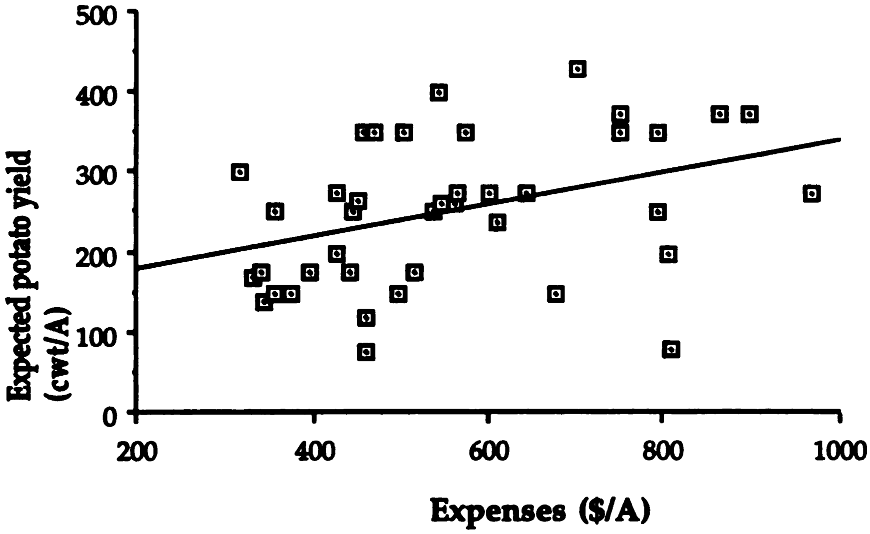


Figure 10. Correlation of direct costs associated with planting and expected yields in Michigan potato production in 1988 ($y=138.2+0.2x$, $r^2=0.147$).

of 251 cwt/A (Table 10). Selling price ranged from \$4.00 to \$11.00/cwt, with an average of \$6.23/cwt for Michigan.

Selling price was correlated to expected yields and it was found that selling price explained only 4.9% of the variability in yields (p=0.172, Figure 11). The final correlation was an attempt to relate expenses to return over direct costs, and it was found that they did not correlate (r^2<0.001, Figure 12).

Farm size model. Michigan farm systems were divided into three size categories. Small farms were classified as 50 acres or less, medium-sized farms as 50 to 250 acres, and large farms were over 250 acres. Approximately 0.5% of total potato acreage consisted of small farms, 30% medium-sized farms and 70% large farms (Table 11). There was no significant differences in how these farming categories used nutrient chemical inputs (Table 12).

The number of years out of potato production was inversely proportionate to farm size. Smaller farms tended to rotate more often than larger farmers (Table 13). Number of years out of potato was correlated to expected yields for each farm size category. Years out of potato was negatively correlated with expected yield for small farms (r^2=0.550, n=4, p=0.229), and positively correlated with potato yields for medium farms (r^2=0.163, n=22, p=0.062), and positively correlated for large farms (r^2=0.097, n=14, p=0.279). When a full model was analyzed, it was found that this farm size/rotation model explained 28.65% of the variability in expected potato yields (Figure 13).

The portion of irrigated land ranged from a mean of 0.5 on small farms to 0.8 on large farms (Table 13). Portion of irrigated acres positively correlated to potato yields for all three farm sizes (Figure 14). An r^2 of 0.595 was not statistically significant for small farms

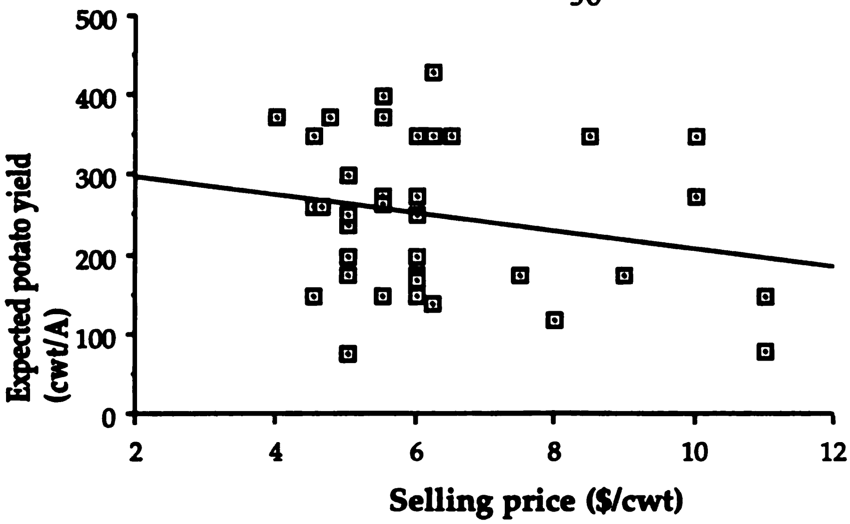


Figure 11. Correlation of tuber selling price to expected yields in Michigan potato production in 1988 ($y=321.6-11.34x$, $r^2=0.049$).

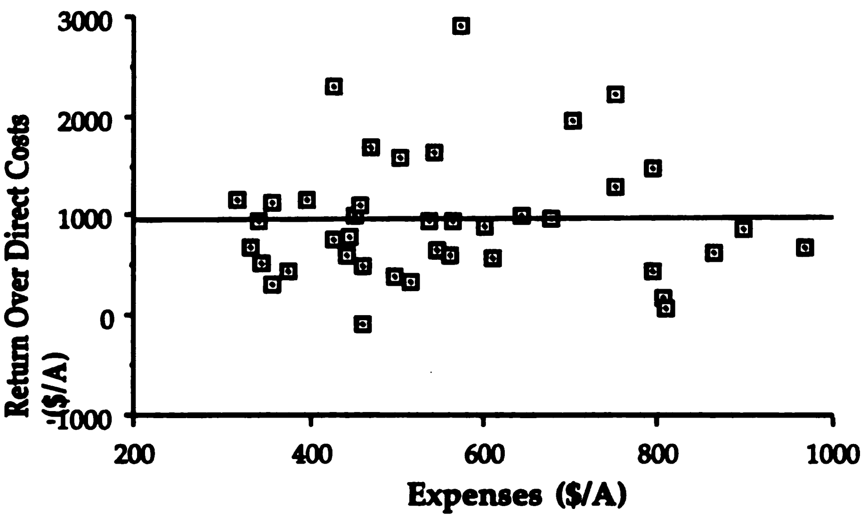


Figure 12. Correlation of direct costs with profit for Michigan potato production in 1988 ($y=941.97+0.04x$, $r^2=0.000$).

Table 11. An estimate of total Michigan potato production by farm size in 1988.

Size of farm	n	Survey acres	Percent of total acres	State estimate (acres)
<=50	4	57	0.005	241.53
50-250	22	3034	0.295	12,855.93
>250	14	7175	0.699	30,402.54
Total	40	10,266	1.000	43,500.00

Table 12. The utilization of chemical inputs (lb/A) by farm size in Michigan potato production in 1988.

Chemical input	Small farms	Medium farms	Large farms
Nitrogen	164.8	171.7	202.8
Phorphorus	150.7	134.8	134.4
Potassium	207.8	213.4	219.3
Sulfur	0.0	17.6	2.4

Table 13. Irrigation and rotation schemes in Michigan potato production by farm size in 1988.

Practice	Small farms	Medium farms	Large farms
Irrigation (portion of farms irrigated)	0.5	0.7	0.8
Rotation scheme (years out of potato)	2.0	1.8	0.9

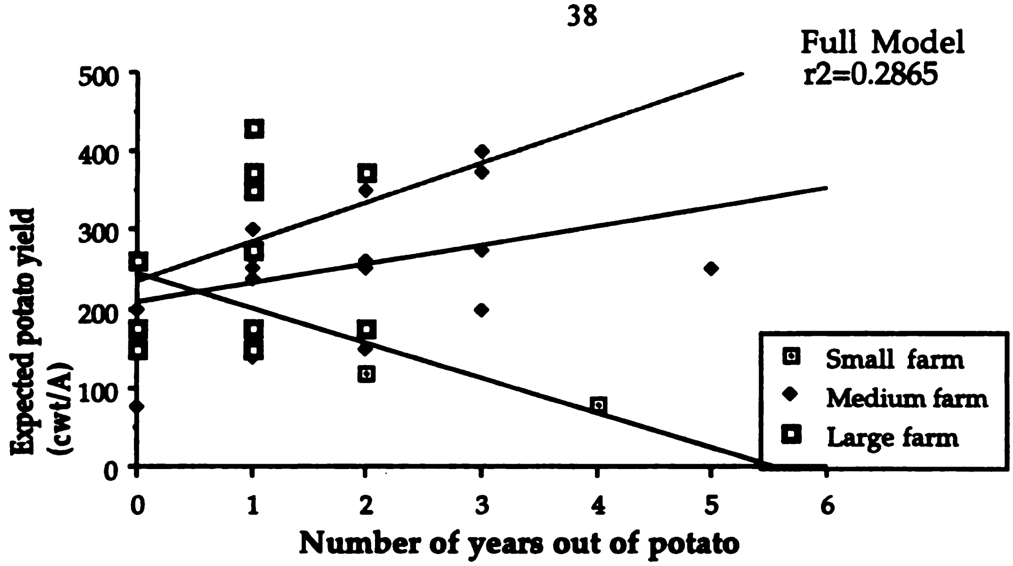


Figure 13. Correlation of rotation (years out of potato) to expected yields in Michigan potato production by farm size in 1988 (Small farm: $y=244.6-44.17x$, $r^2=0.550$; Medium farm: $y=210.1+26.93x$, $r^2=0.163$; Large farm: $y=235.0+50.0x$, $r^2=0.097$).

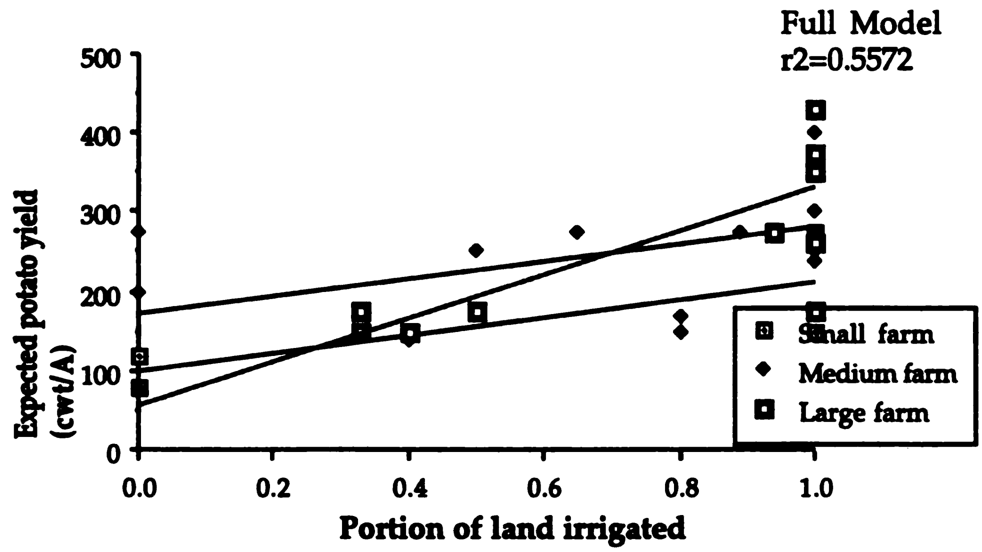


Figure 14. Correlation of poortion of irrigated land to expected yields in Michigan potato production by farm size in 1988 (Small farm: $y=100.0+112.5x$, $r^2=0.595$; Medium farm: $y=165.1+144.96x$, $r^2=0.320$; Large farm: $y=55.8+274.5x$, $r^2=0.628$).

(n=4, p=0.229). However, both the medium farm (n=22, p=0.006) and large farm (n=14, p=0.001) regression models were statistically significant. Testing all three regressions simultaneously as a full model, it was found that collectively 55.72% of the variability in potato yields could be explained by the farm size-irrigation model.

In general, small farms did not use nematicides (Table 14). When small farm growers used Temik 15G they used it below nematicidal rates, as an at-plant insecticide (active ingredient is less than 3.0/acre, Table 15). Medium farms were the most reliant on at-plant nematicides, with 45.5% of the medium-sized farm growers using this type of chemical input (Table 14). While large farms tended to use fumigants and chemigants (50%) (Table 14).

Correlation of Temik 15G inputs with expected potato yields by farm size, indicated that this regression was statistically significant for large farms (n=14, p=0.025); while not for small farms (n=4, p=0.452) and medium farms (n=22, p=0.062). Testing all three regressions simultaneously as a full model, it was found that collectively 36.31% of the variability in potato yields could be explained by the farm size/Temik 15G input model (Figure 15). A regression model based on chemigation was also statistically significant for large farms (n=14, p=0.003) and not for medium farms (n=22, p=0.20). Small farms were not correlated because no small farm used chemigation. Therefore, the full model for farm size/chemigation consisted of two regressions and explained 33.18% of the total variability in potato yields (Figure 16).

A multiple regression model was utilized to assess the impact of the rotation schedule, irrigation usage, amount of Temik 15G applied, and the use of a chemigant by farm size. The following equation has twelve estimated values (n=40, df=32, k=12, s^2=3664.5, r^2=0.6892).

Table 14. Fraction of Michigan potato growers utilizing at-plant insecticides and nematicides by farm size in 1988.

Chemical input	Small farms	Medium farms	Large farms
At-plant insecticide	0.500	0.818	0.929
At-plant nematicide	0.000	0.455	0.357
Pre-plant Fumigant	0.000	0.091	0.143
Pre-plant Chemigant	0.000	0.045	0.357
No nematicide	1.000	0.500	0.357

Table 15. The utilization of at-plant nematicides for Michigan potato production by farm size in 1988.

Chemical input	Small farms	Medium farms	Large farms
Temik 15G (ai/A)	1.088	1.357	1.862
Mocap 10G (ai/A)	0.000	0.191	0.000
Furadan (ai/A)	0.000	0.154	0.000

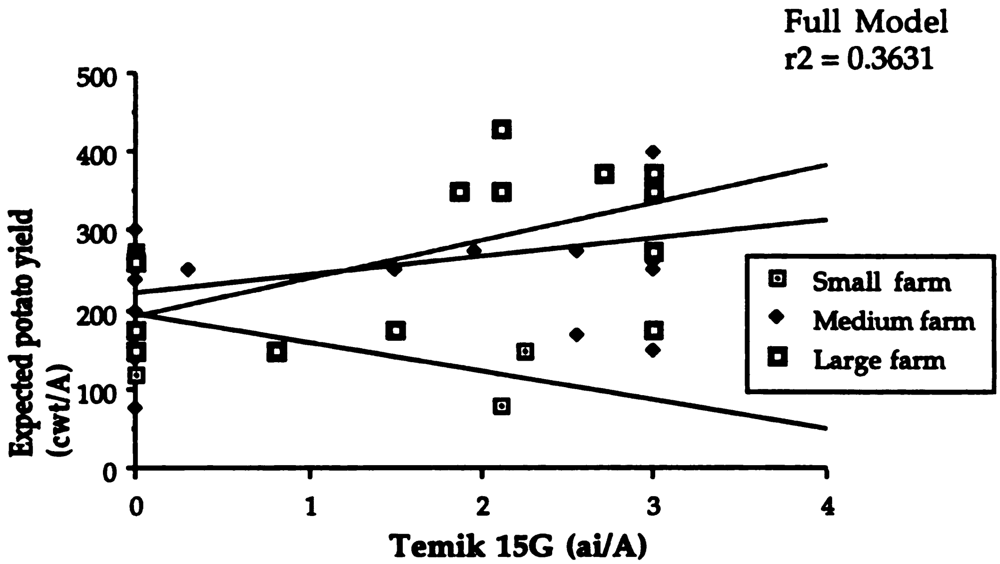


Figure 15. Correlation of Temik 15G inputs to expected yields in Michigan potato production by farm size in 1988 (Small farm: y=196.2-36.73x, r^2=0.301; Medium farm: y=219.5+21.65x, r^2=0.147; Large farm: y=190.6+48.79x, r^2=0.354).

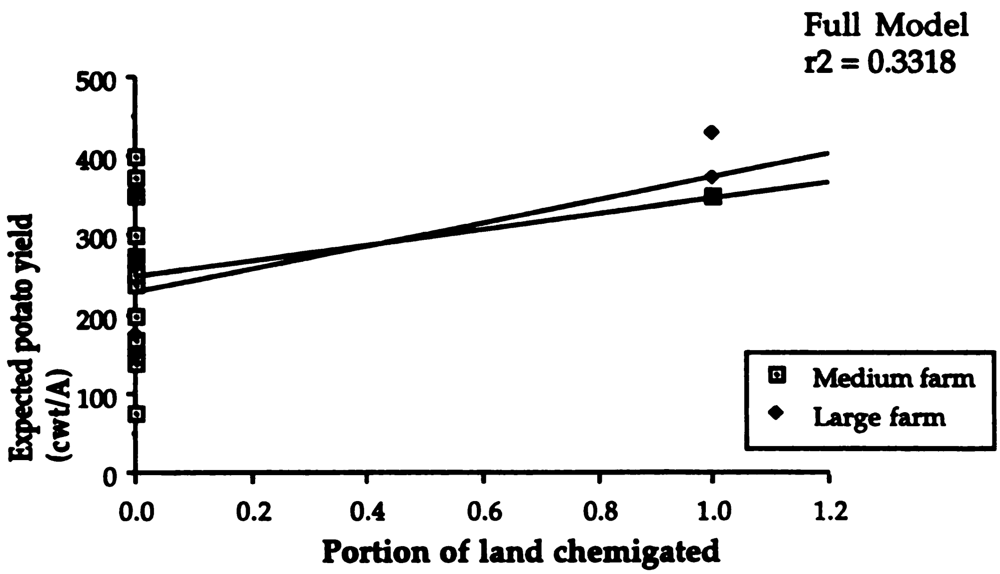


Figure 16. Correlation of portion of acres chemigated to expected yields in Michigan potato production by farm size in 1988 (Medium farm: (y=244.0+105.6x, r^2=0.081; Large farm: y=228.9+147.1x, r^2=0.546).

For small farms: Equation 6a

$$Y = 121.52 + 10.84*X1_R + 131.81*X1_I - 45.93X1_T$$

For medium farms: Equation 6b

$$Y = 121.52 + 10.84*X2_R + 114.87*X2_I - 3.75X2_T + 76.85*X2_C$$

For large farms: Equation 6c

$$Y = 121.52 + 23.99*X3_R + 145.87*X3_I + 3.83*X3_T + 96.62*X3_C$$

where:

X1 = farm 50 acres or less
X2 = farm greater than 50, less than 250 acres
X3 = farm 250 acres or greater

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated
T = Amount of Temik 15G applied (ai/A)
C = 1 if chemigant applied, 0 otherwise

Of these twelve indicators, six were significant at the $p<0.05$ level (Table 16). A smaller model was developed using these six estimators; portion of land irrigated for each of the different farm sizes, years out of potato for medium sized farms and the indicator if chemigant was applied for large sized farms. This model included six parameters ($n=40$, $df=34$, $k=6$, $s^2=3429.6$, $r^2=0.6468$):

For small farms: Equation 7a

$$Y = 117.25 + 95.24X1_I$$

For medium farms: Equation 7b

$$Y = 117.25 + 23.86X2_R + 117.84X2_I$$

Table 16. A multiple regression model correlating potato yields to rotation schedule, irrigation usage, amount of Temik applied, and chemigation usage by farm size.

Coefficient	Beta	Estimator	P-value
Constant	B0	121.52	0.000
Rotation schedule	R1	10.84	0.623
	R2	23.99	0.046
	R3	1.90	0.959
Irrigation	I1	131.81	0.024
	I2	114.87	0.006
	I3	145.87	0.022
Temik	T1	-45.93	0.174
	T2	-3.75	0.756
	T3	3.83	0.881
Chemigation	C2	76.85	0.242
	C3	96.62	0.019

For large farms: Equation 7c

$$Y = 117.25 + 160.73X3_I + 98.01X3_C$$

where:

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated
C = 1 if chemigant applied, 0 otherwise

The revised model provides a good estimate of yield based on half of the estimators. All six estimators were significant at the $p<0.10$ level, and five of the six were significant at the $p<0.05$ level (Table 17).

After analyzing inputs, it is still necessary to examine the economics of potato production by farm size. Large farms have more return over direct costs than medium and small farms (Table 18). Expected yields ranged from 156.25 on small farms to 281.43 cwt/A for large farms. Although smaller farms tended to receive a better selling price (a mean of $7.62), they still average much less return over direct costs (Table 18).

Correlation of expenses ($/A) to return over direct cost ($/A) indicated that small farms tend to lose more money, the more they spend on system inputs (n=4, p=0.510). Medium farms lose somewhat less than small farms (n=22, p=0.159), while large farms tend to increase their profits with increased expenditures (n=16, p=0.131), (Figure 17).

Region model. Michigan was divided into six regions; the Upper Peninsula (UP), northern Lower Peninsula (N), West Central (WC), East Central (EC), Southwest (SW) and Southeast (SE) (Figure 18). The largest potato producing regions are WC and EC Michigan (Table 19). Since only two growers were surveyed in the SE, this region was not statistically analyzed. Statistical results for the UP and the SW are also very limited in their applicability,

Table 17. A revised multiple regression model correlating potato yields to rotation schedule, irrigation usage, and chemigation usage by farm size.

Coefficient	Beta	Estimator	P-value
Constant	B0	117.25	0.000
Rotation schedule	R2	23.86	0.027
Irrigation	I1	95.24	0.050
	I2	117.84	0.000
	I3	160.73	0.000
Chemigation	C3	98.01	0.011

Table 18. The economics of Michigan potato production by farm size in 1988.

Economic indicator	Small farms	Medium farms	Large farms
Expected yield	156.25	248.86	281.43
Expected selling price	7.62	5.95	6.26
Expenses	590.98	536.77	581.74
Expected profit	472.14	906.99	1210.70

Table 19. An estimate of total Michigan potato production by farming region in 1988.

Region	n	Total acres	Survey acres	Percent surveyed
UP	3	3500	260	7.43
North	8	7600	2145	28.22
West Central	12	12,100	3489	28.83
East Central	11	12,800	2205	17.23
Southwest	4	3250	467	14.37
Southeast	2	4250	1700	40.00
TOTAL	40	43,500	10,266	23.60

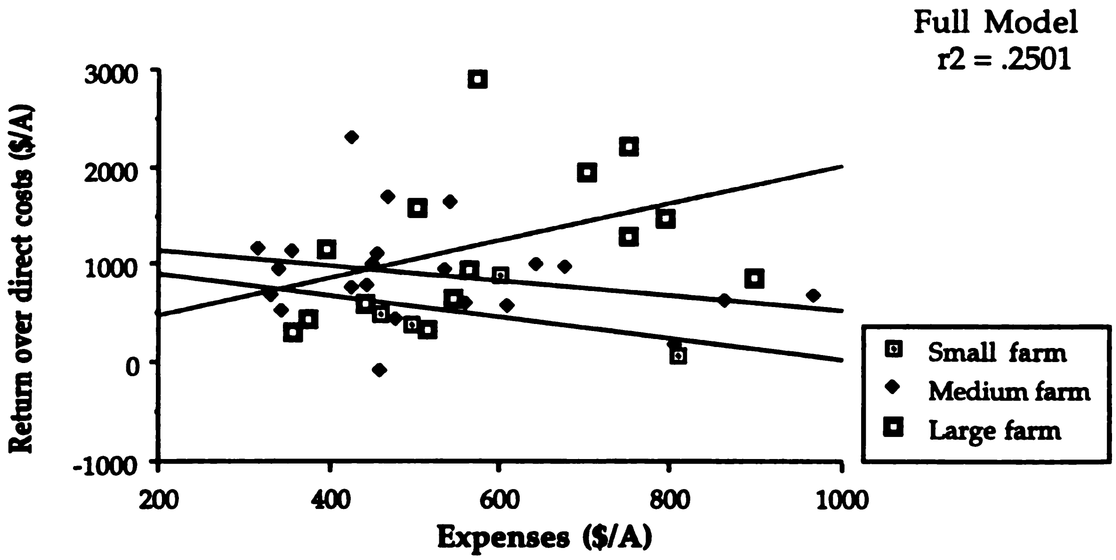


Figure 17. Correlation of direct costs associated with planting and expected yields in Michigan potato production by farm size in 1988 (Small farm: y=1113.8=1.09x, r^2==0.240; Medium farm: y=1374.8-0.87x, r^2==0.097; Large farm: y=94.9+1.92x, r^2=0.179).

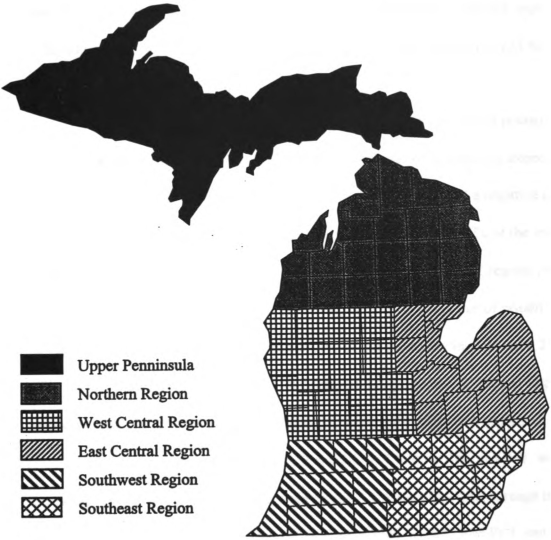


Figure 18. Michigan potato growing regions.

due the small sample sizes (three and four growers, respectively). The six regions did not differ significantly regarding utilization of nitrogen, phosphorus, potassium, and sulfur (Table 20).

Crop rotation schemes ranged from an average of one year out of potato in the SW to two years out in the UP (Table 21). Correlation of rotation schemes to expected potato yields in the UP, N, and NC regions indicated that the best fit produced a negative correlation for all three of these regions. Years out of potato explained about 25% of the variability in both the UP and the N ($p=0.667$ and $p=0.21$, respectively). In the WC region, rotation did not effect yield ($r^2=0.000$, $p=0.981$). However, number of years out of potato correlated positively in the EC and explained about 14.3% of the variability in yield ($p=0.251$, Figure 19). When both number of years out of potato and region were correlated together with expected yield, 53.07% of the total variability in expected yields were explained.

Irrigation ranged from 0.5 in the UP and EC to 1.0 in the WC and SW, where 0.5 is an average of one-half of the acreage is irrigated and 1.0 means that total acreage is irrigated. Irrigation correlated positively in four of the regions (UP, N, WC, and EC), and negatively in the SW (Figure 20). The percent of variability in potato yields ranged from 11.9% in the WC region to 65.6% in the North; with the full model (correlating region and portion of irrigated land simultaneously with expected yield) explaining 71.9% of the variability (Figure 20). The regressions were statistically significant for the N ($p=0.015$) and EC ($p=0.009$), but not for the UP ($p=0.667$), WC ($p=0.272$) or SW ($p=0.580$).

There was no difference among the regions in at-plant insecticide use with portion of growers using these insecticides ranging from two-thirds of the growers in the UP to all of the growers surveyed in the WC and SE regions. The range was greater for at-plant

Table 20. The utilization of chemical inputs (lb/A) by region in Michigan potato production in 1988.

Region	Nitrogen	Phosphorus	Potassium	Sulfur
UP	157.0	181.2	229.4	0.0
North	217.0	144.3	181.3	15.0
West Central	187.4	108.6	244.7	10.1
East Central	156.8	117.5	230.5	9.8
Southwest	183.9	190.6	177.6	18.0
Southeast	180.5	198.0	138.0	0.0

Table 21. Irrigation and rotation schedules in Michigan potato production by region in 1988.

Region	Irrigation (portion of farms irrigated)	Rotation (years out of potato)
UP	0.5	2.00
North	0.6	1.75
West Central	1.0	1.75
East Central	0.5	1.09
Southwest	1.0	1.00
Southeast	0.7	1.50

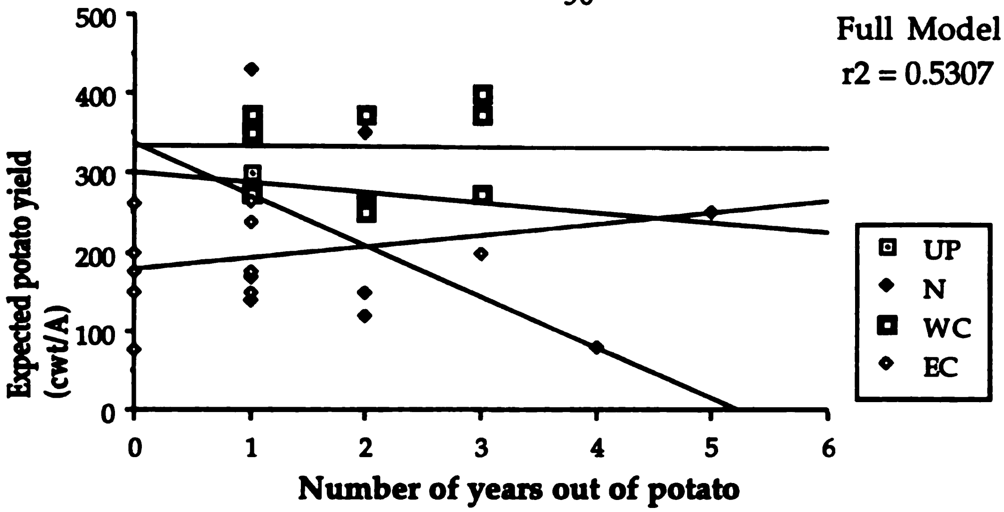


Figure 19. Correlation of rotation (years out of potato) to expected yields in Michigan potato production by farming region in 1988 (UP: y=300.0-12.5x, r^2=0.250; N: y=336.3-64.3x, r^2=0.256; WC: (y=332.9-0.45x, r^2=r2=0.000).

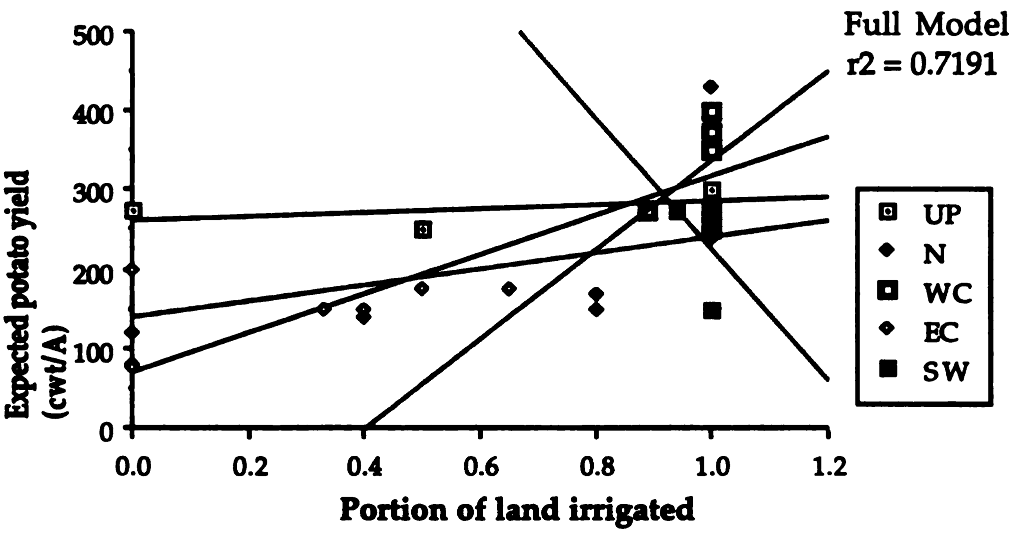


Figure 20. Correlation of portion of irrigated land to expected yields in Michigan potato production by farming region in 1988 (UP: y=262.5+25.0x, r^2=0.250; N: y=70.1+245.8x, r^2=0.656; WC: y=-228.8+560.5x, r^2=0.119; EC: y=140.5+101.3x, r^2=0.549; SW: y=1075.0-850.0x, r^2=0.176).

nematicides, with zero growers using them in the UP, and 75% of the growers using them in the WC region. Fumigants and chemigants were only used by growers in the N and WC regions (Table 22).

Temik 15G was used the most predominately in the WC region. The amount of active ingredient per acre ranged from 0.00 in the UP to 2.613 lb ai/A in the WC region (Table 23). Correlating Temik 15G usage and expected potato yields, it was found that Temik 15G correlated positively in the N, WC, and EC regions; and negatively in the SW. However, none of the regressions were statistically significant (N: $p=0.396$; WC: $p=0.284$; EC: $p=0.950$; SW: $p=0.692$). When both region and Temik 15G usage were correlated simultaneously with expected yield, the model explained much more of the variability in potato yields ($r^2=0.462$) (Figure 21).

In the N and WC region, chemigants were also used by some of the growers. Thirty-seven percent of the growers surveyed used a chemigant in the N region, while 25% of the growers used them in a WC region (Table 22). Chemigant use correlated extremely well with potato yields in the N region ($r^2=0.926$, $p<0.001$). However, the correlation was not statistically significant in the WC region ($r^2=0.160$, $p=0.197$). Correlating chemigant use and region simultaneously, it was found that for the full model 83.57% of the variability in expected yields was explained by the use of a chemigant (Figure 22).

A multiple regression model was also utilized to explain variability in expected potato yield. The variables of years out of potato, portion of land irrigated, the amount active ingredient of Temik 15G utilized, and chemigant usage were regressed with expected potato yields. This model included 16 parameters ($n=38$, $s^2=2232$, $k=16$, $r^2=0.815$).

Table 22. Portion of Michigan potato growers utilizing at-plant insecticides and nematicides by region in 1988.

Region	At-plant insectide	At-plant nematicide	Pre-plant Fumigant	Pre-plant Chemigant	No nematicide
UP	0.667	0.000	0.000	0.000	1.000
North	0.750	0.250	0.125	0.375	0.500
West Central	1.000	0.750	0.250	0.250	0.000
East Central	0.727	0.091	0.000	0.000	0.909
Southwest	0.750	0.500	0.000	0.000	0.500
Southeast	1.000	0.500	0.000	0.000	0.000

Table 23. The utilization of at-plant nematicides for Michigan potato production by region in 1988.

Region	Temik 15G (ai/A)	Mocap 10G (ai/A)	Furadan (ai/A)
UP	0.000	0.000	0.000
North	1.826	0.000	0.000
West Central	2.613	0.000	0.250
East Central	0.388	0.136	0.035
Southwest	1.388	0.675	0.000
Southeast	2.250	0.000	0.000

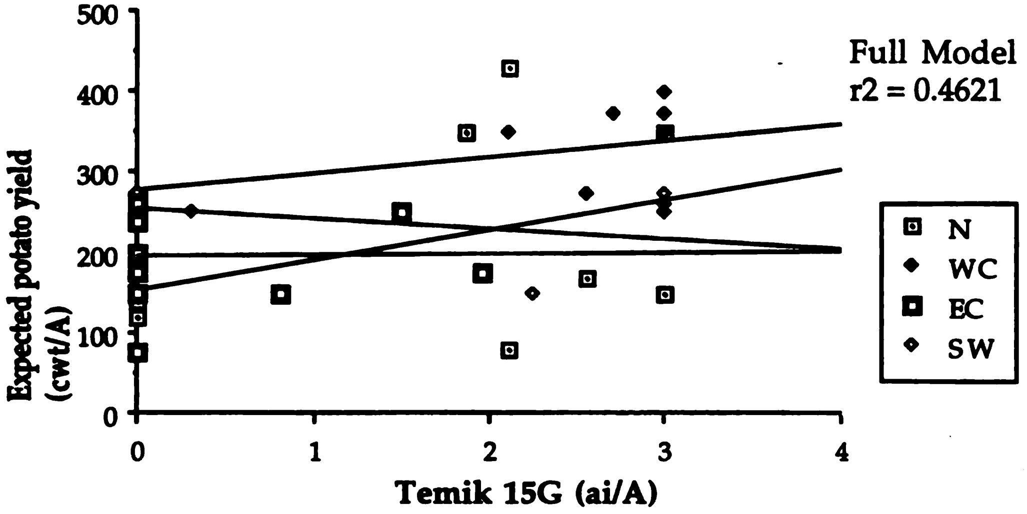


Figure 21. Correlation of Temik 15G inputs to expected yields in Michigan potato production by farming region in 1988 (N: y=153.9+38.3x, r^2=0.112; WC: y=279.2+20.2x, r^2=0.114; EC: y=193.9+1.7x, r^2=0.000; SW: y=254.8-12.5x, r^2=0.095).

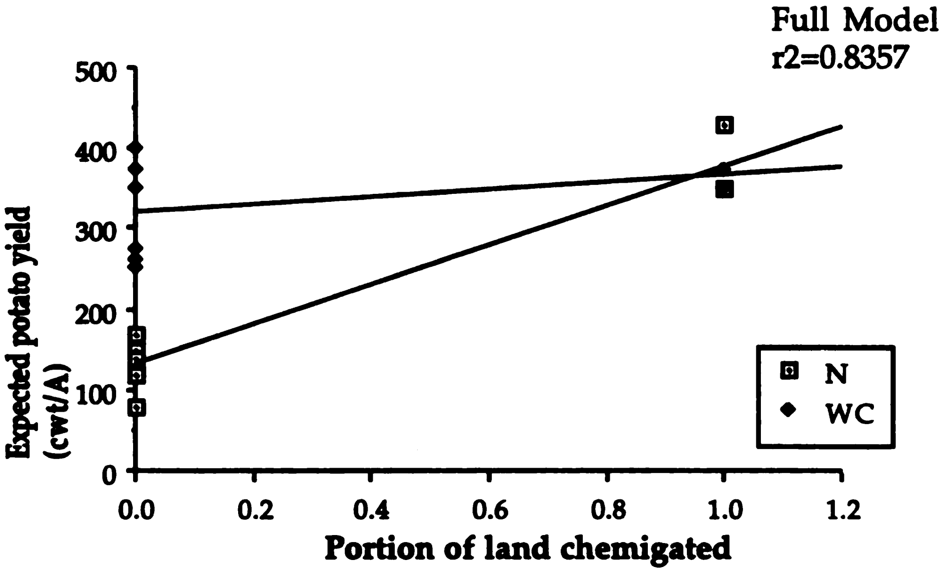


Figure 22. Correlation of portion of acres chemigated to expected yields in Michigan potato production by farming region in 1988 (N: y=132.0+244.7x, r^2=0.926; WC: y=320.6+46.1x, r^2=0.160).

For the Upper Peninsula: Equation 8a

$$Y = 151.49 + 37*X1R + 99.01*X1I$$

For the Northern Region: Equation 8b

$$Y = 151.49 - 19.97*X2R + 33.15*X2I + 3.88*X2T + 209.66*X2C$$

For the West Central Region: Equation 8c

$$Y = 151.49 + 0.85*X3R + 142.57*X3I + 10.61*X3T + 40.71*X3C$$

For the East Central Region: Equation 8d

$$Y = 151.49 + 12.56*X4R + 85.74*X4I - 29.15*X4T$$

For the Southwestern Region: Equation 8e

$$Y = 151.49 + 100.85*X5I - 10.26*X5T$$

where:

X1 = Upper Peninsula
X2 = Northern Region
X3 = West Central Region
X4 = East Central Region
X5 = Southwestern Region

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated
T = Amount of Temik 15G applied (ai/A)
C = 1 if chemigant applied, 0 otherwise

Of the sixteen indicators, seven were significantly different from zero at the $p<0.10$ level (Table 24). These were used to build a smaller model based on region ($n=38$, $df=31$, $k=7$, $s^2=2064.6$, $r^2=0.799$).

For the Upper Peninsula: Equation 9a

$$Y = 135.58 + 42.30*X1R + 109.6*X1I$$

Table 24. A multiple regression model correlating potato yields to rotation schedule, irrigation usage, amount of Temik applied, and chemigation usage by farming region.

Coefficient	Beta	Estimator	P-value
Constant	B0	151.49	0.000
Rotation schedule	R1	37.00	0.023
	R2	-19.97	0.250
	R3	0.85	0.963
	R4	12.56	0.247
Irrigation	I1	99.01	0.051
	I2	33.15	0.677
	I3	142.57	0.017
	I4	85.74	0.014
	I5	100.85	0.015
Temik	T2	3.88	0.886
	T3	10.61	0.580
	T4	-29.15	0.231
	T5	-10.26	0.566
Chemigation	C2	209.66	0.000
	C3	40.71	0.238

For the Northern Region: Equation 9b

$$Y = 135.58 + 241.07*X2C$$

For the West Central Region: Equation 9c

$$Y = 135.58 + 198.68*X3I$$

For the East Central Region: Equation 9d

$$Y = 135.58 + 107.06*X4I$$

For the Southwestern Region: Equation 9e

$$Y = 135.58 + 102.79*X5I$$

where:

X1 = Upper Peninsula
X2 = Northern Region
X3 = West Central Region
X4 = East Central Region
X5 = Southwestern Region

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated
C = 1 if chemigant applied, 0 otherwise

All seven of these parameters were significant at the $p \leq 0.031$ level (Table 25).

After reviewing the impact of specific inputs individually and together, it is important to look at the economics of the production system by region. Average expected yields ranged from 175 cwt/A in the SE to 332 cwt/A in the WC region. Selling prices ranged from 5.50 in the SW, to 8.09 in the N region. Expenses also varied among regions from $366.85/A in the UP to $680.53/A in the WC region. Expected profit ranged from $588.12/A in the EC region to $1549.82/A in the UP (n=3, Table 26). Correlating expenses to return over direct cost (profit), best fit regressions indicated positive correlations in the UP and N regions

Table 25. A revised multiple regression model correlating potato yields to rotation schedule, irrigation usage, and chemigation usage by region.

Coefficient	Beta	Estimator	P-value
Constant	B0	135.58	0.000
Rotation schedule	R1	42.30	0.009
Irrigation	I1	109.60	0.031
	I3	198.68	0.000
	I4	107.06	0.001
	I5	102.79	0.001
Chemigation	C2	241.07	0.000

Table 26. The economics of Michigan potato production by region in 1988.

Region	Expected yield (cwt/A)	Expected selling price ($/cwt)	Expenses ($/A)	Expected profit ($/A)
UP	275.00	7.00	366.85	1549.82
North	223.75	8.09	544.25	1173.45
West Central	332.08	5.56	680.53	1168.53
East Central	194.55	5.51	484.97	588.12
Southwest	237.50	5.50	613.39	680.37
Southeast	175.00	7.00	454.00	771.00

(r^2=0.847, p=0.256; r^2=0.009, p=0.825, respectively), and negative correlations in the WC, EC, and SW regions (r^2=0.023, p=0.638; r^2=0.062, p=0.458; r^2=0.48, p=0.782, respectively). Hence, there is no statistically significant correlation of expenses to profit in any of the regions tested (Figure 23).

Nematicide use model. Of the forty growers surveyed, 50% of them used either a non-fumigant, fumigant, and/or chemigant nematicide as part of their management practice. These growers comprised about two-thirds of the total acreage planted to potato in the surveyed area (Table 27). Two or more nematicides were used in several cases.

There were no significant differences with how these two groups used nutrient inputs. However, there was a greater absolute difference between these two groups in mean nitrogen inputs, so nitrogen was incorporated into the larger regression model (Table 28). Correlating nitrogen inputs to expected potato yield by nematicide usage, it was found that nitrogen inputs did not explain yield variability (r^2=0.000, p=0.947 for growers using nematicides; r^2=0.032, p=0.454 for growers not using nematicides). However, when correlating both nematicide use and nitrogen inputs with expected potato yields simultaneously, it was found that the full model explained 44% of the variability in yields (Figure 24).

Growers that used nematicides tended to rotate for longer periods than those that did not use nematicides (Table 29). Years out of potato did not explain expected yield variability (r^2=0.014, p=0.625 for growers using nematicides; r^2=0.003, p=0.807 for growers not using nematicides). However, when both nematicide usage and number of years out of potato were correlated together, the full model explained 43.74% of the variability in potato yields (Figure 25).

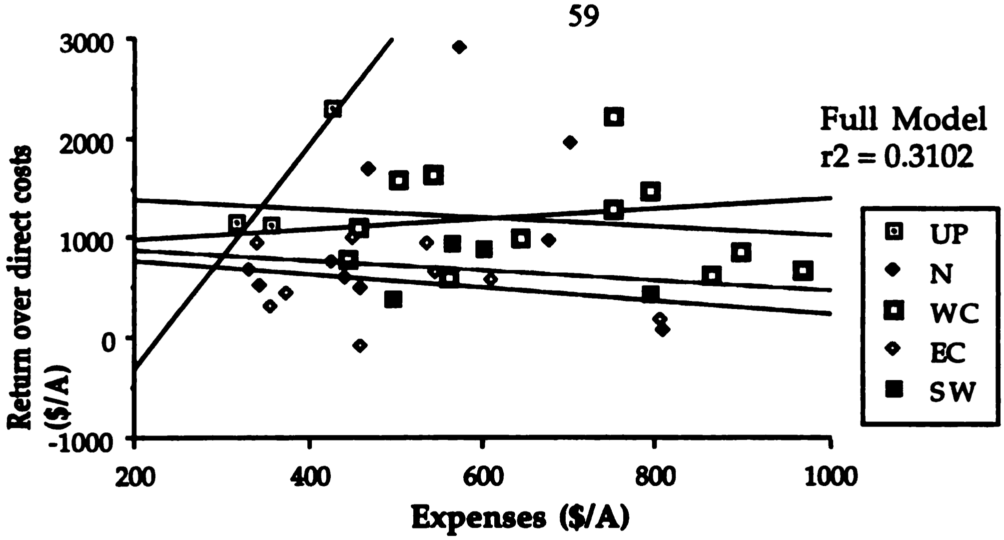


Figure 23. Correlation of direct costs associated with planting and expected yields in Michigan potato production by farming region in 1988 (UP: $y=-2544.4+11.2x$, $r^2=0.847$; N: $y=891.7+0.5x$, $r^2=0.009$; WC: $y=1455.4-0.4x$, $r^2=-0.023$; EC: $y=900.2-0.6x$, $r^2=0.062$; SW: $y=987.6-0.5x$, $r^2=0.048$).

Table 27. An estimate of total Michigan potato production by nematicide use in 1988.

Treatment	Growers (n)	Survey acres	Percent of acreage (%)	State estimate (acres)
Nematicide used	20	6919	67.39	29314.65
No nematicide	20	3347	32.60	14181.00

Table 28. Utilization of chemical inputs (lb/A) by nematicide usage in Michigan potato production in 1988.

Chemical input	Nematicide	No Nematicide
Nitrogen	202.11	161.75
Phorphorus	134.60	137.92
Potassium	221.82	208.00
Sulfur	15.67	5.40

Table 29. Irrigation and rotation schedules in Michigan potato production by nematicide usage in 1988.

Practice	Nematicide	No Nematicide
Irrigation (portion of farms irrigated)	0.982	0.495
Rotation (years out of potato)	1.750	1.250

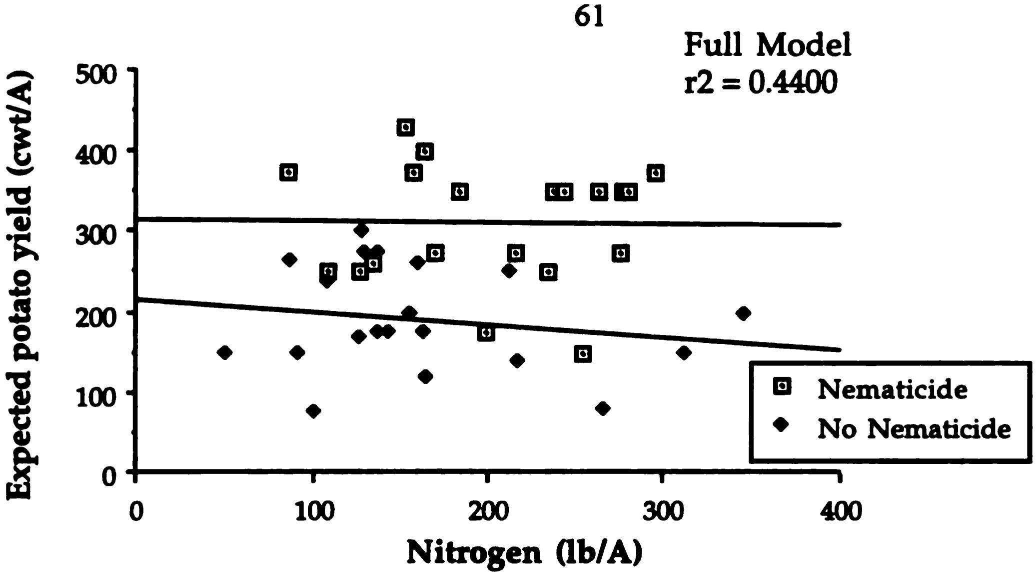


Figure 24. Correlation of nitrogen inputs to expected yields in Michigan potato production by nematicide usage in 1988 (Nematicide: y=314.56-0.02x, r^2=0.000; No Nematicide: y=216.39-0.2x, r^2=0.032).

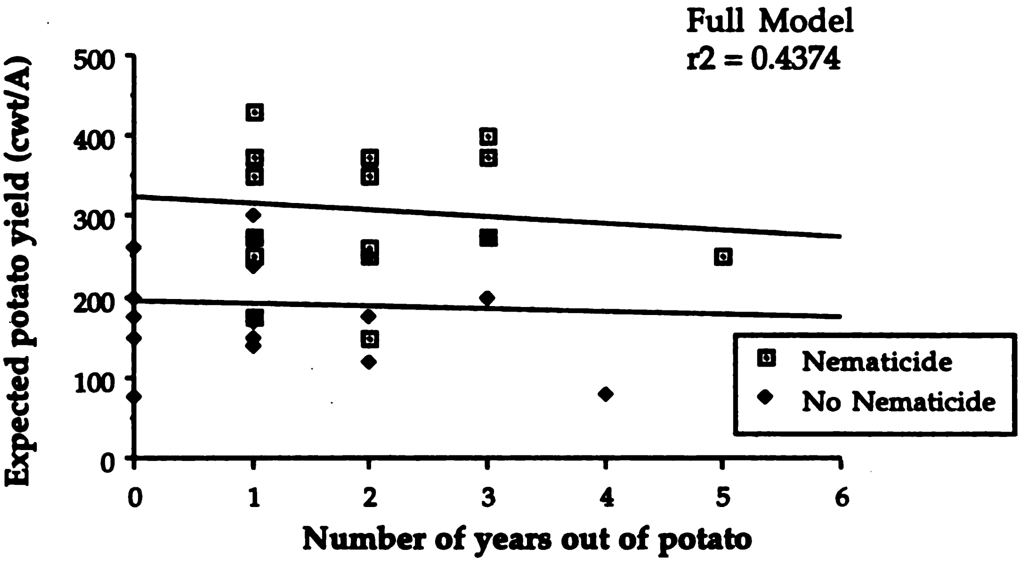


Figure 25. Correlation of rotation (years out of potato) to expected yields in Michigan potato production by nematicide usage in 1988 (Nematicide: y=324.93-8.1x, r^2=0.014; No Nematicide: y=216.39-0.2, r^2=0.032).

In general, growers that used nematicides were also twice as likely to irrigate (Table 29). The correlation of portion of land irrigated to expected potato yields was positive for both nematicide users and non-users alike, although nematicide users were much more dependent on irrigation than non-users (Figure 26). Both correlations were statistically significant (nematicide: r^2=0.283, p=0.016; no nematicide: r^2=0.301, p=0.012). Correlating both nematicide usage and portion of land irrigated simultaneously, increased the r^2 to 0.597.

Sixty-five percent of the growers that did not use nematicides used at-plant insecticides. Of the growers that used nematicides, 100% used at-plant insecticides, 75% used at-plant nematicides, 20% used fumigants and 30% utilized chemigants (Table 30). Growers that used nematicides, applied an average of 2.46 lb ai/A of Temik 15G; while the non-users applied an average of 0.56 lb ai/A (Table 31). Correlating Temik 15G usage with potato yields, nematicide users had a positive correlation with a low r^2 (r^2=0.018, p=0.576) and no nematicide growers had a negative correlation with a higher r^2 (r^2=0.164, p=0.077). Correlating both nematicide usage and Temik 15G simultaneously with expected potato yields, it was found that 47.85% of the variability was explained by both of these factors (Figure 27).

Three multiple regression models were used in an effort to better understand the variability in potato yields. The first model only incorporated pesticide inputs. The second model included these inputs, in addition to the crop rotation schedule, irrigation, and nitrogen inputs. The third model was a revised version of model two.

The chemical input model included a constant and four variables. This model explained 44.99% of the variability in potato yields (n=40, df=35, k=5, s^2=5189.8, r^2=0.4499).

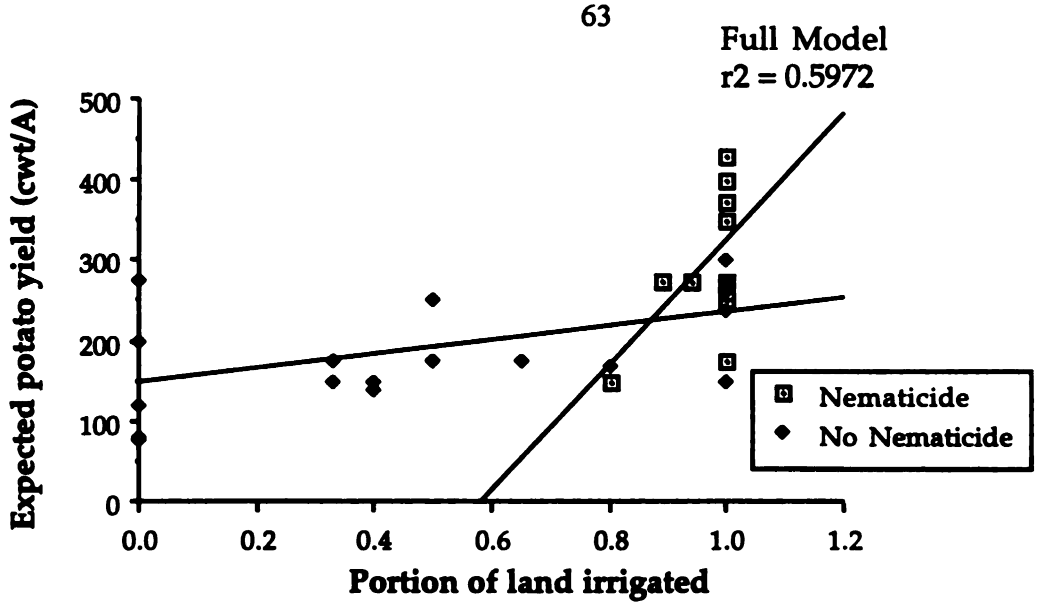


Figure 26. Correlation of portion of irrigated land to expected yields in Michigan potato production by nematicide usage in 1988 Nematicide: y=-455.5+780.7x, r^2=0.283; No Nematicide: y=147.7+87.9x, r^2==0.301).

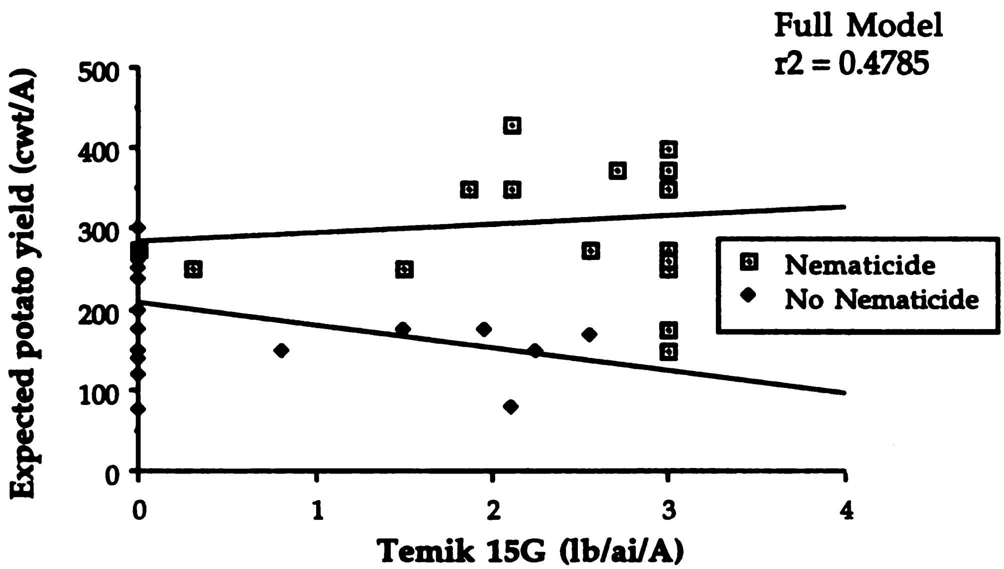


Figure 27. Correlation of Temik 15G inputs to expected yields in Michigan potato production by nematicide usage in 1988 (Nematicide: y=284.09+10.9x, r^2=0.018; Nematicide: y=207.18-28.5x, r^2=0.164).

Table 30. Fraction of Michigan potato growers utilizing at-plant insecticides and nematicides by nematicide usage in 1988.

Chemical input	Nematicide	No Nematicide
At-plant insecticide	1.00	0.65
At-plant nematicide	0.75	0.00
Fumigant	0.20	0.00
Chemigant	0.30	0.00

Table 31. The utilization of at-plant nematicides for Michigan potato production by nematicide usage in 1988.

Chemical input	Nematicide (ai/A)	No Nematicide (ai/A)
Temik 15G	2.46	0.56
Mocap 10G	0.21	0.00
Furadan	0.15	0.02

No nematicide use: Equation 10a

$$Y = 232.12 - 43.66*X1_{API}$$

Nematicide use: Equation 10b

$$Y = 232.12 + 38.908*X2_{NF} + 6.16*X2_{F} + 119.06*X2_{C}$$

where:

X1 = No nematicide use
X2 = Nematicide

Y = Expected potato yield
API = 1 if at-plant insecticide applied, 0 otherwise
NF = 1 if non-fumigant applied, 0 otherwise
F = 1 if fumigant applied, 0 otherwise
C = 1 if chemigant applied, 0 otherwise

Of these five indicators, all except the fumigant were significantly different from zero at the $p<0.20$ level (Table 32). This model did not take into consideration anything other than pesticide inputs. A larger model was developed that included years out of potato, portion of land irrigated and nitrogen inputs as well as pesticide usage. This larger model explained 66.52% of the variability in expected yields ($n=40$, $df=29$, $k=11$, $s^2=3812.2$, $r^2=0.6652$).

No nematicide use: Equation 11a

$$Y = 129.19 + 12.00*X1_{R} + 103.15*X1_{I} - 7.25*X1_{API}$$

Nematicide use: Equation 11b

$$Y = 129.19 - 4.83*X2_{R} + 260.61*X2_{I} - 0.24*X2_{N}$$

$$- 43.36*X2_{NF} - 22.72*X2_{F} + 67.35*X3_{C}$$

where:

X1 = No nematicide use
X2 = Nematicide

Table 32. A multiple regression model correlating potato yields to pesticide input by nematicide usage for Michigan potato growers.

Coefficient	Beta	Estimator	P-value
Constant	B0	232.12	0.000
At plant insecticide	I1	-43.66	0.164
Non-Fumigant	N2	38.91	0.173
Fumigant	F2	6.16	0.876
Chemigant	C2	119.06	0.001

Y = Expected potato yield
R = Number of years out of potato
I = Portion of land irrigated
API = 1 if at-plant insecticide applied, 0 otherwise
NF = 1 if non-fumigant applied, 0 otherwise
F = 1 if fumigant applied, 0 otherwise
C = 1 if chemigant applied, 0 otherwise

Of these eleven indicators, only four were statistically significant at the $p<0.10$ level (Table 33). This smaller model included irrigation and chemigation inputs along with a constant ($n=40$, $df=36$, $k=4$, $s^2=3439.6$, $r^2=0.6250$).

No nematicide use: Equation 12a

$$Y = 144.83 + 91.43*X1_I$$

Nematicide use: Equation 12b

$$Y = 144.83 + 145.25*X2_I + 81.58*X2_C$$

where:

X1 = No nematicide use
X2 = Nematicide

Y = Expected potato yield
I = Portion of land irrigated
C = 1 if chemigant applied, 0 otherwise

All four parameters were statistically significant at the $p<0.05$ level (Table 34).

Of all the individual models presented, the strongest differences in economics is between nematicide users and growers that do not use nematicides. Expected yield, expenses, and expected profit were significantly different from each other at the $p<0.05$ level (t-test, Table 35). The expected yields of potato growers using nematicides averaged 310.75 cwt/acre while farmers that did not use nematicides reported yields that averaged 191.25 cwt/acre. Selling price was not statistically different ($\bar{x}=6.09$ for nematicide users and $\bar{x}=6.37$

Table 33. A multiple regression model correlating potato yields to rotation schedule, irrigation usage, and pesticide usage by nematicide use.

Coefficient	Beta	Estimator	P-value
Constant	B0	129.19	0.022
Rotation schedule	R1	12.00	0.768
	R2	-4.83	0.446
Irrigation	I1	103.15	0.009
	I2	260.61	0.014
Nitrogen inputs	N1	0.00	0.360
	N2	-0.24	0.996
At-plant insecticide	API1	-7.25	0.806
Non-fumigant	NF2	-43.36	0.237
Fumigant	F2	-22.72	0.551
Chemigant	C2	67.35	0.057

Table 34. A revised multiple regression model correlating potato yields to irrigation usage and chemigation inputs by nematicide use.

Coefficient	Beta	Estimator	P-value
Constant	B0	144.83	0.000
Irrigation	I1	91.43	0.000
	I2	145.25	0.008
Chemigant	C2	81.58	0.008

Table 35. The economics of Michigan potato production by nematicide use in 1988.

Economic indicator	Nematicide	No Nematicide
Expected yield*	310.75	191.25
Expected selling price	6.09	6.37
Expenses*	649.37	466.49
Expected profit*	1217.41	722.20

*Indicates a significant difference between nematicide and no nematicide use (t-test).

for non-users). Average expenses ($\bar{x}$=649.37 for users and $\bar{x}$=466.49 for non-users) and expected profit ($\bar{x}$=1217.41 for users and $\bar{x}$=$722.20 for non-users) were statistically different ($p<0.05$ level). Their was a negative correlation when expenses ($/A) were regressed with return over direct costs. When both expenses and nematicide use were correlated simultaneously with return over direct cost, the model only explained 21.85% of the variability in return over direct costs (Figure 28).

Rotation model. Of the 40 growers surveyed 50% of them used a rotation scheme with one year out of potato production (Table 36). This accounted for 63% of the surveyed acreage. About 14% of the acreage was continuous potato, 18% two years out of potato, and the remainder (ca. 5% three or more years out). Four and five years out of potato were not included in the linear model analysis because each had an n=1.

There were no significant differences among these rotation schemes on nutrient inputs (Table 37). Nitrogen inputs averaged from 121.79 lb/A for growers that do not rotate to 193.30 for growers who are out of potato for a single year.

The portion of land irrigated ranged from 37.9% for growers that do not rotate, to 90% for growers out of potato for one year (Table 38). Correlating portion of land irrigated to expected potato yields, each rotation scheme had a positive correlation (Figure 29). The correlation was not statistically significant for 0 years out of potato (r^2=0.515, p=0.172) and 3 years out of potato (r^2=0.387, p=0.141), but was statistically significant for 1 year out of potato (r^2=0.539, $p<0.001$) and for two years out of potato (r^2=0.568, p=0.038). Correlating both portion of land irrigated and years out of potato with expected potato yields simultaneously, the model explained 54.84% of the variability in potato yields.

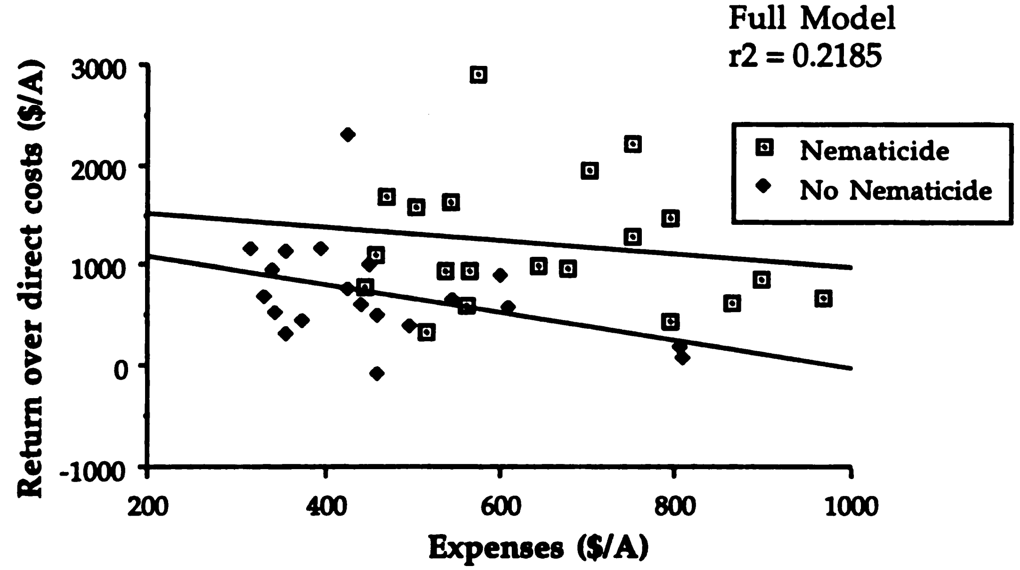


Figure 28. Correlation of direct costs associated with planting and expected yields in Michigan potato production by nematicide usage in 1988 (Nematicide: y=1632.2-0.64x, r^2=0.024; No Nematicide: y=1377.8-1.41x, r^2=0.150).

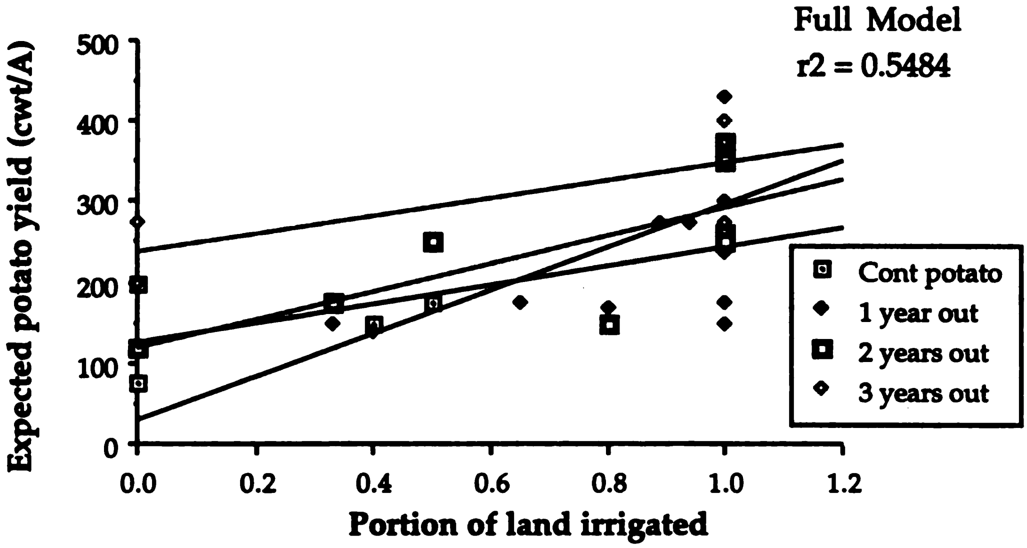


Figure 29. Correlation of portion of irrigated land to expected yields in Michigan potato production by years out of potato in 1988 (Cont potato: y=127.46+117.4x, r^2=0.515; 1 year out: y=29.334+266.0x, r^2=0.387; 2 years out: y=119.2+173.3x, r^2=0.539; 3 years out: y=237.5+112.5x, r^2=0.568).

Table 36. An estimate of total Michigan potato production by rotation schedule in 1988.

Rotation schedule (years out of potato)	n	Surveyed acres	Percent surveyed	Estimated MI production (acres)
0	5	1425	13.88	6038.14
1	20	6532	63.62	27677.96
2	8	1868	18.19	7915.25
3	5	444	4.32	1881.36
4	1	22	0.21	93.22
5	1	75	0.73	317.80

Table 37. The utilization of nutrient inputs (lb/A) by rotation schedule in Michigan potato production in 1988.

Rotation schedule	Nitrogen	Phosphorus	Potassium	Sulfur
0	121.79	70.40	241.67	21.60
1	193.30	154.20	202.42	7.71
2	183.93	145.50	222.75	15.00
3	187.57	114.87	232.31	7.84
4	266.00	114.00	234.00	0.00
5	127.00	162.00	162.00	0.00

Table 38. Portion of farms under irrigation in Michigan potato production by rotation schedule in 1988.

Rotation schedule	n	Irrigation (portion of farms irrigated)
0	5	0.379
1	20	0.900
2	8	0.704
3	5	0.600
4	1	0.000
5	1	1.000

In addition to irrigation, the impact of chemical nematicides and insecticides were analyzed. At least 75% of the growers used an at-plant insecticide. Growers that did not rotate, did not use nematicides. Growers that rotated out of potato at least one year used a variety of types of nematicides (at-plant nematicides, fumigants and chemigants). However, a large portion of each category of grower did not use nematicides (Table 39). Temik 15G was most predominately used by growers that rotated out of potato for two years (Table 40).

A chemical scaling was developed to better understand the relationship between pesticide usage and potato yields. Chemicals were assigned a numerical value based on the toxicology of the pesticide. The following numerical values were assigned:

At-plant insecticide	1 or
At-plant nematicide	2
Fumigant	3
Chemigant	4

The largest value a grower could receive was a 9, because growers were not assigned a number for both an at-plant insecticide and at-plant nematicide. If enough of the pesticide was applied at an appropriate level to have nematicidal properties a 2 was assigned (i.e., if Temik 15 G was applied at the rate of 3.0 lb ai/A). The chemical scaling was correlated with expected potato yields for the four different rotation schemes. It was found that all schemes had a positive correlation with chemical scaling. The only regression that was statistically significant was for one year out of potato (r^2=0.535, $p<0.001$). The other three regressions (no rotation, two years out, and three years out) were not statistically significant (r^2=0.033, p=0.771; r^2=0.459, p=0.065; and r^2=0.138, p=0.539, respectively).

Table 39. Portion of Michigan potato growers utilizing at-plant insecticides and nematicides by rotation schedule in 1988.

Rotation schedule	At-plant insectide	At-plant nematicide	Fumigant	Chemigant	No nematicide
0	0.800	0.000	0.000	0.000	1.000
1	0.850	0.350	0.050	0.200	0.450
2	0.750	0.625	0.250	0.250	0.375
3	0.800	0.400	0.200	0.000	0.400
4	1.000	0.000	0.000	0.000	1.000
5	1.000	1.000	0.000	0.000	0.000

Table 40. The utilization of at-plant nematicides for Michigan potato production by rotation schedule in 1988.

Rotation schedule	Temik 15G (ai/A)	Mocap 10G (ai/A)	Furadan (ai/A)
0	0.000	0.000	0.000
1	1.581	0.135	0.170
2	2.063	0.000	0.000
3	1.710	0.000	0.000
4	2.100	0.000	0.000
5	1.500	1.500	0.000

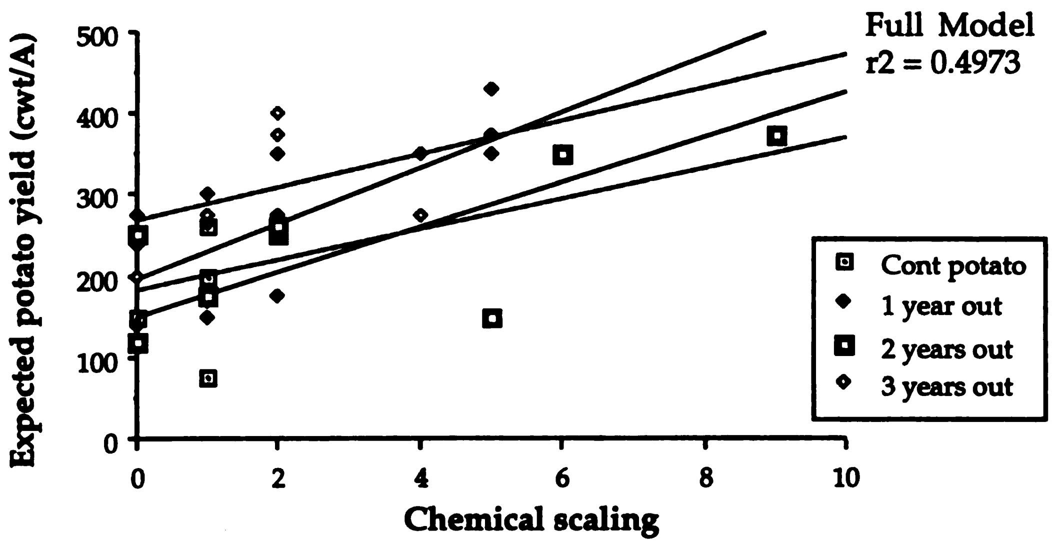


Figure 30. Correlation of chemical nematicide usage and expected yields in Michigan potato production by years out of potato in 1988 (Cont potato: $y=150.0+27.5x$, $r^2=0.033$; 1 year out: $y=195.3+34.6x$, $r^2=0.535$; 2 years out: $y=181.7+19.1x$, $r^2=0.459$; 3 years out: $268.2+20.5x$, $r^2=0.138$).

A multiple regression model was utilized to assess the impact of irrigation and chemical scaling by rotation schedule. The following equation has twelve estimated values ($n=38$, $df=27$, $k=11$, $s^2=3317.6$, $r^2=0.702$):

For continuous potato: Equation 13a

$$Y = 127.46 + 117.44*X0_I$$

For one year out of potato: Equation 13b

$$Y = 44.98 + 194.86*X1_I + 23.48*X1_S$$

For two years out of potato: Equation 13c

$$Y = 126.64 + 120.07*X2_I + 9.62*X2_S$$

For three years out of potato: Equation 13d

$$Y = 237.50 + 175*X3_I - 31.25*X3_S$$

where:

X0 = Continuous potato
X1 = One year out of potato
X2 = Two years out of potato
X3 = Three years out of potato

Y = Expected potato yield
I = Portion of land irrigated
S = Numerical value between 0 and 9, depending on pesticide applications

Of the eleven parameters tested, nine of them were significant at the $p<0.20$ level. The only two parameters that did not pass this evaluation were the constant for one year out of potatoes, and the chemical scaling for two years out of potatoes (Table 41).

Excluding these two parameters from the model, it was found that all parameters were at least significant at the $p<0.20$ level (Table 42). The equations for this model are as follows ($n=38$, $df=29$, $k=9$, s2=3284.2, $r^2=0.753$).

Table 41. A multiple regression model correlating potato yields to irrigation and pesticide scaling by rotation schedule.

Coefficient	Beta	Estimator	P-value
Constant	B0	127.46	0.002
	B1	44.98	0.460
	B2	126.64	0.009
	B3	237.50	0.000
Irrigation	I0	117.44	0.102
	I1	194.86	0.009
	I2	120.07	0.123
	I3	175.00	0.014
Chemical scaling	C1	23.48	0.003
	C2	9.62	0.294
	C3	-31.25	0.137

Table 42. A revised multiple regression model correlating potato yields to irrigation and pesticide scaling by rotation schedule.

Coefficient	Beta	Estimator	P-value
Constant	B0	127.46	0.002
	B2	119.18	0.012
	B3	237.50	0.000
Irrigation	I0	117.44	0.100
	I1	243.55	0.000
	I2	173.34	0.005
	I3	175.00	0.013
Chemical scaling	C1	23.08	0.003
	C3	-31.25	0.134

For continuous potato: Equation 14a

$$Y = 127.46 + 117.44*X0_I$$

For one year out of potato: Equation 14b

$$Y = 243.55*X1_I + 23.04*X1_S$$

For two years out of potato: Equation 14c

$$Y = 199.18 + 173.34*X2_I$$

For three years out of potato: Equation 14d

$$Y = 237.50 + 175*X3_I - 31.25*X3_S$$

where:

X0 = Continuous potato
X1 = One year out of potato
X2 = Two years out of potato
X3 = Three years out of potato

Y = Expected potato yield
I = Portion of land irrigated
S = Numerical value between 0 and 9, depending on pesticide applications

When reviewing the economics of potato production by rotation scheme, mean potato yields ranged from 80 cwt/A in the one farm that was four years out of potato to 305 cwt/A for growers that were three years out of potato (n=5). Selling prices ranged from a low of \$5.23 to \$11.00 per cwt. Expected profit ranged from \$73.17 to \$1107.93 (Table 43).

When correlating the direct costs associated with potato production with returns over direct cost, continuous potato and one year out of potato had a positive correlation. However, expenses did not explain very much of the variability in return over direct costs and these correlations were not statistically significant at the $p<0.05$ level (For continuous potato:

Table 43. The economics of Michigan potato production by rotation schedule in 1988.

Region	Expected yield (cwt/A)	Expected selling price ($/cwt)	Expenses ($/A)	Expected profit ($/A)
0	172.00	5.23	444.52	457.28
1	269.75	6.05	544.75	1107.93
2	241.25	6.81	531.96	976.38
3	205.00	6.10	720.13	1099.87
4	80.00	11.00	806.83	73.17
5	250.00	6.00	536.43	963.57

r^2=0.036, p=0.759); and For one year out of potato: r^2=0.122; p=0.132). The correlation was negative for two and three years out of potato. The negative correlation was not significant for two years out of potato (r^2=0.043, p=0.621). The negative correlation was significant for three years out of potato and this model explained much more of the variability in return over direct costs (r^2=0.798, p=0.041, Figure 31).

DISCUSSION

In comparing the results of the models, it is necessary to divide the models into two basic types. First the series of single effect models will be examined, then a series of multiple regression models.

<u>Single-effect (simple linear regression models)</u>. Comparing the r^2 values for the various models that were developed, the strongest relationship between expected yields and a single-effect is when the data are stratified into regions of the state of Michigan (Table 44). The r^2's range from 0.462 for Temik to 0.836 for chemigation usage as the single effect. Hence, if one had to estimate potato yields with only one input, proportion of chemigation usage would be the input of choice if that farm was located in the northern or north central portion of the state. In all other parts of the state, irrigation would be the best indicator. Chemigation estimates are limited to the north and west central regions because those were the only regions reporting chemigation use in the survey. However, the southwest portion of the state was not included in this analysis because there were only two farmers surveyed in this area and they both reported the same yield. Hence, for growers in the south western part of the state the best indicator would be portion of land irrigated if their nematide usage was known or irrigation based on farm size, if that parameter was known. These r^2 were

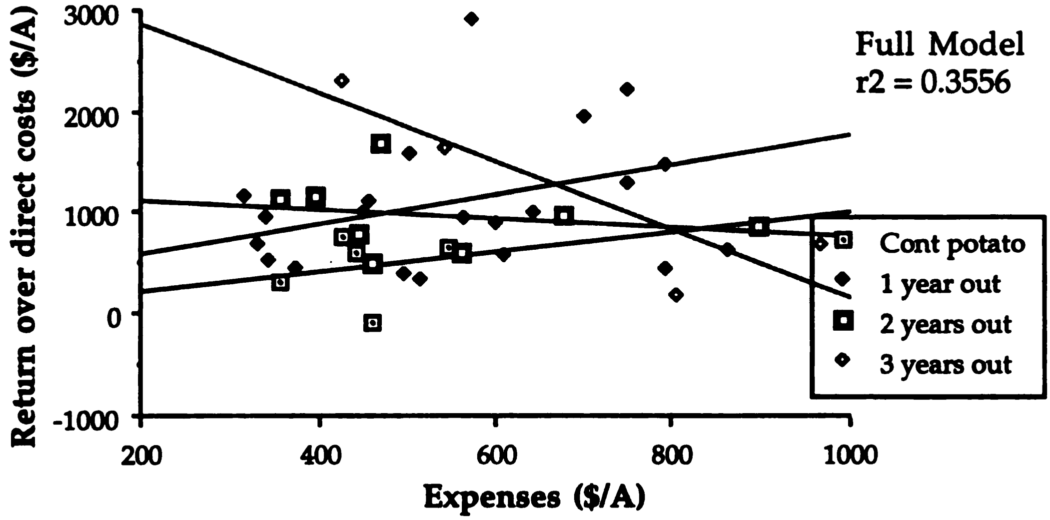


Figure 31. Correlation of direct costs associated with planting and expected yields in Michigan potato production by years out of potato in 1988 (Cont potato: y=27.8+1.0x, r^2=0.036; 1 year out: y=306.6+1.5x, r^2=0.122; 2 years out: y=1213.4+ 0.4x, r^2=0.043; 3 years out: y=3565.6-3.4x, r^2=0.798).

Table 44. A summary of the single effect models for potato yield prediction for the state as a whole, or by farm size, region, nematicide use, or rotation schedule (r^2).

Effect	MI	Farm size	Region	Nema- ticide	Rotation
Irrigation	0.4370	0.5572	0.7191	0.5972	0.5484
Rotation	0.0070	0.2865	0.5307	0.4374	---
Temik	0.1720	0.3631	0.4621	---	---
Chemigant[1]	0.3110	0.3318	0.8357	---	---
Scaling	0.0000	---	---	---	0.4973
Expenses regressed with return over direct cost (profit)					
Expenses	0.0000	0.2501	0.3102	0.2185	0.3556

generated on the basis of the best overall indicator considering a group of farms, for example this might be a good statistic for a state cooperative extension agent to use if the goal was to assess the potential yield for 20 growers.

If a single grower was to use these models, and would like to assess the advantage of irrigation, chemigation, or rotation, then that grower would more than likely use the single regression lines presented in the figures. For example, if a medium size grower in Montcalm county wanted to assess the impact of irrigation on the farm, one would examine the models for region and for size that regressed portion of land irrigated with expected yield and use the model with the highest r^2 value. Regressing portion of land irrigated with expected yield by farm size, one finds an r^2 of 0.320 for medium sized farms (Figure 14) and 0.119 for farms in Montcalm County (Region 3, Figure 20). Therefore, it would be better to use the model associated with farm size. And estimate that going from 0 to 100% of the farm irrigated would roughly double yield ($y=165.1 + 144.96*x$, Figure 14).

In addition, it is interesting to look at the impact of stratifying the data on models regressing return over direct costs with expenses. In the state as a whole, there does not appear to be a relationship between the two. However, after stratifying the data into farm size, region, nematicide use and rotation schedule, it is found that the strongest relationship between expenses and expected profits (excluding fixed costs) is when the data are stratified along the lines of years out of potato (Table 44).

Multiple regression models. Similar to the single effect models or simple linear models, region models provided the best indicator of yield. The large region model gave the best r^2 value, which is not too surprising because it also had the largest number of parameters in the model (Table 45). However, the version with fewer parameters cut the number of

Table 45. A summary of the multiple regression models for the state of MI, and by farm size, region, nematicide usage, and rotation schedule.

Model	r^2	No. of parameters	Inputs required
MI Model	0.639	9	N-P-K-S Irrigation Rotation Temik Chemigation
Farm size	0.689	12	Rotation Irrigation Temik Chemigation
Smaller farm size	0.647	6	Rotation Irrigation Chemigation
Region	0.815	16	Rotation Irrigation Temik Chemigation
Smaller region	0.799	7	Rotation Irrigation Chemigation
Nematicides alone	0.450	5	API Nonfumigant Fumigant Chemigation
Nematicide	0.665	11	Rotation Irrigation Nitrogen API Nonfumigant Fumigant Chemigation
Smaller nematicide	0.625	4	Irrigation Chemigation
Rotation	0.702	11	Irrigation Chemical scaling
Smaller rotation	0.753	9	Irrigation Chemical scaling

parameters in more than half, and still provided a reasonably accurate r^2. Once again, the region models did not apply to the southeast portion of the state, here the best model would be the smaller version of the rotation schedule model ($r^2 = 0.753$).

Summary. In practice, each of these models provided a fairly good r^2 value and an accompanying p-value < 0.001. Therefore, when assessing the most appropriate model to use it is important to examine both the inputs, and the ease, reliability, and cost of obtaining that information, as well as the r^2 value. For example, the difference in r^2 between the small nematicide model and the large region model is about 0.20; however, the number of separate parameters is reduced from 16 to 4. Hence, it may be worth it to sacrifice some accuracy for the economics of collecting the data or for efficacy of data collection.

ASSESSMENT OF INTRA- AND INTER- SOLANUM TUBEROSUM CULTIVAR RESPONSES TO PRATYLENCHUS PENETRANS AND VERTICILLIUM DAHLIAE

INTRODUCTION

The root-lesion nematode, Pratylenchus penetrans (Cobb, 1917) Filipjev and Schurrmans Stekhoven, 1941, and the fungus, Verticillium dahliae, cause a disease complex of potato (Rowe et al. 1988, MacGuidwin and Rouse 1990) which usually results in low in tuber initiation, growth and development. Therefore, the combined presence of these organisms make them an important economic pest complex in the north central region of the United States (Kotcon et al. 1984, Rowe 1984). The disease symptoms often go undetected because the potato plant appears healthy until very late in the growing season. Infected potato plants usually senese about two weeks earlier than normal plants, resulting in low potato yields. In addition, improved cultivars and management techniques can often mask the yield loss (Rowe et al. 1987).

This disease complex can have a synergistic effect on potato tuber production (Riedel and Rowe 1985). Although the exact mechanisms of the interaction are unknown, several other Pratylenchus species (e.g., P. scribneri and P. crenatus have been tested, but none have produced the synergism associated with P. penetrans (Riedel and Rowe 1985). Hence, it is believed that the synergistic reaction is not due to wounding.

The amount of yield loss has been very difficult to predict (Francl et al. 1987, Johnson 1988, Wheeler et al. 1994), and often times varies significantly from year to year (Rowe et al. 1985).

One possible management approach to the control of early die is the use of resistant cultivars (Davis 1985). The following research was an effort to identify the synergistic relationship between the potato early die causal agents and ten different potato cultivars in Michigan and quantitatively compare the relationship among cultivars.

OBJECTIVES

The objective of this study was to assess the potential damage from potato early die both within each cultivar and between cultivars and to assess population densities of Pratylenchus penetrans and Verticillium dahliae.

METHODOLOGY

Three experiments were initiated in an attempt to quantify the response of ten cultivars to predetermined inoculated levels of Pratylenchus penetrans (PP) and Verticillium dahliae (VD). The first experiment utilized microtiles, the second was a greenhouse study, and the third was a field study.

Inoculum preparation

Pratylenchus penetrans was cultured at Michigan State University and was originally obtained in Wisconsin. It was cultured on alfalfa callous in tubes.

The Verticillium dahliae was also received from Wisconsin. Plugs of V. dahliae grown on alcohol-strep medium were transferred to 250 ml flasks containing 50 ml of

Czapek's Box Broth media. Flasks were plugged, placed on a shaker for four days. Then 1-2 ml aliquots were transferred to 100x15 ml petri plates containing 0.25 strength potato dexdrose agar. Plates were placed in dark at room temperature for 14 to 21 days before inoculating potato tubers.

Jolly Road Microtile Study

Ten cultivars of potato were inoculated with four treatments (check, PP, VD, PP/VD) in a randomized block design replicated nine times at a research site on the campus of Michigan State University. A sandy loam soil was used. It was treated with methyl bromide prior to the study and was placed in the microtiles prior to planting. The tubers were placed in ten liter microtiles with one non-treated tuber planted in between each of the microtiles. Nematodes were transferred within the alfalfa callous and placed directly on the tuber. Verticillium was scraped from the petri plate directly onto the tuber as well. The control treatment had pathogen-free callous and medium placed on the tuber. Herbicides and insecticides were used throughout the growing season as needed. The tubers were inoculated with 39 nematodes/100 cc of soil and 700 propagules of Verticillium/100 cc of soil.

MSU Greenhouse Study

Five of the previous ten potato cultivars were inoculated with five treatments (control, low PP, high PP, VD, PP/VD) in a randomized block design replicated thirteen times. Sandy loam soil was steam sterilized prior to the inoculation. Both the nematodes and Verticillium were put into slurries and aliquots were injected into the soil. The pots contained 2500 cc of soil. The low nematode treatment contained 28 PP per 100 cc of soil, with the high level averaging 280 nematodes. Verticillium levels were 2534 propagules per 100 cc of soil.

Montcalm County Potato Research Farm Field Study

The other five cultivars were used for this study (Red Dale, Kennebec, Hudson, Desiree and Rosa). A randomized block design was replaced thirteen times. Soil was fumigated with methyl bromide before planting. Each tuber was placed directly in the soil with a buffer tuber planted in between each experimental unit to act as a barrier. No artificial barrier was placed between tubers. It was estimated that each plant had 20 liters of soil in direct association. Therefore, estimated inoculum levels were 3.5 PP per 100 cc of soil at the low treatment level, 35 PP at the high level, and 316 propagules of Verticillium per 100 cc of soil.

Statistical analysis

Yuber yields (g/plant), the number of Pratylenchus penetrans (1.0 g of root tissue and 100 cc of soil) and propagules of Verticillium dahliae (1 g of stem tissue) were quantified at harvest. Soil nematode counts were processed through centrifugal-flotation technique (Jenkins 1964). Potato root samples were cut, emerged in a mercury solution and placed on a shaker for 48 hr (Bird 1971).

The data were analyzed utilizing two different methods, depending on the objective of the analysis. When the objective was intra-cultivar specific, regression analysis was utilized in an effort to see if the nematode and Verticillium had individual or joint impact on tuber yields. A series of four different regression models were generated for each site. The first two models used the data points for PP and VD as they were quantified. The first model was a multiple regression model that had four parameters:

constant, PP, VD, and PP*VD. The second model had two parameters: constant and PP*VD.

The other two models used a transformation of the PP and VD datum points. The natural log (n+1) was used because it adhered to the hypothesis that the more of either pathogen that is present, the less impact each individual pathogen will have on the yield (Francl et al. 1987). The models were slightly different at Montcalm, because there were no root nematode data. By the time of harvest, the roots had deteriorated on some of the cultivars. Initially, the data were analyzed using the soil PP counts and VD, but the interaction terms were rejected so strongly that in all the cultivars (with p-values ranging from 0.406 to 0.826, Table 13[1]) that the models were analyzed without that term altogether. The second objective was inter-cultivar specific, and a series of ANOVAS were utilized to assess the relative impact of the pathogens on the ten different cultivars studied. SYSTAT and Minitab were the two statistical packages utilized in this study.

RESULTS

The first question that needed to be addressed was whether the inoculations were successful. A three-way ANOVA was used, dividing the source of variation among cultivar, treatment and replication for P. penetrans and V. dahliae for a harvest sampling date. At all three sites nematode inoculation was fairly successful as evidenced by the low p-value for treatment (<0.001, Table 1) and the means themselves (Table 2). The plots were contaminated with Verticillium by harvest (Table 3) at all three sites. The

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All tables are numbered in relation to the sequence of experiments performed. They are found at the end of the chapter.

contamination was greatest at Jolly Road and least in the greenhouse (Table 1). Since there was a great deal of contamination, a series of regressions were used, along with standard mean separation techniques.

Intra-cultivar specific observations

Red Dale. The cultivar Red Dale was evaluated at Jolly Road and at Montcalm. Yield averages ranged from 259 g/plant in the PP/VD treatment to 321 g/plant in the check (Table 4). A two-way ANOVA with treatment and replication as sources of variation returned a p-value of 0.587 (Table 5), which means there is a lot of variability in the replications and one could accept the null hypothesis (there are no differences among treatments) and be correct about 58.7% of the time. At Montcalm, in the field study, all of the treatments out-performed the nematode and verticillium-free control (Table 4). Although the likelihood of rejecting the null hypothesis was much larger (p-value=0.124, Table 5), the yield differences were atypical. In addition, the data were used to fit multiple regression models for each cultivar. The PP values ranged from 0 to 406.9 PP/g of root tissue and 100 cc of soil at Jolly Road (Table 6) and from 0 to 14 PP/100 cc of soil at Montcalm (Table 8). Verticillium ranged from 0 to 3383.3 propagules/g stem tissue (ppg) at Jolly Road (Table 6) and from 0 to 15 ppg stem tissue at Montcalm (Table 8). The best fit regression line at the Jolly Road site came from the natural log transformations which indicated that there was enough population present to cause less damage per individual pathogen (Tables 9 and 10). The best fit had an r^2 of 0.179 associated with it (Table 10). Likewise, with the interaction term only, the natural log had a better fit (r^2=0.069). The regression model has a negative slope (decrease in yield) for PP and a positive slope for VD and VD*PP. Although the r^2 was less at Montcalm, the slope trend was similar in that the only negative parameter was PP in any of the models (Tables 13 and 14).

Kennebec. The cultivar Kennebec was evaluated at Jolly Road and at Montcalm. Yield averages ranged from 261 g/plant in the PP/VD to 318 g/plant in the PP only plot at Jolly Road (Table 4). A two-way ANOVA with treatment and replication as sources of variation returned a p-value of 0.754, which meant that there were no differences among treatments (Table 5). At Montcalm, the yield averages ranged from 1886 in the PP/VD treatment to 2401 g/plant in the check (Table 4). Here, the ANOVA returned a p-value of 0.495 (Table 5). Although variance was too high to give statistical significance to the interpretation, in both trials the lowest yield averages were in the PP/VD plot.

The range of values for the linear models from the Jolly Road data was from 0 to 636 PP/100 cc of soil and 1 g of root tissue, 33 to 4367 VD ppg of stem tissue, and the joint interaction term ranged from 0 to ca. 2 million (Table 6). At the Montcalm site, the PP values ranged from 0 to 7 PP/100 cc of soil and VD ranged from 0 to 52.2 ppg of stem tissue (Table 8). The best fit regression model for Jolly Road resulted in an r^2 of 0.156 (Table 9). It used non-transformed data. The only negative slope was from the PP*VD interaction parameter. However, the parameter was extremely close to zero. At Montcalm, the best fit r^2 was much lower (r^2=0.032, Table 14). It was obtained from the transformed data. Both the PP and VD parameters had negative estimators.

Superior. The cultivar Superior was evaluated at Jolly Road and in the greenhouse. Yield averages ranged from 238 g/plant in the PP/VD treatment to 296 g/plant in the VD only plots at Jolly Road. In the greenhouse, yields were much lower than at either of the other two sites, they ranged from 11.6 in the VD only plot to 23.1

g/plant in the check. An ANOVA detected no treatment differences at Jolly Road (p-value=0.897), but there may have been differences in the greenhouse (p-value=0.102).

To fit the regression models, PP ranged from 0 to 900 nematodes per 1 g of root tissue and 100 cc of soil and VD ranged from 0 to 2850 ppg of stem tissue. Their interaction ranged from 0 to 1.9 million (Table 6). In the greenhouse, PP ranged from 0.0 to 560 while VD ranged from 0 to 39.4 propagules. The interaction term ranged from 0.0 to 4761 (Table 7). The best fit model for Jolly Road was with the untransformed data (r^2=0.194, Table 9). In this case, the only parameter that was negative was the interaction term. Although the interaction parameter coefficient was small (-0.001), it had a p-value of 0.061 associated with it, which meant that it was nearly statistically significant (p-value=0.05). The fit was much lower for the greenhouse regression (r^2=0.051), but the untransformed data fit better than the natural log transformation as well. However, none of the pathogen parameters had negative coefficients in the natural log transfer.

Russet Burbank. The cultivar Russet Burbank was evaluated at Jolly Road and at the greenhouse. Yield averages ranged from 210 g/plant in the PP/VD plots to 353 g/plant for the check treatment at Jolly Road (Table 4). The two way ANOVA partitioning the variance into treatment, replication and error resulted in a significant p-value of 0.037 (Table 5). In the greenhouse, yield averages ranged from 0.5 in the PP/VD treatment pots to 4.2 g/plant in the low PP plot (Table 4). The ANOVA was much less likely to reject the null hypothesis for the greenhouse study (p=0.549, Table 5).

The data set for the multiple linear regression models for the Jolly Road site ranged from 0 to 550 PP/1 g of root tissue and 100 cc of soil with VD ranging from 16.7 to 2750 propagules per gram of stem tissue. Their joint interaction ranged from 0 to

273,000 (Table 6). Although both full models had a negative coefficient of joint interaction, the transformed data provided a slightly better fit (Tables 9 and 10). In the greenhouse, the range for PP was from 0 to 823 nematodes per gram of root tissue plus 100 cc of soil, while VD went from 0 to 19 propagules per g of stem tissue. Their joint interaction ranged from 0 to 368 (Table 7). Neither regression fit as well as the previous data set (r^2=0.036 for untransformed data; r^2=0.075 for transformed data set, Tables 11 and 12).

Norkota Russett. The cultivar Norkota Russett was evaluated as Jolly Road and in the greenhouse. Yield averages at Jolly Road ranged from 270 g/plant in the VD only plot to 314 g/plant in the check. There were no differences among treatments (p-value=0.774, Table 5). In the greenhouse, the ranges were from 16.3 in the PP only to 24.0 g/plant in the check. The probability of Type I error (rejecting the null hypothesis, when it should have been accepted), was much lower in this experiment (p-value=0.324).

At harvest PP ranged from 0 to 171 and VD from 0 to 1668 at the Jolly Road site, while their joint interaction ranged from 0 to ca. 200,000 (Table 6). The best fit was with the transformed data (r^2=0.117, Table 10). In this case, both pathogens had negative coefficients associated with their parameters and the interaction had a positive coefficient. In the greenhouse, the pathogen counts ranged from 0 to 288 PP/1 g of root tissue and 100 cc of soil and 0 to 18.6 VD/1 g of stem tissue, with the joint interaction ranging from 0 to 297.6. The best fit linear model once again was with transformed data. However, this time the only negative coefficient was with the interaction parameter. Both others were positive. The fit was not as good (p-value=0.070, Table 12).

Hudson. The cultivar Hudson was evaluated at Jolly Road and at Montcalm. At Jolly Road the average yields ranged from 212 g/plant in the PP/VD plots to 350 g/plant in the VD only treatment ($p=0.200$, Table 5). Similar results occurred at Montcalm, the lowest yield was also in the PP/VD with 1900 and the highest in the VD only (1900 g/plant). However, this experiment had more variability associated with it ($p=0.710$, Table 5).

At Jolly Road, at harvest PP counts ranged from 0 to 636 per 1 g of root tissue plus 100 cc of soil, while VD counts ranged from 0 to 7050 propagules/1 g of stem, which was almost twice the level in any other cultivar (Table 6). The natural log transformed data provided the best fit ($r^2=0.189$, Table 10), with negative coefficient parameters for PP and VD, and a positive coefficient for the interaction. The PP range at Montcalm was from 0 to 8.0 nematodes per 1 g of root tissue and 100 cc of soil, while the VD ranged from 0 to 29.8 propagules/1 g of stem tissue. The best fit at Montcalm was with the untransformed data ($r^2=0.125$, Table 14). The only negative coefficient was with the PP parameter.

Desiree. The cultivar Desiree was evaluated at Jolly Road and at Montcalm. At Jolly Road, the average tuber yields ranged from 230 g/plant in the PP only plot to 301 g/plant in the VD only treatment (p-value=0.624, Table 5). At Montcalm, the lowest average yield was in the check and the highest was also in the VD only (Table 4). The p-value was lower than at Jolly Road (p-value=0.292, Table 5).

PP ranged from 0 to 171 per g of root tissue and 100 cc of soil at Jolly Road with VD ranging from 33 to 4100 propagules/g of stem tissue. Their joint interaction ranged from 0 to ca. 2.5 million. The best fit linear model for Desiree was with the natural log transformed data. In fact, this model explained more of the variability in tuber yield than any of the other models for any of the cultivars (r^2=0.347). The model was statistically significant. Both PP and VD had negative coefficients for their parameters, with a positive interaction coefficient. At Montcalm, PP ranged from 0 to 5.0/100 cc of soil. VD ranged from 0 to 32.4 propagules/g of stem tissue. Joint interaction ranged from 0 to 162. None of the models fit the data, all three models had p-values greater than 0.975 (Tables 13 and 14).

Rosa. The cultivar Rosa was evaluated at Jolly Road and at Montcalm. Tuber yield averages at Jolly Road ranged from 284 g/plant in the VD only plot to 354 g/plant in the check (p-value=0.844, Table 5). At Montcalm, the average yield was the lowest in the PP/VD plot (513 g/plant) and the highest in the low PP (1117 g/plant). The p-value was much lower for Montcalm (p-value=0.144).

The PP ranged from 0 to 500/g of root tissue and 100 cc of soil at Jolly Road with VD ranging from 0 to 3250 propagules/g of stem tissue. Joint interaction ranged from 0 to ca. 600,000 (Table 6). The best fit regression model was with untransformed data (r^2=0.118, Table 9). However, the only negative coefficient was with the interaction term, and it was close to 0.0, with a high p-value associated with it (Table 9). At Montcalm, PP ranged from 0 to 11/100 cc of soil and VD ranged from 0 to 37 propagules/g stem tissue. Their joint interaction ranged from 0 to 68 (Table 8). The r^2 was much lower than at Jolly Road (r^2=0.065) and was best with the untransformed data (Table 14). At Montcalm, both PP and VD had negative coefficient, and there was no interaction term.

Snowden. The cultivar Snowden was evaluated at Jolly Road and in the greenhouse. Tuber average yields at Jolly Road ranged from 287 g/plant in the PP/VD plot to 394 g/plant in the check (p-value=0.557, Table 5). In the greenhouse, the lowest yield was in the VD only (14.7 g/plant), and the highest in the PP/VD (27.0 g/plant, Table 4). Although these differences were atypical, the p-value was much lower than at Jolly Road (p-value=0.314, Table 5).

The ranges for the linear regression model were 0 to 537 PP/1 g of root tissue and 100 cc of soil and 0 to 2467 propagules of VD/g of stem tissue. The joint interaction ranged from 0 to ca. 600,000. The natural log transformation provided the best fit, with an r^2=0.254 (Table 10). The coefficient for the PP parameter had the only negative coefficient. The greenhouse ranges were 0 to 347 PP/1 g of root tissue and 100 cc of soil and 0 to 46.4 propagules of VD/g of stem tissue. Their interaction ranged from 0 to ca 14,000. This was the broadest range in the greenhouse study. Similarly to the Jolly Road study, the best fit was the natural log transformation (r^2=0.117, Table 12). Likewise, the only negative parameter was the coefficient for PP.

Atlantic. The cultivar Atlantic was evaluated at Jolly Road and in the greenhouse. Yield averages at Jolly Road ranged from 179 g/plant in the VD only to 268 g/plant in the check (p-value=0.471, Table 5). In the greenhouse, the lowest yields were in the low PP treatment, and the highest yields were in the PP/VD plot (Table 4). Treatment differences in the greenhouse were more pronounced than at the Jolly Road site (p-value=0.239, Table 5).

At the Jolly Road site, the PP ranged from 0 to 500/g of root tissue and 100 cc of soil. VD ranged from 0 to 4000 propagules/g of stem tissue. Their joint interaction ranged from 0 to ca. 300,000 (Table 6). The best fit regression model resulted with the natural log transformed data (r^2=0.127). Both PP and the interaction coefficients had negative values. However, neither value had a very strong p-value associated with it (Table 10). PP ranged from 0 to 502/g of root tissue and 100 cc of soil in the greenhouse, while VD went from 0 to 23.4 propagules/g stem tissue. Their joint interaction ranged from 0 to 220. The best fit resulted from the untransformed linear model (r^2=0.066, Table 11). With this model, only the VD coefficient was negative.

Inter-cultivar specific findings

There are several methods that can be used to compare across cultivars. Relative yield (Table 15), relative ranking of tuber yields (Table 16) and percent yield loss (both total yield and marketable yield, Tables 17, 18 and 19) were used to provide inter- and intra-cultivar comparisons. In order to test pairwise significance, number of replications have to be utilized (Table 21). Relative yield was obtained by dividing each yield by the largest yield on a cultivar by cultivar basis. The potential range, therefore, could go from 0 to 1, with 1 being the maximum by definition, and zero being the minimum only if a plot contained no yield. Ranking was done by ordering the yields from lowest to highest, and numbering them from 1 to n. Yield loss was done on a replication by replication basis. The treatment was subtracted from the control. Therefore, a negative yield loss would be in cases where the treated plot did better than the check.

Relative yields. The variance in relative yields was assessed utilizing a three way ANOVA with cultivar, treatment, and replication as sources of variation. All three sources had statistically significant p-values associated with their f-statistics. The same was true for the greenhouse. At Montcalm, the treatment source of variation had a larger p-value (p-value=0.254, Table 1). The MSE from the ANOVA was used in pairwise comparisons using the t-test to determine statistical significance (p-value <= 0.05).

Jolly Road site. Russet Burbank is the only cultivar that had statistically significant (p-value <= 0.05) intra-specific differences among treatments. All three treatments differed from the check. Examining inter-cultivar differences among the different treatments, it can be seen that the greatest number of pairwise differences can be found in the check. Both Russet Burbank (0.669) and Atlantic (0.663) are statistically different from Superior (0.414), Hudson (0.385) and Rosa (0.369). Kennebec (0.626) was different from Hudson and Rosa. Russet norkota (0.594) differed only from Rosa. In the low PP treatment, Kennebec (0.652) differed from Rosa (0.342), Hudson (0.359), Superior (0.399), Snowden (0.406), and Russet Burbank (0.409). In the VD treatment, only two cultivars differed from each other, Desiree (0.569) and Rosa (0.297). In the interaction plot (PP/VD), Norkota Russett (0.567) differed from Rosa (0.314) and Hudson (0.324). Kennebec (0.536) also differed from Rosa (Table 15).

Greenhouse study. The only statistical intra-cultivar specific difference occurred in Atlantic, where the check (0.420) and PP/VD (0.427) differed from the low PP (0.230). The cultivar Russet Burbank differed from the other four cultivars in all five of the treatments (Table 15). There were no inter-cultivar specific significant pairwise differences among the other four cultivars in the check, low PP, high PP, or PP/VD treatments. In the VD only treatment, Snowden (0.426) and Atlantic (0.380) differed from Superior (0.199).

Montcalm research site. There were two statistically significant intra-cultivar specific differences at this research site. The VD treatment in the cv. Desiree (0.542) was different from the check (0.344); and the low PP in the cv. Rosa (0.373) was different from the PP/VD treatment (0.171). There were no inter-cultivar differences in the check and low PP treatments. In the high PP treatment, Desiree (0.461) was different from Rosa (0.249). The relative yields of Red Dale (0.568) and Desiree (0.542) were greater than Rosa (0.232) in the VD only treatment. In the PP/VD treatment, Desiree (0.498), Red Dale (0.453) and Kennebec (0.358) had statistically different relative yields from Rosa (0.171).

Relative ranking of potato yields. A three way analysis of variance, distributing the variance among cultivar, treatment and replication, was run on the ranked values for tuber yields. This resulted in no significant statistical differences among cultivars. Treatments had lower p-values than cultivar differences, but not as low as the p-values for replication. The p-values for replication were statistically significant at all three locations (Table 1).

Jolly Road site. At the Jolly Road site the only cultivar that had statistically significant intra-cultivar differences was Russet Burbank. Similarly to relative yield, all three treatments differed from the check (Table 16). There were no inter-cultivar significant differences.

Greenhouse study. There were three cultivars that had statistically significant intra-cultivar differences. The cv. Superior had significant differences between the check (36.6) and VD only (19.1) and between the PP/VD treatment (33.5) and VD. For Russet Burbank, the VD treatment (36.6) differed from the PP/VD (27.2). In addition, high PP (37.2) and PP/VD (36.1) did significantly better than the low PP in the cv. Atlantic (22.5). As for inter-cultivar comparisons, the only statistical difference was in the VD treatment. Here, cvs. Russet Burbank (39.9), Snowden (34.9) and Atlantic (33.9) did statistically better than Superior (19.1).

Montcalm research site. The only statistically significant difference among treatments within cultivars was for the cv. Desiree. The VD only treatment (35.9) was different from the check (19.8). Among cultivars, there were some differences in the check and PP/VD treatments, but no differences among the cultivars in the low PP, high PP and VD only treatments. Within the check, both Kennebec (35.9) and Hudson (36.9) responded better than Red Dale (18.9) and Desiree (19.8). Rosa (33.6) was statistically different from Desiree (17.8) in the PP/VD treatment.

Yield Loss. Another method of determining yield loss is to examine how the treatments differed from the check. Because all of the treatments had a low p-value for replication in yield measurements (Table 1), it was decided to use the difference between the treatment and each individual check for the yield loss statistic. Here, three different statistics will be explored. The first, is a series of one-sample t-tests that will determine how different the check is from each of the treatments. The second will look at intra-cultivar differences, and the third will examine inter-cultivar differences.

Jolly Road site. At the Jolly Road microtile plot, only one treatment with the cv. Russet Burbank was the yield loss statistically different from 0.0 at the p-value <=0.5 level. There were no statistical differences among treatments within each individual cultivar. However, when examining inter-cultivar differences, it was found that in the low PP treatment, the cv. Russet Burbank (+31.7 g/plant) had a more significant loss of yield than Desiree (-138.5 g/plant). In the VD treatment, Desiree (-202.4 g/plant) was statistically different from every other cultivar except Hudson (-108.2 g/plant). There were no significant differences in the PP/VD treatment.

Greenhouse study. There were no statistically significant differences in the greenhouse for any of the statistics.

Montcalm research site. At Montcalm, there were statistical differences between the treatment and the check for Red Dale low PP and high PP. However, in both cases the treatment did better than the check (Table 19). The cv. Rosa had statistically significant intra-cultivar differences. The low PP was different from the other three treatments. The only statistical difference between cultivars in the same treatment was with the low PP as well. Here again, cv. Rosa was different from the rest.

DISCUSSION

Comparing the ten cultivars, it was necessary to assess their relative susceptibility to Potato Early Die. This was done through relative yields, ranking, yield loss, and assessing goodness of fit of regression lines. The cultivars were rated as being susceptible (H), tolerant (M), or resistant (L). Since, even single cultivar potato early die research results tend to be highly variable, it is not surprising to find a high amount of variability within these ten cultivars. However, it is necessary to examine the trends that develop rather than the statistically significant overall differences among the cultivars.

The three statistics (relative yield, ranking and yield loss) have a high degree of variability within their results (Table 22). Each test statistic has associated strengths and weaknesses. Relative yield uses actual yield data, however, some disparities are a reflection of true differences among the treatments and others are a function of the range. For example, if a replication has one unusually small yield and another unusually large yield, it might produce a wide range of values between 0 and 1 that is due largely to random variability within the specific cultivar rather than true differences among different cultivars. Ranking the yields from small to large will reduce this random error, but it will also reduce it if the difference is from treatment rather than natural variation. Perhaps, yield loss is a good estimate in this particular case because there were distinct differences in replication (Table 1). However, it is still susceptible to a great deal of influence from an outlier, particularly if the outlier is in the control treatment.

Hence, to get an overall understanding of the relationship among the cultivars concerning their relative impacts or susceptibility to potato early die a test statistic was developed that summed the responses from all of the analyses. For each cultivar, the number of H, M, and L were counted and summed together on the basis of each H receiving 3 points, M 2 points and a L 1 point. Only the best fit data was used for the regressions. Hence there were 8 separate assessments for each cultivar (two for relative yield, two for ranking, two for yield loss, and two for the regression lines).

In summary, Hudson, Russet Burbank, Snowden and Superior were most susceptible to potato early die. Tolerant varieties included Rosa, Red Dale, and Kennebec. The most resistant cultivars were Atlantic, Norkota russet and Desiree.

Comparing this analysis to published literature was difficult because most potato early die studies are done with a single cultivar with various levels of PP and VD both alone and in combinations. The single most prevalent cultivar for the study of this disease cycle is cv. Superior (Botseas & Rowe 1994; Francl et al. 1987a, 1987b, 1990; Kotcon & Loria 1986; Martin et al. 1982; Riedel & Rowe 1985; Rowe et al. 1984, 1987; Wheeler et al. 1992, 1994; Wheeler & Riedel 1994). The second most studied cultivar is Russet Burbank (Davis 1985, Johnson 1988, 1992; Kotcon & Rouse 1984; Kotcon et al. 1984, 1985; MacGuidwin 1990, Nicot & Rouse 1987, Rouse 1985). Ohio State University has done the most published research on cv. Superior, while University of Wisconsin has used the cv. Russet Burbank. Although the specific findings were not as conclusive as the Ohio State study, Superior was ranking as one of the most susceptible cultivars.

Table 1. Three way analysis of variance p-values for variation due to cultivar, treatment and replication for Pratylenchus penetrans and Verticillium dahliae inoculations and different methods for the quantification of Solanum tuberosum tuber yields at three experimental sites.

ANOVA	Experiment Site	Cultivar	Treatment	Replication
Pratylenchus penetrans	Jolly Road	0.001	0.000	0.481
	Greenhouse	0.967	0.000	0.000
	Montcalm	0.186	0.000	0.149
Verticillium dahliae	Jolly Road	0.001	0.651	0.041
	Greenhouse	0.139	0.080	0.001
	Montcalm	0.180	0.396	0.000
Tuber weight	Jolly Road	0.025	0.047	0.011
	Greenhouse	0.000	0.650	0.000
	Montcalm	0.000	0.254	0.000
Relative tuber weight	Jolly Road	0.000	0.034	0.004
	Greenhouse	0.000	0.034	0.000
	Montcalm	0.000	0.256	0.000
Tuber ranking by weight	Jolly Road	0.994	0.211	0.008
	Greenhouse	0.825	0.052	0.000
	Montcalm	0.065	0.359	0.010
Yield loss	Jolly Road	0.015	0.642	***
	Greenhouse	0.283	0.437	***
	Montcalm	0.238	0.554	***

Table 2. Number of Pratylenchus penetrans (PP) recovered at harvest (1.0 g of root tissue + 100 cc soil) from four treatments x 10 cultivars at Jolly Road, five treatment x five cultivars for the Greenhouse study and five treatments x five cultivars at the Montcalm Potato Research Farm.

Cultivar	Jolly Road site				Greenhouse study					Montcalm research site*				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	5.0	176	0.13	112	***	***	***	***	***	0.0	0.3	5.4	0.0	0.8
Kennebec	0.0	180	5.7	198	***	***	***	***	***	0.0	1.1	4.1	0.1	0.3
Superior	10.0	230	7.5	77	0.1	3.2	176.6	0.1	25.1	***	***	***	***	***
Russet Burbank	0.0	205	11.0	115	0	5.0	138.8	0.2	6.7	***	***	***	***	***
Norkota Russett	0.1	108	4.6	84	0.1	5.1	139.7	0.0	11.8	***	***	***	***	***
Hudson	8.0	237	0.4	89	***	***	***	***	***	0.0	0.6	4.3	0.0	0.6
Desiree	19.0	342	207.0	608	***	***	***	***	***	0.1	0.1	2.0	0.0	0.6
Rosa	0.8	236	0.0	97	***	***	***	***	***	0.0	0.5	4.4	0.0	0.5
Snowden	1.2	269	5.3	102	0.2	5.5	149.4	0.0	13.8	***	***	***	***	***
Atlantic	1.8	207	0.0	127	0.0	5.5	112.2	0.0	9.3	***	***	***	***	***

*Nematodes/100 cc soil only.

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 3. Number of Verticillium dahliae (VD) recovered at harvest (propagules/g of root tissue) from four treatments x 10 cultivars at Jolly Road, five treatment x five cultivars for the Greenhouse study and five treatments x five cultivars at the Montcalm Potato Research Farm.

Cultivar	Jolly Road site				Greenhouse study					Field study				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	225	845	1053	492	***	***	***	***	***	2.3	3.7	1.2	0.7	2.3
Kennebec	1339	1344	338	1215	***	***	***	***	***	2.1	4.1	2.0	8.1	7.2
Superior	275	615	698	881	0.05	1.58	1.27	6.38	7.40	***	***	***	***	***
Russet Burbank	819	392	690	1000	0.94	1.20	0.33	2.16	0.42	***	***	***	***	***
Norkota Russett	133	669	411	438	1.28	0.62	0.20	0.27	2.94	***	***	***	***	***
Hudson	1531	2194	879	796	***	***	***	***	***	0.9	0.4	3.4	5.0	0.9
Desiree	1625	1437	1733	508	***	***	***	***	***	1.2	2.8	5.3	1.8	1.9
Rosa	1331	655	576	285	***	***	***	***	***	1.5	2.4	4.9	7.8	1.7
Snowden	877	1057	550	405	1.80	0.76	4.49	6.38	0.85	***	***	***	***	***
Atlantic	530	489	1450	1367	1.15	1.62	0.40	3.18	2.62	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 4. Potato tuber yields (g/plant) from four treatments x 10 cultivars at Jolly Road, five treatment x five cultivars for the Greenhouse study and five treatments x five cultivars at the Montcalm Potato Research Farm.

Cultivar	Jolly Road site (g/plant)				Greenhouse study (g/plant)					Field study (g/plant)				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	321	301	264	259	***	***	***	***	***	1051	1408	1150	1490	1189
Kennebec	305	318	267	261	***	***	***	***	***	2401	2298	2066	2077	1886
Superior	259	250	296	238	23.1	15.7	15.7	11.6	19.3	***	***	***	***	***
Russet Burbank	353	215	232	210	2.5	4.2	2.9	3.2	0.5	***	***	***	***	***
Norkota Russett	314	273	270	300	24.0	16.3	23.5	20.1	20.2	***	***	***	***	***
Hudson	251	234	350	212	***	***	***	***	***	1880	1742	1864	1900	1392
Desiree	243	230	301	242	***	***	***	***	***	1312	1584	1756	2065	1900
Rosa	354	328	284	301	***	***	***	***	***	972	1117	747	694	513
Snowden	394	327	303	287	25.1	17.6	20.6	14.7	27.0	***	***	***	***	***
Atlantic	268	204	179	193	18.8	10.3	18.5	17.0	19.1	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 5. Two way analysis of variance (treatment and replication) p-values for source of variation due to treatment for each cultivar at the three experimental sites (Jolly Road, the Greenhouse and Montcalm Potato Research Farm).

Cultivar	Jolly Road	Greenhouse	Montcalm
Red Dale	0.587	***	0.124
Kennebec	0.754	***	0.495
Superior	0.897	0.102	***
Russet Burbank	0.037	0.549	***
Norkota Russett	0.744	0.324	***
Hudson	0.200	***	0.710
Desiree	0.624	***	0.292
Rosa	0.844	***	0.144
Snowden	0.557	0.314	***
Atlantic	0.471	0.239	***

Table 6. Ranges for final counts of pathogens and joint interaction for Jolly Road microtile site with 10 potato cultivars.

Cultivar	n	*Pratylenchus penetrans*			*Verticillium dahliae*			PP/VD		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Red Dale	26	0.0	406.9	39.1	0.0	3383.3	645.5	0.0	224000.0	20849.7
Kennebec	28	0.0	636.4	62.4	33.0	4366.7	1090.2	0.0	2206069.2	126393.4
Superior	28	0.0	900.0	48.8	0.0	2850.0	541.1	0.0	1980000.0	78992.6
Russet Burbank	31	0.0	550.0	47.3	16.7	2750.0	721.5	0.0	273181.9	27690.8
Norkota Russett	28	0.0	171.4	17.8	0.0	1666.7	378.6	0.0	205716.0	9839.2
Hudson	31	0.0	636.0	57.1	0.0	7050.0	1344.0	0.0	1038778.8	87467.6
Desiree	29	0.0	1152.0	149.5	33.3	4100.0	1395.4	0.0	2640400.0	252736.2
Rosa	28	0.0	500.0	50.3	0.0	3250.0	716.7	0.0	605206.8	37365.0
Snowden	32	0.0	537.0	47.4	0.0	2466.7	742.7	0.0	644400.0	38223.8
Atlantic	25	0.0	500.0	62.7	0.0	4000.0	826.9	0.0	301670.0	41040.4

Table 7. Ranges for final counts of pathogens and joint interaction for Greenhouse study for five potato cultivars.

Cultivar	n	Pratylenchus penetrans			Verticillium dahliae			PP/VD		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Superior	42	0.0	560.0	44.8	0.0	39.4	3.3	0.0	4761.6	210.2
Russet Burbank	54	0.0	823.0	29.1	0.0	19.0	1.0	0.0	368.0	13.4
Norkota Russett	51	0.0	288.0	27.2	0.0	18.6	1.1	0.0	297.6	13.3
Snowden	47	0.0	347.0	35.9	0.0	46.4	2.9	0.0	14244.8	317.3
Atlantic	54	0.0	502.0	29.2	0.0	23.4	1.8	0.0	220.8	13.6

Table 8. Ranges for final counts of pathogens and joint interaction for Montcalm Study with five potato cultivars.

Cultivar	n	Pratylenchus penetrans			Verticillium dahliae			PP/VD		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Red Dale	40	0.0	14.0	1.3	0.0	15.0	1.7	0.0	36.0	2.7
Kennebec	49	0.0	7.0	1.2	0.0	52.2	5.0	0.0	42.0	3.0
Hudson	40	0.0	8.0	0.9	0.0	29.8	2.8	0.0	62.4	3.2
Desiree	51	0.0	5.0	0.6	0.0	32.4	2.5	0.0	162.0	4.7
Rosa	38	0.0	11.0	1.2	0.0	37.0	4.6	0.0	67.8	4.1

Table 9. A series of linear regression tuber yield models [(tuber yield = constant + PP + VD + PP/VD) and (tuber yield = constant + PP/VD)] for each of ten cultivars utilizing the data from the Jolly Road site (highlighted cultivars signify the best fit equation).

Cultivar	Stat	Full Regression					Interaction Term Only		
		Constant	PP	VD	PP/VD	r^2	Constant	PP/VD	r^2
Red Dale	Coef.	257.211	0.071	0.036	0.000	0.066	279.739	0.000	0.026
	p-value	0.000	0.886	0.348	0.800	0.675	0.000	0.434	0.434
Kennebec	Coef.	253.022	0.499	0.044	-0.000	0.156	306.569	-0.000	0.039
	p-value	0.000	0.424	0.091	0.194	0.246	0.000	0.311	0.311
Superior	Coef.	249.465	1.137	0.055	-0.001	0.194	290.233	-0.000	0.063
	p-value	0.000	0.124	0.189	0.061	0.152	0.000	0.199	0.199
Russet Burbank	Coef.	267.681	0.018	0.020	-0.001	0.152	280.754	-0.001	0.138
	p-value	0.000	0.944	0.510	0.065	0.210	0.000	0.040	0.040
Norkota russet	Coef.	310.120	-0.650	-0.062	0.001	0.077	279.981	0.000	0.012
	p-value	0.000	0.470	0.240	0.270	0.579	0.000	0.571	0.571
Hudson	Coef.	303.372	-0.966	-0.009	0.000	0.139	279.981	-0.000	0.052
	p-value	0.000	0.113	0.622	0.298	0.249	0.000	0.217	0.217
Desiree	Coef.	270.045	-0.155	0.022	-0.000	0.185	286.889	-0.000	0.063
	p-value	0.000	0.349	0.303	0.902	0.156	0.000	0.190	0.190
Rosa[1]	Coef.	287.836	0.006	0.078	-0.000	0.118	333.849	0.000	0.000
	p-value	0.000	0.986	0.096	0.475	0.382	0.000	0.981	0.981
Snowden	Coef.	248.932	-0.764	0.116	0.001	0.330	321.598	0.000	0.007
	p-value	0.000	0.336	0.004	0.339	0.010	0.000	0.641	0.641
Atlantic	Coef.	189.780	0.092	0.031	-0.000	0.087	212.519	0.000	0.001
	p-value	0.000	0.669	0.175	0.605	0.581	0.000	0.865	0.865

[1]wt = 290.782 + 0.06*Vert; r^2 = 0.092, p-value = 0.117.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 10. A series of linear regression tuber yield models using the natural log transformation [(tuber yield = constant + ln(PP) + ln(VD) + ln(PP/VD)) and (tuber yield = constant + ln(PP/VD))] for each of ten cultivars utilizing the data from the Jolly Road site (highlighted cultivars signify the best fit model).

Cultivar	Stat	Full Regression					Interaction Term Only		
		Constant	PP	VD	PP/VD	r^2	Constant	PP/VD	r^2
Red Dale	Coef.	196.730	-34.969	12.975	20.570	0.179	262.589	7.237	0.069
	p-value	0.030	0.360	0.382	0.223	0.219	0.000	0.195	0.195
Kennebec	Coef.	164.813	10.578	24.989	-8.083	0.059	313.483	-2.212	0.009
	p-value	0.242	0.814	0.272	0.661	0.685	0.000	0.624	0.624
Superior	Coef.	259.114	-26.331	1.466	15.730	0.042	266.003	5.202	0.033
	p-value	0.001	0.667	0.917	0.550	0.790	0.000	0.357	0.357
Russet Burbank	Coef.	191.591	28.742	19.164	-22.073	0.153	296.248	-9.124	0.120
	p-value	0.090	0.493	0.325	0.230	0.205	0.000	0.056	0.056
Norkota russet	Coef.	316.605	-70.042	-9.259	35.475	0.117	275.092	4.728	0.028
	p-value	0.000	0.172	0.350	0.122	0.286	0.000	0.391	0.391
Hudson	Coef.	431.448	-49.241	-17.621	8.817	0.189	309.981	-9.775	0.123
	p-value	0.002	0.172	0.389	0.555	0.123	0.000	0.053	0.053
Desiree	Coef.	354.333	-72.884	-8.339	26.879	0.347	309.423	-4.729	0.061
	p-value	0.001	0.003	0.562	0.015	0.012	0.000	0.197	0.197
Rosa	Coef.	206.262	29.942	26.865	-17.901	0.095	357.927	-5.306	0.022
	p-value	0.093	0.710	0.176	0.613	0.484	0.000	0.452	0.452
Snowden[1]	Coef.	129.885	-40.223	36.677	10.349	0.254	330.317	-0.923	0.001
	p-value	0.213	0.218	0.051	0.461	0.040	0.000	0.875	0.875
Atlantic	Coef.	140.369	-6.225	16.069	-0.756	0.127	224.468	-1.880	0.012
	p-value	0.034	0.860	0.147	0.961	0.405	0.000	0.597	0.597

[1]wt = constant + 40.79*ln(Vert), $r^2 = 0.183$, $p = 0.015$.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 11. A series of linear regression tuber yield models [(tuber yield = constant + PP + VD + PP/VD) and (tuber yield = constant + PP/VD)] for each of five cultivars utilizing the data from the greenhouse study (highlighted cultivars represent best fit models).

Cultivar	Stat	Full Regression					Interaction Term Only		
		Constant	PP	VD	PP/VD	r^2	Constant	PP/VD	r^2
Superior	Coef.	15.005	0.010	0.156	0.000	0.051	15.645	0.002	0.028
	p-value	0.000	0.460	0.463	0.876	0.570	0.000	0.289	0.289
Russet Burbank	Coef.	1.895	-0.002	0.306	0.015	0.036	2.144	0.014	0.016
	p-value	0.065	0.807	0.340	0.392	0.608	0.025	0.366	0.366
Norkota russet	Coef.	18.286	0.032	0.492	0.019	0.068	19.295	0.049	0.044
	p-value	0.000	0.298	0.515	0.680	0.341	0.000	0.139	0.139
Snowden	Coef.	20.944	-0.014	0.531	0.000	0.078	21.542	0.001	0.038
	p-value	0.000	0.627	0.237	0.983	0.314	0.000	0.186	0.186
Atlantic	Coef.	16.537	0.009	-0.351	0.063	0.066	16.254	0.058	0.044
	p-value	0.000	0.662	0.369	0.111	0.329	0.000	0.127	0.127

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 12. A series of linear regression tuber yield models using the natural log transformation [(tuber yield = constant + ln(PP) + ln(VD) + ln(PP/VD)) and (tuber yield = constant + ln(PP/VD))] for each of five cultivars utilizing the data from the greenhouse study (highlighted cultivars signify the best fit model).

Cultivar	Stat	Full Regression					Interaction Term Only		
		Constant	PP	VD	PP/VD	r^2	Constant	PP/VD	r^2
Superior	Coef.	14.068	0.953	1.374	-0.366	0.044	15.444	0.570	0.018
	p-value	0.000	0.331	0.559	0.774	0.626	0.000	0.396	0.396
Russet Burbank	Coef.	1.044	0.209	2.639	0.145	0.075	1.878	0.829	0.029
	p-value	0.405	0.757	0.122	0.876	0.266	0.058	0.218	0.218
Norkota Russett	Coef.	17.009	1.566	3.137	-0.300	0.070	19.198	1.470	0.026
	p-value	0.000	0.171	0.347	0.870	0.328	0.000	0.260	0.260
Snowden	Coef.	20.915	-1.296	2.821	1.838	0.117	20.585	1.875	0.056
	p-value	0.000	0.359	0.303	0.267	0.145	0.000	0.108	0.108
Atlantic	Coef.	15.777	0.313	0.116	1.224	0.033	16.059	1.378	0.031
	p-value	0.000	0.781	0.962	0.418	0.638	0.000	0.203	0.203

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 13. A series of linear regression tuber yield models [(tuber yield = constant + PP + VD + PP/VD) and (tuber yield = constant + PP/VD)] for each of five cultivars utilizing the data from the Montcalm research site (highlighted cultivars signify the best fit equation).

Cultivar	Stat	Full Regression					Interaction Term Only		
		Constant	PP	VD	PP/VD	r^2	Constant	PP/VD	r^2
Red Dale	Coef.	1218.192	-32.533	52.748	3.301	0.127	***	***	***
	p-value	0.000	0.375	0.070	0.826	0.175	***	***	***
Kennebec	Coef.	2300.476	-8.348	-3.917	-15.193	0.024	***	***	***
	p-value	0.000	0.917	0.792	0.406	0.775	***	***	***
Hudson	Coef.	1718.749	0.446	60.322	-4.256	0.127	***	***	***
	p-value	0.000	0.996	0.035	0.807	0.176	***	***	***
Desiree	Coef.	1790.005	-37.906	-4.172	3.417	0.004	***	***	***
	p-value	0.000	0.759	0.912	0.736	0.983	***	***	***
Rosa	Coef.	838.640	-42.281	-13.992	4.794	0.077	***	***	***
	p-value	0.000	0.239	0.176	0.511	0.429	***	***	***

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 14. A series of linear regression tuber yield models using harvest pathogen data (tuber yield = Constant + PP + VD) and the natural log transformation [(tuber yield = constant + ln(PP) + ln(VD))] for each of five cultivars utilizing the data from the Montcalm research site (highlighted cultivars signify the best fit model).

Cultivar	Stat	Regression with harvest pathogen counts				Regression (ln)			
		Constant	PP	VD	r^2	Constant	PP	VD	r^2
Red Dale	Coef.	1216.247	-26.953	54.982	0.126	1150.079	-114.123	266.460	0.151
	p-value	0.000	0.301	0.042	0.083	0.000	0.294	0.017	0.048
Kennebec	Coef.	2301.971	-34.869	-7.071	0.009	2438.219	-125.120	-139.787	0.032
	p-value	0.000	0.635	0.622	0.816	0.000	0.532	0.259	0.475
Hudson	Coef.	1727.053	-15.560	57.777	0.125	1755.635	-33.612	184.037	0.037
	p-value	0.000	0.838	0.027	0.027	0.000	0.885	0.241	0.498
Desiree	Coef.	1769.868	-17.674	5.380	0.001	1757.246	6.200	18.722	0.001
	p-value	0.000	0.869	0.829	0.974	0.000	0.980	0.896	0.988
Rosa	Coef.	836.233	-22.261	-11.558	0.065	835.464	-77.513	-60.492	0.031
	p-value	0.000	0.311	0.225	0.308	0.000	0.504	0.436	0.580

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present.

Table 15. Intra- and inter-cultivar comparisons of relative tuber yield* for each cultivar at the three experimental sites (Jolly Road, the Greenhouse and Montcalm Potato Research Farm).

Cultivar	Microtile study				Greenhouse study					Field study				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	0.509	0.478	0.418	0.410	***	***	***	***	***	0.400	0.536	0.438	0.568	0.453
Kennebec	0.626	0.652	0.549	0.536	***	***	***	***	***	0.455	0.435	0.391	0.393	0.358
Superior	0.414	0.399	0.473	0.380	0.397	0.271	0.270	0.199	0.332	***	***	***	***	***
Russet Burbank	0.669	0.409	0.440	0.398	0.058	0.100	0.069	0.076	0.012	***	***	***	***	***
Norkota Russett	0.594	0.517	0.511	0.567	0.402	0.273	0.394	0.336	0.338	***	***	***	***	***
Hudson	0.385	0.359	0.537	0.324	***	***	***	***	***	0.410	0.380	0.407	0.415	0.304
Desiree	0.460	0.435	0.569	0.457	***	***	***	***	***	0.344	0.416	0.461	0.542	0.498
Rosa	0.369	0.342	0.297	0.314	***	***	***	***	***	0.324	0.373	0.249	0.232	0.171
Snowden	0.489	0.406	0.377	0.357	0.440	0.309	0.360	0.426	0.330	***	***	***	***	***
Atlantic	0.663	0.505	0.442	0.476	0.420	0.230	0.413	0.380	0.427	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 16. Intra- and inter-cultivar tuber yield ranking comparisons for the three research sites.

Cultivar	Microtile study				Greenhouse study					Field study				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	19.4	19.3	15.5	15.8	***	***	***	***	***	18.9	29.3	20.0	29.6	23.7
Kennebec	17.5	18.6	15.1	14.8	***	***	***	***	***	35.9	36.9	34.3	25.0	29.6
Superior	17.8	17.2	20.9	14.1	36.6	27.9	28.8	19.1	33.5	***	***	***	***	***
Russet Burbank	26.6	15.8	15.9	15.8	31.0	32.7	36.6	39.9	27.2	***	***	***	***	***
Norkota Russett	21.7	16.3	16.8	19.2	36.2	26.5	35.2	29.5	32.5	***	***	***	***	***
Hudson	17.0	16.3	21.5	15.4	***	***	***	***	***	36.9	34.3	29.6	29.5	25.0
Desiree	17.4	16.3	21.0	17.1	***	***	***	***	***	19.8	25.8	30.5	35.9	33.6
Rosa	16.8	22.0	16.3	18.9	***	***	***	***	***	28.3	29.3	21.6	21.6	17.8
Snowden	18.9	20.8	16.7	17.7	33.9	26.5	30.2	34.9	29.7	***	***	***	***	***
Atlantic	21.6	16.3	12.5	14.0	32.8	22.5	37.2	33.9	36.1	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 17. **Individual, intra- and inter-cultivar yield loss comparisons at the Jolly Road microtile site.**

Cultivar	Low PP (%)		VD (%)		PP/VD (%)	
	g/plant	p-value	g/plant	p-value	g/plant	p-value
Red Dale	-46.3	0.480	-25.0	0.700	-17.4	0.633
Kennebec	-10.9	0.530	2.4	0.870	10.1	0.530
Superior	2.6	0.910	-6.3	0.690	-2.5	0.940
Russet Burbank	31.7	0.048	26.4	0.240	28.1	0.180
Norkota Russett	11.4	0.260	14.1	0.380	4.9	0.760
Hudson	-33.2	0.360	-108.2	0.110	-7.3	0.700
Desiree	-138.5	0.310	-202.4	0.250	-20.9	0.610
Rosa	-81.9	0.240	-27.6	0.460	-103.4	0.320
Snowden	-6.6	0.730	0.9	0.960	5.5	0.810
Atlantic	-1.7	0.950	6.6	0.830	5.8	0.840

Table 18. Individual, intra- and inter-cultivar yield loss comparisons for the greenhouse study.

Cultivar	Low PP (%)		High PP (%)		VD (%)		PP/VD (%)	
	g/plant	p-value	g/plant	p-value	g/plant	p-value	g/plant	p-value
Superior	7.09	0.220	9.52	0.110	4.88	0.160	4.80	0.280
Russet Burbank	-2.13	0.420	-0.55	0.790	-1.04	0.140	1.90	0.320
Russet norkota	6.50	0.120	-1.45	0.720	4.30	0.280	2.75	0.590
Snowden	6.23	0.270	2.86	0.570	-0.53	0.940	-3.76	0.430
Atlantic	7.78	0.170	-1.25	0.790	1.02	0.860	-0.44	0.910

Table 19. **Individual, intra- and inter-cultivar yield loss comparisons for the four treatments vs. the control at the Montcalm research site.**

Cultivar	Low PP (%)		High PP (%)		VD (%)		PP/VD (%)	
	g/plant	p-value	g/plant	p-value	g/plant	p-value	g/plant	p-value
Red Dale	-98.4	0.028	-27.0	0.033	-89.3	0.097	-51.6	0.180
Kennebec	-255.3	0.360	-186.3	0.370	-189.4	0.390	-17.8	0.650
Hudson	-99.3	0.250	-45.7	0.330	-12.5	0.630	6.3	0.740
Desiree	-10.1	0.690	-35.4	0.270	-66.7	0.140	-15.3	0.470
Rosa	-1388.9	0.350	34.4	0.260	35.5	0.140	33.6	0.230

Table 20. Number of replications for each of the experiments (except the yield loss experiments).

Cultivar	Jolly Road site				Greenhouse study					Montcalm research site				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	9	8	8	9	***	***	***	***	***	9	8	9	10	12
Kennebec	8	8	8	8	***	***	***	***	***	13	11	13	13	11
Superior	9	9	8	8	10	13	12	11	11	***	***	***	***	***
Russet Burbank	9	9	9	9	12	13	13	13	13	***	***	***	***	***
Norkota Russett	9	9	9	9	12	12	13	13	13	***	***	***	***	***
Hudson	9	9	8	8	***	***	***	***	***	10	9	10	8	12
Desiree	9	9	9	8	***	***	***	***	***	10	12	12	11	13
Rosa	9	9	9	9	***	***	***	***	***	10	10	9	8	10
Snowden	9	9	9	9	12	13	13	13	13	***	***	***	***	***
Atlantic	9	9	6	8	12	13	13	13	13	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 21. Number of replications for the yield loss experiments.

Cultivar	Jolly Road site				Greenhouse study					Field study				
	CK	PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD	CK	L PP	H PP	VD	PP/VD
Red Dale	***	8	8	9	***	***	***	***	***	***	6	7	8	8
Kennebec	***	8	7	8	***	***	***	***	***	***	11	13	13	11
Superior	***	9	8	8	***	10	9	8	8	***	***	***	***	***
Russet Burbank	***	9	9	9	***	12	12	12	12	***	***	***	***	***
Norkota Russett	***	9	9	9	***	11	12	12	12	***	***	***	***	***
Hudson	***	9	8	8	***	***	***	***	***	***	6	9	8	9
Desiree	***	9	9	8	***	***	***	***	***	***	8	8	7	9
Rosa	***	9	9	9	***	***	***	***	***	***	6	6	4	6
Snowden	***	9	9	9	***	12	12	12	12	***	***	***	***	***
Atlantic	***	9	6	8	***	12	12	12	12	***	***	***	***	***

***Combination not tested.

Note: CK: Pratylenchus penetrans and Verticillium dahliae-free control; PP: Pratylenchus penetrans, VD: Verticillium dahliae; and PP/VD: both pathogens present; LPP: low levels of P. penetrans (below damage threshold); HPP: high levels of P. penetrans (above damage threshold).

Table 22. Summary of comparative statistics among the three experiments for the Pratylenchus penetrans and Verticillium dahliae treatment.

Cultivar	Relative Yield[1]			Ranking			Yield Loss			Untransformed r^2			Transformed r^2		
	J	G	M	J	G	M	J	G	M	J	G	M	J	G	H
Red Dale	M	***	L	M	***	H	L	***	L	L	***	H	H	***	H
Kennebec	L	***	M	H	***	L	H	***	L	H	***	L	L	***	M
Superior	H	M	***	H	L	***	M	H	***	H	L	***	L	L	***
Russet Burbank	M	H	***	M	H	***	H	M	***	M	L	***	M	H	***
Norkota Russett	L	L	***	L	M	***	M	H	***	L	H	***	L	M	***
Hudson	H	***	H	H	***	M	L	***	H	M	***	H	H	***	H
Desiree	L	***	L	L	***	L	L	***	M	H	***	L	H	***	L
Rosa	H	***	H	L	***	H	L	***	H	L	***	M	L	***	L
Snowden	H	H	***	L	H	***	H	L	***	H	H	***	H	H	***
Atlantic	L	L	***	H	L	***	H	L	***	L	M	***	M	L	***

For Jolly Road: The four most susceptible = H
The two in the buffer = M
The four least susceptible = L

For Greenhouse and for Montcalm: The two most susceptible = H
The one in the buffer = M
The two least susceptible = L

***Combination not tested.

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