Modeling economic, biophysical, and environmental dynamics of potato production system

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Abstract
The adoption and use of diversified cropping practices has become widely accepted by producers. However, the profitability of an enterprise is dependent on the biophysical and economic factors. The biophysical factors determine the enterprise relationship among the various crops, their interactions with the ecosystem, and how each of them fits into the overall management plan. The economic factors determine the relative advantage of each crop and service in the farm plan. Although there have been experimental studies in Canada examining the impacts of rotations on the agronomics of field crops, there is limited research in modeling economic and environmental dynamics of the potato production system. Potato production in Manitoba has rapidly increased in recent years and became the second largest potato producer in Canada producing about 22.2% of the total Canada's potato production as of 2004. Alberta has had similar expansion with the highest yield per acre in Canada. The expansion of potato industry in these two provinces and other parts of Canada has created some concerns about agro-environmental indicators such as water contamination, soil erosion and long-term profitability of potato production practices. The objective of this study was to address some of these concerns and develop a dynamic model that integrates environmental and economic components of potato production systems and estimates sustainability of some of the agricultural practices.

A Stella Modeling framework was developed to provide crop production and environmental input to an economic model of potato rotations. The economic performance of different potato rotations ranging from two to four years in duration, and containing potatoes in combination with oilseed, cereal, forage, and legume crops was evaluated based on standard budgeting techniques. Net income was estimated as the income remaining above cash costs (i.e., seed, fertilizer, chemical, fuel and oil, repairs, crop insurance premium, miscellaneous, land taxes, and interest cost on variable inputs), ownership costs (depreciation, interest on investment, and insurance and housing) for machinery and grain storage, and labour. All annual inputs used in each phase of rotation for each management treatment, the type and frequency of field operation, year and replicate including pre-plant activities, tillage, fertilization, planting, insects and pests control, harvesting, storage, and transportation were included in the analysis.

Modelling the economics of irrigated potato rotations required input from an agro-environmental model. This agro-environmental model was developed to simulate nutrient dynamics, soil moisture dynamics, soil characteristics and erosion, soil organic matter content, residue decomposition, and crop growth. The economic model takes into account economic factors and costs that are influenced by yield function, nutrients and crop water thus establishing the link between the agro-environmental module and the economic module. Farm operation costs in our model are divided into two categories: dependent costs and base costs. Dependent costs are costs that are controlled by the agro-environmental module, including yield dependent costs, irrigation dependent costs and fertilizer dependent costs. Base costs were developed through experimental evaluation with E-Views and remain constant throughout the rotation. On the agro-environmental side, the model outputs the changes in soil organic matter, soil loss due to erosion, and carbon dioxide emission due to decomposition and mineralization. Results of the model show that changes in these variables are dependent upon the length of, and the crops involved in, the rotation. The economic model results showed highest average net revenue was found in shorter two-year rotations due to the greater frequency of potato.

Introduction
The adoption and use of diversified crop rotation practices has become widely accepted by producers. However, the profitability of an enterprise is dependent on the physical and economic factors. The physical factors determine the enterprise relationship among the various crops and how each of them fits into the overall management plan. The economic factors determine the relative advantage of each crop and service in the farm plan.

Although there were some benefits to chemical usage for agricultural activities, there can also be drawbacks, including the significant cost of chemical inputs, pest resistance, environmental problems associated with chemical and consumer concern about food that is being produced using chemicals. The concern about global warming and its implications toward agriculture in the recent past brings another important consideration, which is an environmental consideration. These concerns, combined with economic and physical factors, have led to a search for alternative or sustainable agricultural systems.

Manitoba is the second largest potato producer in Canada (Figure 1). Prince Edward Island produces about 25% of the total Canada's potato production while Manitoba's production is about 22.2%, as of 2004. While 70 percent of the existing area of processing potatoes is under irrigation, almost all new potato land is irrigated.
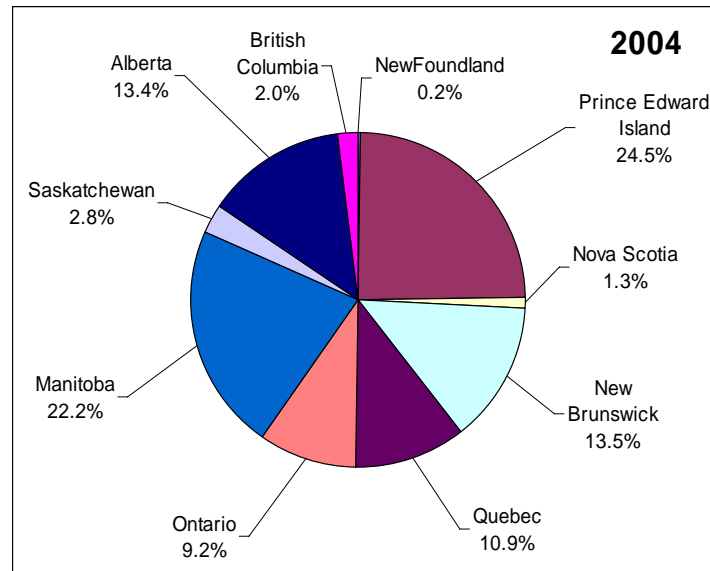
Figure 1. Area of Potato Seeded by Province, 2004, Source: Statistics Canada.

The recent expansion of potato processing industry in southern Manitoba, coupled with an increased demand for potato around the world, has resulted in significant increases in potato production. Empirical evidence suggests that crop rotation may increase not only the total yield of the primary crop but also the marketable yield (Guertal et al 1997). Although most crop rotation experiments in Canada have examined the impact of rotations on the agronomic of field crops, there is very little research has been conducted to include environmental and economic impacts of crop rotation systems.

While the economic and environmental benefits of crop rotations have been known for many years (Heady 1957), in practice, considerably less attention has been paid to quantifying such underlying benefits up to the recent past. Among these benefits, increased yield, reduced incidence of disease, less pests and decreased weed populations influence cost of production while reducing the risk faced by the producer. In addition, for many years, researchers use a neoclassical production function approach to explain production and economic efficiency without regard for the sustainability of the production process. The problem in the production function approach is the presumption that a uniform set of production factors can substitute freely for one another to increase efficiency without any regard for the environmental and structural variability that occurs in agricultural and social systems (Gillespie et al 1995). Although crop rotation is one of the oldest methods for managing pests, diseases, and soil fertility, emphasis on crop rotation continues because of its beneficial effects on crop yield and soil fertility. Crop rotation may affect crop yield and improve soil properties, including soil organic matter and nutrient availability. Crop rotation may center on a primary crop such as potato, while the other crops of the rotation may be selected for diversity, fertilizer and nutrient management. Rotation with legume crops, such as alfalfa, may contribute to soil N because of its ability to fix nitrogen and produces forage for the livestock industry.

Lazarus and White (1984) evaluated the economic feasibility of crop rotations on Long Island Potato Farms in New York. Changes in returns over variable costs were used to rank various crop rotation options. The authors found that, by including non-potato crops in the rotation,

potato acreage was reduced and total pesticides use decreased significantly, contributing to improvement in environmental quality. They found that a potato–cauliflower rotation was a good alternative to continuous potato production, if they could overcome the managerial problems related to seasonal labour. Essentially, they noted that both continuous potatoes and potato-cauliflower rotations are relatively profitable alternatives even with increased pesticide costs and reduced yields.

Honeycutt et al (1995) examined the influence of crop rotation and N fertilization, along with their interactions, on several soil properties in potato cropping systems. Potato was grown continuously and in two-year rotations with annual alfalfa, hairy vetch, white lupin and oat. Results showed that there were substantial N related effects associated with these rotations in potato cropping systems. In particular, inorganic N concentrations in potato soils were related to the previous crop's residue N content, and were highest following vetch and alfalfa and lowest following oat and potato.

In a study of short-term effects of crop rotations and wood-residue amendments on potato yields and soil properties of a sandy loam soil, Gasser et al (1995) showed that faster changes of soil carbon content occurred with ligneous material incorporation as compared to a fall rye cover crop. They concluded that soil amendments would improve potato yield and quality through improved soil water content induced by ligneous materials and a 3-year crop rotation with barley.

Gillespie et al (1995) indicated that potato producers in New York use a 'logic of production' tailored to their specific environmental and socio-economic situations, stating that there is no specific, or even a dominant, pattern that fits all producers. They found that the most important reason for rotating crops was the reduction plant pests (78.6%), followed by: maintenance of soil nutrients (42.9%), maintenance of soil tilth (37.5%), reduction of plant diseases (25%), increased yield sustainability (21.4%) and improved product quality (14.3%).

Kachanoski and Carter (1999) examined the effect of soil type and cropping practices on soil loss rate in Prince Edward Island. Two cropping systems, one intensive of potato rotated with vegetables and/or cereals and the other less intensive with continuous pasture with occasional cereal were implemented on three soil types to determine the soil loss rate. They concluded that the soil losses were greater under the intensive cropping system and, that the inclusion of grass/pasture in the crop rotation was useful in reducing the adverse effects of intensive potato cultivation.

Carter and Sanderson (2001) noted that a major concern in potato production is the sustainability of the system in terms of the method of tillage and the quality of soil. To investigate this hypothesis, they carried out a study to assess the feasibility and long-term effects of using conservation tillage practices, in combination with crop residue mulches, on potato production in two- and three-year potato rotations on a fine sandy loam soil in Prince Edward Island. They assessed the influence of rotation length, tillage system, and soil management on potato productivity and indicators of soil quality. The authors found that the 2-year rotation tended to develop problems with disease resulting in reduced tuber quality compared to the 3-year rotation. Compared to the 3-year rotation, the 2-year rotation produced more off-type potatoes. The

authors concluded that conservation tillage has the potential to improve soil properties such as structure and organic matter, and therefore identified conservation tillage as a promising method of soil management for intensive potato production.

The term 'sustainable' is a relative term so care should be taken in comparing enterprises. According to Patterson and Stark (1995), sustainable production practices must meet three general criteria: environmentally sound, economically viable and socially acceptable. Thus, what is sustainable and what is not sustainable for one individual depends on the weight given to each of these criteria. Though conventional agriculturists have adopted the neoclassical production function approach to dictate efficiency of production, sustainable agriculturists begin their inquiry by acknowledging the social and environmental aspects of farming. This approach takes production diversity as a starting point and places farm in environmental and social contexts.

Potato farming systems generally use excessive tillage and produce low levels of crop residue in the potato year, which is the most important factor of soil quality (Carter and Sanderson, 2001). A major concern in potato cultivation is the sustainability of the production system. Therefore, it is important to maintain soil quality in order to obtain higher return for the invested capital. One production alternative to help maintain soil quality is the use of crop rotation.

The physical characteristic of the soil and the indirect effects one crop has on yields of another determines the choice of crops for the rotation. Crops in rotation can have competitive, complementary or supplementary effects on production (Westra and Boyle, 1990). The complementary relationship exists when one crop or soil management practice associated with the crop provides a nutrient or other inputs required by another crop.

When the crops in rotation complement each other, the outputs of both crops increase while the opposite occurs for competitive crops. For example, grasses and legumes may serve in a complementary capacity to grains where the grasses and legumes provide nitrogen, control erosion, eliminate disease and pests, and maintain or improve soil fertility to an extent that facilitates greater production of grains. Commercial fertilizer often can be used as a substitute for the complementary nitrogen furnished by legumes. The larger amount of crop residue may also serve as a partial substitute for organic matter provided by grasses and legumes.
Economic theory related to production of two outputs (or product-product model) can be represented as a production possibility frontier, which represents all combination of two crops that can be produced with a fixed input (Westra and Boyle, 1990).

Materials and Methods
Potato Rotation Experiment
In 1998, the potato crop rotation study was initiated at the Canada-Manitoba Crop Diversification Centre (CMCDC, Carberry) by research scientists at the Brandon Research Centre. This is an on-going experiment conducted in order to develop recommendations for irrigated potato management in southern Manitoba by identifying viable potato rotations that minimize yield and quality losses due to disease and weeds, maximize economic return, and maintain soil quality. Six crop rotations ranging in duration from two to four years, and containing potatoes in combination with oilseed, cereal and/or legume crops were included in

this study. Each phase of each rotation was present in each year for a total of 18 treatments. The six rotations were Potato-Canola (P-C), Potato-Wheat (P-W), Potato-Canola-Wheat (P-C-W), Potato-Oat-Wheat (P-O-W), Potato-Wheat-Canola-Wheat (P-W-C-W), and Potato-Canola (underseeded to alfalfa)-alfalfa-alfalfa (P-C(A)-A-A).

All crops were managed using best management practices with respect to tillage, seeding, nutrient management, and weed, insect and disease control. Nitrogen, phosphorus, potassium and sulfur in the form of urea, monoamonium phosphate, potassium chloride and ammonium sulfate were applied as required.

It is worthy to note that, in selecting the crops and rotations, the potential impacts of two factors, rotation duration and crop species, were considered. Rotations ranging from 2 to 4 years were included to allow an assessment of the impact of rotation length on the viability of the cropping system. Cereals and canola were included as the primary non-potato crops because they were identified as realistic options for producers in the region.

The potato rotation model incorporates all six rotations from the experiment as well as a potato-corn-wheat rotation. A potato survey was sent to potato growers in Southern Manitoba asking about their typical rotations and agronomic practices. Based on the survey feedback, it was decided to add the potato-corn-wheat rotation to the list of rotations investigated for economic and environmental modeling and analysis.

The potato rotation model was developed to provide crop production and environmental input to an economic model of potato rotations. The model was based upon quantitative relationships found in published and online literature. A systematic perspective of the environmental and crop-production components in the model is represented in Figure 2
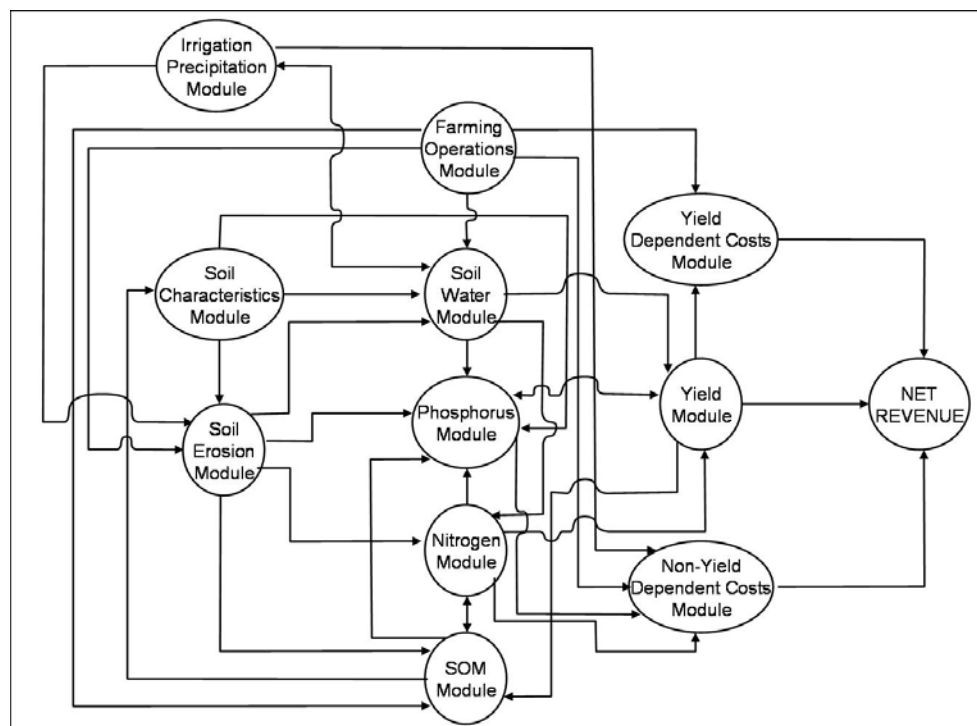
Figure 2. Overview of potato rotation model emphasizing the interaction between components.

Environmental Module

The agro-environmental portion of the model was developed to model a simplified concept of crop growth and yield. This module takes into consideration soil properties, such as texture, available water, infiltration and organic matter, and uses these properties to look into plant available nutrients and moisture. Through the simulation of yield, the agro-environmental module outputs applied N and P fertilizer, yield and irrigation water to the economic module for calculation of economic costs and returns. The potato rotation model was based upon the model created by Belcher et al (2003) which looked at economics and changes in soil quality. The agro-environmental module consists of several sub-modules, such as nutrients, moisture, erosion and yields, interconnected to create the dynamic model. The potato model was developed to simulate potato rotations in the experiment near Carberry, MB, on a Wellwood soil which is a moderately well drained Orthic Black clay loam, with medium organic matter and high natural fertility. The soil has good soil aggregation (structure) which reduces the potential for erosion.

Crop yield in the model is determined, in part, from water and nutrient response curves based upon a literature review for the crop in question. The normalized response curve increases from a deficient state to an optimum (or adequate) level of the nutrient in question. When nutrient levels are deficient, crop yield is limited (Beegle 1995). Westermann and Kleinkopf (1985) suggest that the transition between the deficient and adequate levels of the nutrient occurs at a yield that would be 10% less than the maximum. At higher nutrient levels, crop yield can decrease due to lodging or toxicity, though this is not common to all crops and may not be a significant factor for potato (Westermann and Kleinkopf 1985, Kelling 1999, Beegle 1995). Since most data found through literature was reported in terms of yield, and maximum yields varied across the studies, normalized response curves were obtained from the data that was provided with an estimation of a quadratic regression of the data. Normalized curves were obtained by dividing the quadratic fit by the peak yield. By normalizing response curves, comparison between different data set could by done, with a maximum relative yield of 100%. By using the normalized response curves, the deficiencies, or excessive nutrients/water, gives a value less than one, which is used in the yield sub-module to determine the effect of the deficiency on final yield.

The erosion sub-module was developed to estimate annual loss of soil due to wind and water erosion and farming practices. The module calculates rates of erosion and soil formation, which affect the top-soil productivity (solum depth). The rate of erosion in this model depends upon the rotation and the crop management. In general, erosion rates were higher in potato production years due to intensive tillage and low levels of crop residue compared to years where an established alfalfa stand was present. Rates of erosion vary between rotations for the same crop due to effect of tillage management on aggregate size distribution and cover of crop residue.

Erosion diminishes the surface of the soil, usually the A-horizon (Bauer and Black 1992). As such, erosion will have an influence on plant growth as most of the nutrients and organic mater are found in the topsoil (TAHRC 2004). The importance of organic matter is that it influences available water storage capacity and infiltration rate, which also affects the plant-water

relationship. Studies by Larney et al (1992) have shown that wind erosion reduces soil productivity and thus crop yield. They found that wheat yields could be reduced by 47 to 214 kg/ha, depending upon soil texture, due to the loss of a single centimetre of topsoil.

With erosion and soil formation, the depth of the top soil (solum) can change over the years. In the model by Belcher et al (2003), the original solum depth was recorded at 130 cm for Brown soil in Saskatchewan. The Wellwood soil of the potato study has a solum depth of approximately 60 cm (Mills and Haluschak 1995), which is the value used in the model. Soil depth in the model changes with erosion and soil formation annually, and thus influences the level of soil organic matter (SOM).

The soil organic matter carbon sub-module (Figure 3) was used to determine the change in SOM under differing tillage practices for different potato rotations. Soil organic matter losses were determined as erosion- and mineralization-based, with additions to SOM coming in the form of surface crop residue.
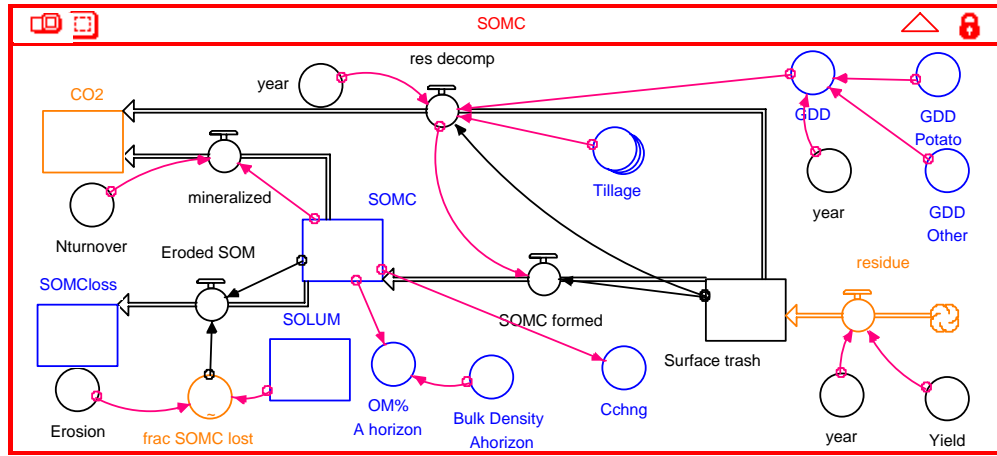
Figure 3. Soil organic matter module schematic.

Residue remaining after harvest contributes to the soil's organic matter levels and quality (Greer and Schoenau 1992). The added value of residue, according to Canola Council of Canada (2001(c)) is increased infiltration, shading of the soil to protect against evaporation of valuable water, and reduced wind speed, which affects both erosion and evaporation. The potato rotation model assumes that only the grain/tuber portion of the crop is removed from the system, leaving the remaining biomass to contribute to soil organic matter. For a forage crop such as alfalfa it was assumed that after harvest 10% of the yield remained on the field. The harvest index of a crop is used to determine the amount of biomass remaining after harvesting the crop, and is calculated through the following equation from Arnold et al (1995):

$$HI = \frac{B_{aboveground}}{Y} \qquad (1)$$

where HI is the harvest index in kg of yield per kg of residue; $B_{aboveground}$ is the above ground biomass in kg/ha; and Y is the yield in kg/ha. By knowing the previous years yield, the amount of crop residue can be calculated from product of yield and the inverse of HI.

Surface residue carbon follows one of two courses: it is either converted to CO2 through decomposition or is converted into SOM. Rates of residue decomposition were estimated using the equation developed by Douglas and Rickman (1992):

$$Rr = Ir \exp(fN * fW * k * GDD)$$ (2)

where Rr is remaining residue; Ir is initial residue; f N is a coefficient based on initial residue nitrogen; f W is a water coefficient based on residue and field management; GDD is the number of growing degree days; and k is a general decomposition coefficient, set to a value of –0.0004. The factor f N accounts for the fact that residue high in N content decays at a higher rate as compared with residue with low N content (Douglas and Rickman 1992). The factor f W expresses the difference in decay rates under wet versus dry conditions, influenced by tillage practices. Douglas and Rickman (1992) suggested that the values of f W range from 0.2 to 1.0, depending upon the farming system. In Manitoba, the number of growing degree days for potato and corn (May through September) was in the range of 1550 to 1650, and for all other crops of the rotation (May through August) 1400 to 1500.

The amount of carbon lost to the atmosphere through the decomposition process is then calculated as:

$$CO_{2decomp} = C_{surface} * [1 - \exp(fN * fW * k * GDD)]$$ (3)

where $CO_{2decomp}$ is the amount of CO_2-C that is released to the atmosphere as a result of the decomposition process; $C_{surface}$ is the amount of crop residue carbon, dependent upon crop type and yield. Mineralization of SOM to CO_2 also occurred and was calculated as:

$$CO_2 = SOMC * N_{turnover}$$ (4)

where CO_2 is the amount of CO_2-C removed from the SOMC stock to the atmosphere; SOMC is the amount of soil organic matter; and $N_{turnover}$ is the nitrogen mineralization rate, which is based in part on soil temperature and moisture.

The formation of soil organic matter carbon was taken as the difference between the amount of crop residue carbon left on the surface and the amount of carbon lost to the atmosphere through decomposition.   The initial amount of soil organic matter carbon (100000 kg) was taken from Mills and Haluschak's data (1995) for Wellwood soil to approximately 30 cm depth. Loss of SOMC can also occur through the removal of soil due to erosion. Solum depth and erosion rate are used to determine SOMC loss, as described by Belcher et al (2003). The relation states that at low erosion rates, the amount of SOMC lost is small; at high erosion rates, after the solum has been depleted, the loss of SOMC is very high.

The nitrogen dynamics developed for the potato rotation model are influenced by soil dynamics. Nitrate nitrogen is a mobile, soil nutrient, subject to leaching losses as well as runoff losses, especially in association with irrigated soils (CSIDC 2001, Penas and Sander 1993, Hopkins and Ellsworth 2003); however, the loss of nitrogen through leaching is not a major concern of soils with high clay content (McKenzie 2001, Canola Council of Canada 2001(b)). Nitrate nitrogen can be lost to the atmosphere through the process of denitrification in soils with high water content. Additionally, ammonia can also be lost to the atmosphere through volatilization of ammonia from urea, under alkaline or slow drying conditions for a soil initially at or near field capacity (Tisdale et al 1993; Hopkins and Ellsworth 2003; McKenzie 2001). Soil nitrogen can be determined from the levels of SOM and the factors, which influence the rate of microbial activity, such as soil moisture and temperature (Bowen et al 1998, de Neve et al 2003, Knoepp

and Swank 1998, Alva et al 2002(b), Stanford and Epstein 1974, Walse et al 1998, Myers et al 1982). Additional factors, which influence microbial activity, but were not included in the model, are soil pH, soil compaction, salinity, and concentrations of soil nutrients (de Neve et al 2003, Purdy 2004).

The relation of decomposition rate has been widely studied. The general concept is that SOM decomposition can be calculated as (Paul 2001):

$$N_{min} = kT_mW_m\beta \qquad\qquad\qquad (5)$$

where N_{min} is the net mineralization rate; K is the net mineralization under optimal conditions; T_m is the effect of soil temperature on microbial activity; W_m is the effect of soil moisture on microbial activity; and β are other factors. Both T_m and W_m have values between 0 and 1 in this model.

Aside from nitrogen, phosphorus is the most important nutrient for crop growth (Johnston and Roberts 2001). While P demands of crops are much lower as compared with nitrogen (Penas and Sander 1993), most soil P is unavailable to plants (less than 1%) (Bauder et al 2003, MDS Harris 2000). For example, in Manitoba almost three quarters of agricultural fields have medium or lower soil P test levels (Johnston and Roberts 2001).

As phosphorus is taken from the system, unavailable phosphorus slowly becomes available. This process is slow and often doesn't meet the demands of crops (CSASC 1994). Available phosphorus is a characteristic of soil type, dependent upon SOM and soil texture, and does not change drastically from year to year (Canola Council of Canada 2001(a), Potash and Phosphate Institute 1999) unless erosion results in changing the soil texture and SOM levels.

Losses of phosphorus to leaching are low as compared to nitrogen as phosphorus in the soil is quite immobile. Nor is phosphorus subject to gaseous losses as nitrogen is (Hopkins and Ellsworth 2003). Losses can be found through the removal of phosphorus bound in soil particles through wind erosion and runoff (Busman et al 2002, Brady 1974). In a study by Johnston and Roberts (2001), it was found that losses under conventional tillage could be as much as six times that found under zero tillage operations.

The yield sub-module brings all of the agro-environmental sub-modules together. Nutrients, moisture, weeds, disease, and, in the case of canola, temperature all contribute to the final yield which is output to the economic module. The final yield after the application of losses due to deficiencies/excesses of nutrients and water, weeds, diseases and temperature was calculated in the model to be used in the economic module, as well as being reintroduced into the agro-environmental module through phosphorus use and crop residue, for example. Thus, the final yield calculated in the module influences the economic aspects of the current year as well as influencing both economics and environment of the following year.

Economic Module
The economic performance of seven different potato rotations was evaluated based on standard budgeting techniques by computing annual net income of each treatment by subtracting production and all input expenses from gross revenue as described by Zentner et al. (2002). For this purpose, we first developed a database using Econometric View (E-view Version 4.1)

software and, then, an appropriate command file was written in E-view syntax to evaluate each system in regard to costs of production, gross return, and net income. Net income was calculated as the income remaining above cash costs (i.e., seed, fertilizer, chemical, fuel and oil, repairs, crop insurance premium, miscellaneous, land taxes, and interest cost on variable inputs), ownership costs (depreciation, interest on investment, and insurance and housing) for machinery and grain storage, and labour. The labour costs and lifespan of machinery for farm operations were calculated according to the machinery work rate per hectare (Saskatchewan Agriculture and Food, 2002). All annual inputs used in each phase of rotation for each management treatment, the type and frequency of field operation, year and replicate including pre-plant activities, tillage, fertilization, planting, insects and pests control, harvesting, storage, and transportation were included in the analysis. Coefficient of variation (CV) was used to measure relative variability of net income of each treatment. The research plot data were extrapolated to the farm-level using a 907-ha representative farm, with a typical complement of machinery and labour supply for each treatment. The cost of inputs was held constant at their 2001 levels. The use of constant prices facilitates to compare net income of crops between years without inflationary effect.

Farm operation costs in our model are divided into two categories: Dependent costs and Base costs. Dependent costs are costs that are controlled by the agro-environmental module, including yield dependent costs, irrigation dependent costs and fertilizer dependent costs. Base costs were developed through experimental evaluation with E-View and remain constant throughout the rotation.

Results and Discussion
The model for each rotation was run five times simulating 50 years of crop rotation per run. The resulting data was then averaged over the rotation, by rotation, crop and year, depending upon the data. These averaged results are summarized below.

Average annual net revenue by rotation was greatest in the two-year crop rotations, P-C and P-W. These two rotations have average annual net revenues in the $475 to $480/ha range (Figure 4), about $100/ha greater that the next closest rotations of P-C-W and P-O-W. This should be expected since in a shorter rotation there is a greater frequency of the potato crop. For example, over a 12-year period, a two-year rotation would result in 6 potato years, a three-year rotation would have 4 years of potato and a four-year rotation would only have three years of potato. With potato being a high value crop, and average net revenues of potato being much higher than other crops of the rotation study, the greater the frequency of potato, the higher the average annual net revenue.
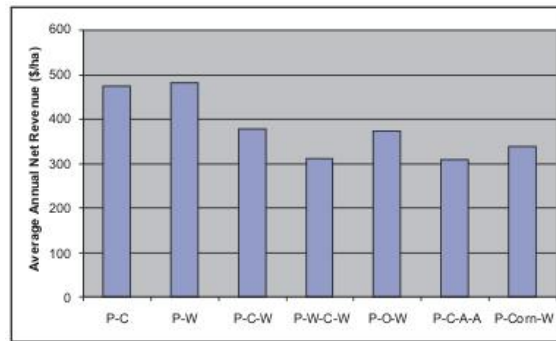
Figure 4. Average annual net revenue by rotation.

Average fertilizer costs included costs for nitrogen and phosphorus plus costs for other fertilizer that may be applied. Fertilizer demand is lowest in the model for alfalfa ($8.68/ha) and is highest in potato ($150 to $165/ha). It should be noted that the model does not take into account the nitrogen fixing capabilities of established alfalfa nor does it take into account the amount of nitrogen that is not taken up by the previous year's crop. Incorporating these factors into the model would change the amount of required nitrogen calculated by the model, and thus the average fertilizer costs. It should be noted that phosphorus uptake by the previous years crop is included in the determination of phosphorus requirements, though in many cases, there is little to no phosphorus applied since the level of P turnover is high enough as to result in near peak sufficiency in most crops and fertilizer recommendations would indicate that at these soil levels phosphorus need not be applied.

As mentioned, potato fertilizer costs are the highest of the crops used in the potato rotations. As such, rotations with a greater frequency of potato, for example two-year rotations as compared to three-year rotations, will have higher average annual fertilizer costs as shown in Figure 5.
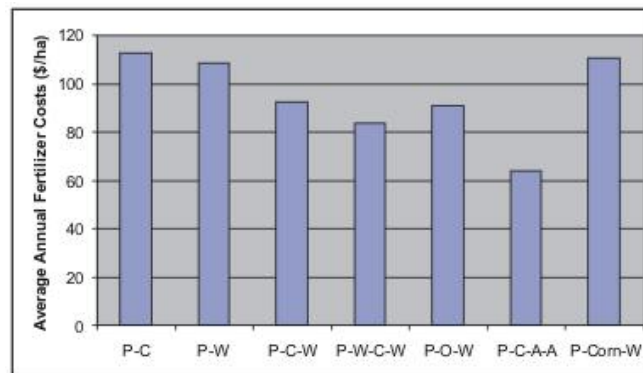
Figure 5. Average annual fertilizer costs by rotation.

Distribution of total costs
Experimental Results

The costs incurred on different inputs such as machinery, seed, fertilizer, chemical, labour and other inputs for six different crop rotations were shown in the following diagrams (Figure (b) of Figure 6). It is evident from these results that machinery cost is the highest cost in all six

12

rotations. The machinery cost varies between 30 to 34 % of the total cost of production depending on the rotation systems. For example, machinery cost on potato-wheat rotation was 32% of its total cost while it was 34% for potato-canola rotation. The seed cost represents about 9 to 10% of the total cost of all these rotations while costs of fertilizer vary from 5 to 7%. The chemical cost represents significant amounts of its total cost and varies between 18 to 27% while labour cost represents only about 5 to 6% of the total costs on all these rotations.

Simulated results

As with the experimental results, machinery costs (oil and fuel and fixed and repair costs) were the highest cost in each of the rotations, being between 41 and 45% of the total costs. As compared to the experimental distribution of costs, the model costs amounted to a larger proportion of the overall costs.

Comparison of other costs of production, seed costs were 8% of costs, as compared to 9 to 10% for the experiment; labour costs, at 5% were comparable to those for the experiment; fertilizer costs ranged from 4 to 6% of total costs, which is comparable to the experiment; chemical costs amounted to 22 to 25% of costs.

Aside from the small differences in these costs, there were larger differences between other costs. The simulated other costs accounted for 15 to 16% of total costs. In the experimental data the other costs where related to 22 to 26% of the total cost of production. Figure 6 shows is presented for a comparison between the experimental and simulated results for the distribution of total costs in the Potato-Canola-Wheat rotation.
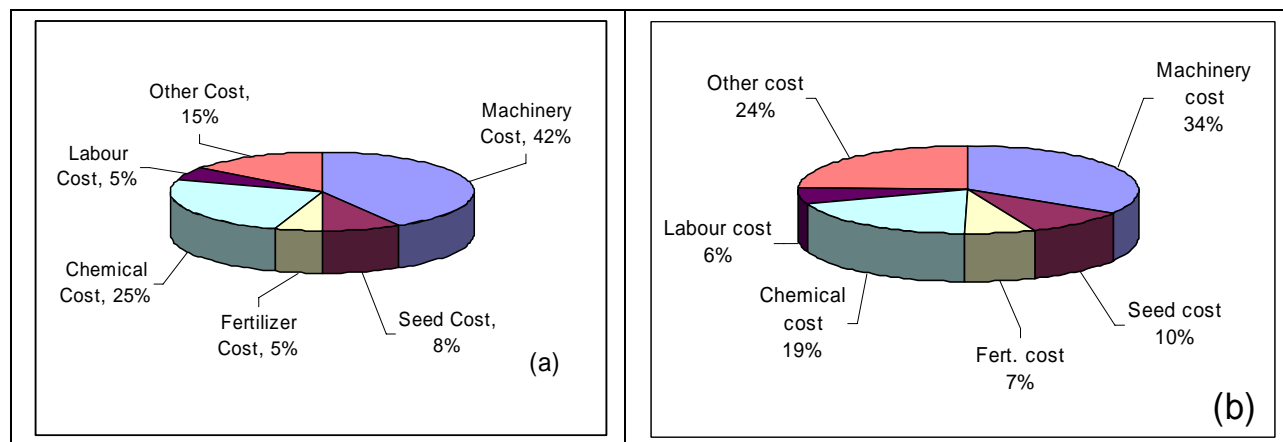

Figure 6. Distribution of Total Costs: Potato-Canola-Wheat Rotation (a) Simulated averages; (b) Experimental averages (1999 to 2001).

Environment Indicators

The change in solum depth within the model was dependent upon the soil erosion and formation rates of the rotation in question. In general, potato had the highest associated erosion, thus it would be expected that in shorter rotations with a higher frequency of potato crop the change in solum would be the greatest. Figure 7 shows the average change in solum as a function of time as the system is run over a 50-year span. Both the P-C and P-W, overlaid data in the figure, show an increased rate of solum loss as compared to the other rotation of the experimental

model. Only the P-Corn-W rotation, which was not part of the experimental research, showed higher rates of change due to the higher erosion rates predicted for the soil under corn. Over the 50 years, average losses were 5.000 cm for two-year rotations, 4.525 cm for three-year rotations, with the exception of the P-Corn-W, which has average solum losses of 5.068 cm, and 4.390 cm for the four-year rotations.
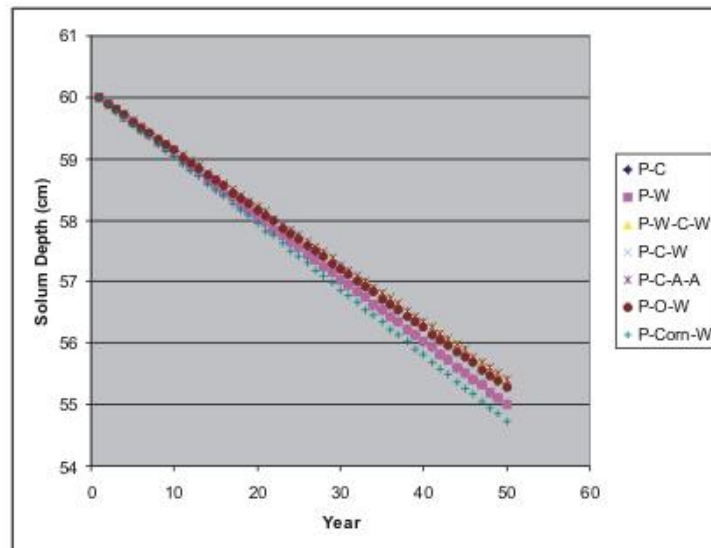

Figure 7. Change in solum depth.

Annual soil loss did not change over the course of the model run. The values were selected based upon the crop in question and the following crop. The annual soil loss was determined as the difference between soil formation and the soil erosion. In terms of average annual soil loss, the greatest rate of soil loss was found in the P-Corn-W rotation, due to more intensive production practices. This is shown in Figure 8, with the four-year rotations showing the least amount of annual soil loss and the shorter rotations showing increased losses.
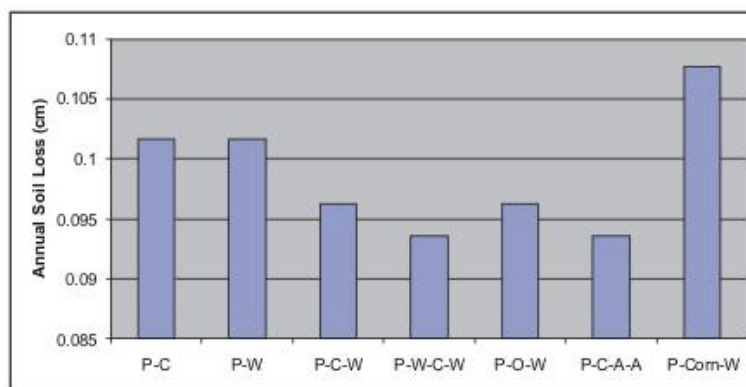
Figure 8. Average annual soil loss by rotation.

As crop residue is important in the infiltration of moisture into the soil, the levels of crop residue can be partially related to the moisture available for the crop that they are affecting. For potato, as shown in Figure 9, average crop residue was greater than 2500 kg C/ha for P-C-W, P-W-C-W, P-O-W and P-Corn-W rotations. In the two-year rotations of P-W and P-C, crop residue carbon

was much lower on average with values between 1900 and 2200 kg C/ha. This decrease can be associated with the yields found in the canola and wheat crops of the two-year rotation. As compared to the other rotations, with the exception of P-C-A-A, the crop residue of the crop prior to potato was smaller in the shorter, two-year rotations. This directly influences the amount of residue present and also the formation of soil organic matter.
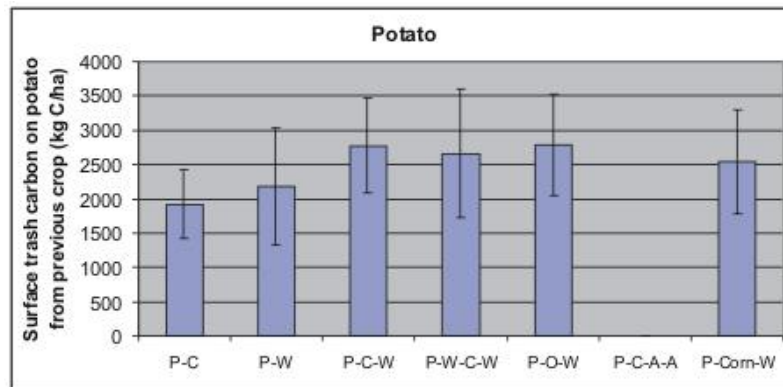

Figure 9. Carbon found in residue on potato planted soils.

The model tracks the changes in soil organic matter carbon (SOMC). The system starts with 100000 kg C/ha, based on the study by Mills and Haluschuk (1995). Figure 10 shows how the level of SOMC changes as the model progresses through 50 years of the rotation. SOMC changes were observed to increase or decrease, at differing rates, depending upon rotation. The model was built in such a way that the SOMC stock is replenished through crop residue and depleted through mineralization and erosion losses. Rotations, which saw a decrease in SOMC, were P-C and P-W. For the P-C-A-A rotation, there is no change over the 50 years of the study in the level of SOMC. It should be noted that the alfalfa is cut and harvested as hay, and only 10% of the yield remained as crop residue, thus limiting the contribution to the formation of SOMC. In terms of the P-C and P-W rotations, the SOMC losses were developed through the higher erosion rates found in these two rotations combines with lower canola and wheat yields, as compared to other rotations, which in turn produce decreased levels of crop residue.

The remaining rotations showed increased SOMC levels over the course of the study. Aside from the P-C-W rotation, these rotations increased SOMC by 12000 to 15000 kg C/ha. The average increase in the P-C-W rotation, over the 50 years of simulation was about 8000 kg C/ha. These results would suggest that these rotations are beneficial to soil quality and thus soil productivity.
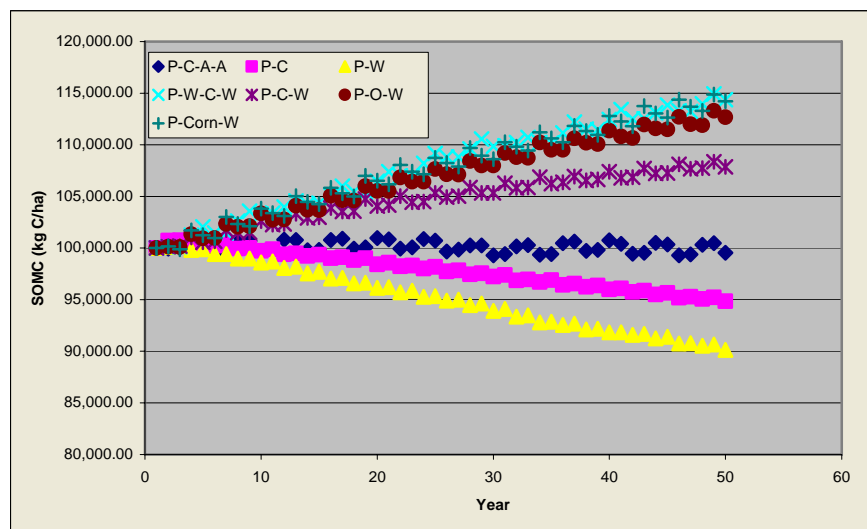
Figure 10. Changes in SOMC as a function of time.

SOMC loss in the model is representative of the amount of SOMC that would be removed from the system due to soil erosion/loss. As such SOMC loss should be similar to average annual soil loss, discussed previously. The P-Corn-W rotation showed a SOMC loss due to erosion of 25000 kg C/ha over 50 years. Losses in the P-C-A-A rotation, with the lowest average annual soil loss, are on average about 18000 kg C/ha. The remaining five rotations of the study have related SOMC losses in the range of 21000 to 22300 kg C/ha.

Carbon dioxide formation was determined from the decomposition of crop residue and the CO_2 lost to the atmosphere in the mineralization process, a process that also depletes the level of SOM. Figure 11 shows the levels of CO_2-C, carbon in the form of carbon dioxide, lost to the atmosphere, dependent upon rotation. The value of this data, aside from determining the changes in the SOMC stock of the soil, is the potential for determining which rotation would have the smallest environmental effect through a decreased contribution of CO_2 to the atmosphere. While this component only simulates CO_2 from the soil, and not CO_2 equivalent emissions from other components, such as farm machinery, it is a good start to allow for an evaluation of crop rotation for environmental purposes.

From the figure, it is shown that, on average, the P-W rotation contributes the most to lost SOMC, of the rotations in the study, with the P-C-A-A releasing the least amount of CO_2 to the atmosphere. The data suggests that the longer the rotation, the smaller the amount of CO_2 that will be lost.
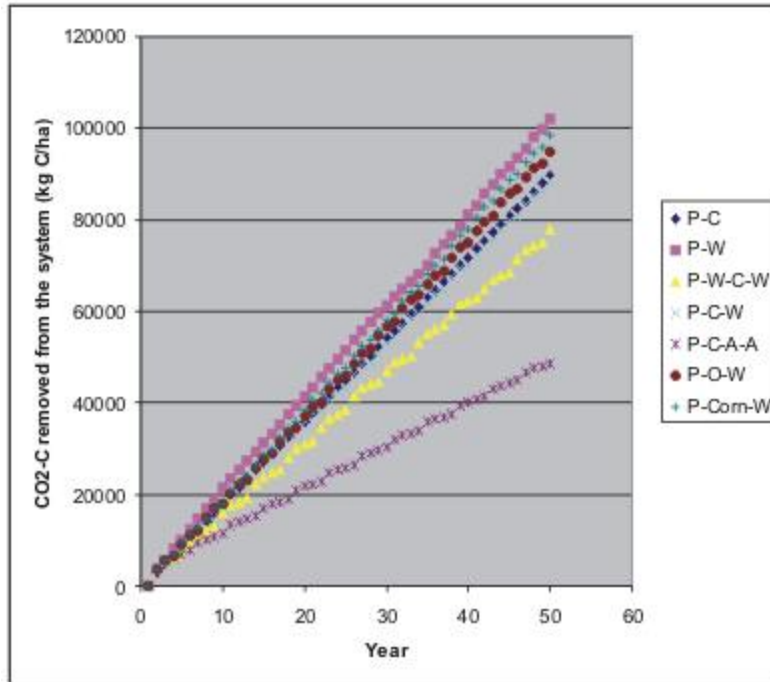
Figure 11. Carbon lost to the atmosphere as CO_2.

Infiltration residue was calculated from the type and amount of residue from the previous years crop and the farming practices and environmental conditions that occurred from the time of harvest of the previous years crop until the time of planting the crop in question. The percent cover is used in determining the infiltration rate of the soil, and thus relates the amount of water that will be available to the crop. As farming practices and type of previous-years crop will depend upon the rotation in use, the percent of cover will change from rotation to rotation. Table 1 lists the average percent cover during the particular crop year in the particular rotation.

Table 1. Percent surface cover due to the previous year's residue.

| Rotation	Crop	Average	St. Dev.
P-C	Potato	4.49%	1.47%
	Canola	13.01%	0.39%
P-W	Potato	6.04%	2.35%
	Wheat	25.36%	0.56%
P-W-C-W	Potato	7.66%	2.75%
	Wheat	25.26%	0.64%
	Canola	72.22%	19.75%
	Wheat	65.96%	7.15%
P-C-W	Potato	7.88%	2.07%
	Canola	13.08%	0.46%
	Wheat	65.71%	9.11%
P-O-W	Potato	7.93%	2.18%
	Oat	25.36%	0.67%
	Wheat	69.53%	5.13%
P-Corn-W	Potato	7.01%	2.08%
	Corn	20.98%	0.69%
	Wheat	36.12%	4.04%

Lower surface cover, on average, was found in rotations that were only two years in length. These lower values can be related to lower yields and thus smaller amounts of residue left after the removal of the grain.

Figure 12 shows the effect of rotation, in particularly the timing of canola within the rotation, on the level of surface cover at the start of the canola growth season. When canola follows potato, the level of surface cover is in the range of 10 to 13%. This is expected as potato residue is quite fragile and there are increased farming practices used in field preparation for the following canola crop as compared to canola following wheat. In the P-W-C-W rotation, the average level of surface cover is just over 70%. Reduced tillage practices used in this rotation allow for greater amounts of surface cover with residue not being as incorporated into the soil as compared to the other rotations containing canola. Additionally, from Figure 12, wheat residue produces more surface cover per tonne of residue per hectare as compared to potato. So while levels of crop residue are generally similar for wheat and potato, there is more surface cover due to wheat.

As with canola, surface cover at the start of the wheat growing-season was much higher when wheat did not follow potato or corn. When wheat followed potato, surface cover was around 25%; following canola or oat, average surface cover was greater than 65%. These differences can be attributed to farming practices and the relation of crop residue to percent surface cover. In Figure 13, residue after corn was higher than after potato, but lower than rotations where wheat was after canola or oat.
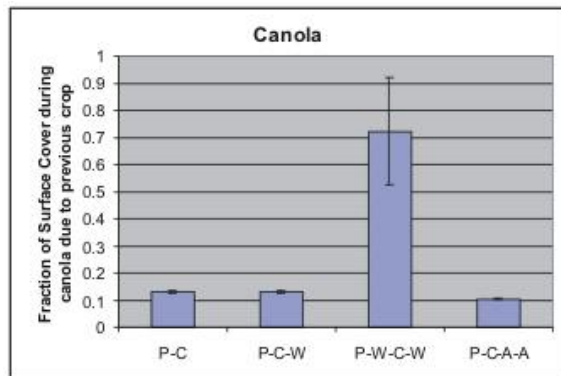
Figure 12. Fraction of surface cover during canola year.
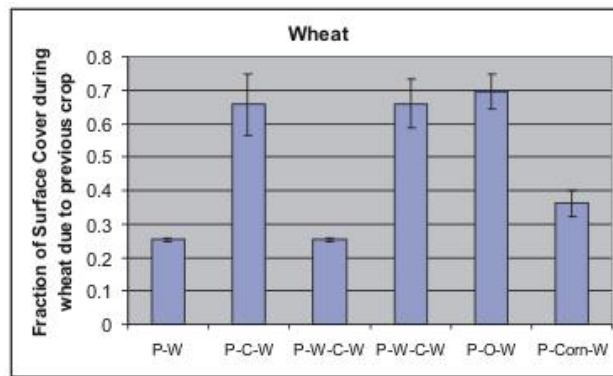
Figure 13. Fraction of surface cover during wheat year.

Conclusion

While the crop rotation model still requires work in areas related to weeds and diseases, and how their effects change based on rotation, the crop and economic modelling proved to be effective estimations of crop rotations and dynamics. With rapid growth of potato production in Manitoba, the potato rotation model helps develop a framework for the determination of which production system is economically sound for the producer and environmentally friendly.

In terms of the environmental significance of the model, several environmental components were examined. The influence of rotation on soil organic matter showed interesting results with some rotations improving the SOM of the soil while others slowly depleted the stock. Release of CO_2-C was also modelled and specific trends were seen depending upon the rotation. While in a very simple form, soil erosion was also studied in the model. With further development, the erosion sub-module could prove to be an important tool in the crop development model, underlining some important concerns related to erosion, irrigation and crop rotations. Inclusion of a root-based crop in the model allows for the evaluation of the sustainability of the production system under a combination of high disturbance practices with no-till or minimal tillage methods. The modelling of optimal nutrient levels for crop growth also has environmental significance. Concerns regarding high levels of nitrogen and phosphorus in the soil are addressed with the model, with the influence of rotation on average annual nutrient application being emphasised. With potato production under irrigation, the concern of nutrient losses through nitrate leaching could be further modelled in order to evaluate this environmental concern. While not fully modelled, the influence of weed and disease on crop growth and the effect of rotation on the incidence and severity of weeds and diseases both play a significant role in environmental concerns related to application of chemicals (pesticides, herbicides, fungicides, etc.) and related contamination of ground and surface waters.

While the environmental model shows the effects of many of these environmental concerns, producers will still find it difficult to implement environmentally friendly rotations without the knowledge of the effect on the farm's economic sustainability. By modelling fifty years of potato production under different rotation systems, the model informs both the producers and potato industry of the long and short-term environmental and economic effects of specific potato production practices. Crop rotations are currently selected based on the agronomic and environmental constraints. However, crop rotation and the selection of a particular rotation will

not become a "farmer's optimal choice" until several economic, and perhaps environmental aspects are clearly understood. Farmers constantly evaluate the relative benefits of crops. The opportunity of producing a crop is the forgone value of producing the next best alternative crop. Therefore, it is essential to compare production costs, yields and other economic factors of different rotation systems to make the best choice. The model provides producers with environmental and economic criteria to help in the selection of the best-irrigated potato rotation. Integration of these criteria provides an opportunity for producers, the potato industry, and policy makers to make environmentally and economically sound decisions.

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