Sustainable Farming Systems Model

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Introduction

The Sustainable Farming Systems (FS) in Saskatchewan model is intended to function as a policy analysis tool for assessment of the environmental and economic sustainability of specific grains and oilseeds production systems at the ecodistrict level in Saskatchewan. The model produces economic and environmental indicators of sustainability for comparative farming systems under defined land and economic conditions. It functions on an annual time-step and at a regional scale, with linkages and feedback between the environmental and economic components of the model. It is being developed within the Centre for Studies in Agriculture, Law, and Environment in the College of Agriculture by an interdisciplinary team of resource scientists and economists.

General model description

The pilot version of the model is being developed for ecodistricts H6 (Whitewood Hills Upland, #733), **Hl 1** (Touchwood Hills Upland, #748), and H16 (Indian Head Plain, #754) within the Aspen Parkland Ecoregion. These ecodistricts represent a broad range of soil, landscape, climate, and productivity conditions. Crop production simulated in the model is based on three farming systems:

i. a cereal- based crop-fallow system with a high relatively high frequency of tillage and low inputs (WF);

ii. a longer-rotation system of cereal and oilseeds; fallow every 4 or 5 years; a combination of chemical and tillage fallow (WFC); and,

iii. a continuous cropping system based on cereal, oilseed, and pulse crops in rotation; minimum or zero tillage (WCP).

The environmental and economic indicators produced as model output for comparative assessment of the farming systems are listed below. Indicators in italics are being developed or proposed.

i. Soil N and N balance,
ii. Available water storage capacity,
iii. Soil organic matter,
iv. Net CO_2 balance and net N_2O balance,
v. Profit,
vi. Profit risk,
vii. Land use,
viii. ***Wind and water erosion,***
ix. Fossil fuel use,

X. ***Pesticide loss, including run-off and drift; human and wildlife exposure,***
xi. Biodiversity/wildlife habitat, and
xii. ***Water quality.***

The model is being developed with STELLA® Research 4.0, a numerical integration software for temporal. modeling that can be used with Windows95. STELLAR Research 4.0 was selected as the model-building environment because its use does not require programming experience, it can be used on either IBM or Macintosh based systems, it is designed for modeling at an aggregated level and it easy to change the values of exogenous variables as simulations are run, and it is transparent.

Environmental model

This section contains a general description of the environmental components of the FS model. To provide more detailed information, the STELLA interface, model algorithms and values for the wheat-pea-canola rotation are available on the inter-net at the CSALE homepage at http://eru.usask.ca/csale under the heading Farming Systems Model.

Crop production. The crop production component of the environmental model was developed from a continuous wheat rotation model (SimPLE) developed by Greer and Schoenau (1992) to simulate the effect of erosion on continuous wheat production. The SimPLE model was developed on the premise that wheat yields in Saskatchewan are limited mainly by available water, available N, and available P, such that the most limiting of those three factors will determine wheat yield. Greer et al. (1992) developed their continuous wheat model on the basis of boundary-line yield predictions, which reflect water, N and P sufficiency relative to potential maximum wheat yields.

Boundary-line yield relationships were developed for canola and peas, relative to nitrogen and water use. The method, demonstrated in Figure 1 for canola yield and total water use (TWU), involved plotting available empirical data for yield and TWU. Maximum canola yield (Ymax) was determined and other yields (Y) were calculated as a proportion of Ymax (Y/Ymax). For canola, maximum yield (Y/Ymax =l) was about 2.6 t/ha (-45 bu/ac) associated with -37 cm of total water. Canola yields declined for TWU values less than or greater than 37 cm of total water. Values of Y/Ymax less than one result from either insufficient moisture (TWU<37cm) or excess moisture (TWU>37cm). The effect of moisture may be direct or indirect. For example, yields reductions at TWU greater than 37 cm may result directly from flooding, or indirectly as a result of increased disease under humid conditions.

Phosphorus sufficiency for all of the crops is defined as a function of available P (Greer and Schoenau, 1992):

for available P > 2, P sufficiency = $1-^{(-0.19*\text{available P - 2})}$, else, $1-^{(0-0.19*0.00001)}$

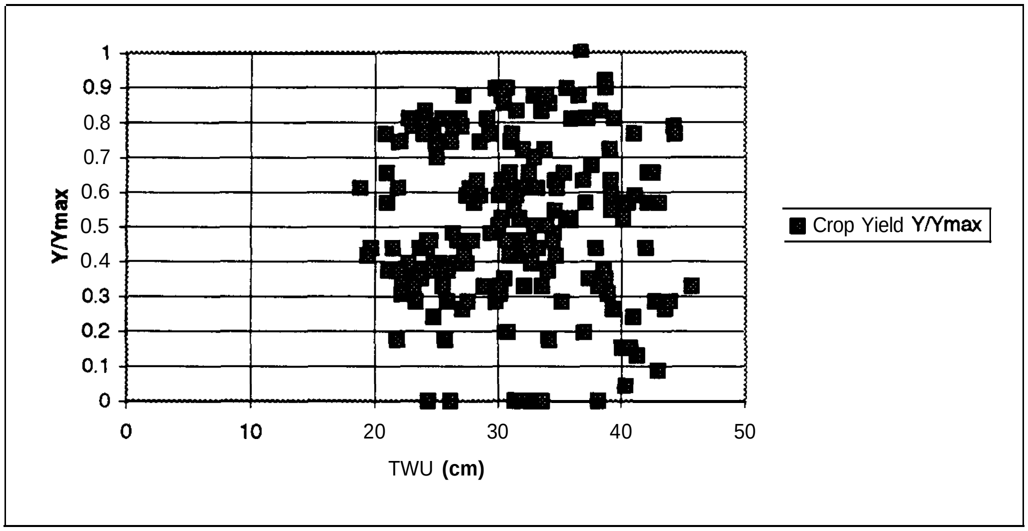

Figure 1. Relationship between total water use (TWU) and yield as proportion of maximum yield for determination of water sufficiency for canola.

Once sufficiency curves were developed for each factor, the fractional sufficiencies were combined in a multiplicative way (Fig. 2). It was assumed that the yield resulting from a single factor (N, P, or water) would be further limited by the other factors, up to sufficiency = 1. This method of multiplying the sufficiencies to estimate the fraction of maximum yield potential is consistent with the Law of the Minimum (Wild, 1988) and accounts for interactions among the most crop-limiting factors.

An additional temperature constraint was applied to canola yield, based on canola yield reductions caused by high temperatures during their flowering period. It was assumed that canola yield was reduced by 0.2 t/ha for each day that the mean daily temperature (MDT) exceeded 22°C.

Since crop production is assumed to be a function of water, N and P sufficiency, the rest of the environmental model was developed to predict annual values of soil moisture, available N and available P as a function of ecodistrict environmental parameters and farming system rotation. Ecodistrict climate and land data were obtained from the Soil Map Unit databases of the Saskatchewan Soil Survey.

The soil water component. Water available for crop growth is the sum of growing season precipitation (Gsppt) and the snow-melt equivalent precipitation received and stored in the soil from September to March (SWE ppt) for each ecodisttict. The model generates an annual precipitation value from mean GS and SWE values based on an assumption of normal distribution and a variance of 0.1. The proportion of precipitation that becomes available to the crop (crop water) is influenced by the infiltration of precipitation into the soil (infil rate), the recharge rate and a storage factor (Fig. 3). Annual infiltration rate (infil rate) is calculated using the K (runoff) factor from the USLE (Wischmeier and Smith, 1978) such that l- K (l-runoff) is the proportion of water which enters the soil (Greer et al., 1992). Precipitation outside of the growing season enters the soil at one half of the infiltration rate, reflecting

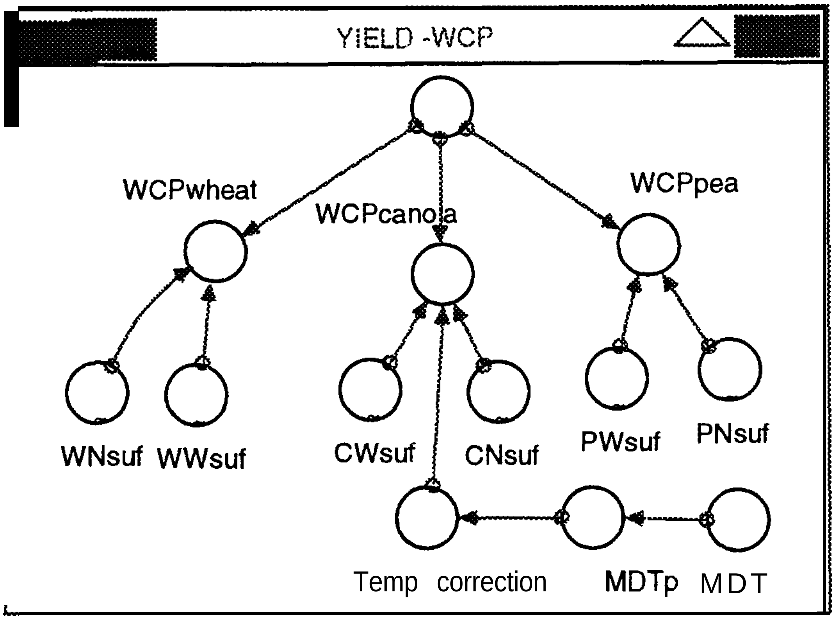

Figure 2. Crop production sufficiencies.

research findings that over-winter recharge of stubble is equivalent to about half of the snow water received over the winter (Innovative Acres Report, 1988; Greer et al., 1992).

The available water storage capacity (awsc) of a soil is based on the clay and SOC content of the soil, as determined in the Universal Soil Loss Equation. (Fig. 3). The storage

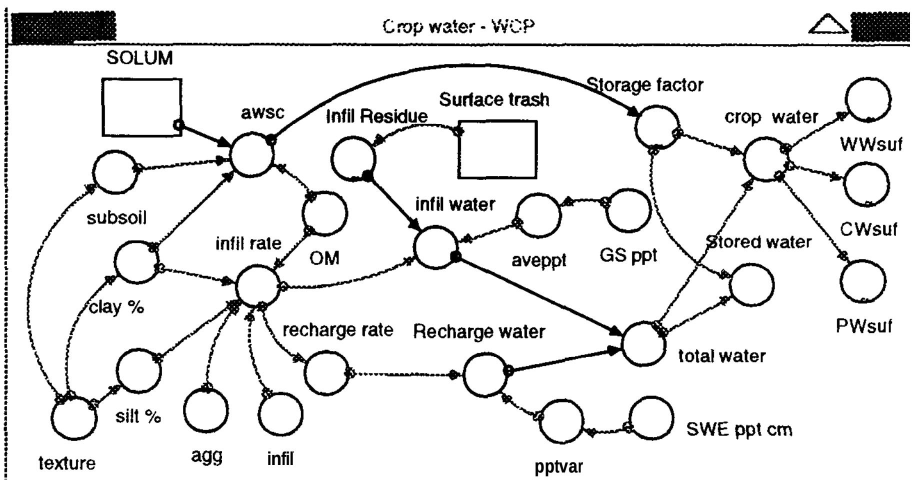

Figure 3. The crop water component of the FS model.

factor determines the amount of crop water available for crop use according to a sufficiency function in which the proportion of the total available water stored in the soil increases as the awsc increases (Greer et al., 1992).

The **soil organic matter carbon component. The** SOC component of the SFS model simulates the conversion of crop residues to SOC or CO_2 (Fig 4). Crop residues are returned to the soil after harvest each year. The amount of C in the added residue is determined as a function of grain yield and the type of residue (Moulin and Biemuts, 1995). Residues flow into the stock of surface trash, which then flows into either the SOMC pool, determined by the rate of SOMC formation or into the CO_2 pool, at a rate determined by the rate of decomposition. The rate of decomposition is based on a model for the Black soil zone developed by Moulin and Beimuts (1995) and Douglas and Rickman (1992):

res decomp = f(N, water, GDD, and a constant k)

where: N= 0.570 + (0.126[N])

[N] = 11.9 g/kg cereals, 14.23 g/kg pulses, and 6.84 g/kg oilseeds

Water = 0.3 in fallow, 0.2 in stubble

k= -0.0004

GDD = growing degree days

SOMC level is a function of the rate of loss (residue decomposition and soil erosion) relative to the rate of gain from surface trash and determines the level of soil organic matter (OM).

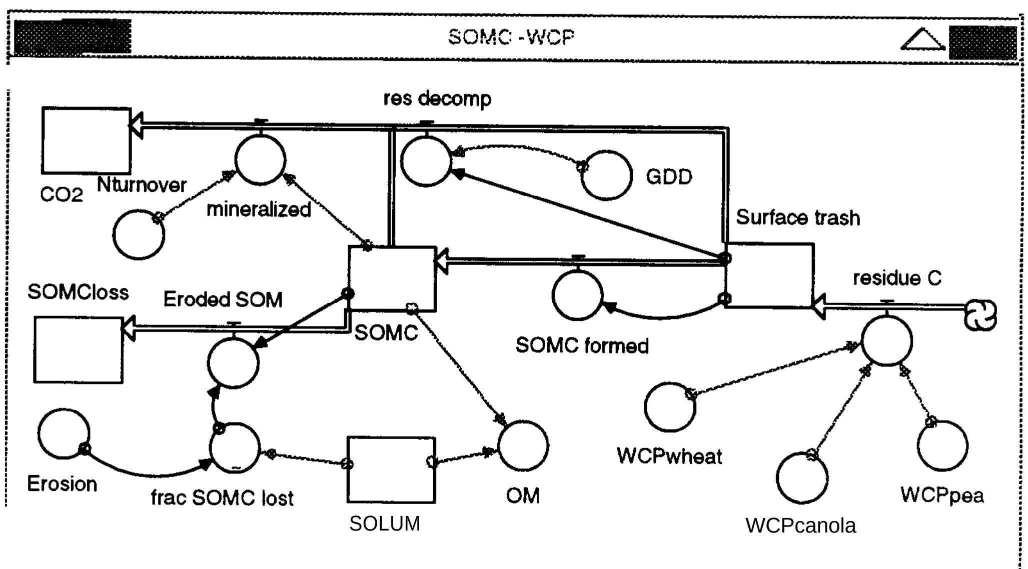

Figure 4. The soil organic matter component of the FS model.

The **soil** N **component.** The supply of soil N is controlled by SOMC levels and the N turnover rate (Fig. 5). The rate of N turnover is a function of soil water content (NtWATER), soil temperature (NtTEMP) and soil thickness (NtSOLUM). Erosion, through its effect on soil thickness, reduces soil N, whereas increasing SOMC content, soil temperature and soil moisture will N turnover and soil N. Available N is soil N plus fertilizer N (N fert) and is used to determine the N sufficiency curve for each crop.

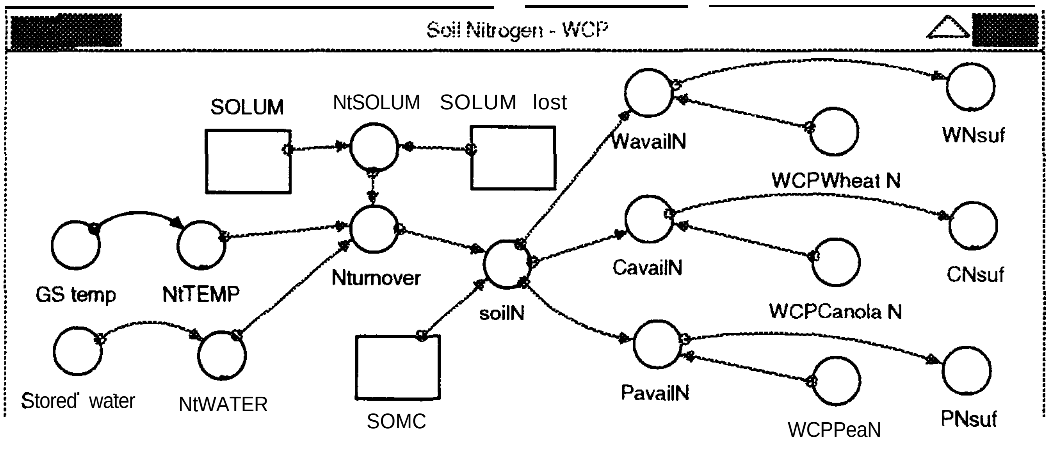

Figure 5. The soil nitrogen component of the FS model.

The soil P component. Soil P is determined by the rate of P release from mineral (Pi), organic (Po) and fertilizer (P fert) sources (Fig. 6). Organic P is supplied relative to SOMC turnover, assuming a C:N:P ratio of 100: 10: 1, and inorganic P (Pi) is determined by soil clay content. Only 25% of fertilizer P is considered to be available for plant growth (Greer et al., 1992). Available P is the sum of mineral, organic and fertilizer P, and is used to determine P sufficiency.

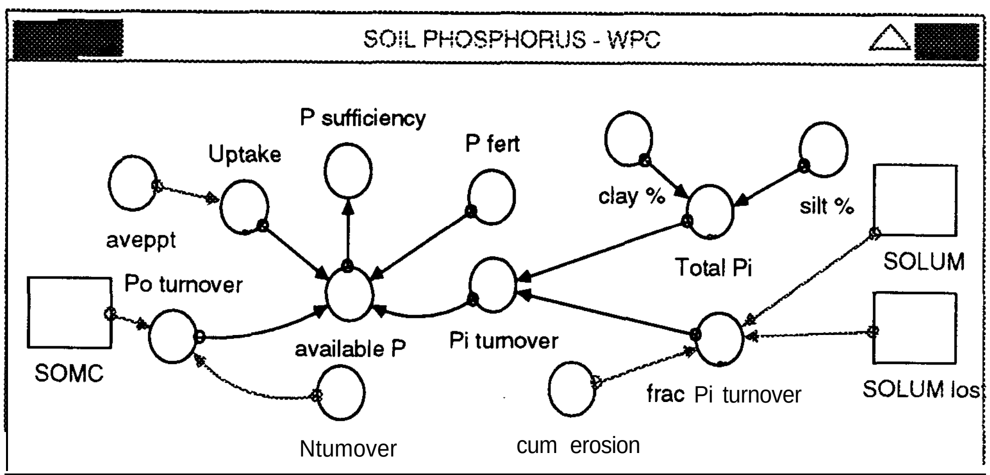

Figure 6. The soil phosphorus component of the FS model.

Erosion of Surface Soil. In the model, erosion is assumed to strip away some depth of surface soil per year (0 t $ha^{-1} yr^{-1}$). As erosion limits fertility and grain yield, lower levels of surface trash decrease water infiltration and available crop water, further limiting grain yield potential (Greer et al., 1992).

Net gain or loss of soil N. Soil net N is the difference between N added to the soil and exported as grain. The amount of N exported is based on the amount of N in grain and the total grain yield. N inputs is the amount of N fertilizer added to the soil..

Summary. Soil organic carbon and available N and P can accumulate in the soil if the rate of organic matter additions exceeds the rate of soil organic matter loss and if fertilizer additions of N and P exceed N and P losses in exported grain. Aggrading stocks of soil organic matter result in increased availability of N and P and an increase in the infiltration and storage capacity of the soil which cause a relative increase in grain yield. Conversely, farming systems in which the rate of crop residue additions to the soil is lower than their rate of decomposition result in degrading stocks of soil organic matter, less available N and P, lower infiltration and water storage, causing lower subsequent yield and higher input costs.

Biodiversity Model.

Biodiversity/wildlife habitat was selected as an environmental indicator for the sustainable farming systems project. Work has begun on creating a biodiversity model which is dynamically linked to the economic and environmental models. At this stage the only variable which is being tracked by the biodiversity model is microbial biomass (kg/ha) based on a linear regression developed using data collected from the literature (Biederbeck *et al.*, 1981, 1994 and1996; Campbell et al., 1991; Carter and Rennie, 1982; Fyles *et al.*, 1988; McGill *et al.*, 1986):

$$Cmic_x = -0.18506 + (0.022826 * Corg_x)$$

t-stat: (-2.70791) (10.1613)

R square = 0.757802

n = 35

where:

$Cmic_x$ - soil microbial biomass for rotation x (kg/ha)

$Corg_x$ - soil organic matter carbon for rotation x (kg/ha)

Data used to develop the regression came from studies carried out in various regions in Saskatchewan. Soil organic matter carbon is input from the environmental component of the SF model.

Economic Model

The economic model has three components, an accounting model that calculates revenues, costs and profits for each rotation, a base line component that is used to derive the supply and demand schedules for the fixed proportions model, and a fixed proportions model (FPM) that allocates land to each rotation based on rotation profits.

Accounting model. For each rotation there is a separate accounting model that calculates revenues, costs, and profits at each time step for each rotation. The accounting model provides the link between the environmental model and the economic model. There are currently two variables, yield data and nitrogen fertilizer requirements, that link the environmental model to the economic model. The accounting model performs basic accounting calculations which include rotation revenues, costs, profits and net present value (NPV) based on a 5% discount rate. Figure 7 is the STELLA interface of the accounting model for the WCP rotation.

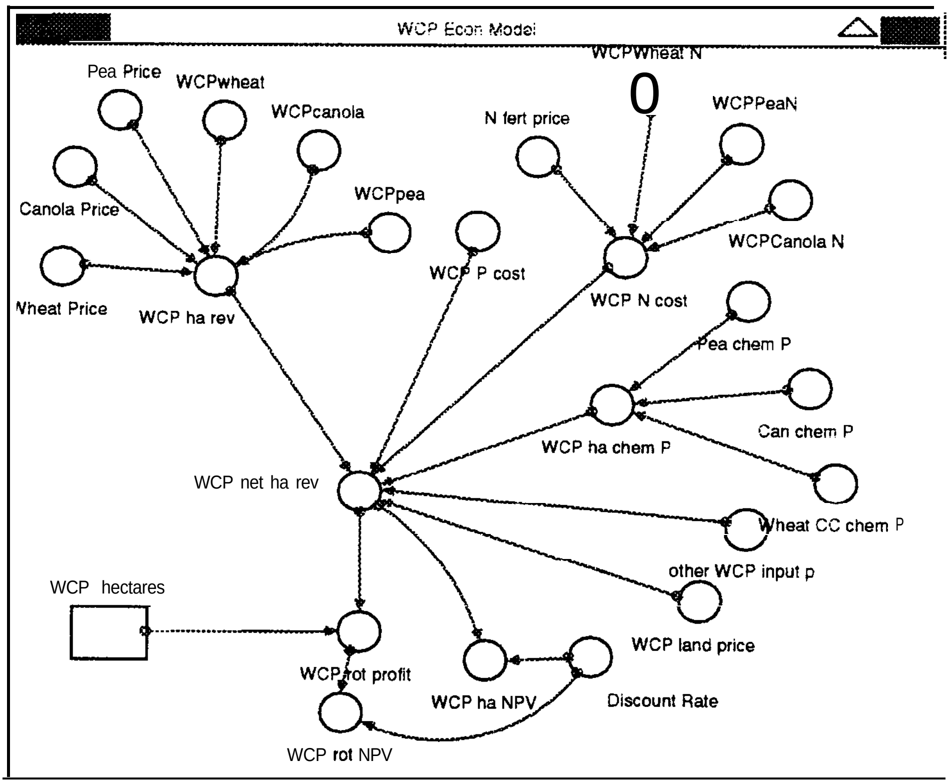

Figure 7. The accounting component of the economic model.

The model uses fixed wheat, pea, and canola prices and multiplies by the yields calculated from the environmental model to produce revenue on an average per hectare basis. The model assumes that for a three year rotation, WFC for example, l/3 of the land base allotted to the WFC rotation is dedicated to each of the represented crops, wheat, fallow, and canola. The yields and prices are multiplied for each respective crop and divided by the number of stages in that rotation, 3 in the WFC rotation, which gives hectare revenue. Prices are in dollars per tonne and yields are tonnes per hectare.

The second link between the environmental and economic model occurs through nitrogen requirements. An average of the nitrogen fertilizer required by the environmental component is multiplied by a fixed nitrogen price determined exogenously. This gives a variable nitrogen fertilizer cost per hectare which is used to calculate hectare costs and profits for each rotation.

The per hectare costs for the inputs nitrogen, phosphorus, chemical, land, and other inputs are summed and the total input cost is subtracted from the hectare revenue to calculate a net hectare revenue. The net hectare revenue, or rotation profit, is used in the FPM model to allocate land to the different rotations. Profit is assumed to be the base for decision making in the FPM model. Rotation profit is calculated by multiplying the hectare profit by the number of hectares in that rotation.

Fixed Proportions Model

Base Line Data, The base line data is used to set up the original supply and demand schedules used in the FPM. The base data provide a starting point for the model by dictating the intercept and slope of the supply and demand curves used in the FPM model. Output prices (wheat, canola, and pea) are three year averages based on the crop years 1993 to 1995, taken from "Agriculture Statistics 1995" and the "1996 specialty crop report" (Sask. Ag. and Food, 1996). Input cost for each of the three rotations are calculated using the "Crop Planning Guide 1997: Black Soil Zone" (Sask. Ag. and Food, 1997).

Eco-district ha are based on 1991 census data. Cultivated hectares were calculated by adding cropped land (less alfalfa and timothy ha) to fallow hectares. The hectares in each of the three rotations, wheat-canola-peas (WCP), wheat-fallow-canola (WFC), and wheat fallow (WF) were based on 85%, 10% and 5% of the cultivated hectares respectively.

Elasticities are used to derive the supply curves for land and other input markets. The elasticity of supply for the land market was assumed to be 0.1 and the elasticity of supply for other inputs was assumed to be 0.8.

Fixed Proportions Model. The purpose of the fixed proportions segment of the economic model is to allocate land in the target ecodistricts to the representative cropping rotations. Land allocation is driven by profit maximization, which is represented in this model by the zero profit position. Input and output prices are used to calculate profits.

The fixed proportions component roughly follows the framework described by Gardner (1987) and an application of the framework developed by Watson (1995). The output categories used are wheat - fallow (WF), wheat - fallow - canola (WFC) and wheat - canola - peas (WCP). The inputs for this model are assigned to four separate input types; land, fertilizer, chemicals (pesticides), and other inputs. The other input category captures all inputs not represented by the remaining categories.

Two major assumptions are required for the FPM. The first assumption is that output is produced in fixed proportions with the required inputs. The fixed proportions assumption indicates that for each additional unit of output produced, one more unit of each of the inputs is required. For the present model input and output units are tied to hectares such that one unit of output is the per hectare quantity of output (tonnes of grain) and one unit of input is that amount of input required to produce that hectare of output.

The second major assumption of the FPM is that long run profits **are** equal to zero. this is an assumption of perfect competition such that at equilibrium the gross revenue for the firm is equal to the total input costs. The zero profit assumption can be summarized with the following relationships:

$$P\,(C) = P_L\,(L) + P_F\,(F) + P_{ch}(Ch) + P_O\,(0) \quad \text{or}$$

$$\Pi = P\,(C) - P_L\,(L) - P_F\,(F) - P_{ch}(Ch) - P_O\,(0) = 0$$

where:

II = Profit ($)

P = Price of output ($/unit)

P_L = Price of land input ($/hectare)

P_F = Price of fertilizer input ($/unit)

P_{ch} = Price of chemical input ($/unit)

P_O = Price of all other inputs ($/unit)

By combining the fixed proportions and zero profit assumptions the following important relationship can be developed:

$$P = P_L + P_F + P_O$$

This equation indicates that, at equilibrium, the price per unit of output, received by the producer, is equal to the sum of the per unit input prices faced by the producer.

Based on these relationships, a vertically linked system of supply and demand curves for output, fertilizer, chemical, other input, and land markets were developed. The vertical systems are linked horizontally by land which is considered the common input across the rotations. This work is ongoing as part of Ken Belcher's PhD project and will be presented fully in his dissertation. The FPM allows dynamic linkage of the economic and environmental components of the SFS model in which any exogenous change to input or output prices will result in a shift of all relevant curves towards a new equilibrium point.

Solution sector. The STELLA modelling procedure for the solution sector is included as Figure 8. the hectares dedicated to each of the rotation are included as stock variables (WF hectares, WFC hectares, and WCP hectares). The solution sector uses expected gross per hectare revenue (Exp ha revenue) in its land allocation procedure. This variable is calculated using crop prices and a forecast yield based on actual yields from the environmental model from the previous three years. The solution sector then calculates rotation profit on a per hectare basis as in the following equation for the WF rotation:

Profit WF = Exp ha revenue {WF} - WF land price - other WF input p -Fert Input Price {WF} - Chem input Price {WF}

Incorporating the zero profit assumption the model allocates land to the three rotations. the profit per hectare is also affected by input costs. Although the fertilizer and chemical markets are represented by fixed prices (perfectly elastic supply curve) the land and other input prices are affected by quantity demanded. Of particular importance is land, since it represents a

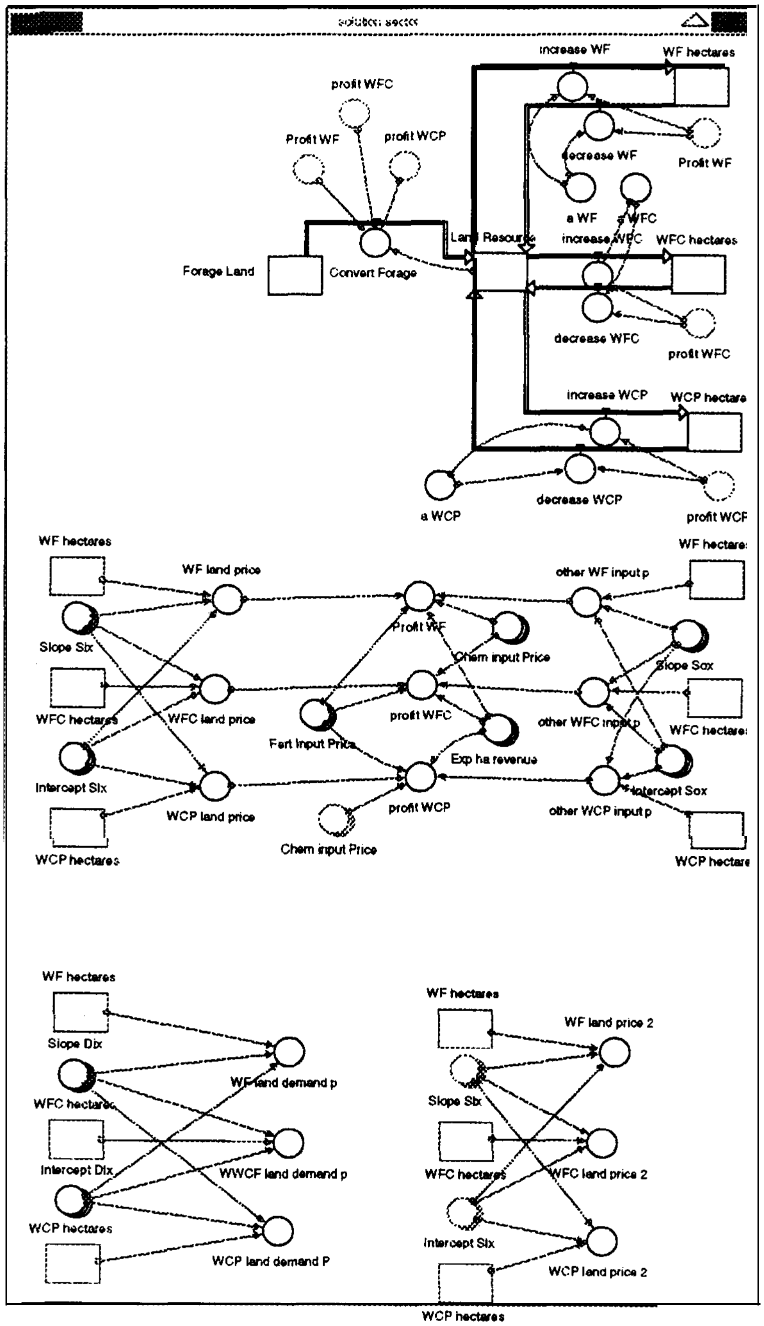

Figure 8. The solution sector of the economic model.

common input across rotations and therefore is represented by a common input price. Land is moved among rotations based on the opportunity cost of that land which is represented by the common input price of land. If the per hectare profit values are positive (negative) then the hectares dedicated to the relevant rotation are increased (decreased). The magnitude of the increase or decrease is a function of the magnitude of the profit such that a large profit stimulates a large change in rotation hectares whereas a small profit will stimulate a small change, zero profit will result in no change. The effect of this variable response is that the system will move toward an equilibrium (zero profit) position each year but will not instantaneously reach equilibrium after each shock.

The economic and environmental components of the FS model are dynamically linked through the fertilizer and yield. The economic model uses the yield values from the environmental model to calculate the height of the output demand curves and thereby the hectare revenue values. In addition, the economic model uses the nitrogen requirements of each crop in each rotation, as calculated in the environmental model, to describe the cost of fertilizer input for each rotation. These two links ensure that management decisions made at time t, which have an effect on soil quality and therefore yields and fertilizer requirements, can affect revenues and input costs at time t + n, which can have an impact on future land use decisions.

Future work

Although the model provides output that is reasonable for the target areas, work will continue to modify and refine the model to improve simulation. The purpose of the FS model is not to simulate all aspects of the real system, but rather to highlight the relationships that are most essential. The goal is to develop a system that will produce appropriate indicator output based on readily available input data. There will always be a trade-off between "improving" the model and making it too complex for use in basic policy scenario analyses.

Ongoing work includes endogenization of some variables, such as N fertilizer rate and soil erosion, which are currently set exogenously. Determination of those variables within the model would allow testing of the resilience of the rotations to shocks, such as from price or weather. Modification in cost factors to introduce some variability in freight charges, input costs and commodity prices is also being done. At present those costs are set exogenously in the base line and remain static for the duration of the simulation. The stochastic nature of the prices could be based on historical data to simulate the variability faced by producers.

The supply curve for land in the general land market represents all land in the ecodistrict. Although the upward slope of the supply curve in this model implies an increasing marginal cost of land, it is felt that another form of supply curve may more closely simulate the existing system. The land resource within an ecodistrict exists in a range of qualities and cover types. In general, the cost of bringing lands into annual crop production will increase as the resource changes from, for example, cultivated land, to tame forage to native uplands to wetlands. To reflect these different costs the model will be developed with a modified supply curve for land. The land supply system will mimic the thresholds which exist between land being dedicated to a range of uses.

The biodiversity model in the present FS model is capturing only microbial biomass within the annual cropping system. An essential piece of information in the building of a more complete biodiversity model is the area of the various habitat types (tame forage, native grassland, shrub and bush land, wetland). The revised supply curve for land, as discussed above, should provide a means of quantifying the area of each of the habitat types found in the ecodistrict. This work is currently being done by Ken Belcher as part of his PhD research.

Summary

The FS model integrates agronomic, resource and economic data to simulate crop production systems on the Prairies. The dynamic links among the model components make it possible to track the effect of a change in one model component through the other linked components. Changes are assessed by comparing baseline output to output resulting from a change to the system. It is possible to derive either increasing or decreasing trends (i.e., yield, profit, or soil nitrogen levels) for a farming system by varying input parameters (i.e., initial organic matter levels, fertilizer applications, erosion rates, etc.). Interpretation must always be done relative to the input parameters used to derive the output and results need to be assessed relative to known conditions for the region and system being tested.

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