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Soil Quality Attribute Time Paths: Optimal Levels and Values

Elwin G. Smith, Mel Lerohl, Teklay Messele, and H. Henry Janzen

We develop a dynamic soil quality model to evaluate optimal cropping systems in the northern Great Plains. Modeling soil quality attributes is feasible, and attribute model results apply to a wide range of soils. A crop production system with continuous spring wheat and direct planting is the most profitable system. This system has low soil erosion and high quality attributes, indicating the benefits of increased soil quality exceed the higher maintenance costs. On-site value of additional soil organic carbon (OC) ranges from $1 to $4/ton OC/hectare/year. These values for soil OC impact the optimum tillage practice, but not the crop rotation.

Key words: cropping systems, marginal user benefit, nonlinear programming, organic carbon, soil quality, tillage

Introduction

The ability of a soil to produce crops on a sustained basis will depend on attributes of the soil and changes over time to these attributes. Soil quality more broadly defined includes sustainability of soil health, biological activity, and intrinsic value (Parr et al.; Warkentin). There are many possible indicators of soil quality and sustainability. Indicators must directly affect the function of the soil, be measurable, and be sensitive enough to detect differences (Karlen et al.). Pierce et al. used a productivity index as an indicator of sustainability to measure changes in productivity resulting from soil erosion over time, but an index does not preserve information on changes to the individual factors.

Economic studies have not directly addressed soil quality indicators or attributes. Soil quality changes have been indirectly modeled through soil erosion and either an estimated or assumed productivity impact (Miranowski), and by changes to a productivity index (Hoag). Substitution options in these models have been limited, even when erosion impacts are estimated by process models. One indicator of soil quality, organic matter, was included as a state variable by Burt, but topsoil depth was also included as a state variable. The use of topsoil depth in the analysis of soil erosion and conservation has produced results specific to a site and soil, and there is often little consideration of the potential substitution of inputs for reduced topsoil depth. Some soil types show little to no impact from erosion, others have productivity restored with additional inputs, and

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Smith is research scientist, Lethbridge Research Centre, Lethbridge, Alberta; Lerohl is professor, Department of Rural Economy, University of Alberta, Edmonton, Alberta; Messele is research assistant, Lethbridge Research Centre; and Janzen is research scientist, Lethbridge Research Centre.

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still others have high yield reductions from erosion even with the addition of inorganic fertilizers (Smith and Hallam). The solution offered for these varying results has been to model sites and soil types separately. The ability to extend results from quantity models across sites and soil types has been limited.

Chemical and physical attributes of soil types include depth, water holding capacity, structure and stability, hydraulic conductivity and infiltration, bulk density and penetration, organic and inorganic carbon, cation exchange and nutrient retention, pH, electrical conductivity, and exchangeable sodium (Arshad and Coen). Organic carbon is a microbial indicator of soil quality (Kennedy and Papendick) and is tied to many of the above soil quality indicators (Reeves). Soil erosion and production practices change many of the chemical and physical attributes of a soil. An economic modeling approach more applicable to a wider range of management practices and soil types is to include input substitution possibilities and the important soil attributes, or quality indicators, directly. Modeling the quality attributes and attribute substitutes would provide results that could be extended to a broader management set, area, and more soil types.

A farm-level soil quality economic model needs to: (*a*) be dynamic; (*b*) contain crop yield functions that incorporate soil attributes, substitution possibilities, and management variables; (*c*) include relationships which capture the impact of choices on the soil attributes; and (*d*) include variables which reflect changes in soil quality (Saliba). Soil quality can be measured by a vector of attributes that influence production and are sensitive to changes in production practices. Changes to attributes, as a result of management practices, can be accounted for over time in a dynamic modeling framework.

Many different economic models of soil erosion have been developed. Models using continuous time generally specify a current valued Hamiltonian with soil depth as the state variable and one or two control variables. Some examples include McConnell; Saliba; van Kooten, Weisensel, and de Jong; and Hoag. The resource will be used until the marginal value product (MVP) of the resource equals the factor cost plus the user cost. Along the optimal path of the resource, the marginal returns from the resource plus the indirect marginal contribution will equal the opportunity cost of the resource plus the indirect contribution of another unit of the resource less the change in the price of the resource. Dynamic programming model formulations have been utilized to study soil erosion time paths (Weisensel and van Kooten). Multi-period linear programming models have been used to evaluate soil erosion and cropping systems that allow limited substitution of inorganic fertilizer for topsoil (Smith and Shaykewich).

The optimal control model specification requires input and control variables that are continuous. However, two of the most important control variables in crop production are not continuous—the crop rotation and the tillage practice. Crop rotations have been modeled as percentage of row crop (Saliba) and as percentage of wheat (Burt) in the rotation. Tillage practices have generally been modeled through the soil erosion associated with tillage, so the control variable is erosion (the result of the tillage practice) rather than the actual controls (crop rotation and tillage practice). These simplifications miss the important consequences that the lumpiness of rotations and tillage practices can have on production decisions (Taylor et al.).

The objective of this study is to determine optimal cropping systems for dryland grain production in the northern Great Plains, taking into account the impact of the cropping system on soil quality attributes, the substitution of inorganic fertilizers for attributes, initial attribute levels, exogenously determined growing season precipitation, and economic factors of grain prices, inorganic fertilizer costs, and the discount rate. A dynamic cropping system model including soil quality attributes is developed to meet the above objective. The values of the attributes are determined for the optimal systems. The cropping system is defined as a crop rotation and tillage practice. The biological and economic factors affect not only the costs and returns of production, but also the long-term level of soil attributes through soil erosion and the net appreciation or depreciation of soil quality attributes. Inorganic fertilizers have the potential to substitute for soil quality and reduce the impact of changes in the level of soil quality attributes, and hence alter their optimum level and value in production.

The Model

Production of a crop on a unit-area basis (Q) can be represented as a function of soil quality attributes that are factors of production (S), inputs (X) where the inputs impact on yield as well as the soil attributes (positive or negative), and inputs (Z) that impact on yield but are soil-attribute neutral:

$$(1) \qquad Q = f(S, X, Z).$$

Soil quality attributes over time can be described by inputs X. Fertilizer, crop rotation, and tillage practice will determine long-term soil quality levels through biological processes in the soil. Crop rotation and tillage practice will determine potential soil erosion, and that will alter the physical and chemical soil properties of the soil attributes. Soil quality attribute changes over time combine both soil-building and soil-reducing factors, and can be described by the following:

$$(2) \qquad \dot{S} = e(X),$$

where the dot over S denotes the time derivative. This specification differs from previous erosion studies by taking into account biological processes of the production system on soil quality, in addition to soil loss impacts from erosion. Previous models (e.g., Hoag) have modeled productivity changes only as a function of soil loss.

Cropping systems are characterized by a limited number of crop rotations and tillage practices that are not continuous and are best modeled as discrete activities (Taylor et al.). An optimization model with a discrete set of crop rotations, tillage practices, land types, and crops is specified in equations (3)–(5):

$$(3) \quad \max_{X,Z} \prod = \sum_{t=0}^{T-1} (1+\rho)^{-t} \left[\begin{array}{l} \sum\limits_{r} \sum\limits_{k} \sum\limits_{l} \sum\limits_{c \in r} \big(PR_{ct} g(t) f(S_t, X_t, Z_t) Y_{r,k,l,t} - \sum\limits_{i} w_i X_{i,c,r,k} Y_{r,k,l,t} \\ \qquad\qquad - \sum\limits_{j} v_j Z_{j,c,r,k} Y_{r,k,l,t} \big) - FC_{r,k} Y_{r,k,l,t} \end{array} \right]$$

$$- (1+\rho)^{-T} \sum_{m} \left[\left(SS_m - S_{mT} \right) * LND * g(T) * \left(\frac{\partial f}{\partial S_m} \right) * PR_T / \rho \right],$$

subject to:

$$\mathbf{A}Y \leq \mathbf{B} \tag{4}$$

and

$$S_t = S_{t-1} + h(S_{t-1}, X_{t-1}), \tag{5}$$

where

Π = the net present value of returns over a 50-year time period less a penalty function at year 50,
ρ = the discount rate,
PR = the crop price,
g = technology yield growth rate,
f = the crop production function,
S = the soil quality attribute,
X = inputs per activity that impact on soil quality,
Z = inputs per activity that do not impact on soil quality,
Y = the activity level (area),
w = cost for inputs that impact on soil quality,
v = cost for inputs that do not impact on soil quality,
FC = fixed costs,
SS = soil quality attribute standard level,
LND = total land area,
$\mathbf{A}$ = the matrix of production input-output coefficients,
$\mathbf{B}$ = the vector of resource constraints, and
h = the soil quality attribute function.

The subscripts are defined as follows:

t = year in the time horizon,
r = the crop rotation,
k = the tillage practice,
l = the land class type,
c = the crop within crop rotation r,
i = production inputs that impact soil quality,
j = production inputs that do not impact soil quality,
m = soil quality attributes, and
T = the end of the time horizon.

The model formulation is deterministic and assumes zero risk. Long-run changes to net returns are not modeled to feed back and influence the choice of technology or the scale of the farm.

Application and Data

The farm-level soil quality model specified above requires a yield component and a farm-level dynamic optimization model component. Descriptions of these components and derivations of input requirements for the optimization model are provided below.

Yield Component

The model specified in equation (3) requires estimation of a yield function, $f(S_t, X_t, Z_t)$. Crop yields on dryland in the northern Great Plains will depend on plant nutrient availability, soil quality attributes, and precipitation. Nitrogen (N) and phosphorus (P) are the most limiting nutrients in these soils. The effective amount of precipitation available to a crop can be altered with the use of summer fallow in a rotation. Soil moisture is increased during the fallow year to effectively increase the moisture available for the next-year crop. Summer fallow also increases soil mineral N and reduces the soil quality attributes.

Four soil quality attributes for a Dark Brown Chernozem (Typic Boroll) that impact on productivity, that are measurable, and for which we have field data include organic carbon, inorganic carbon, pH, and salt (electrical conductivity). Organic carbon (OC) increases water infiltration and retention, nutrient content, buffering capacity, and biological activity, and is a good proxy for other quality attributes that are difficult to measure (Reeves). Inorganic carbon (IC) on these dryland soils is primarily in the form of calcium carbonate, which tends to bind soil P, resulting in P nutrient deficiencies (Larney, Janzen, and Olson). The application of P fertilizer to these soils will increase the P available for plant growth, and with fertilizer application the total P available to the plant will not be directly correlated with soil inorganic carbon. Soil pH accounts for differing tolerances to acidic or alkaline environments, and salt concentration will impact on the ability of plants to grow. A quadratic yield function has been used in other studies related to soil quality (Williams and Tanaka) and can be specified as:

$$\begin{aligned}(6)\qquad Q = {} & \beta_0 + \beta_1 N + \beta_2 N^2 + \beta_3 P + \beta_4 P^2 + \beta_5 OC + \beta_6 OC^2 + \beta_7 IC \\ & + \beta_8 IC^2 + \beta_9 RN + \beta_{10} RN^2 + \beta_{11} pH + \beta_{12} EC + \beta_{13} NP \\ & + \beta_{14} NOC + \beta_{15} NIC + \beta_{16} NRN + \beta_{17} POC + \beta_{18} PIC \\ & + \beta_{19} PRN + \beta_{20} OCIC + \beta_{21} OCRN + \beta_{22} ICRN + \varepsilon,\end{aligned}$$

where

Q = yield (kg/ha);
N = soil mineral nitrogen in the surface 60 cm plus applied nitrogen (kg/ha);
P = soil mineral phosphorus in the surface 15 cm plus applied phosphorus (kg/ha);
OC = organic carbon concentration in the surface 15 cm (g OC/kg soil);
IC = inorganic carbon concentration in the surface 15 cm (g IC/kg soil);
RN = precipitation during May, June, and July (mm), the growing season;
pH = soil pH;
EC = electrical conductivity, measured in deciSiemens/meter (dS/m);
β = parameters to be estimated; and
ε = the error term.

The marginal products of N, P, OC, and RN are expected to be positive, IC and EC negative, and pH unknown. Interactions among N, P, OC, IC, and RN were included because of expected substitutability or complementarity among these inputs. Interaction terms with pH and EC were not included because there is no biological reason to expect an interaction with the other inputs.

Data to estimate the yield function are derived from two sources. The first data set is from a soil quality experiment at Lethbridge, Alberta (Olson et al.). In 1990, the topsoil from a site was removed and replaced with 36 different topsoil types, replicated three times. These plots were further split to include no additional N application and 80 kg/ha N. Yields from 1991, 1993, 1994, and 1995 are used in the yield estimate. The second data set is from an experiment at Lethbridge, Alberta, where the topsoil was mechanically scalped to 0, 10, and 20 cm, with four replicates. Imposed on each scalped depth were four rates of N fertilizer times three rates of P fertilizer (Larney, Janzen, and Olson). The 1990 yields from this experiment are used in the yield estimation. Attributes such as texture, bulk density, and rooting depth are not used in this study because they were similar across all plots, except in the upper 15 cm in the soil quality experiment.

The above sources provided a broad cross-section of soil qualities, while controlling many difficult-to-measure biological variables that vary across geographical and field locations. The concern about scalped soils not reflecting the natural erosion process, while important when soil is modeled on a quantity basis, is not an issue when using soil quality attributes. It does not matter how the soil got to its current state because it is the current attribute levels that are of interest.

The pooled data from the two data sets include the variables identified in equation (6). The mean value (and range) for each of the variables in the sample are given as follows: yield = 2,579.3 (14–6,949) kg/ha, $N = 83$ (11–173) kg/ha, $P = 43$ (3–348) kg/ha, $OC = 15.56$ (5.9–28.5) g OC/kg soil, $IC = 5.64$ (0.075–26.1) g IC/kg soil, $pH = 6.58$ (5.6–7.5), $EC = 0.739$ (0.25–7.0) dS/m, and $RN = 247.2$ (186–309) mm.

Optimization Component

The optimization model [equations (3)–(5)] is nonlinear in yield, soil quality attributes, and fertilizer. The model has a 50-year time horizon with end-of-year periods of 1, 2, 3, 4, 5, 10, 20, 30, 40, and 50 years. Periods with multiple years are assumed to have the same resource level each year for the entire period. Price and costs are Canadian dollars, and input costs are real 1998 dollars. Yield growth from new technologies is incorporated into the $g(\cdot)$ function, determined from long-term fixed rotation yields to be 0.87% per year. Taylor and Young determined that the inclusion of multiplicative technology advances strengthened the long-term payoff from soil conservation. The penalty function accounts for the impact of decreased soil quality attributes past the time horizon (year 50); it is the present cost of cumulative productivity losses discounted into perpetuity at year T. The maximum soil quality attribute value would occur with continuous cropping, zero tillage, and proper fertilization. The yield impact in the penalty function is determined by the marginal product of the soil quality attribute in equilibrium with continuous cropping, zero tillage, and proper fertilization.

The first constraint [equation (4)] is a general constraint that resource use does not exceed resource availability. Land is constrained to 1,000 hectares for determination of the machinery complement and fixed production costs. Labor is constrained for pre-seeding, seeding, harvest, post-harvest, and the remaining of the summer season.

Remaining constraints are transfers through time periods and resource balances within a year.

The second constraint [equation (5)] tracks soil quality attributes over time. Attribute quality is reduced by soil erosion, and either increased or decreased by the cropping practice (crop rotation and tillage) and the fertility program. The function h incorporates attribute changes to move toward an equilibrium plus any changes due to soil erosion. The S variable includes soil quality attributes, OC and IC concentration. Soil pH, electrical conductivity, soil mineral N, and soil mineral P are not tracked over time as these variables are stable in a long-term equilibrium state. Soil OC is modeled to adjust to the cropping practice long-term equilibrium over a 20-year period if there is no soil erosion. This adjustment time frame also assumes the soil is not irreversibly damaged from excessive soil erosion. Soil erosion alters the attribute levels, and the long-term equilibrium might never be reached if soil erosion is high. Soil IC is altered only by soil erosion, with an increasing value indicating lower soil quality.

The first item required in the soil quality adjustment is the biological long-term equilibrium of soil OC. The biological long-term equilibrium concentration of soil OC is primarily determined by climate, cropping practice, fertilizer use, and tillage intensity (Janzen et al.). Lowest OC will occur in a dry climate with frequent summer fallow, tillage, and limited or no fertilizer use. A wetter climate, more frequent cropping, and fertilizer use will increase plant biomass production, directly increasing soil OC. Zero tillage will reduce the rate of biomass decomposition, thereby increasing OC. For the Dark Brown Soil zone of the Canadian Prairies, the biological long-term concentration of soil OC can be approximated by the following (Janzen):

$$OC = 15.0 + 2.0I + 1.0F + (1 - k)(2.0I), \tag{7}$$

where I is a measure of cropping intensity [0 for wheat-fallow (WF), 0.3 for wheat-wheat-fallow (WWF), 0.45 for wheat-wheat-wheat-fallow (WWWF), 0.6 for continuous wheat (W), and 1.0 for grass forage]; F indicates no fertilizer (0) or fertilizer (1); and k denotes tillage (1) or no tillage (0). The results from this equation are used in the optimization model to specify the long-run OC concentration target for a given production system. The yearly increase in OC will depend on the difference between the long-term equilibrium and the current OC, with a 20-year adjustment time assumed to reach the long-term equilibrium.

Soil erosion will reduce the OC concentration. The relationship between soil depth and OC is estimated from mechanically scalped plots adjacent to the experimental plots used to estimate yields (Larney et al.). Soil OC and IC are obtained from measurements for six depth intervals, for each of five scalped depths, and four replicates. Soil depth is converted to the midpoint of the interval plus the scalped depth. The OC relationship with eroded soil depth (ESD) is estimated as:

$$\begin{array}{llll} (8) \quad OC = & 17.694 & - 0.45117ESD & + 0.0035869ESD^2 \\ & (33.19) & (-14.47) & (8.95) \end{array}$$

$$N = 120, \quad R^2 = 0.84,$$

where t-values are reported in parentheses. All variables are significant ($p = 0.05$), and the R^2 value is high. This relationship is utilized in the soil adjustment function (h) to reduce the OC concentration from soil erosion determined within the model. This relationship was estimated for a major soil group, a Dark Brown Chernozem, in the northern Great Plains. The relationship will hold within this major soil group. Soil differences within this major soil group will generally be reflected in differences in the initial OC and IC concentrations. The rate of soil erosion that will negate a yearly OC increase, when moving to a higher long-term OC concentration, will depend on the magnitude of the OC increase. Erosion rates of 30 tons/ha will negate the maximum increase in OC, but erosion rates of 15–20 tons/ha will negate the OC increase for most situations.

The IC concentration in the top 15 cm of soil is estimated as three grafted linear segments because IC tends to be near zero for uneroded soils, increases at a high rate as soil is eroded into the C horizon (subsoil), and is fairly constant moving down through the C horizon:

$$\begin{array}{lccccccc} IC = & 1.193 & - & 0.109S1 & + & 1.5346S2 & - & 0.0582S3 \\ & (0.19) & & (-0.13) & & (10.90) & & (-1.36) \end{array} \tag{9}$$

$$N = 116, \quad R^2 = 0.61,$$

where the t-values are reported in parentheses; $S1 = ESD$ when $ESD \leq 8$, $S1 = 8$ otherwise; $S2 = 0$ if $ESD \leq 8$, $S2 = ESD - 8$ if $8 < ESD \leq 24$, $S2 = 16$ otherwise; and $S3 = 0$ if $ESD \leq 24$, $S3 = ESD - 24$ otherwise. The nonsignificant coefficient for $S1$ indicates that IC does not change in this soil with eroded depths up to 8 cm. From 8–24 cm of eroded topsoil, IC increases 1.53 g IC/kg soil for each cm of soil eroded. At depths greater than 24 cm, IC is nearly constant with increased eroded depth. The depths for the line segments (8 and 24 cm) are dependent on the specific soil and will differ by soil, field, and eroded condition.

Inputs (X) that impact yield and soil quality include applied nitrogen, applied phosphorus, the crop rotation, and the tillage practice. The model has four spring wheat-based crop rotations: WF, WWF, WWWF, and W. Four tillage practices commonly used in the area are conventional, minimum, direct planting, and zero tillage. Pesticides, harvesting, and growing season precipitation are inputs (Z) that are assumed to have no effect on soil quality. It is recognized, however, that across climatic zones the growing season precipitation will impact on soil quality through long-term biomass production, but for a specific climatic zone this effect is incorporated into the long-term equilibrium level of the attribute.

The number of field passes specified for the four systems are listed in table 1 by crop sequence. Wheat and summer fallow are the only crops in this study, resulting in three crop sequences: wheat after summer fallow, wheat after wheat, and summer fallow after wheat. The direct planting and zero tillage systems specified in this study are similar, except the seeding equipment used in the direct planting system has a high degree of soil disturbance.

Yearly soil erosion potential is estimated for wind and water erosion for the four crop rotations and four tillage practices, utilizing the field passes in table 1. Water erosion is estimated from the universal soil loss equation (Wischmeier and Smith). Wind erosion is estimated from the wind erosion equation (Skidmore and Woodruff). The wind plus water erosion rates (tons/hectare/year) are reported in table 2. The potential erosion estimates in table 2 possibly overestimate actual soil erosion, given the historical

Table 1. Number of Field Passes by Tillage and Crop Sequence

Tillage Practice	Crop Sequence[a]	Heavy-Duty Cultivator	Heavy-Duty Cultivator w/Harrows	Blade	Rodweed	Spray	Hoe Drill	Air Seeder	Zero-Tillage Drill	Swath	Combine
Conventional Tillage	W–F	1	1			1	1			1	1
	W–W	1	2			1	1			1	1
	F–W	1	2	1	1						
Minimum Tillage	W–F		1			2	1			1	1
	W–W		2			2	1			1	1
	F–W		2	1		1					
Direct Planting	W–F					3		1			1
	W–W					3		1			1
	F–W					4					
Zero Tillage	W–F					3			1		1
	W–W					3			1		1
	F–W					4					

[a] Crop sequence: W–F is wheat after summer fallow, W–W is wheat after wheat, and F–W is summer fallow after wheat.

Table 2. Water Plus Wind Erosion Estimates by Crop Rotation and Tillage Practice (tons/hectare/year)

	Tillage Practice			
Rotation[a]	Conventional Tillage	Minimum Tillage	Direct Planting	Zero Tillage
W-F	19.7	9.6	1.1	1.1
W-W-F	13.8	6.9	0.9	0.9
W-W-W-F	10.9	5.5	0.8	0.8
W	2.1	1.5	0.6	0.6

[a] The rotations are specified on a yearly basis; W is spring wheat and F is fallow.

observation of erosion in the study area. In the area of study, wind erosion is the major erosion threat, but does not occur every year. Soil erosion with direct planting and zero tillage is near zero. In contrast, soil erosion with conventional tillage and minimum tillage is high when summer fallow is present.

The X inputs are the variables the producer can control. These inputs affect the objective function in the current time period through the production function, and future time periods through the soil attribute constraint (state equation). Soil attributes will change due to both the production practice and soil erosion. The solution will determine optimal inputs and the path of the soil quality attributes.

The value of an attribute can be expressed as the marginal user benefit (MUB) of the attribute. The concept is similar to the marginal user cost that has been employed in soil erosion modeling (Hertzler, Ibañez-Meier, and Jolly), except it is interpreted as a benefit. The MUB is the increase in the present value of the income stream resulting from a unit increase in the attribute level. For this analysis, MUB is the increase in the present value at the initial time period for a 1.0 g C/kg soil increase in the concentration of attributes OC or IC. The MUB of IC, as defined here, would be less than or equal to zero because increased IC reduces yield by immobilizing available P. The MUB is obtained from the shadow value of the attribute constraint in the first time period. For comparison purposes, a marginal user cost of eroded soil can be estimated from the optimal solution MUB of OC and IC by using equations (8) and (9) to convert to a soil quantity.

Factors that will impact on the optimum cropping practice and the value of soil organic carbon include the price of wheat, technology, initial OC level, OC adjustment, the relative water available for wheat after wheat relative to wheat after summer fallow, and the use and cost of N fertilizer. The base model has a wheat price of \$165/ton, N cost of \$0.60/kg, technology-increasing yield of 0.87%/year, OC of 16.0 g OC/kg soil, IC of 1.5 g IC/kg soil, available water for wheat after wheat of 175 mm and for wheat after fallow of 200 mm (Chang et al.), and a real discount rate of 5%.

Alternate scenarios are specified and listed in table 3. Wheat prices are lowered and increased from the base, because output price will directly impact the resource value and the production system. Technology, OC adjustment, and OC adjustment plus N application are set at a zero level to determine the importance of these factors on the solution and the attribute value. The OC adjustment assumption is critical in evaluating

Table 3. Scenarios and Changes from Base Model

Scenario	Change from Base Model
Wheat \$105/ton	Wheat price reduced by \$60/ton
Wheat \$225/ton	Wheat price increased by \$60/ton
No technology	Yield technology = 0.0
No OC adjustment	OC adjustment = 0.0
No N or OC adjustment	Applied N and OC adjustment = 0.0
OC 12.0 g OC/kg	Initial OC reduced by 4.0 g OC/kg soil
OC 20.0 g OC/kg	Initial OC increased by 4.0 g OC/kg soil
N cost \$0.45/kg	N cost reduced by \$0.15/kg
N cost \$0.75/kg	N cost increased by \$0.15/kg
165 mm	Available water after wheat reduced by 10 mm
170 mm	Available water after wheat reduced by 5 mm
180 mm	Available water after wheat increased by 5 mm
Discount rate 1%	Discount rate reduced by 4%

the value of the soil attribute because its ability to recover will impact its value. Restricting OC adjustment will determine the magnitude of the error in valuing OC if improperly modeled. Initial OC levels are specified at lower and higher concentrations. Nitrogen prices are specified at lower and higher costs because of the potential substitution between applied N and soil OC. The available water for plant growth for the recropped land (wheat after wheat) is altered from the base because the relative yield of recropped to fallowed wheat will be a major determinant of the crop rotation. The final scenario set a real discount rate of 1% to place a higher value on future returns.

The GAMS modeling system (Brooke, Kendrick, and Meeraus) and the MINOS solution procedure (Murtagh and Saunders) are used to solve the model. The nonlinearity of the problem can result in this solver having difficulty attaining an optimum. Initial values for OC and N fertilizer are the primary determinants to obtaining a solution that is both feasible and optimal. More than one set of initial conditions is used for each scenario to check whether the model will produce the same solution. While this will not guarantee the solution is a global optimum, it does indicate solution robustness.

Results and Discussion

Yield Component

The quadratic yield coefficients are reported in table 4. The estimated model explains 87% of the yield variability, and most of the coefficients are significant. The marginal products (MPs) of N, P, OC, IC, and RN were determined at the mean values. The signs are as expected and at the means: $MP_N = 5.3$, $MP_P = 2.6$, $MP_{OC} = 42.9$, $MP_{IC} = -9.5$, $MP_{pH} = -129.3$, $MP_{EC} = -356.2$, and $MP_{RN} = 3.4$. The marginal products of N and P are relatively low, but the mean values of N and P at which these marginals were computed are high.

Table 4. Coefficients and *t*-Values for the Yield Function

Variable	Coefficient	*t*-Value	Variable	Coefficient	*t*-Value
Intercept	-14,046	-18.31	EC	-129.348	-4.08
N	4.1903	1.39	$N*P$	0.00898	0.88
N^2	-0.01865	-1.61	$N*OC$	-0.4049	-3.28
P	6.0727	2.36	$N*IC$	-0.02946	-0.35
P^2	-0.00819	-1.91	$N*RN$	0.04167	5.32
OC	161.016	3.64	$P*OC$	-0.07013	-0.65
OC^2	-2.5712	-2.53	$P*IC$	0.08937	1.18
IC	104.244	2.98	$P*RN$	-0.01164	-2.17
IC^2	-2.46	-3.88	$OC*IC$	-4.2556	-2.52
RN	142.412	28.50	$OC*RN$	0.09092	1.09
RN^2	-0.2907	-28.90	$IC*RN$	0.05442	0.95
pH	-356.187	-4.69			

No. of Observations = 718, $R^2 = 0.87$

Optimization Component

The optimum cropping system in the base solution is continuous wheat using direct planting (table 5). This production system is in agreement with the trend in current production systems in the region. Producers are increasing cropping frequency by reducing summer fallow (Alberta Agriculture, Food, and Rural Development; Saskatchewan Agriculture and Food; U.S. Department of Agriculture), and direct and zero tillage seeding are more common (Statistics Canada; U.S. Department of Agriculture). Nitrogen application is 13 kg/ha in the first period, increasing to 22 kg/ha by year 50; these rates tend to be lower than producer rates. Soil OC increases from 16 to 18 g OC/kg soil as a result of continuous cropping and direct planting. Soil erosion is 1 ton/ha, and at this low level has little impact on the model solution. The low level of soil erosion results in IC being constant over the entire time horizon. The objective function value, expressed as an annuity, is \$312/ha/year. The objective function is a return to fixed costs, labor, land, and capital, with only seed, fertilizer, herbicide, and machinery costs taken into account. The MUB of soil OC in the first period is \$103/g OC/kg soil/ha, declining to \$3.8/g OC/kg soil/ha in year 50 due to the increase to 18 g OC/kg soil and the discounting of future benefits. By year 30, the model attained the maximum biological long-term equilibrium OC level. The maximum was reached because the small losses in OC from soil erosion of 1 ton/ha were much less than the biological adjustment potential toward the long-term equilibrium.

The MUB of OC is the present value of benefits from a higher OC level. A comparison of MUB with the marginal value product (MVP) of OC (from the yield equation reported in table 4) requires annualizing the MUB and expressing as an annuity. The annuity value of the MUB is \$5.64/g OC/kg soil/ha/year. The MVP for a single period is \$11.48/g OC/kg soil/ha/year using the base values from the optimization model in the yield equation. The MVP overstates the benefits of OC, even though it is single-period and future

Table 5. Optimization Results

Scenario	OBJ[a] ($/hectare/ year)	Rotation[b]	Tillage[c]	Nitrogen (kg/ hectare)	Erosion (tons/ hectare)	OC (g OC/kg soil)	MUB[d] ($/g OC/kg soil/ hectare)	OC Value ($/ton/ hectare/year)
Base	312	W	D	13→22	1	16→16.5→18	103.0	3.13
Wheat $105/ton	145	W→WF→W	C→D	0	20→20→1	16→15→17.4	34.0	1.02
Wheat $225/ton	461	W	D	≈ 40	1	16→16.5→18	126.4	3.85
No technology	256	W	D	13→0	1	16→16.5→18	91.6	2.79
No OC adjustment	293	W	M&D	15→47	3	16	256.2	7.80
No N or OC adjustment	290	W	M&D	0	3	16	296.6	9.03
OC 12.0 g OC/kg	290	W	D	55→20	1	12→13.5→18	106.6	3.24
OC 20.0 g OC/kg	332	W	D	0→14	1	20→19.6→18	88.7	2.70
N cost $0.45/kg	316	W	D	≈ 38	1	16→16.5→18	89.8	2.74
N cost $0.75/kg	311	W	D	0→16	1	16→16.5→17	108.0	3.29
165 mm	241	WF	C→M	0→25	20→10	16→15.5→15	45.8	1.29
170 mm	255	WF→WF→W	C→D	5→20	20→1	16→15.5→18	49.9	1.52
180 mm	353	W	D	19→28	1	16→16.5→18	101.9	3.10
Discount rate 1%	332	W	D	14→22	1	16→16.5→18	162.2	4.94

[a] The objective function value expressed as an annuity.

[b] W = wheat and WF = wheat/fallow. An arrow (→) indicates a change during the time horizon. If one arrow, the values are for years 1 and 50; if two arrows, the values are for years 1, 5, and 50, respectively.

[c] C = conventional tillage, M = minimum tillage, and D = direct planting.

[d] The marginal user benefit of soil organic carbon is for a 1.0 g OC/kg soil increase in the organic carbon concentration in period one.

benefits of OC are not taken into account. The MVP cannot take into account the net cost to the production system that facilitates increasing OC, and that the ability of OC to adjust reduces the long-term benefit of the initial level of OC. The OC value (table 5), when converted to a soil basis, is less than the soil value estimated by Williams, Tanaka, and Herbel. They used a single-period stochastic model, which (given the results above) likely overestimated the value of soil. Burt reported a marginal value of organic matter (defined the same as MUB in this study) that is similar to the MUB for the base solution of $103/g OC/kg soil/ha/year. At 2.75% organic matter (16 g OC/kg soil), and adjusting for the higher wheat price in this analysis, the marginal value estimated by Burt would be approximately $117/g OC/kg soil/ha/year.

The value of soil OC can be expressed in terms of weight rather than concentration. Using a soil bulk density of 1.2 g/cc and the top 15 cm of soil, the annuity value of the MUB can be converted from $/g OC/kg soil/year to $/ton OC/ha/year by using a factor of 0.5556. The value of soil OC on a weight basis is reported in the last column of table 5. The base scenario value of OC ($3.13/ton/ha/year) is equivalent to the 1998 cost of about 5 kg/ha/year of nitrogen fertilizer.

An estimate of the marginal user cost of soil erosion, from the MUB of OC, is $0.37/ton/ha (280 tons of soil for a one-unit change in OC). This value is within the range of marginal user costs for soil reported by van Kooten, Weisensel, and de Jong of $0.31 to $0.56/ton/ha, and those reported by Smith and Shaykewich of $0.00 to $0.99/ton/ha for different soils and areas in the northern Great Plains. The user cost of soil reflects that: (*a*) fertilizer is a partial substitute for soil; (*b*) soil erosion levels are relatively low, resulting in little yield impact from erosion; and (*c*) OC can adjust over time.

Wheat prices alter the optimum cropping system, and the MUB of OC. The lower wheat price of $105/ton results in a shift to a WF conventional tillage cropping system for the early periods, shifting to W with direct planting (table 5). The lower wheat price, combined with the cropping system change, decreases the MUB of OC in the first period to $34, a 67% decrease. The higher wheat price of $225/ton increases the MUB about 13%. The relatively smaller increase with higher wheat prices occurs because the cropping system does not change from the base, and higher N use reduces the benefit of OC.

When technological advances in yields are excluded, the cropping practice remains unchanged, except no N is applied in the later periods. The objective function value and the MUB of OC are lower because yields do not increase over time. The marginal user cost of soil erosion would be less if multiplicative technological advances in yield are excluded. The level of OC is the same as the base because the cropping system is the same.

The scenario of no OC adjustment (table 5) reflects the importance of including the dynamics of soil attributes in an economic model. This scenario shows a small change to the objective function value, no change to the crop rotation, and the chosen tillage practice is a combination of minimum tillage and direct planting. There is no benefit from using direct planting to increase soil OC because OC is held constant in this scenario; as a result, minimum tillage is the most profitable tillage system. However, minimum tillage and direct planting entered the solution in combination because of a labor resource constraint in the spring season due to higher labor and machinery time requirements for minimum tillage compared with direct planting. N use increases because of lower OC over the entire time horizon. The MUB of OC is nearly 2.5 times the base value because OC is not allowed to adjust. The scenario that prevents the application of N to substitute for OC when OC is held constant increased the MUB of OC to 2.9 times the base value. This scenario reflects the distortions in carbon valuations which can occur when models fail to permit appropriate profit-maximizing input substitution and resource adjustments.

Initial OC levels do not significantly alter the solution. With lower initial OC, additional N fertilizer is used in the early periods, decreasing to levels comparable with the base solution. The objective function value is lower as a result of lower yields and higher N inputs. The converse held with higher initial OC. The MUB of OC declines with increased OC (as Burt found in a study in the Palouse).

With an N fertilizer cost of $0.45/kg, the production system does not change from the base, except N fertilizer use increases to a level similar to that of the high wheat price scenario (table 5). The MUB of OC decreases to $89.8/g OC/kg soil/ha. With increased N use as a result of lower N costs, OC has less value in production because of the substitution between N and OC. The N fertilizer cost of $0.75/kg results in lower N application and a lower objective function value. It is not profitable to apply N fertilizer in the initial periods, but with technology yield increases over time, low rates of N are applied. The MUB of OC is higher than the base solution because of less N application.

Relatively lower soil moisture for continuous wheat cropping compared to wheat on fallow results in an optimum production system with a rotation of WF and conventional tillage. The 165 mm scenario (table 5) is the drier scenario for continuous cropping. In the later periods, there is a switch from conventional to minimum tillage because the soil erosion costs with conventional tillage through reduced OC and crop yield are greater than the additional costs of minimum tillage in the WF cropping system. With conventional and minimum tillage, OC declines below the long-term equilibrium OC level for WF due to reductions from erosion exceeding production system additions. Even though erosion is high, it is not high enough for IC to change in the 50-year time horizon. The MUB of OC in a WF production system is less than one-half the base solution value. In the early periods, the 170 mm scenario has results similar to those of the 165 mm scenario. Over time with technological yield growth, there is a switch to continuous wheat with direct planting. However, the MUB of OC is only 10% higher than under the 165 mm scenario. A scenario of higher moisture for wheat after wheat results in the same production system as the base solution. The objective function value, N input use, and the MUB of OC are higher because of higher moisture and the associated higher crop yield.

A discount rate of 1% has no impact on the base solution (table 5). The objective function value is slightly higher, but the MUB of OC in the first period is lower. The lower MUB of OC in the first period occurs because the future returns have a higher present value, reducing the relative importance of the first time period.

Conclusions

The model results are consistent with the current trend toward more intensive cropping, and direct planting and zero tillage seeding in the northern Great Plains. Modeling soil quality attributes directly in economic soil erosion and soil quality models is a feasible approach, if there are adequate technical data to model: (*a*) the relationship between yield and the attributes that incorporate all relevant substitution effects, and (*b*) the biological and physical changes in the attributes over the time period as influenced by production practices.

The soil attribute model provides results that are robust across initial soil attribute levels. Modeling the attributes directly, rather than indirectly through an index of quality or as a quantity of eroded soil, provides results that can be applied to a broader set of soils, sites, and conditions. However, they should only be applied to soils within the major soil group used to estimate the attribute-soil depth relationship, 11 million hectares in Canada plus part of Montana and North Dakota. Modeling soil attributes, such as soil OC, must be done in a dynamic setting and include biological impacts from the cropping practice as well as physical impacts from soil erosion. Neglecting the attribute adjustment that can occur in the production system will overstate the value of the attribute. Likewise, not taking into account the future benefits of current changes to the attribute will undervalue the attribute.

Wheat price and growing season precipitation are the two major factors that will impact the results of the analysis through the optimum crop rotation, and to a lesser extent the value of the product. Purchased input costs, N in particular, are also important because of the substitutability of some inputs for soil quality. The initial soil quality attribute level had little impact on the long-run results because the adjustment process of soil quality attributes overcame initial soil quality differences. Finally, it is essential to properly model attribute adjustments over time.

The marginal user benefit of the soil attribute, organic carbon concentration, ranged from a low of $34 to a high of $296.6/g OC/kg soil/ha over the scenarios. However, most values are in the range of $40 to $125, and are consistent with other reported studies. The MUB of OC depends upon the value of the output (spring wheat), the level of the attribute, the optimum cropping system, the cost of substitutes (N fertilizer), and the dynamic adjustment process. While output price directly impacts on the MUB of OC, a larger indirect impact can occur if there is a shift in the production system as a result of an output price change. The MUB of OC declines with increased OC, a result of declining marginal productivity of OC.

The value of soil OC expressed on a weight basis ranges from $1 to $4/ton OC/ha/year for most scenarios. The benefit of soil OC, while positive, is relatively small, and putting additional resources into the production system for the sole purpose of increasing soil OC will be unprofitable. Soil OC of a production system with an inherently low long-term equilibrium soil OC level cannot be increased and maintained without significantly increasing production inputs and costs. If the optimum production system has a higher long-term soil OC level, then with proper management the system will move to having higher soil OC without additional resource input.

Drier areas, where a spring wheat-fallow crop rotation has the highest returns over time, place less value on soil OC, and have lower long-term equilibrium OC levels. The cropping system is the major factor determining soil OC level and value. Situations of frequent summer fallow do not have technically or economically feasible means of increasing soil OC. The low value in production may partially explain why producers do not adopt many of the soil organic matter-increasing practices promoted by agronomists.

The crop rotations in the solutions are either spring wheat-fallow or continuous wheat; there are no intermediate cropping intensity rotations. Including stochastic growing season precipitation and producer risk preferences might result in intermediate cropping intensity rotations. All soil OC value estimates in this analysis are private benefits to the producer from the increase in productivity associated with increased soil quality. Social benefits, such as the sequestration of carbon to reduce atmospheric carbon dioxide concentration and the greenhouse effect or airborne dust particles from erosion, and social costs of off-site erosion, were not considered. Off-site benefits of carbon sequestration have received reported projections of $US15 to $US348 per ton (Sandor and Skees).

There can be an economic incentive for grain producers in the northern Great Plains to use production systems that improve and maintain the quality of the soil. The major factor determining soil quality is the optimum cropping system. Cropping systems that frequently crop (limited use of summer fallow) will result in higher soil quality. The economic optimum level of soil quality parameters will depend on economic, biological, and geographic parameters, and the feedback the production system has on the quality parameters.

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