Optimum Soil Quality Attribute Levels and Values

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Abstract

We develop a dynamic optimal cropping systems model for the northern Great Plains, taking into account the impact of the system on soil quality attributes organic and inorganic carbon. Continuous wheat and direct planting is the most profitable system under most economic conditions. This system has low soil erosion and results in high soil quality.

Optimum Soil Quality Attribute Levels and Values

Sustainable production will depend on soil health, biological activity, functions of soil ecosystems, and intrinsic value (Parr et al.; Warkentin). Parameters selected as indicators of soil quality must have a direct impact on the function of the soil, be measurable, and be sensitive enough to detect differences (Karlen et al.).

Economic studies have tended to address quantity rather than quality indicators. Models use soil erosion quantity and either an estimated or assumed productivity impact (Miranowski), or an impact determined from a productivity index (Hoag). Substitution options with inorganic fertilizers have been limited, even when erosion impacts are estimated by process models. Burt included organic matter, a quality attribute, but topsoil depth was also included as a state variable. The use of soil depth in analysis of soil erosion and conservation has produced results specific to a soil because productivity impacts vary greatly by soil type.

There are many chemical and physical attributes of soils that determine the quality of the soil (Arshad and Coen). Organic carbon, a microbial indicator of soil quality (Kennedy and Papendick), is tied to many other soil quality indicators (Reeves). Soil erosion and production practices will cause changes to chemical and physical attributes of a soil. An economic modelling approach more applicable to a wider range of soil types is to model the important soil attributes, or quality indicators, directly.

A farm-level soil quality economic model needs to: 1) be dynamic, 2) contain crop yield functions that incorporate soil attributes and management variables, 3) include relationships which capture the impact of choices on soil attributes, and 4) include variables which reflect changes in soil quality (Saliba). Crop production (Q) can be represented as a function of a soil quality attribute vector (SQ), an input vector (X) that has an effect on yield and the soil attributes, and an input vector (Z) that impacts on yield but is soil attribute neutral: $Q=f(SQ,X,Z)$. Hoag provides a similar model, except soil quality attributes are incorporated into a productivity index, rather than modelling each individual attribute. Changes in soil quality attributes will be a function of the level of the attribute, the production system, inputs that directly affect the attributes, and soil erosion.

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. Dynamic programming model formulations have been utilized to study soil erosion time paths (Weisensel and Van Kooten). A multi-period linear programming model was used by Smith and Shaykewich to evaluate soil erosion, cropping systems and input substitution.

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 modelled as percent of row crop (Saliba) and as percent of wheat (Burt) in the rotation. Tillage practices have generally been modelled through the soil erosion associated with tillage, so the control variable is erosion (the result of the tillage practice) rather than the actual control - the tillage practices.

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. The value of the attributes are determined for the optimal systems. The cropping system includes the crop rotation, tillage practice and inorganic fertilizer application rate.

Model

The farm level soil quality model requires two model components. A yield function is incorporated into an optimization model. Crop yields on dryland in the northern Great Plains will depend on plant nutrient availability (nitrogen (N) and phosphorus (P)), soil quality attributes, and precipitation. Four soil quality attributes that impact on productivity and are measurable include organic carbon (OC), inorganic carbon (IC), pH (PH) and salt (EC - electrical conductivity). A quadratic yield function is:

(1)
$$\begin{aligned} Q = {} & \beta_0 + \beta_1 N + \beta_2 N^2 + \beta_3 P + \beta_4 P^2 + \beta_5 OC + \beta_6 OC^2 + \beta_7 IC + \beta_8 IC^2 + \beta_9 RN \\ & + \beta_{10} RN^2 + \beta_{11} pH + \beta_{12} EC + \beta_{13} NP + \beta_{14} NOC + \beta_{15} NIC + \beta_{16} NRN + \beta_{17} POC \\ & + \beta_{18} PIC + \beta_{19} PRN + \beta_{20} OCIC + \beta_{21} OCRN + \beta_{22} ICRN + \varepsilon \end{aligned}$$

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

The optimization model in this study utilizes a discrete set of crop rotations, tillage practices, land types, and crops to better reflect the technology limitations of current cropping systems in the northern Great Plains. The model is non linear in yield, soil quality attributes, inorganic fertilizer, and precipitation.

(2)
$$\max_{X,Z} \prod = \sum_{t=0}^{T-1} (1+\rho)^{-t} \left[\begin{array}{l} \sum_r \sum_k \sum_l \sum_{c \in r} (PR_{ct} g(t) f(SQ_t , X_t , Z_t) Y_{r,k,l,t} - \sum_i w_i X_{i,c,r,k} Y_{r,k,l,t} \\ - \sum_j v_j Z_{j,c,r,k} Y_{r,k,l,t}) - FC_{r,k} Y_{r,k,l,t} \end{array} \right]$$
$$-(1+\rho)^{-T} \sum_m [(SS_m - SQ_{mT}) * LND * g(T) * (\frac{\partial f}{\partial SQ_m}) * P_T / r]$$

subject to

(3)
$$\begin{array}{l} SQ_t = SQ_{t-1} + h(SQ_{t-1} , X_{t-1}) \\ AY \le B \end{array}$$

where: Π is the net present value of returns over a 50-year time period less a penalty function at year 50; PR is the crop price; g is technology yield growth rate; f(.) is the crop production function; SQ is a soil quality attribute vector; X is an activity vector of inputs that impacts on soil quality; Z is an activity vector of inputs that does not impact on soil quality; Y is the activity level (area); w is the input cost vector for X; v is the input cost vector for Z; FC is fixed costs; SS is the soil quality attribute standard level; LND is total land area; and ρ is the discount rate. The subscripts are: t is year in the time horizon; r is the crop rotation; k is the tillage practice; l is the land class type; c is the crop within r; i is production inputs in X; j is production inputs in Z; m is soil quality attributes; and T is the end of the time horizon.

The model has a 50-yr time horizon with end-of-year periods of 1, 2, 3, 4, 5, 10, 20, 30, 40 and 50 years. Yield growth from new technologies is incorporated into the g(.)

function and is included because Taylor and Young determined that technology impacts on the long-term payoff from soil conservation. The penalty function is the present cost of cumulative productivity losses discounted into perpetuity at year T. The yield penalty is the marginal product of the soil quality attribute in equilibrium.

The first constraint tracks soil quality attributes over time. Soil quality attributes will be reduced by soil erosion, and either increased or decreased due to the cropping practice (crop rotation and tillage) and fertility program through the function *h*. Soil pH, EC, N and P are not tracked as these variables are not sensitive enough to detect changes due to cropping practices in a long-term equilibrium state. The second constraint is a general constraint that resource use does not exceed resource availability.

Inputs in the X vector include applied N and P, the crop rotation, and the tillage practice. Four crop rotations are: wheat-fallow (WF), wheat-wheat-fallow (WWF), wheat-wheat-wheat-fallow (WWWF) and continuous wheat (W). Four tillage practices are conventional, minimum, direct plant and zero tillage. Pesticides, harvesting, and growing season precipitation are in input vector Z.

The value of an attribute can be expressed as a marginal user-benefit (MUB). The concept is similar to the marginal user cost employed in soil erosion modelling (Hertzler et al.). The MUB is the increase in 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. A marginal user cost of eroded soil can be estimated from MUB of OC and IC because there is a relationship between erosion and OC and IC.

The base model has a wheat price of $165/t, N cost of $0.60/kg, technology increasing yield by 0.87%/yr, OC of 16.0 g C/kg soil, IC of 1.5 g C/kg soil, available water for wheat after wheat of 175mm and for wheat after fallow of 200 mm (Chang et al.), and a discount rate of 5%. Alternative values for some of the parameters were: wheat prices of $105/t and $225/t; technology increase of 0.0%; a constant OC over time; changes in OC, and applied N were set to 0.0; OC levels of 12.0 g C/kg soil and 20.0 g C/kg soil; N costs of $0.45/kg and $0.75/kg; water for wheat after wheat of 165mm, 170mm, and 180mm; and a discount rate of 1%.

The GAMS (Brooke et al.) modelling system and the MINOS (Murtagh and Saunders) solution procedure are used to solve the model. More than one set of initial conditions are used for each scenario to check for global optimality because the nonlinearity of the problem could result in local optima.

Data and Estimation of Empirical Relationships

Data to estimate the yield function are from two sources. The first is from a soil quality experiment at Lethbridge, Alberta (Olson et al.). Topsoil from a site was removed and replaced with 36 different topsoil types, replicated 3 times, and the plots were further split to include no additional N 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 were the topsoil was mechanically scalped to 0, 10 and 20 cm, with four replicates. Imposed on each scalped depth were four rates of nitrogen fertilizer times three rates of phosphorus fertilizer (Larney, Janzen, and Olson). The 1990 yields from this experiment are used in the yield estimation.

The data used from the two data sets includes the variables listed in equation 1. The mean sample values are: yield is 2579.3 kg/ha, OC is 15.56 g C/kg soil, IC is 5.64 g

C/kg soil, pH is 6.58, EC is 0.739 dS/m, and RN is 247.2 mm. The quadratic functional form is used to increase simplicity of the optimization model. The economic properties of interest (marginal products and rates of substitution) have the correct signs. A translog form was estimated, but did not improve the fit or explanatory power. The estimated equation is reported in Table 1.

The soil depth - OC and IC relationships are estimated from the mechanically scalped data. The OC relationship with soil depth (SD) is:

(4)
$$OC = 17.694 - 0.45117\ SD + 0.0035869\ SD^2$$
$$(3319)\quad(-14.47)\qquad\qquad(8.95)$$

N = 120, R^2 = 0.84

A grafted linear equation for IC was estimated but not reported since eroded soil depth did not impact on IC until about 8 cm of topsoil are eroded.

The long-term equilibrium for OC is determined by the cropping practice and fertilizer use. For the Dark Brown Soil zone

Table 1. Coefficients and t-values for the Yield Function

Variable	Coefficient	t-value
Intercept	-14046.	-18.31
N	4.1903	1.39
N^2	-0.01865	-1.61
P	6.0727	2.36
P^2	-0.00819	-1.91
OC	161.016	3.64
OC^2	-2.5712	-2.53
IC	104.244	2.98
IC^2	-2.4600	-3.88
RN	142.412	28.50
RN^2	-0.2907	-28.90
pH	-356.187	-4.69
EC	-129.348	-4.08
*N*P*	0.00898	0.88
*N*OC*	-0.4049	-3.28
*N*IC*	-0.02946	-0.35
*N*RN*	0.04167	5.32
*P*OC*	-0.07013	-0.65
*P*IC*	0.08937	1.18
*P*RN*	-0.01164	-2.17
*OC*IC*	-4.2556	-2.52
*OC*RN*	0.09092	1.09
*IC*RN*	0.05442	0.95
Observ.	718	
R^2	0.87	

where, t-values are reported in parenthesis.

on the Canadian Prairies, the equilibrium OC level can be expressed as (Janzen 1998; Janzen et al. 1998):

(5) $$OC = 15.0 + 2.0I + 1.0F + (1 - T)(2.0I)$$

where, I is cropping intensity (0 for WF, 0.3 for WWF, 0.6 for W, and 1.0 for forage), F indicates no fertilizer (0) or fertilizer (1), and T indicates tillage (1) or no tillage (0).

Soil erosion is estimated for wind and water erosion for each crop rotation and tillage practices. Water erosion is based on 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 (t/ha) are reported in Table 2. The number of field passes specified for the four tillage systems are listed in Table 3 by crop sequence.

Table 2. Water and Wind Erosion Estimates (t/ha)

	Tillage Practice			
Rotation	Conventional	Minimum	Direct Plant	Zero Tillage
Wheat - Fallow	30.7	15.3	1.7	1.7
Wheat x2 - Fallow	23.5	12.0	1.5	1.5
Wheat x3 - Fallow	19.9	10.3	1.4	1.4
Wheat	9.1	5.2	1.0	1.0

Optimization Results

The optimum cropping system in the base solution is continuous wheat using direct planting (Table 4). Nitrogen application is 13 kg/ha in the first period, increasing to 22 kg/ha by the tenth period. Soil OC increases from 16 to 18 g C/kg soil as a result of continuous cropping and direct planting. Soil erosion is 1 t/ha and 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/yr. The objective function is a return to fixed costs, labor, land and capital, with seed, fertilizer, herbicide, and machinery costs taken into account. The MUB of soil OC in the first period is \$103.0/g C/kg soil/ha.

Table 3. Number of Field Passes by Tillage and Crop Sequence

Tillage	Crop Sequence	HD Cult.[a]	Cult. + H.	Wide Blade	Rod-weed	Spray	Hoe Drill	Air Seeder	ZT Drill	Swath	Combine
Conv.	W - F	1	1			1	1			1	1
	W - W	1	2			1	1			1	1
	F - W	1	2	1	1						
Min.	W - F		1			2	1			1	1
	W - W		2			2	1			1	1
	F - W		2	1		1					
Direct	W - F					3		1			1
	W - W					3		1			1
	F - W					4					
Zero	W - F					3			1		1
	W - W					3			1		1
	F - W					4					

[a] Table abbreviations are: HD Cult. = heavy duty cultivator, H. = harrows mounted on the cultivator, ZT = zero tillage, Conv. = conventional tillage, Min. = minimum tillage, crop sequence W - F is wheat following summer fallow, W - W is wheat following wheat, and F - W is summer fallow following wheat.

The MUB of OC is the present value of benefits from a higher OC level in the first time period. A comparison of MUB with the marginal value product (MVP) of OC (from the yield equation reported in Table 1) requires expressing MUB as an annuity. The annuity value of the MUB is \$5.54/g C/kg soil/ha/yr. The MVP of OC for a single period is \$11.48/g C/kg soil/ha/yr using the base values of the variables in the yield equation. The single-period MVP overstates the benefits of OC, even though the future benefits of current changes in OC are not taken into account. The MUB is less than the MVP because there is a net cost to the production system that facilitates increasing OC and the ability of OC to adjust reduces the long-term benefit of a specific level of OC. Both the annuity value of MUB and the MVP, when converted to a soil basis to estimate the MVP of soil, are less than the soil value estimated by Williams et al. who used a single period stochastic model and given the results above likely overestimated the value of soil. Burt reported a marginal value of organic matter that is similar to the MUB for the base solution. Converting organic matter value to OC, at 2.75% organic matter (16 g C/kg soil), and adjusting for a higher wheat price in this analysis, the marginal value in terms of OC is 117.2. This value is remarkably similar to the base MUB value of 103.0.

An estimate of the marginal user cost of soil erosion, from the MUB of OC, is $0.37/t/ha. This value is within the range of marginal user costs for soil reported by VanKooten et al. and Smith and Shaykewich for different soils and areas in the northern Great Plains. The user cost of soil reflects: 1) fertilizer is a partial substitute for soil, 2) soil erosion levels are relatively low resulting in little yield impact from erosion, and 3) the soil quality attribute OC can adjust over time.

Wheat prices, initial OC level, OC adjustment over time, moisture, fertilizer costs, and the rate of discount all impact on the optimum production system. The results of these alternative systems are all reported in Table 4.

Conclusions

Modelling soil quality attributes directly in economic soil erosion and soil quality models is a feasible approach, if there are adequate technical data to model: 1) the

Table 4. Optimization Results

Scenario	OBJ[a] ($/ha/yr)	Rotation[b]	Tillage	Nitrogen (kg/ha)	Erosion (t/ha)	OC (g C/kg soil)	MUB[c] ($/g C/kg soil/ha)
Base	312	W	D	13→22	1	16→16.5→18	103.0
Wheat $105/t	145	WF→WF→W	C→D	0	31→31→1	16→15→17.4	34.0
Wheat $225/t	461	W	D	≃40	1	16→16.5→18	126.4
No Technology	256	W	D	13→0	1	16→16.5→18	91.6
No OC Adjustment	293	W	M&D	15→47	3	16	256.2
No N or OC Adjmt.	290	W	M&D	0	3	16	296.6
OC 12.0 g C/kg	290	W	D	55→20	1	12→13.5→18	106.6
OC 20.0 g C/kg	332	W	D	0→14	1	20→19.6→18	88.7
N cost $0.45/kg	316	W	D	≃38	1	16→16.5→18	89.9
N cost $0.75/kg	311	W	D	0→16	1	16→16.5→17	108.0
165mm	241	WF	C→M	0→25	31→15	16→15.5→15	45.8
170mm	255	WF→WF→W	C→D	5→20	31→1	16→15.5→18	49.9
180mm	353	W	D	19→28	1	16→16.5→18	101.9
Discount Rate 1 %	332	W	D	14→22	1	16→16.5→18	162.2

[a] The objective function value expressed as an annuity.
[b] The "→" indicates a change during the time horizon. If three arrows, the values are for periods 1, 5 and 10, respectively.
[c] The marginal user cost of soil organic carbon is for a 1.0 g C/kg soil increase in the organic carbon concentration in period one.

relationship between yield and the attributes, and 2) the changes in the attributes over the time as influenced by production practices. Modelling 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 and conditions. Neglecting the direct and indirect costs of altering the attribute, such as a change in the crop rotation or tillage practice, will overstate the value of the attribute. Also, not taking into account the future benefits of current changes to the attribute will undervalue the attribute.

The marginal user benefit of the soil attribute, organic carbon concentration, ranged from a low of \$34.0 to a high of \$296.6/g C/kg soil/ha, but most values are in the range of \$50 to \$125. The MUB of OC depends upon the value of the output (wheat), the level of the attribute, the optimum cropping system, the cost of substitutes (N and P fertilizer), and the dynamic adjustment process. While wheat price directly impacts on the MUB of OC, a larger indirect impact occurrs if there is a shift in the production system as a result of the output price change. The MUB of OC declines with increased OC, a result of declining marginal productivity of OC. There is an economic incentive to have a high long-term level of OC because it increases crop yield and reduces N requirements.

Drier areas, where a 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 systems is the major factor determining soil OC levels. Situations of frequent summer fallow do not have a technical or economic feasible means of increasing soil OC.

There is 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 economic benefits of these systems will depend on economic, biological and geographic parameters.

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