The Interaction of Crop Rotations and Soil Quality: An Economic Analysis

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Abstract

A model is briefly described that integrates an environmental component that simulates crop yields and changes in soil quality and an economic component that calculates rotation scale costs and revenues based on yield and input data provided by the environmental component. The model is used to simulate crop yield, soil quality and economic performance of a number of alternative annual crop rotations over a 50 year period. This information is used to quantify the impact of alternative crop rotations on soil organic carbon and the economic value of on-site SOC to the rotations, with values ranging from $0.20 to $2.50/ton SOC/hectare/yr.

Introduction

Ongoing changes in agricultural commodity and input markets, production technology and increasing concerns about the impact of agricultural production systems on the environment have stimulated changes in land use patterns across western Canada. Producers have decreased their reliance on cereal production and the frequency of summerfallow use, extended and diversified crop rotations, and increased the quantity of land dedicated to the production of alternative crops. In addition, producers have adopted more conservation tillage, integrated pest management, organic management and precision farming practices. The long-term economic and environmental implications of these land use changes are important to the farm decision-maker and to society. However, management decisions are often based primarily on short-term cost and benefit expectations, and little is known about the longer-term benefits and costs of these management changes from an economic or environmental perspective.

This paper examines the long-term implications of alternative annual crop management practices on soil quality and, in turn, the influence of soil quality dynamics on the economic performance of the management practices. A simulation model framework is used to evaluate the dynamic relationship between soil function and the economic performance of a series of dry-land cropping rotations for two contrasting environments in Saskatchewan. This model facilitates a systems-level analysis of the long-term value, in economic and sustainability terms, of soil organic carbon (SOC) as a soil health indicator, in the context of alternative crop and management strategies.

The Model

The simulation model used in this research was constructed using the STELLA® Research modelling software, and is comprised of environmental and economic sub-models. The environmental component simulates crop yields and soil quality dynamics based on the ability of soil to provide nitrogen (N), phosphorus (P) and water for crop growth. The economic component calculates rotation scale costs and revenues based on yield and input requirements provided by the environmental sub-model. The simulations function at a one-year time step with each simulation reflecting a 50 year time horizon. The level of spatial aggregation in the model is the ecodistrtict, a unit of the Canadian Ecological Land Classification System defined by relatively homogeneous land form, vegetation and soil conditions (Acton et al. 1998).

The model was parameterized using biophysical data for two ecodistricts in Saskatchewan; 1) the semi-arid Brown soil zone of the Mixed Grassland Ecoregion; and 2) the humid Black soil zone of the Boreal Transition Ecoregion. The modelled soils in both regions are clay-loam textured Chernozems. Biophysical data used included: 1) soil type – soil texture, soil thickness; 2) climate – growing season precipitation, over winter precipitation, growing degree days, mean daily temperature; and 3) initial soil stocks – soil surface residue, soil N, soil P and SOC content. Crop production potential for each ecodistrict is determined by the ability of the soil to provide nutrients and water for crop growth over time, hereafter referred to as soil quality. Soil quality is an endogenous variable determined by the biophysical characteristics including soil texture, cropping practices, crop types and tillage practices.

The environmental model was developed around a series of annual crop rotations for each soil zone. A “conventional” (C) rotation, representing the traditional cropping system in each soil district served as the benchmark management practice in the analysis. The alternative rotations were selected to be agronomically and technically appropriate for the target regions but were designed to include crops (pulses, oilseeds and forages), tillage regimes (minimum tillage and zero tillage) and management practices (organic production) that are less common (Table 1).

The economic model was parameterized using output prices and cost of production data appropriate for the modelled crops in the Brown and Black soil zones of Saskatchewan (Saskatchewan Agriculture and Food, 2000a; 2000b). Output prices were based on 1999 farm-gate commodity prices for Saskatchewan. To ensure that the specific costs of production were captured for each crop under different management regimes, the costs were divided into nine categories: 1) seed; 2) pesticides; 3) N fertilizer; 4) P fertilizer; 5) fuel; 6) transportation; 7) labour; 8) land; and 9) other inputs. The “other input” category included those variable (machinery repair, custom work, hired labour, crop insurance and interest costs) and fixed (machinery investment, machinery depreciation, building costs, management costs) production costs not captured by the other cost categories. The costs for seed, pesticides, fuel, labour, land and other costs were assumed to be constant for each crop with values based on average costs for the specific crops and management schemes in the respective soil zones. N fertilizer and P fertilizer costs were endogenous variables based on fixed fertilizer costs and application rates determined by the environmental model. Transportation costs included freight, trucking, dockage and elevation charges for each specific crop ($/t) with the rotation costs dependent on crop yield.

Results

Validation of the model requires a comparison of simulation results with appropriate historical data. Simulated crop yields for the Brown soil zone where similar to the ten year yield averages for the region, although the model tended to slightly overestimate durum, barley and spring wheat yields when grown on fallow. Since water, N and P are more available following summerfallow than on stubble, it is likely that other limiting factors not simulated in the model (disease, insects, weeds, etc.) reduced the long-term average yields relative to the predicted yields. Simulated yields in the Black soil zone were generally higher than ten year regional averages. Compared to the Brown soil zone, available moisture, N and P are less yield limiting in the Black soil zone, and other yield limiting factors, such as insects, disease and weed competition not captured in the model, are comparatively more yield-limiting than in the Brown soil zone. Consequently, simulation results for the Black soils represent conditions in which management to control weeds, insects and disease is optimal and the economic and biophysical outcomes are therefore also optimal.

Table 1. Conventional and Alternative Cropping Rotations Simulated in Each of the Study Regions.

Rotation and crops - Brown Soil Zone

Year	Conventional (C)	Minimum tillage (M)	Zero tillage (Z)	Organic[a] (O)
1	Tillage fallow	Chem fallow	Chem fallow	Sweet clover / AC Greenfix[b]
2	Wheat	Canola	Canola	Durum
3		Wheat	Wheat	Lentils / Pea[c]
4			Pea-Lentil [b]	Barley / Flax[b]
5			Durum	

Rotation and crops - Black Soil Zone

Year	Conventional (C)	Minimum tillage (M)	Zero tillage (Z)	Zero tillage2 (Z2)	Organic (O)
1	Tillage Fallow	Wheat	Wheat	Flax	Alfalfa
2	Canola	Pea	Pea	Wheat	Alfalfa
3	Wheat	Barley	Barley	Pea	Alfalfa
4	Barley	Canola	Canola	Barley	Wheat-Barley[c]
5				Canola	Flax
6				Winter Wheat	Wheat
7					Pea
8					Barley[d]

[a] In the fourth year of the organic rotation. the annual crop is underseeded to a green manure legume. The sweet clover / AC Greenfix is incorporated as a green manure in the subsequent year.

[b] The choice of crop alternates each rotation cycle between the two crops listed.

[c] The choice of crop is randomly chosen each rotation cycle between the two crops listed

[d] In the eighth year the barley is underseeded to alfalfa.

Simulated SOC stocks were non-decreasing for all rotations in both soil zones at average rates similar literature values (Sampson and Scholes 2000; Bruce et al. 1999). In our results, SOC stocks increased at the highest rate under zero tillage management and at the lowest rate (near equilibrium) under conventional and organic management in both soil zones. However, the rate at which the SOC stocks changed was significantly different across rotations and soil zones. Within the Brown soil zone, SOC stock increases ranged from 0.36t/ha/yr for the O rotation to 0.75 t/ha/yr for the Z rotation, whereas in the Black soil zone SOC stock increases ranged from 0.12 t/ha/yr for the O rotation to 1.56 t/ha/yr for the Z rotations. In addition, soil N stocks increased under all rotations, closely mirroring changes in SOC stocks; soil P stocks were maintained in all rotations.

The conventional, minimum-till and zero-till rotations (except Z2 in the Black soil zone) reported negative mean net revenues over the simulation period in both the Brown and Black soil zones (Table 2). In contrast, the Z2 rotation in the Black soil zone had positive net revenues; the organic rotations in both regions had very high net revenues reflecting the significant (up to 100%) price premiums paid for organically grown grains, and 35 to 50 % lower input costs. It should be noted that since labour and land, as the fixed factor of production, are included as costs of production landowners would be receiving the full opportunity cost of land and labour when net revenues equal zero. Therefore, the simulation results indicated that for producers that own their land, none of the rotations imposed a strict economic loss. However, only the Z2 and organic rotations earned the producers more than the full opportunity cost of land and labour inputs. In contrast, producers who rent their land experienced an economic loss with the minimum and zero till rotations in the Brown soil zone.

Table 2. Simulated Mean Net Revenues ($/ha/yr) for Rotations in the Brown and Black Soil Zones.

			Rotation		
Soil Zone	C	M	Z	Z2	O
Brown Soil Zone	-$24.00	-$76.00	-$49.00	n/a	$300.00
Black Soil Zone	-$70.00	-$16.00	-$13.00	$58.00	$303.00

The biophysical and economic data provided by the model were used to estimate the economic value of SOC within the rotation context. Specifically, a simple linear regression was developed for each rotation with SOC stock as the independent variable and rotation net revenue as the dependent variable. Two indices were calculated: 1) marginal user cost (MUC) – the present value of the change (decrease) in net returns due to changes (often through erosion) in soil quality (McConnell 1983); and 2) marginal user benefit (MUB) – the present value of the increase in net revenue that is attributable to an increase in soil quality (Smith et al 2000).

SOC stock changes were relatively small in many rotations and as a result the regressions had low explanatory power, with the Black providing slightly better results than the Brown soil zone output. To address this issue, additional simulations were performed where SOC stock increases were artificially inflated by 2% per year throughout the simulation. While these simulations resulted in relatively large SOC stocks, the data provided for a more significant relationship between soil quality and rotation profits for all but rotation Z in the Brown soil zone. Based on these results the MUB of SOC in the Brown soil zone ranged from $36.59/t/ha ($1.90/t/ha in year 1) for the organic rotation to $3.85/t/ha ($0.20/t/ha in year 1) for the C rotation. In the Black soil zone MUB ranged from $48.14/t/ha ($2.50/t/ha in year 1) for the organic rotation and $9.63/t/ha ($0.50/t/ha in year 1) for all other rotations (Table 3). The relatively large economic response of the organic rotations to SOC primarily reflect that organically grown crops depend on organic and mineralized sources of N and P in the absence of synthetic fertilizer sources of N and P. This effect was more pronounced in the Black soil zone where N and P are relatively more yield limiting than available water.

Table 3. Simulated Marginal User Benefit in Year 1 ($/t/ha/yr) With Value of 50 Year Benefit Stream in Parentheses ($/t/ha) and Marginal User Cost Reported as 50 Year Stream of Costs Associated with the Erosion of 1 Tonne of Soil ($/t/ha).

Rotation	MUB		MUC	
	Brown	Black	Brown	Black
C	$0.20 ($3.85)	$0.50 ($9.63)	$0.10	$0.31
M	$0.30 ($5.78)	$0.50 ($9.63)	$0.16	$0.38
Z	-	$0.50 ($9.63)	-	$0.41
Z2	n/a	$0.50 ($9.63)	n/a	$0.43
O	$1.90 ($36.59)	$2.50 ($48.14)	$0.94	$1.53

The MUB of SOC estimated by Smith et al. (2000a) were in the $77.02/t ($4.00/t/ha in year 1) to $19.26/t ($1.00/t/ha in year 1) range for continuous wheat and wheat-fallow rotations in the transition Dark Brown soils of Alberta. MUB values obtained in our study are generally lower than the values reported in the Smith study. The Dark Brown soil zone is transitional in terms of precipitation and temperature between the Brown and Black soil zones, so it would be expected that MUB values for Dark Brown soils should be within the range estimated for Brown and Black soils.

Estimates of the marginal user cost (MUC)of soil erosion was calculated based on MUB and soil bulk densities of 1300 kg/m^3 for the C and O rotations, 1250 kg/m^3 for the M rotation and 1200 kg/m^3 for the Z rotation. In the Brown soil zone the MUC of soil erosion ranged from $0.10/tonne/ha for the C rotation to $0.94/tonne/ha for the O rotation. In the Black soil zone the MUC of soil erosion ranged from $0.31/tonne/ha for the C rotation to $1.53/tonne/ha for the O rotation (Table 3). These value are consistent with the range of MUC estimated by van Kooten et al. (1989) of $0.34 to $0.62/t/ha for wheat in the Brown soil zone in Saskatchewan, and Smith and Shaykewich (1990), $0.00 to $1.09/t/ha for a range of mixed-crop rotations in the Black soil zone in Manitoba.

Conclusion

The simulation model used in this research provides a framework for analysis of the economic and environmental impacts of a range of crop and management alternatives within a rotation context. In addition, the framework facilitates the tailoring of the model to reflect the specific biophysical and economic characteristics of an agricultural region. The resulting simulations capture the important interactions between changes in soil quality and management decisions and their effect on production and economic returns. This approach helps ensure that the valuation of a production input, such as soil quality, is determined within the context of the dynamic interactions of management and environment over time.

The MUB of SOC ranged from $3.85/t to $48.14/t over the various rotations in the Brown and Black soil zones. While the present study evaluated crop types, management practices and rotations not addressed in other studies, the MUB values for the conventional rotations tended to be lower than values reported for similar rotations in other studies.

In general the economic value of soil quality, whether interpreted as a benefit associated with increases in SOC stocks or as a cost associated with loss of SOC through erosion, was relatively small. These results indicate limited economic incentive for producers to invest in crop and soil management practices that will conserve or increase SOC stocks if these systems were even slightly more costly or risky than the most profitable of the alternatives. From a policy perspective, this implies that soil conservation systems must offer economic efficiency in addition to conservation potential to achieve wide-spread adoption.

However, it should be noted that the economic value of soil quality will be strongly influenced by output prices and the cost of inputs, most importantly the cost of partial substitutes for soil quality such as N and P fertilizer. In addition, the relatively high MUB estimated for the organic rotations is at least partly determined by the high premiums received for organic commodities and the low input costs associated with this method of management.

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