Valuing Trade-Offs between Net Returns and Stewardship Practices: The Case of Soil Conservation in Saskatchewan

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In this paper, a trade-off function between net returns and soil quality is developed for farmers in southwestern Saskatchewan using a Markov decision model. The results show that farmers who are concerned with soil levels or stewardship employ chem-fallow more often at lower soil moisture levels and also tend to crop more intensively to conserve soil. The major conclusion is that concern for soil quality, as documented by some researchers, does have practical significance in changing agronomic practices; but, when soil is relatively deep, it takes a fairly substantial concern about soil quality before it is possible to distinguish clearly the agricultural practices of farmers who are truly concerned with stewardship from those who are not.

Key words: dynamic programming, economic trade-off, soil conservation.

Research indicates that agricultural producers do not behave solely as profit maximizers, but that they usually maximize some form of utility function (Lin, Dean, and Moore; Van Kooten, Schoney, and Hayward). As Paterson discovered, soil stewardship is a priority for many farmers and should be included in the utility function. Stewardship implies that the soil resource be used so that long-term productivity is not diminished; however, in practice, interpretation of the term "stewardship" varies among individuals. The purpose of this study is to investigate the relevance of stewardship to farming practices and, in particular, to investigate the ability and willingness of individual farmers to sacrifice profits for soil quality. Therefore, soil quality is explicitly included in the farmer's utility function along with profit, and a trade-off function between soil quality and net returns is constructed in a dynamic framework.

An example of the approach used here is provided by Thampapillai and Sinden (TS) who determine trade-offs for multiple objective planning in northern New South Wales in Australia. Their model consists of a function with two objectives—a monetary objective, income maximization, and a nonmonetary objective, maintenance of environmental quality. The trade-off function was derived by changing the relative weights on these objectives. Unlike TS, who employed deterministic linear programming, we use a (dynamic) Markov decision model here to study trade-offs among objectives.

Our focus is on how optimal farm management practices are affected by various levels of concern for stewardship. We assume that agricultural producers in the brown soil zone of southwestern Saskatchewan maximize discounted utility as a function of net returns and soil quality, where soil quality is measured by soil depth. We examine flexcropping of spring wheat in conjunction with either tillage fallow or chem-fallow for moisture conservation. As opposed to a fixed crop rotation, such as the dominant two-year, wheat-fallow rotation in the study region, the flexcrop strategy relies on a measure of spring soil moisture to determine whether to plant or fallow (Burt and Allison).

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The critical soil moisture level and, hence, the cropping strategy and extent of subsequent erosion are affected by stewardship concerns.

The following sections develop a theoretical foundation for the problem and describe the empirical model. Then, stochastic dynamic programming (SDP) is used to solve the Markov decision process and find the optimal flexcrop strategy under various weights for the two objectives in the utility function. A trade-off function between the attributes is developed and time paths of soil erosion under various weightings of the soil quality objective in the utility function are investigated.

Theory: Trade-off between Net Returns and Soil Quality

It is assumed that farmers maximize the discounted value of a multi-objective utility function. The parameters of the utility function are net returns (π) and soil quality (Q), where soil quality is synonymous with minimizing soil erosion (i.e., soil conservation).[1] As a practical matter, soil quality is converted into a money measure by determining the productive value of soil depth. A model for analyzing the trade-off between soil quality and profit is illustrated in figure 1. Soil quality is plotted along the abscissa while profits are plotted along the ordinate. Because erosion is a dynamic concept, both the profit and soil quality axes can be expressed in present value terms.

Point *A* defines the initial distribution of profits and conservation, i.e., soil quality or depth, prior to any decision making on the part of farmers. Curve *GF* is the transformation frontier or trade-off function. This envelope of feasible alternatives includes all possible farming strategies, that is, agricultural practices or uses for the land over time. Along the frontier, the marginal rate of transformation (*MRT*) measures the sacrifice of discounted profit for a unit increase in present value of soil quality. The *MRT* is defined as

$$MRT = -d\pi/dQ = (\delta g/\delta Q)/(\delta g/\delta \pi),$$

where $g(\pi, Q)$ is a convex function, the transformation locus.

An indifference map is superimposed on the transformation curve in figure 1. The farmer's discounted utility function is expressed by iso-present value of utility (indifference) curves in which the marginal rate of substitution (*MRS*) between soil quality and profits is defined as

$$MRS = -d\pi/dQ = (\delta U/\delta Q)/(\delta U/\delta \pi).$$

Farmers attain their highest indifference contour at point *E*, where *MRT* = *MRS* in the feasible set. The line (*MM'*) passing through *E* and tangent to both the transformation locus and

[1] Soil conservation is a shift of extraction rates toward the future, while soil depletion or erosion is a shift of use rates toward the present (Ciriacy-Wantrup).

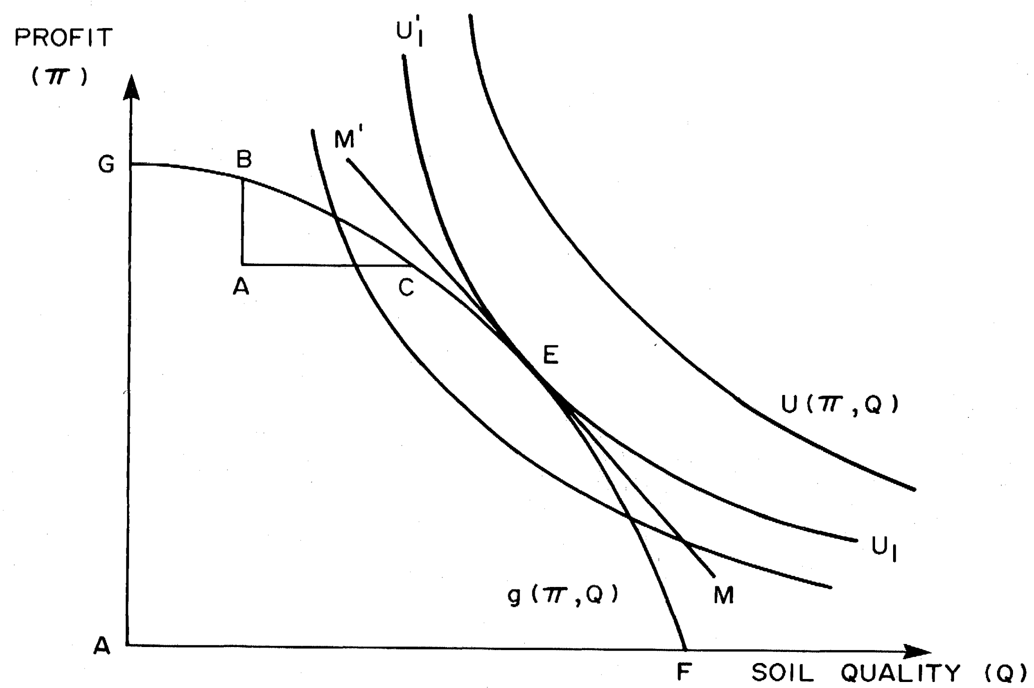

Figure 1. Trade-off function for profit and soil quality

U_1U_1' is important because the negative slope of MM' indicates the relative marginal values of π and Q held by the decision maker. We refer to the marginal trade-off of Q for the other objective as a weight. Therefore, the slope of U_1U_1' at point E is the negative of the ratio of the soil quality weight in the utility function to the weight for profits. If the latter weight is one and the soil quality weight is λ, the slope of MM' is then $-\lambda/1 = -\lambda$. In equilibrium, therefore, $MRT = MRS = \lambda$. By choosing different values of λ in a dynamic decision model, it is possible to find GF.

Given the dynamic nature of soil erosion and cropping systems, a dynamic optimization model is used to determine the trade-off function between net returns and soil depth. The objective function is

$$\sum_{t=0}^{T} U_t(\pi_t, Q_t)\, \beta^t, \tag{1}$$

where $\beta = 1/(1 + r)$ is the discount factor, with rate of discount r, and T is the length of the planning horizon. Net returns depend upon the choices available to the decision maker. In the model, farmers can select from the following choices (d) at spring planting time: (a) plant wheat; (b) summerfallow to store soil moisture for next year's crop, using tillage operations to keep fields free of weeds; or (c) use chem-fallow to store moisture and protect the soil from eroding to the extent it does under tillage fallow. The state variables in the model are soil depth (D) and available soil moisture (M) at spring planting time (early May).

The utility function is assumed to be strongly separable in net returns and soil quality. After a monotonic transformation of the utility function, the objective function (1) can be written as

$$\sum_{t=0}^{T} [(1 - \lambda)\, \pi_t + \lambda\, Q_t]\, \beta^t, \tag{2}$$

where $0 \leq \lambda \leq 1$ is the utility weight attached to the soil quality objective. Soil quality is a function of the state variables, moisture and soil depth; that is $Q(D_t, M_t)$.[2] The soil quality function itself remains invariant with respect to time.

The objective function (1) is maximized subject to the following state transformation equations:

$$D_{t+1} = D_t - h(d_t, D_t), \text{ and} \tag{3}$$

$$M_{t+1} = M_t + g(d_t, M_t). \tag{4}$$

Dynamic constraint (3) states that soil depth in the next period is equal to the current period value minus the soil extracted by farming operations (tillage fallow, chem-fallow, or crop). Transformation equation (4) states that available soil moisture next year is related to current soil moisture and the agronomic decision either to exploit moisture (crop) or enhance moisture (tillage fallow or chem-fallow).

Both the state variables—available soil moisture at planting time and soil depth—are stochastic variables. Soil moisture is stochastic because annual precipitation is unpredictable. However, the distribution of moisture available at the beginning of a crop year is dependent on the decision in the preceding year. Similarly, the soil erosion experienced in a given year depends on the agronomic decision taken, with uncertainty attributed to vagaries in weather conditions. Unlike soil moisture, however, soil depth is continually declining in random fashion because soil regeneration is considered insignificant.

A particular state is defined as a pair of observations on soil moisture and soil depth. Hence, the SDP recursive equation can be written as

$$V_t(i) = \max_{d(t)} E[R^d(i) + \beta \sum_{j=1}^{m} p^d(i, j)\, V_{t+1}(j)], \tag{5}$$

where $V_t(i)$ is the discounted value of future net returns, given the state variable is at level i at the beginning of the T-stage process,[3] $V_{t+1}(j)$ is the discounted value of future net returns over the remaining $T - 1$ years of a T-year horizon, given the state conditions are at level j and that the optimal path is followed; $p^d(i, j)$ is the probability of moving from state i to state j, given that alternative d is chosen; $R^d(i)$ is the reward in state i, given decision d; and there are a total of m states. Equation (5) is solved recursively to yield the optimal solution.

Data for the Study Region

The data used in the study come from the Innovative Acres Project administered by the Department of Soil Science at the University of

[2] This relationship is described further in the empirical section.

[3] Each of a finite number of states consists of a combination of some level of soil moisture and soil depth.

Saskatchewan. The major objectives of this project are to maximize crop productivity and sustain high soil quality through the implementation of water-efficient farming practices. For each Saskatchewan farm in the program, data have been collected from an average of twenty-four plots spread over two research fields; but, for each plot, data are only available for a period of four years. (The few years of available data, unfortunately, will affect the generality of the conclusions.) Only data from the eleven Innovative Acres farms located in the brown soil zone of Saskatchewan are used in this study.

The following variables are included in the data; (*a*) the depth of the *A* and *B* soil horizons (solum depth), (*b*) the level of available soil moisture at planting time, and (*c*) the type of crop seeded and its yield. The data include observations of both conventional and chemical fallow, and the dominant crop in the region is hard spring wheat. The average wheat yield for the farms in the study area is 1,622.87 kilograms per hectare (24.1 bushels per acre), which accords with historical yields for wheat. The ten-year (1977–86) average spring wheat yield in the region was 1,649.93 kg/ha (24.5 bu/ac). Further information regarding the data is found in Weisensel.

If no crop is grown, then yield is zero and only a cost of fallowing is incurred. The cost of the fallowing strategy depends upon whether tillage fallow or chem-fallow is employed. Cost of production data, which is based on total variable costs of production, was obtained from Schoney and is provided in table 1. The cost of chem-fallow is from the Innovative Acres data, but it is comparable to the other cost data. Adjustments were made to the cost structure as solum depth changed in order to keep production on the expansion path (see Weisensel). In addition, the costs of chem-fallow and tillage fallow are adjusted to account for lower seeding costs on fallow as opposed to stubble (table 1). However, because the model does not include decisions regarding optimal investment in machinery and equipment, it is assumed that fixed costs remain the same over the length of the planning horizon. Thus, the focus is on variable profits.

Table 1. Cost of Production Data for Brown Soil Zone of Saskatchewan

Description	Cost
	($Cdn/hectare)
Wheat on fallow	98.60
Wheat on stubble	112.73
Cost adjustment for seeding on summer-fallow vs. stubble	14.13
Tillage summer-fallow	20.85
Chem-fallow	47.42

Source: Schoney and Innovative Acres annual reports.

Estimated Yield Function and the Measurement of Soil Quality

The net return (variable profit) in any given year is the price of output (*P*) multiplied by yield (*Y*) minus the cost of the activity (*c*). Yield is a function of the state variables solum depth (*D*) and available soil moisture (*M*) at spring planting time. Of course, yield is zero if the land is not cropped. The yield function is stationary, price is fixed, and the cost or production depends only on the decision (*d*), which is fixed for each activity. Thus, net returns can be written as

$$\pi_t(d_t, M_t, d_t) = P \cdot Y(D_t, M_t, d_t) - c(d_t).$$

This expression is then substituted into (2).

The yield function is assumed to take a modified Mitscherlich-Spillman functional form:

$$Y = a + b\,(1 - R_1^D)\,(1 - R_2^M),$$

where a, b, R_1, and R_2 are parameters to be estimated, D is centimeters of solum depth, and M is centimeters of available soil moisture.[4] The estimated relationship is

$$(6)\quad \underset{(0.27)}{Y = 84.02} + \underset{(7.67)}{2808.1}(1 - \underset{(2.16)}{0.634^D}) \cdot (1 - \underset{(28.3)}{0.926^M}),\ R^2 = 0.22,$$

where the t-statistics are provided in parentheses and there are 484 observations. Equation (6) represents the expected yield function for farmers, assuming that solum depth and available soil moisture are known at planting time.

The soil quality objective is made commensurable with net returns by specifying the value of soil in monetary terms. A dollar value for soil quality is obtained by integrating the value of marginal product (*VMP*) curve for solum depth [obtained from (6)] between zero and the amount of solum depth in the field. The value of the marginal product of solum depth is

[4] Other functional forms were also examined, but this form gave the best results from both a statistical and agronomic viewpoint (Weisensel).

$$VMP = P\ \delta Y/\delta D = P[-b\ \ln R_1\ R_1^D\ (1 - R_2^M)].$$

Suppose q is a given solum depth. Then the value of q to the producer, say Q, is found by integration.

$$\begin{aligned} Q &= \int_0^q VMP\ dD \\ &= \int_0^q [-P\ b\ \ln R_1\ R_1^D\ (1 - R_2^M)]dD \\ &= Pb(1 - R_2^M)\ (1 - R_1^q). \end{aligned}$$

In (7), Q measures the shadow value of soil quality and is our surrogate for soil quality in the utility function.

To reflect a distaste for fallow in the current period as opposed to planting a crop, the soil quality metric in the objective function is multiplied by a factor μ determined by the ratio of expected soil loss under the particular decision taken to the soil loss expected when land is cropped. Thus, if the decision is to crop, then the adjustment factor is 1.0; it is less than 1.0 for either of the fallow decisions (table 3).

Because the objective function (2) is separable in the two objectives, profit and soil quality, it can now be written as

$$(8)\quad \sum_{t=0}^{T} \{(1 - \lambda)\ P\ [84.02 + 2808.0\ (1 - 0.634^{D_t}) \cdot (1 - 0.926^{M_t}) - c(d_t)] + \lambda\ \mu\ P\ [2808.0\ (1 - 0.634^{D_t}) \cdot (1 - 0.926^{M_t})]\}.$$

Although the dual objectives are commensurable in expression (8), this does not imply that the agricultural producer considers \$1 of net return to be identical to \$1 from soil conservation. Rather, one can think of π as realized returns and Q as unrealized or psychological returns. This explains the similarity (but not equality) of expressions (6) and (7).

State Transformation Equations: The Transition Matrix

In the SDP model, the state transformation equations (3) and (4) are represented by a probability transition matrix giving the probability $P^d(i, j)$ of moving from state i in time t to state j in time $t + 1$ given that decision d was made at time t. In order to compute the entire transition matrix, a transition matrix for each of the state variables, soil moisture and solum depth, must first be calculated.

The following procedure was employed to calculate the soil moisture transition probabilities. Spring soil moisture in the year following a spring wheat year is regressed on spring soil moisture of the preceding crop year. The data on soil moisture are described in detail by Chinthammit. Similarly, spring soil moisture in the year following fallow is regressed on spring soil moisture of the fallow year for each of tillage fallow and chemical fallow. A double logarithmic functional form was used for the three regressions. The results are as follows:

(9a) Spring wheat:

$$\ln M_t = \underset{(12.33)}{1.6017} + \underset{(4.07)}{0.2271}\ \ln M_{t-1},$$

$R^2 = 0.0434$, $SEE = 0.5075$, and $n = 367$;

(9b) Regular fallow:

$$\ln M_t = \underset{(18.66)}{2.0212} + \underset{(4.95)}{0.2286}\ \ln M_{t-1}$$

$R^2 = 0.1052$, $SEE = 0.3075$, and $n = 210$;

(9c) Chemical fallow:

$$\ln M_t = \underset{(10.71)}{1.9693} + \underset{(3.04)}{0.2587}\ \ln M_{t-1}$$

$R^2 = 0.1371$, $SEE = 0.3301$, and $n = 60$.

Here, SEE is the standard error of the estimate, n is the number of observations, and the t-statistics are provided in parentheses.

As expected, the intercept and slope for the spring wheat equation are lower than for both the fallow equations. A Breusch-Pagan test was employed to test for heteroscedasticity in the soil moisture state equations. The null hypothesis that the error term is independently and identically distributed could not be rejected at the 95% level.

Soil moisture is divided into ten discrete intervals in the SDP model. The intervals and their midpoints are provided in table 2. The probability transition matrix has a dimension of 30 by 10 to account for the three alternatives—tillage fallow (F), chem-fallow (C), and planting spring wheat (W). The soil moisture transition matrix is constructed using the results in equations (9).

To illustrate the method used to construct the matrix, consider alternative W in the fifth state (i.e., row 15 of table 2). Substitute the soil moisture value of 11.25–the midpoint of soil moisture interval 5—in the right-hand-side of (9a). This gives an expected mean of 8.60 centimeters of moisture. Assuming soil moisture has

Table 2. Soil Moisture Transition Matrix

		Soil Moisture Interval States (period $t+1$)									
M_t	d_t	1	2	3	4	5	6	7	8	9	10
1	*F*	.0001	.0661	.3599	.3470	.1568	.0508	.0142	.0038	.0001	.0012
0–2.5 cm	*C*	.0004	.1026	.3824	.3126	.1365	.0459	.0139	.0040	.0012	.0005
	W	.0735	.3928	.2962	.1375	.0574	.0239	.0102	.0045	.0021	.0019
2	*F*	.0000	.0101	.1479	.3151	.2716	.1497	.0656	.0255	.0093	.0052
2.5–5.0 cm	*C*	.0000	.0168	.1679	.3048	.2525	.1432	.0671	.0285	.0115	.0077
	W	.0261	.2561	.3058	.1970	.1054	.0534	.0269	.0137	.0071	.0085
3	*F*	.0000	.0035	.0800	.2440	.2823	.1985	.1068	.0495	.0211	.0143
5.0–7.5 cm	*C*	.0000	.0058	.0914	.2377	.2636	.1901	.1091	.0551	.0260	.0212
	W	.0150	.1954	.2871	.2149	.1290	.0716	.0388	.0211	.0116	.0155
4	*F*	.0000	.0016	.0497	.1916	.2685	.2214	.1364	.0710	.0335	.0263
7.5–10.0 cm	*C*	.0000	.0026	.0566	.1859	.2493	.2104	.1378	.0781	.0407	.0386
	W	.0101	.1595	.2681	.2214	.1431	.0844	.0481	.0273	.0155	.0225
5	*F*	.0000	.0009	.0336	.1539	.2487	.2309	.1572	.0893	.0455	.0400
10.0–12.5 cm	*C*	.0000	.0014	.0379	.1482	.2289	.2171	.1570	.0969	.0543	.0583
	W	.0075	.1353	.2512	.2231	.1525	.0940	.0557	.0326	.0191	.0290
6	*F*	.0000	.0005	0240	.1263	.2285	.2331	.1719	.1047	.0567	.0543
12.5–15.0 cm	*C*	.0000	.0008	.0269	.1205	.2082	.2167	.1695	.1119	.0667	.0788
	W	.0058	.1177	.2364	.2225	.1590	.1016	.0620	.0372	.0223	.0355
7	*F*	.0000	.0003	.0179	.1055	.2094	.2310	.1821	.1174	.0669	.0695
15.0–17.5 cm	*C*	.0000	.0005	.0198	.0997	.1889	.2124	.1773	.1239	.0776	.0999
	W	.0047	.1042	.2234	.2207	.1637	.1077	.0674	.0413	.0252	.0417
8	*F*	.0000	.0002	.0137	.0893	.1921	.2266	.1890	.1280	.0762	.0858
17.5–20.0 cm	*C*	.0000	.0004	.0151	.0836	.1715	.2060	.1818	.1334	.0871	.0332
	W	.0039	.0935	.2120	.2182	.1670	.1128	.0720	.0450	.0279	.0477
9	*F*	.0000	.0002	.0108	.0765	.1766	.2208	.1935	.1369	.0846	.1001
20.0–22.5 cm	*C*	.0000	.0002	.0118	.0710	.1561	.1986	.1841	.1408	.0954	.1420
	W	.0033	.0849	.2018	.2154	.1694	.1170	.0761	.0483	.0304	.0534
10	*F*	.0000	.0001	.0077	.0610	.1550	.2100	.1972	.1480	.0963	.1247
>22.5 cm	*C*	.0000	.0002	.0082	.0558	.1349	.1858	.1843	.1494	.1066	.1748
	W	.0026	.0738	.1876	.2104	.1719	.1224	.0817	.0530	.0340	.0626
Soil moisture midpoints		1.25	3.75	6.25	8.75	11.25	13.75	16.25	18.75	21.25	25.27

Note: The alternative decisions in period t (d_t) are as follows: *F* is conventional fallow, *C* is chemical fallow, *W* is planting of spring wheat.

a log-normal distribution, with variance given by *SEE* (=0.5075), it is possible to determine the probability that soil moisture will fall into a particular interval next year given that a crop is grown this year. This process is repeated for each row; each row constitutes a probability distribution and thus must sum to 1.0. In table 2, both the rows and columns are unimodal or exhibit monotonicity, but there is some inconsistency in the last several columns of the transition table. However, this problem does not significantly affect the results because the differences in probabilities are small.

The solum depth transition matrix is constructed from the erosion estimates of table 3; the last column in table 3 gives the adjustment factors μ for a 10%–24% slope. The transition matrix is based on the assumption that the erosion estimates are normally distributed (Kiss, de Jong, and Rostad). Given the estimates and their standard deviations, distribution theory can be used to calculate each row of the matrix. For each initial state i at time t, the normal distribution was integrated over each interval j, where j is the corresponding value of the state variable in time period $t+1$, using the rate of erosion associated with particular alternative d. The result is the probability of moving from state i to state j, given alternative d is chosen. Repeating this operation for all intervals j in row i will complete the first row of the transition matrix. To complete the remainder of the matrix, the distribution function must be integrated for all states i, over all intervals j, and for all alternatives d (Weisensel).

The solum depth transition matrix for a slope grade of 10%–24% is provided in table 4 with a format similar to the soil moisture matrix in table 2. The higher slope grade represents a serious risk of erosion; it is used here for illustrative purposes, although similar results hold for lower slope grades. The solum depth transition

Table 3. Estimated Annual Rates of Soil Erosion and the Adjustment Factor by Decision and Slope Grade Position

	0%–3%		3%–10%		10%–24%		
Crop	Erosion	Std Dev	Erosion	Std Dev	Erosion	Std Dev	μ[a]
	(tons per hectare per year)						
Wheat	7.5	2.6	8.7	2.9	15.5	5.2	1.00
	(0.61)[b]	(0.21)	(0.71)	(0.27)	(1.26)	(0.42)	
Fallow	38.5	13.4	45.3	15.1	80.4	26.8	0.19
	(3.13)	(1.09)	(3.68)	(1.23)	(6.53)	(2.18)	
Chem-fallow	14.3	5.00	16.9	5.60	29.9	9.96	0.52
	(1.16)	(0.41)	(1.37)	(0.46)	(2.43)	(0.81)	

[a]Adjustment factor calculated for a slope grade of 10%–24%.
[b]Figures in parentheses are estimates of soil erosion in millimeters per year, assuming a 15-centimeter hectare furrow slice of solum weighing 1,800 tons per hectare.

Table 4. Solum Depth Transition Matrix, Slope Grade 10%–24%

		Solum Depth Interval States (period $t + 1$)							
M_t	d_t	1	2	3	4	5	6	7	8
	F	0.0056	0.0471	0.1887	0.3439	0.286	0.1085	0.0187	0.0015
1	C	0.0388	0.7203	0.2402	0.0007	0	0	0	0
	W	0.268	0.7319	0.0001	0	0	0	0	0
	F	0	0.0056	0.0471	0.1887	0.3439	0.286	0.1085	0.0187
2	C	0	0.0388	0.7203	0.2402	0.0007	0	0	0
	W	0	0.268	0.7319	0.0001	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Note. See table 2 for further explanation.

matrix, which is based on 20 centimeters (cm) of solum depth with 2-milimeter intervals, has dimensions 300 by 100 because, for every solum depth state, there are three possible alternatives. The majority of values in the matrix are zero because it is highly unlikely, even on high risk soils, that more than 2 to 3 centimeters of topsoil can be eroded in a single year. Furthermore, the model does not account for soil deposition or regeneration; thus, the probability of increasing solum depth is zero.

Every third row of the solum depth transition matrix is exactly the same except that it is shifted to the right one column. This result occurs between each row of the matrix (for the same alternative) is calculated using the same erosion estimate from table 3. Finally, solum depth cannot be eroded below zero. Because the probabilities in the bottom rows of the solum depth matrix must reflect this phenomenon, the final rows of the matrix are modified so that the probabilities in each row still add to one. This is done by calculating the probability of the 100th column as one minus the sum of the previous 99 columns for the given row. Because of the size of the solum depth transition matrix, the number of zeros in it and the similarity of the rows (except for the last several), only the first three rows and eight columns are shown in table 4.

The solum depth and moisture probabilities are assumed independent of each other. Therefore, the total transition matrix for the system is found by multiplying each entry for a given solum depth state by the row associated with a particular soil moisture state. The new states created in this way consist of a paired observation on solum depth and available spring soil moisture.

Optimal Flexcrop Strategies

Because soil is continually being eroded, value-iteration over a period of thirty years is used to solve the SDP problem. A price of $Cdn.128.52 per tonne ($3.50/bu) and erosion rates comparable to those for a 10%–24% slope are employed. Optimal strategies for different values of the soil quality weight, λ, and for different levels of available soil moisture and solum depth are determined. The present value of net returns depends upon the level of soil moisture as well as solum depth. For a solum depth of 20 centimeters the present value of net returns for the strategy associated with $\lambda = 0.0$ (no weight on soil quality) increases from approximately $1,140 per hectare to $1,390 per hectare as available spring soil moisture increases from the lowest to the highest level; for $\lambda = 0.8$, the associated range is $1,050 per hectare to $1,340 per hectare.

The optimal strategies and critical soil moisture values also change as solum depth declines. For example, the strategy for a producer with $\lambda = 0.4$ is to employ tillage fallow whenever available soil moisture is below 2.5 centimeters, use chem-fallow when it is between 2.5 centimeters and 5.0 centimeters, and plant spring wheat whenever spring soil moisture is greater than 5.0 centimeters, but only when solum depth exceeds 12.8 centimeters. For solum depths between 4.4 and 12.8 centimeters, the optimal strategy is to employ chem-fallow whenever available soil moisture in the spring is below 5.0 centimeters and to plant wheat otherwise. Finally, if solum depth is below 4.4 centimeters, the optimal strategy is to employ chem-fallow if soil moisture is below 2.5 centimeters and plant wheat if it is above this level, at least until the present value of net returns becomes negative. No allowance is made for alternatives other than fallowing and planting of spring wheat. It is likely that land will be turned into pasture at low solum depth levels, although this was not investigated in the model.

In summary, the optimal strategies obtained from the Markov decision model indicate that a producer will employ chem-fallow as opposed to tillage or conventional fallow at higher values of λ.[5] For example, at 20 centimeters of soil, the farmer with $\lambda = 0.6$ will chem-fallow when soil moisture is less than 5.0 centimeters, while a producer with $\lambda = 0.0$ will employ tillage fallow whenever soil moisture is below 7.5 centimeters. Further, at lower solum depths, the farmer concerned with soil quality will tend to crop at lower levels of soil moisture and use chem-fallow more frequently compared with the producer who does not share this concern for soil quality.

The flexcrop results can be used to estimate how long it takes to erode a given amount of soil. Given an initial soil moisture level of 11.25 centimeters, flexcrop strategies take between 129 and 200 years to erode 32 centimeters of solum down to 4 centimeters, depending upon assumptions about the importance farmers place on solum depth in their objective function (Chinthammit).[6] If a farmer's only concern is with maximizing net returns, the optimal flexcrop strategy will erode 28 centimeters of solum in approximately 129 years. When soil quality is a concern (higher values of λ), the rate of erosion is lower. However, the major benefits of soil conservation are obtained without requiring a steep trade-off between returns and concern for soil quality because erosion time paths for $\lambda > 0.4$ are almost identical to those for $\lambda = 0.4$.

The cropping strategy that prevails in the study region is a fixed, two-year, wheat-fallow rotation. The main reason for the dominance of this rotation is that, while expected returns are lower, the variance of return is also lower. For a slope grade of 10%–24%, the fixed crop rotation erodes away 28 centimeters of solum in about 73 years compared to 129 years for the profit-maximizing flexcrop rotation and 199 years for a flexcrop rotation obtained when $\lambda = 0.6$.

The Trade-off Function

Aggregate values of each of the profit and soil quality objectives can be derived for each level of λ and plotted to give the trade-off function. The trade-off functions in figures 2 and 3 correspond to (current) solum depth levels of 20 centimeters and 10 centimeters, respectively, and average spring soil moisture (11.25 cm). For a solum depth of 20 centimeters, optimal choices change very little over the range $0 \leq \lambda \leq 0.3$, but they decline sharply thereafter, until $\lambda = 0.6$; the largest trade-offs occur in the range $0.3 \leq \lambda \leq 0.6$. For a solum depth of 10 centimeters, the comparable range is approximately $0.1 \leq \lambda \leq 0.8$. This indicates that, at 20 centimeters of solum depth, a producer must have a substantial concern with soil quality before agronomic practices are clearly distinguishable from profit-maximizing practices. At lower solum depths (fig. 3), the stewardship concern does not need to be as great in order to be able to distinguish stewardly agronomic activities.

The loss in profit when decisions based on

[5] In all of the scenarios investigated (but not reported here), conventional summerfallow was no longer a viable strategy whenever $\lambda > 0.5$.

[6] It is assumed that after 4 cm of solum depth the land will no longer be used for cropping.

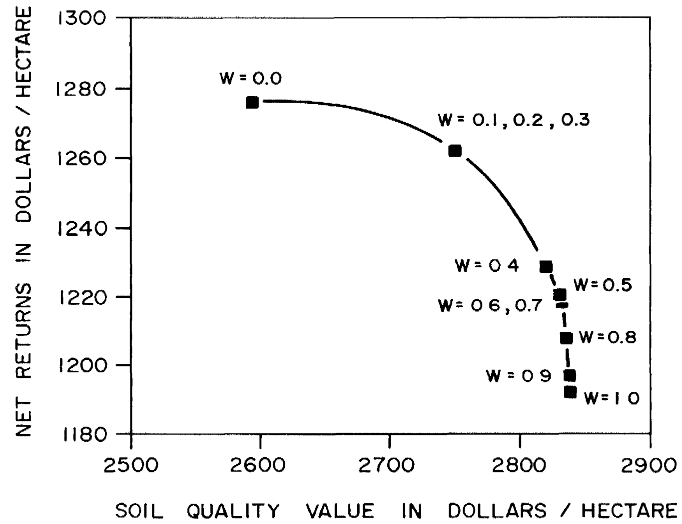

Figure 2. Trade-off function derived at solum depth = 20 centimeters and soil moisture = 11.25 centimeters

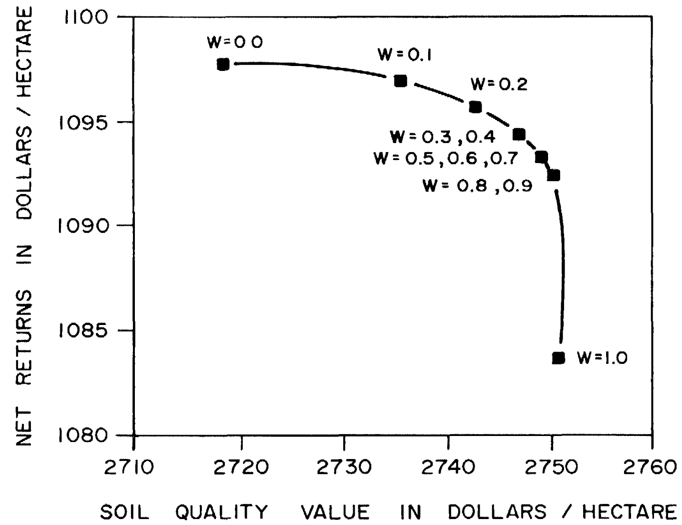

Figure 3. Trade-off function derived at solum depth = 10 centimeters and soil moisture = 1.25 centimeters

soil quality are taken can be calculated using the method described by Thampapillai and Sinden (p. 1033). The opportunity costs of the Q objective at 20 centimeters and 10 centimeters of solum, and at 11.25 centimeters soil moisture, are provided in table 5. The opportunity cost measures the sacrifice in discounted net returns required to achieve the soil quality associated with a particular level of stewardship. The opportunity costs at higher solum depth are greater than those at lower levels of solum depth. For $\lambda = 0.4$, the opportunity cost is \$41.22 per hectare when solum depth is 20 centimeters. If a farmer has 10 centimeters of solum, the opportunity cost is \$4.53 per hectare. When $\lambda = 0.9$, the opportunity cost in present value terms is \$73.13 per hectare for the high solum depth (20 cm) and \$5.69 per hectare at the lower solum depth (10 cm). The actual point on the transformation curve chosen by a producer, or the amount of profit he is willing to sacrifice, depends upon his utility function.

Conclusions

Farmers generally say that they are concerned about soil stewardship, but the results presented here indicate that it will take a substantial concern for soil quality before one observes a change in agronomic practices. Further, soil-conserving practices require sacrifices in profits that tend to be quite small, usually less than 5% of net returns. To the extent that our model is representative of actual farming practices and conditions, the results suggest that educating farmers about cropping alternatives and the low costs associated with soil conservation may yield sub-

Table 5. The Opportunity Cost of Soil Quality (Soil Moisture at 11.25 cm)

Weight (λ)	Value of Net Returns Objectives (\$)	Opportunity Cost of the Soil Quality Objective (\$)	Weight (λ)	Value of Net Returns Objective (\$)	Opportunity Cost of the Soil Quality Objective (\$)
(Solum Depth = 20 cm)			(Solum Depth = 10 cm)		
0.0	1,269.97		0.0	1,097.70	
0.1	1,263.81	6.16	0.1	1,096.89	0.81
0.2	1,263.81	6.16	0.2	1,095.62	2.08
0.3	1,263.81	6.16	0.3	1,094.29	3.41
0.4	1,228.75	41.22	0.4	1,093.17	4.53
0.5	1,220.37	49.60	0.5	1,092.32	5.38
0.6	1,218.46	51.51	0.6	1,092.26	5.44
0.7	1,217.55	52.42	0.7	1,092.20	5.50
0.8	1,207.94	62.03	0.8	1,092.01	5.69
0.9	1,196.84	73.13	0.9	1,092.01	5.69
1.0	1,192.19	77.78	1.0	1,083.58	14.12

stantial improvements in the study region's annual soil loss. Because the opportunity costs of alternative management practices are also low compared to current government transfer payments, perhaps conservation compliance can be used as a prerequisite to receiving benefits, something that is now not done in Canada.

Four areas warrant further research. (*a*) Farmers in the study region currently do not employ the flexcrop strategy which is used as the basis of our calculations. While the prevailing two-year, wheat-fallow rotation is not optimal from an expected returns point of view (Weisensel), it may be optimal for risk-averse producers. Future research should address the implications of this possibility (Young and Van Kooten). (*b*) Only one crop is considered in the model (spring wheat), and cropping and chem-fallow are the only conservation alternatives considered. The model should be expanded to take into account other crop possibilities (e.g., winter wheat, barley) and other conservation strategies (e.g., strip cropping). (*c*) Only four years of data are available. Except for yield comparisons, the extent to which the data are representative of conditions over a longer period of time is unknown. Even the yield data may not be representative of average yields in the region because the data are from experimental plots where, for example, fertilizer-use recommendations are based on information which may not be generally available on other fields. (*d*) The analysis ignores optimal farmland purchase and machinery replacement (fixed costs). Inclusion of these decision variables would improve the model's ability to represent the real world.

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