Estimation of Soil Erosion Time Paths: The Value of Soil Moisture and Topsoil Depth Information

Ward P. Weisensel and G. C. Van Kooten

Rates of soil erosion in the dryland cropping region of Saskatchewan are investigated under alternative cropping strategies. Chemical fallow is examined as an alternative to tillage fallow for moisture and soil conservation. Conclusions include: (*a*) flexible cropping increases net discounted returns and substantially reduces soil erosion compared to the predominant crop rotation; (*b*) chemical fallow is a viable alternative to tillage fallow but only when topsoil already has been eroded substantially; and (*c*) an increase in the discount rate is soil conserving, since it causes producers to plant more often rather than fallow.

Key words: chemical fallow, discount rate, flexcropping, soil erosion rates.

Soil conservation is a world-wide problem, but, until recently, it has been a relatively neglected area of economics research, particularly empirical research.[1] One reason for this neglect is that conservation and depletion are defined with respect to an intertemporal distribution of the use of a resource (capital) fund (Ciriacy-Wantrup), in this case, topsoil. Given the dynamic nature of soil conservation, it is necessary to employ dynamic, economic optimization models, but such models are difficult to devise and implement (C. R. Taylor). Further, practical (on-farm) concern about soil erosion is often mitigated by the fact that increased yields due to technological change may offset any reductions in yield resulting from soil erosion (Walker and Young).

In Canada, the public has become more aware of soil erosion but only as a result of a number of high-profile studies by the Prairie Farm Rehabilitation Administration (PFRA), the Canadian Senate (Sparrow), which held public hearings regarding the problem, and the Science Council of Canada. These studies indicate that the annual on-farm costs of soil erosion are quite high and that additional research on the economics of soil erosion is required.[2]

One purpose of the current study is to investigate the use of chemical summerfallow in place of tillage summerfallow in dryland cropping regions as a method for conserving water while reducing soil erosion. In this regard, we explore flexcropping of spring wheat in conjunction with either tillage fallow or chemical fallow for moisture conservation. Flexcropping implies that the farmer does not employ a fixed crop rotation, as is now the case for much of the dryland cropping region, but, rather, decides whether to plant or fallow based on information about soil moisture and soil depth at planting time in the spring (Burt and Allison; Burt and Johnson). Using a Markov decision model, it is possible to find the critical values

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Ward P. Weisensel is a research associate in the Department of Agricultural Economics at the University of Saskatchewan. G. C. Van Kooten is an associate professor in the Department of Agricultural Economics at the University of British Columbia. Order of authorship was determined by a coin toss.

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[1] Some recent studies are by Burt; D. B. Taylor; Walker; Pope, Bhide, and Heady; McConnell; and Saliba. Several of these studies present no empirical data whatsoever.

[2] PFRA estimates the annual on-farm cost of soil erosion to Canadian prairie farmers to be $239 million; Rennie provides an estimate of $430 million per year. In both cases, however, it is unclear how these estimates are obtained (see Van Kooten, Weisensel, and de Jong). Prices and other value data used in this study are in Canadian funds.

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of soil moisture at various levels of topsoil depth for making decisions that are optimal over time. Soil erosion rates under flexcropping, which includes chemical fallow as a decision alternative, then can be compared with those expected under current agronomic practices.

Another purpose of the study is to investigate the impact of the discount rate on soil erosion. Farzin shows that lowering the discount rate has an ambiguous effect upon the rate of depletion of a nonrenewable resource. The direct or conservation effect of a lower discount rate is to reduce the rate of depletion as noted by Hotelling. However, reducing the discount rate results in the use of more capital which serves to increase the rate of depletion (disinvestment effect). We obtain a similar conclusion regarding the ambiguity of the discount rate but without the need of a disinvestment effect. Our result holds because the resource stock (soil) is not directly sold but is used in production of crops. In our model, soil conservation occurs when a crop is planted, while moisture conservation occurs when a crop is not produced (fallow). Hence, conserving moisture is soil depleting and conserving soil is moisture depleting.

A Flexible Cropping Model for Dryland Agriculture

A major limitation to crop production in the drier regions of the Great Plains is growing-season rainfall. One cropping strategy used for some time is to employ summerfallow to store up precipitation over a two-year period in order to grow a single crop. Hence, a fixed, two-year, wheat-fallow rotation is frequently employed, and this strategy can be expected to become more dominant if the droughts experienced recently continue. Tillage fallow is the usual alternative to cropping in this rotation; tillage kills weeds but depletes the soil. As an alternative method for storing water, chem-fallow relies on chemical weed control with no tillage and, consequently, results in lower soil erosion than tillage fallow. Chem-fallow is more expensive, but, in general, slightly more moisture can be stored compared to tillage fallow (Rennie). Both continuous cropping and chem-fallow have been suggested as means for reducing soil erosion.

In this study, it is assumed that farmers maximize the present value of net returns (R) which are a function of available soil moisture (M) at planting time, soil depth (D), and the agronomic decision (u). The objective function is:

$$(1)\qquad \sum_{t=0}^{T-1} R_t(D_t, M_t, u_t)\beta^t + \beta^T S(D_T),$$

where β is the discount factor, $S(D_T)$ is the value of the land at the end of the time horizon as a function of soil depth,[3] and the length of the planning horizon is T. Net returns depend upon the choices available to the decision maker. In the current model, it is assumed that farmers have three choices at spring seeding time: (*a*) plant spring wheat, (*b*) use tillage fallow to store soil moisture for next year's crop, or (*c*) use chem-fallow to store moisture.

The net return in any given year is assumed to be known with certainty and is simply the price of output (P) multiplied by yield (y) minus the cost of the activity. Of course, yield is zero if the land is not cropped. The yield function is assumed to be invariant across time, price is taken to be fixed, and the cost of production (c) depends only on the decision taken, which is fixed for each activity.[4] Thus, net returns can be written as:

$$(2)\qquad R_t(D_t, M_t, u_t) = P\, y(D_t, M_t, u_t) - c(u_t).$$

The objective function obtained when (2) is substituted into (1) is maximized subject to the transformation equations for the state variables, soil depth and soil moisture.

To derive the equations of motion, suppose the state transformation equation for a dynamic deterministic system is:

$$(3)\qquad x_{t+1} = h(t, x_t),$$

where $t \in T = \{0, 1, \ldots\}$. To incorporate uncertainty in this system, we assume that x_{t+1} is a random variable so equation (3) becomes:

$$(4)\qquad x_{t+1} = H(t, x_t) + w_t, \qquad t \in T,$$

where h is the conditional mean of the random variable x_{t+1}—conditioned on x_t—and w is a

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[3] It is unlikely that land values fluctuate with spring soil moisture at time T. A review of recent literature on the relationship between soil quality and land price indicates that land prices do not reflect investments in conservation (Peterson; Gardner and Barrows; Ervin and Mill). Thus, it is not possible to find $S(D_T)$ in practice, implying that "salvage" value will be the same regardless of the agronomic decisions that are taken.

[4] Decisions about optimal machinery and land purchases are not included in the model as this would add to its complexity. These decisions are beyond the scope of the current study.

random variable with mean zero and finite variance σ^2. The distribution of the random variable w is independent of x_s, $s < t$; that is, the process $\{x_t\}$ is assumed to be first-order Markovian. Now assume that the distribution of w is normal and define the random variable $z_t = w_t/\sigma_t$. Then z_t is normally distributed with mean zero and unit variance, and z_t is independent of x. Thus, $\{z_t\}$ is a sequence of identical, independently distributed normal random variables each with zero mean and unit variance. Equation (4) then becomes the stochastic state transformation equation

$$(5) \qquad x_{t+1} = h(t, x_t) + \sigma z_t, \qquad t \in T.$$

For the current problem, we write the stochastic state equation (5) as follows:

$$(6) \qquad D_{t+1} = D_t - f(u_t, D_t) + e_{1t}, \text{ and}$$

$$(7) \qquad M_{t+1} = M_t + g(u_t) + e_{2t}.$$

The random processes $\{e_{1t}\}$ and $\{e_{2t}\}$ are assumed to be independent of each other, and the initial conditions for the problem are:

$$D_0 = \bar{D}_0 \text{ and } M_0 = \bar{M}_0.$$

Equation (6) states that soil depth in the next period is equal to what it is in the current period minus that amount which is extracted via farming operations (fallow or crop). State transformation equation (7) indicates that available soil moisture next year is related to current soil moisture and the agronomic decision taken either to exploit moisture (crop) or enhance moisture (fallow). The term $f()$ in (6) is always nonnegative, since, assuming negligible soil regeneration, it is the amount of soil lost, which always must be some positive amount. The term e_{1t} indicates that soil erosion is a random variable that depends not only upon the agronomic decision taken and the depth of soil but also on weather factors which are unpredictable. Assuming that soil regeneration is negligible, soil depth continually declines but at a stochastic rate. On the other hand, $g()$ in (7) may be positive, negative, or zero. Available soil moisture at planting time in a given year is a random variable (as indicated by e_{2t}) that depends not only upon soil moisture and the decision taken in the previous period but also on unknown and unpredictable precipitation throughout the year.

Since the levels of both soil moisture and soil depth in the next period are known only with some probability, we specify our problem as a stochastic dynamic programming (SDP) model. The fundamental SDP equation is:

$$(8) \quad v_t(D_t, M_t) = \max_{u_0,\, u_1 \ldots u_{T-1}} E \; \{[P\, y(D_t, M_t, u_t) - c(u_t)] + \beta v_{t+1}(D_{t+1}, M_{t+1})\},$$

where $v_t()$ is the discounted value of future net returns, given the values of the state variables at time t; $v_{t+1}()$ is the discounted value of future net returns at time $t + 1$, given the state conditions in $t + 1$ and that the optimal path is followed; and E is the expectations operator.

Estimation of Empirical Relationships

For empirical implementation of the model, we examine crop production in the brown soil zone of southwestern Saskatchewan where growing-season rainfall is the limiting input. The data needed to estimate the required relationships are available from the Innovative Acres project of the Soil Science Department at the University of Saskatchewan. Data from 11 farms in the brown soil zone of Saskatchewan are used. Each farm averages 24 plots with four years of data on each. Unfortunately, the years for which data are available may be somewhat atypical since annual precipitation was lower than average on the prairies during those years.[5] The data include (*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. As well, the data include observations for both tillage and chemical fallow. Average spring wheat yield for the data is 24.1 bu./acre (1,622 kg/hectare), which is not unreasonable considering historical wheat yields for the brown soil zone.

For agronomic reasons 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 the parameters to be estimated; D and M are centimeters of solum depth and available soil moisture, respectively; and Y represents yield in kilograms per hectare. Using nonlinear least squares estimation, the estimated relationship is:

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[5] The data may be a harbinger of what one might expect as a result of global climate change.

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

Description	Cost ($/acre)
Wheat on fallow	39.92
Wheat on stubble	45.64
Cost adjustment for seeding on summerfallow vs. stubble	5.72
Regular summerfallow	8.44
Chem-fallow	19.20

Sources: Schoney and Innovative Acres Annual Reports.

$$\begin{array}{l} (9) \\ \quad Y = \underset{(.27)}{84.02} + \underset{(7.67)}{2{,}808.0}\,(1 - \underset{(2.16)}{.634^{D}})(1 - \underset{(28.3)}{.926^{M}}), \\ \quad R^2 = .22 \end{array}$$

where the asymptotic t-statistics are provided in parentheses. Equation (9) represents the expected yield function for farmers, assuming that solum depth and available soil moisture are known at planting time.

Net returns in a given year are defined in expression (2), with the yield function as estimated in (9). If no crop is grown, then yield is zero and only a cost is incurred. This cost 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 was not available from Schoney but was available from Innovative Acres data; however, further investigation indicated that the data can be considered roughly comparable. Adjustments were made to the cost structure as solum depth and soil moisture changed to keep production on the expansion path. For cropping, the cost adjustment was $[\alpha - \alpha(1 - \phi^{D})]$; for the case of tillage fallow and chem-fallow, the cost adjustment was $\beta\,\Omega\,(1 - \phi^{D})$.[6] Parameter α represents the market value of nutrients mineralized during a cropping period on a good quality soil (α = \$7.50/acre); Ω represents a cost adjustment to recognize the lower cost of seeding after summerfallow as opposed to stubble (from table 1, Ω = \$5.72/acre); and ϕ is a nonlinear adjustment factor set equal to .8 (see Weisensel).

The state transformation equations are represented by a state transition matrix, P, which gives the probability, $p^{u}(i, j)$, of moving from state i in time t to state j in time $t + 1$ given that decision u was made at time t. In order to compute the entire transition matrix, it is necessary first to calculate a transition matrix for each of the state variables, soil moisture and solum depth.

For the soil moisture transition probabilities, the following procedure is employed. Spring soil moisture in the year following a harvest of spring-planted wheat is regressed on spring soil moisture of the preceding crop year.[7] Similarly, spring soil moisture in the year following fallow is regressed on spring soil moisture of the preceding fallow year; this is done for both tillage fallow and chemical fallow. A double-logarithmic functional form was used for the three regressions. The results are as follows:

(10a) Spring wheat:

$$\ln M_t = \underset{(12.33)}{1.6017} + \underset{(4.07)}{.2271} \ln M_{t-1}$$

$$R^2 = .0434,\ \text{SEE} = .5075,\ \text{and } n = 367,$$

(10b) Regular fallow:

$$\ln M_t = \underset{(18.66)}{2.0212} + \underset{(4.95)}{.2286} \ln M_{t-1}$$

$$R^2 = .1052,\ \text{SEE} = .3075,\ \text{and } n = 210,$$

(10c) Chemical fallow:

$$\ln M_t = \underset{(10.71)}{1.9693} + \underset{(3.04)}{.2587} \ln M_{t-1}$$

$$R^2 = .1371,\ \text{SEE} = .3301,\ \text{and } n = 60.$$

In the regressions, 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.

For the current application, soil moisture is divided into 10 discrete intervals of 2.5 centimeters (cm) (approximately one inch) each. The smallest interval is 0–2.5 cm, while the largest interval includes soil moisture values exceeding 22.5 cm. The probability transition matrix has dimensions 30 by 10 as there are three alternatives—tillage fallow (F), chem-fallow (C), and planting spring wheat (W). The

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[6] The adjustment parameters α, ϕ, and Ω, and the relationships in the text were determined from discussions with soil scientists at the University of Saskatchewan.

[7] The data on soil moisture is described in greater detail by Chinthammit. Statistical tests indicated that the soil moisture transitions followed a first-order Markov process. Thus, soil moisture this year is a function of the previous year's soil water but not two or more years prior.

soil moisture probability transition matrix is constructed using the approach outlined in the derivation of (5) and the results of (10). Additional information is provided by Chinthammit.

Construction of the solum depth transition probabilities depends upon assumed rates of erosion and the size of the intervals used. We use 2-millimeter (mm) intervals so that the topsoil depth transition matrix based on 20 cm of solum has dimensions 300 by 100 since, for every solum depth state, there are three possible agronomic alternatives. The transition matrix is constructed from the erosion estimates indicated in table 2 and 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*, we integrate the normal distribution 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 agronomic alternative *u*. The result is the probability of moving from state *i* to state *j* given alternative *u* 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 *u*. Obviously, the majority of values in the matrices are zero since 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. The probability of increasing solum depth is assumed to be zero.

The solum depth transition probabilities do not change as one moves down the rows of the matrix. Every third row of the matrix is exactly the same except that it is shifted to the right one column. This result is due to the fact that each row of the matrix (for the same alternative) is calculated using the same erosion estimate from table 2. Further, solum depth cannot be eroded below zero; it is impossible to experience negative solum depth. As 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. Additional details and the solum depth transition matrices are found in Weisensel.

Table 2. Estimated Annual Rates of Soil Erosion by Decision and Slope Grade Position[a]

	0–3% (Low)		10–24% (High)	
Agronomic Decision	Erosion	Std. Dev.	Erosion	Std. Dev.
	Metric Tons/Hectare/Year			
Plant Wheat	7.5 (0.61)	2.6 (0.21)	15.5 (1.26)	5.2 (0.42)
Tillage Fallow	38.5 (3.13)	13.4 (1.09)	80.4 (6.53)	26.8 (2.18)
Chem-fallow	14.3 (1.16)	5.00 (0.41)	29.9 (2.43)	9.96 (0.81)

[a] Figures in parentheses are estimates of soil erosion in millimeters/year, assuming a 15 cm hectare furrow slice of solum weighing 1,800 metric tons/hectare.

Finally, in order to construct the overall transition matrix, we assume that the solum depth and soil moisture probabilities are independent of each other. Then it is a simple matter to find the total transition matrix for the system. This is done by multiplying each entry for a given solum depth state by the row associated with a particular soil moisture state or vice versa. The new states created in this way consist of a pair of observations on solum depth and available spring soil moisture.

Optimal Flexcrop Strategies

The fundamental SDP equation (8) can be rewritten as:

$$(11) \quad v_n(i) = \max_{u(i)} \left[R^u(i) + \beta \sum_{j=1}^{m} p^u(i, j) v_{n-1}(j)\right],$$

where $v_n(i)$ is the discounted value of future net returns, given the state variable is at level *i* at the beginning of the *n*-stage process;[8] $v_{n-1}(j)$ is the discounted value of future net returns over the remaining $n - 1$ years of a *T*-year horizon, given the state level is *j* and that the optimal path is followed; $p^u(i, j)$ is as defined previously; $R^u(i)$ is the net reward in state *i*; and there are a total of *m* states. Since solum depth is continually being eroded, value iteration (Howard) is used to (backward) recur-

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

Table 3. Optimal Agronomic Decisions for Soil Moisture and Selected Solum Depth Levels and Time Required to Erode 36 cm of Solum: Various Scenarios[a]

	Scenarios							
	S1	S2	S3	S4	S5	S6	S7	S8
Price ($/bu.)	2.50	2.50	2.50	2.50	4.50	4.50	4.50	4.50
Discount Rate (%)	0	5	0	5	0	5	0	5
Erosion Rate (% Slope)	0–3	0–3	10–24	10–24	0–3	0–3	10–24	10–24
States[b]								
$M \leq 2.5$ cm								
$D = 20$ cm	F	F	F	F	F	F	F	F
$D = 7$ cm	F	F	C	C	C	F	C	C
2.5 cm $< M \leq 5.0$ cm								
$D = 20$ cm	F	F	F	F	F	F	F	F
$D = 7$ cm	F	F	C	C	C	F	W	C
5.0 cm $< M \leq 7.5$ cm								
$D = 20$ cm	F	F	F	F	W	W	W	W
$D = 7$ cm	W	F	W	C	W	W	W	W
$M > 7.5$ cm								
$D = 20$ cm	W	W	W	W	W	W	W	W
$D = 7$ cm	W	W	W	W	W	W	W	W
Years Required to Erode 36 cm Topsoil[c]	285	269	157	135	373	362	195	185

[a] Decisions are: W = plant wheat; F = tillage fallow; C = chem-fallow.
[b] M is available spring soil water; D is solum depth; cm is centimeters.
[c] Expected number of years to erode 40 cm of solum to 4 cm.

sively solve (11) and find the optimal flexcrop strategy for a 30-year planning horizon.

To better understand the relationship between management strategies and soil erosion, eight alternative scenarios are considered. The characteristics of the scenarios are presented on the top portion of table 3. They are based on wheat prices of $4.50/bu. and $2.50/bu., a 0% and a 5% real rate of discount, and two rates of soil erosion—a "high" potential rate of erosion on a slope grade of 10–24%; a "low" potential rate of erosion on a slope grade of 0–3%. The low price illustrates the farm gate price when subsidies are nonexistent, while the higher price represents a subsidized price. A real discount rate of 0% represents a concern for future generations, while 5% is a realistic real rate of discount. The higher slope grade represents a parcel of land which has serious risk of erosion and is used here mainly for illustrative purposes—a worst case scenario.

In the empirical model, there are 10 soil moisture states and 100 solum depth states corresponding to a beginning solum depth of 20 cm. The optimal flexcrop decision is found for each of the 1,000 possible states. The model could be extended from 20 cm of solum depth to 40 cm or more, but 20 cm is used in order to reduce the dimensionality of the problem. (The average solum depth for the sample was 38.27 cm or 15 inches.) This did not pose a problem since preliminary analysis indicated that the optimal decisions for these two values of solum depth are identical and the optimal expected net present values are less than $10 apart at a discount rate of 5%. For all of the scenarios, the optimal decision for each soil moisture state and two levels of solum depth (20 cm and 7 cm) are provided in the lower portion of table 3. The solum depth of 20 cm represents the optimal decision rule given that solum depth is not a constraint in the farmer's decision. This is the optimal profit-maximizing decision rule for producers who farm on deep soils. The other solum depth illustrates the case where a producer's soil has been eroded considerably.

As topsoil erodes, the profit-maximizing producer will switch his or her optimal policy. At lower solum depths, in order to conserve remaining soil, cropping is optimal at lower soil moisture levels and chem-fallow may be employed rather than tillage fallow. However, the solum depth level at which the first switch in strategy occurs, and the frequency of strategy switching, varies depending upon the particular scenario. For example, although not shown in table 3, the optimal decision rule first changes at 13.2 cm of solum for S3 (high rate of erosion) as opposed to 7.6 cm for S1 (low rate of erosion). A switch to a more soil-conserving strategy, one with more frequent cropping or greater use of chem-fallow, occurs because excessive erosion today lowers future profits enough to warrant a change in the optimal decision rule.

For low wheat prices of $2.50/bu. (scenarios S1–S4), the optimal decision at 20 cm of solum depth is to crop if soil moisture is greater than 7.5 cm and to fallow if it is less than or equal to 7.5 cm, and this is unaffected by changes in the discount rate.[9] As soil erodes, the optimal decision for low erosion rates (S1 and S2) does not change until solum depth is substantially reduced. The change in the optimal policy, if it occurs, is to crop if soil moisture is greater than 5.0 cm and to employ tillage fallow if it is less than or equal to 5.0 cm (S1). In contrast, with high erosion rates (S3 and S4), the optimal decision policy is more soil conserving. Chem-fallow replaces tillage fallow in the optimal policy at low levels of solum in order to conserve soil that is subject to rapid erosion. In other words, the results indicate that for erosive soils chem-fallow is a viable alternative to tillage fallow.

For higher wheat prices of $4.50/bu. (scenarios S5–S8), the optimal policy is more soil conserving at all solum depth levels; in particular, the land is cropped more intensively. For low rates of erosion (S5 and S6), the optimal decision rule at 20 cm of solum depth is to crop wheat if available soil moisture in the spring is greater than 5.0 cm and to fallow when it is less than or equal to 5.0 cm. Higher grain prices cause the profit-maximizing farmer to seed more often, thereby conserving soil. If solum depth is constraining, the optimal decision rule changes to chem-fallow if soil moisture is below 5.0 cm and if the discount rate is sufficiently low (S5).

Scenarios S7 and S8 provide optimal decision policies given highly erodible soil and high prices. The optimal decisions are identical to those for S5 and S6 at 20 cm of solum, but, as erosion takes place, switches in policy occur at higher levels of solum depth. At 7 cm of remaining topsoil, the optimal policy when erosion rates are high is to employ chem-fallow if soil moisture is below 2.5 cm. This illustrates the relative importance of the impact of current decisions on future returns. The greater the potential rate of erosion, the more costly it is to use agronomic practices which are erosive. When available spring soil moisture is between 2.5 and 5.0 cm and solum depth is 7 cm, the optimal decision is to employ chem-fallow at the higher discount rate (S8) but to plant wheat at the lower discount rate (S7).

Erosion Time Paths and the Value of Information

It is also possible to illustrate how soil is depleted over time for the various optimal flex-cropping strategies and for the study region's predominant fixed rotation, namely, a two-year, wheat-fallow rotation. This is an important component of the current study because we would like to know how soil is conserved under an optimal, flexible cropping strategy as opposed to the fixed rotation.

The time required to deplete 40 cm (15.8 in.) of solum to 4 cm (1.6 in.) is provided in the last row of table 3 for scenarios S1–S8.[10] The expected depletion times are determined from a Monte Carlo simulation using 30 experiments over a 400-year horizon. The simulations employ a random number generator to simulate changes in soil moisture from one year to the next using the results of (10); these randomly determined soil moisture levels then are used in conjunction with the optimal policies determined in the preceding section. Changes in solum depth are not stochastic within the simulation but are based on average soil loss due to a particular cropping decision. Although stochastic in the original model, us-

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[9] There is nothing in this model to prevent two fallow years in a row. In practice, this is unlikely to occur, although the current drought in the study region appears to be an exception. When it does occur, erosion at rates higher than those on which decisions are based would take place, and the model would underestimate the extent of erosion. While adding a state variable for the decision taken in the previous period would add considerably to the dimensions of the problem, Monte Carlo simulation indicated that the problem of fallowing in subsequent years was insignificant. At prices of $2.50/bu., double fallowing occurred approximately 4.5% of the time, while at prices of $4.50, it occurred in less than 1% of the simulations.

[10] It is assumed that erosion stops at 4 cm of solum depth, because below this level it is generally no longer profitable to crop, although exceptions occur. Land is assumed to be put into pasture or some other alternative use at this point.

ing the mean loss is asymptotically an equivalent procedure over the longer horizon. The same procedure is used to determine soil depletion over time for a fixed wheat-fallow rotation.

With erosion rates based on a 10–24% slope, a two-year, wheat-fallow rotation will erode 36 cm (14.2 in.) of soil in approximately 93 years. This figure highlights the seriousness of soil erosion on the prairies, but it also indicates that the problem is not as serious as suggested (but not detailed) in the Canadian studies cited above. The flexcrop strategy, given wheat prices of $2.50/bu., extends the erosion process by about 50%. If wheat prices are $4.50/bu. or higher, it takes over 180 years to erode 40 cm of topsoil to 4 cm. However, due to the higher price, it is still profitable to continue farming the land until there is only 1 cm of topsoil left. Consequently, higher commodity prices mean that the profit-maximizing farmer is able to conserve soil, but, in contrast, he will erode the soil to a lower depth than a farmer facing lower commodity prices.

The same basic results hold for the scenarios based on a slope grade of 0–3%. A fixed, wheat-fallow rotation erodes 36 cm of topsoil in less than 200 years. In contrast, an optimal flexcrop strategy at wheat prices of $2.50/bu. (S1) takes more than 280 years to erode the same amount of soil. If wheat prices are $4.50/bu. or higher (S5), the profit-maximizing farmer takes substantially more than 350 years to erode 36 cm of soil, at least a 75% improvement from a soil conservation point of view!

Finally, a simulation of 1,000 experiments of 30 years each is used to determine expected discounted net returns; the simulation assumes (*a*) a discount rate of 5%, (*b*) a high rate of soil erosion, (*c*) a beginning soil moisture of 11 cm (4.33 in.),[11] and (*d*) starting topsoil depths of 40 cm and 15 cm. Expected discounted net returns are found for the optimal flexcrop strategy and the fixed rotation under prices of $2.50/bu. and $4.50/bu. The results are reported in table 4. By comparing these results, it is possible to estimate the value of added information. This is the information about spring soil moisture and solum depth that is used in the flexcrop decision-making process but is not used in the fixed, wheat-fallow rotation. As reported in table 4, information about soil moisture and topsoil depth, if combined with an optimal flexcrop policy, is worth an average of $86.27/acre for low wheat prices and $314.32/acre for high prices when beginning topsoil depth is 40 cm. Information is worth $114.13/acre for low prices and $265.83/acre for high prices if starting solum depth is 15 cm.

These results provide an important contribution to the debate over the costs of soil erosion in Canada. PFRA estimates that the annual cost of soil erosion to prairie farmers in Canada is $239 million and that this primarily is due to the practice of tillage summerfallow.[12] There are approximately 74 million acres of cultivated land in the three prairie provinces, and about half of these are found in the dryland cropping regions (those where summerfallow predominates). If this area accounts for the entire $239-million cost of erosion, then the annual per-acre cost of erosion is $6.46 and the discounted cost over 30 years is $99.30/acre at a 5% rate of discount. Compare this to the aforementioned gain that can be realized by employing a flexcrop strategy based on information about spring soil moisture and topsoil depth. It would appear that a flexcrop strategy not only results in reduced erosion, but that the returns from such a strategy greatly exceed the reported losses due to erosion caused by current agronomic practices.

The Effect of the Discount Rate

Our earlier analysis suggests that a higher discount rate could result in conservation, contrary to what the resource economics literature indicates. Support for this hypothesis is provided upon comparing the erosion times for two scenarios (SL and SH). For both scenarios, a high rate of erosion and price of $3.50/bu. are assumed; for SL a discount rate of 0% is assumed, for SH a rate of 15% is used, representing a farmer with pressing financial obligations. At 20 cm of solum depth, the critical spring soil moisture values below which the

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[11] The initial soil moisture state had an appreciable effect upon the net discounted return. Since we are interested in making comparisons, it is important that each of the simulations start in the same state.

[12] PFRA makes no attempt to estimate the time required to erode the soil completely and actually uses a lower rate of erosion than that presented in our calculations. (In radio talk shows in Saskatchewan during the spring of 1988, Senator Sparrow indicated that current agronomic practices could completely erode the topsoil in less than 40 years.)

optimal decision is to tillage fallow and above which it is to plant wheat are 7.5 cm and 5.0 cm for SL and SH, respectively. The soil depletion time path for SL is more erosive than that of SH; policy SL causes 36 cm of solum to be eroded in 169 years, compared to 192 years for SH. Since the only difference between the two scenarios is the discount rate, this provides empirical evidence that, in some cases, a higher discount rate will lead to conservation rather than depletion. This result appears consistent with current farming practices in Saskatchewan. A farmer with a pressing short-term financial obligation likely has an unusually high discount rate because, if he or she is unable to meet commitments today, he or she will be out of the industry tomorrow. Farmers in this situation tend to crop more often than farmers who have no pressing short-term obligations, thereby conserving soil.

Table 4. Comparison of Expected Returns over 30-Year Period: Optimal Flexcrop Policy versus Fixed Rotation

Scenario	Discounted Expected Net Return	Value of Information
	$/acre	
Price = $2.50/bu.	Topsoil Depth = 40 cm	
Flexcrop Policy	231.31	
Fixed Rotation	145.04	86.27
Price = $4.50/bu.		
Flexcrop Policy	865.48	
Fixed Rotation	551.16	314.32
Price = $2.50/bu.	Topsoil Depth = 15 cm	
Flexcrop Policy	217.65	
Fixed Rotation	103.52	114.13
Price = $4.50/bu.		
Flexcrop Policy	783.08	
Fixed Rotation	517.25	265.83

Conclusions

Compared to prevailing fixed crop rotations, flexible cropping of spring wheat can be used to reduce the rate of soil erosion in dryland cropping regions of the northern Great Plains. Based on our results, several conclusions emerge:

(*a*) Flexible cropping increases expected net discounted returns and substantially reduces soil erosion compared to the predominant fixed crop rotation in the dryland cropping region.

(*b*) However, this does not guarantee that farmers will adopt flexcropping as an agronomic practice even if there is no obstacle (e.g., measurement problem) to its implementation. The reason is likely due to the variance of returns and risk attitudes, an issue not addressed in this study. However, if society desires to reduce erosion, it may be possible to alleviate variability in net returns by providing a form of government-funded crop insurance to those farmers who employ a flexcrop strategy.

(*c*) Higher crop prices lead to more intensive cropping and, hence, to greater soil conservation.

(*d*) Further, higher prices may result in greater use of chem-fallow as opposed to tillage fallow as a soil conservation practice. However, upon comparing the various policies in greater detail, some contradictory evidence to this conclusion was found. For example, the results indicate that, for scenarios S3 and S7, at $2.50 wheat prices chem-fallow is implemented at a higher solum depth than at $4.50 wheat prices (13.2 cm of soil compared to 12.6 cm). Therefore, higher wheat prices may make chem-fallow a more affordable agronomic practice but not necessarily a more profitable one.

(*e*) In addition, even where chem-fallow is a viable alternative to tillage fallow, this appears to be true only when topsoil already has been eroded substantially.

(*f*) Finally, higher discount rates could lead to greater soil conservation contrary to the simple comparative static result associated with Hotelling. Unlike Farzin, this result does not depend upon the disinvestment effect. However, this is due to the peculiar nature of the exploitation process studied here: the more intensively one crops, the greater the level of soil conservation.

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