The Economics of Erosion and Sustainable Practices: The Case of the Saint-Esprit Watershed

Jean-Christophe Dissart, Laurie Baker and Paul J. Thomassin

Master's student, assistant professor and associate professor, respectively, Department of Agricultural Economics, McGill University, Montréal, Québec.

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This paper examines the economics of the adoption of sustainable production practices for soil erosion control. The research was conducted on three case farms within the Saint-Esprit watershed in Quebec using a two-stage process. The first stage involved the use of GIS (Geographical Information Systems) to record erosion characteristics (slope, etc.) for these farmers' fields. This erosion information was then included as input information in the second stage of the process. Mixed integer linear programming (MILP) was used to model both individual farms and the watershed. Increasing erosion constraints were applied to these models to investigate changes in crop production mixes for farms and the watershed. A comparison of the results (farms versus watershed) was used to investigate policy questions concerning an optimal erosion constraint for society. Results generated indicate that farms with higher net incomes would be advantaged by erosion constraints set at the watershed level, whereas farms with lower net revenues would be disadvantaged. Thus, trading of pollution permits could be encouraged.

Cet article examine les aspects économiques de l'adoption de pratiques de production durables visant à réduire l'érosion du sol. La recherche fut effectuée sur trois fermes situées dans le bassin du Saint-Esprit au Québec, et impliqua un processus à deux étapes. Le premier étape consiste en l'utilisation du système d'informations géographiques « SIG » afin de noter les caractéristiques de l'érosion (pente, etc.) dans ces champs agricoles. Ces renseignements servirent de données au sein du deuxième étape. La méthode de programmation linéaire à nombres entiers mixtes fut employée afin de modéliser les fermes individuelles, ainsi que le bassin. Ensuite, les contraintes d'érosion furent appliquées sur ces modèles de manière croissante, et ce afin d'étudier les changements dans le mélange des productions de cultures pour les fermes et le bassin. Une comparaison des résultats (fermes vs. bassin) fut accomplie pour examiner les questions de politiques pouvant mener à une contrainte d'érosion optimale pour la société. Les résultats obtenus démontrent que les fermes ayant des revenus nets élevés seraient avantagées par des contraintes d'érosion établies au niveau du bassin, tandis que les fermes aux revenus nets plus bas en seraient désavantagées. En conséquence, l'échange de permis de pollution est recommandé.

INTRODUCTION

Public concern over agriculture's effect on soil and water resources has created a need to develop relevant agricultural policies. Policy revisions should recognize both the impacts of agricultural practices on the environment and the economic consequences to the farm of adopting practices that are more compatible with resource protection. Although there is wide disagreement over whether sustainable agriculture is more profitable than conventional agriculture, there is anecdotal evidence of successful alternative farming systems (Batie and Taylor 1989). However, such evidence is not usually sufficiently rigorous to be used for policy development or legislative purposes, nor does it tend to incite the farming community at large to adopt sustainable alternatives independently of policy or legislation. It is also difficult to generalize results from one site or region because differences in factors such as type of crop, soil, weather, topography and others can significantly influence profitability at the individual farm and larger scale levels, as well as the susceptibility of the resources to degradation.

In this context, case studies based on individual farms and watersheds may provide information for analysis at a scale relevant to regional policy development. This paper presents the economic evaluation of a pilot project to reduce soil erosion and improve water quality at the outlet of the Ruisseau Saint-Esprit watershed in Quebec, Canada. The pilot project was requested of the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) by the Saint-Jacques-de-Montcalm agricultural society. The scientific partner was McGill University. The project included technical assistance to 29 of the 52 farmers that had agreed to implement sustainable farming practices. This accounted for approximately 90% of the agricultural area of the watershed. Sustainable practices included reduction of fertilizer applications in corn production, reduced tillage and green manuring for other crop productions. Base data included water contamination indicators and sedimentation at the watershed outlet, as well as farm input and output data. The objective of the economic component of the project was to assess the costs to individual farm enterprises and to the watershed as a whole, of implementing soil and water conservation strategies. The analyses reported in this paper were based on a mixed linear programming (MILP) model, and involved an erosion constraint using erosion estimates derived from the Universal Soil Loss Equation for Application in Canada (RUSLEFAC) applied to base data obtained from a Geographical Information System (GIS).

BACKGROUND

The profitability of sustainable versus conventional farming is often a contentious issue. Individual profitability may result from good management as well as employing fewer purchased inputs. Disparities may result from on- farm unmeasured benefits such as less vulnerability to drought, nutrient conservation and better seasonal distribution of inputs (Batie and Taylor 1989). Other reasons range from the definition of sustainable agriculture to the assumptions regarding agricultural subsidies and price differentials, the scale of application, the importance of the farmer's management ability and the viewpoint from which the economic comparison is made (society, farmers or future generations). Finally, most economic studies of crop production focus exclusively on profitability and neither incorporate environmental criteria nor the dynamic characteristics inherent in alternative systems (Roberts and Swinton 1996). One exception is the paper by Turvey and Weersink (1991), which explicitly incorporated an erosion constraint.

Hession and Shanholtz (1988) used a pollution density index derived from the USLE (Universal Soil Loss Equation) with a GIS to estimate potential sediment loading to streams from agricultural land. More recent models have tended to provide a better integration of economic and environmental dimensions of water quality management (Bockstael et al 1995; Prato and Wu 1995). This paper combines GIS and optimizing techniques to develop farm-level and watershed models that can provide insight into distributional questions of erosion control.

CHOICE OF REPRESENTATIVE FARMS

A two-stage process was used to select the farms to be included in the model. Initially, seven farmers were selected from the 29 participating farmers. This group was reduced to three after application of the following criteria:

Table 1. Data input on farm size, number of fields, crop net incomes and animal nutrient requirements for sample farms A, B and C

	Farm A	Farm B	Farm C
Hectares (ha)	47.77	30.26	119.13
Number of fields	15	8	16
Conventional barley ($/ha)	105,24	—	—
Green manure barley ($/ha)	85.61	—	—
Plowed corn ($/ha)	—	843.65	1,109.89
Reduced-till corn ($/ha)	633.77	840.84	
No-till corn ($/ha)	600.32	—	1,042.10
Plowed soybeans ($/ha)	—	311.21	694.14
No-till soybeans ($/ha)	—	173.65	543.58
Hay ($/ha)	100.76	100.76	100.76
Animal production	dairy	swine	poultry
Estimated nutrients[a]	DMI, TDN, NEM, NEG, NEL, ME, DE, CP	ME, DE, CP	ME_n, CP

[a]DMI = dry matter intake; TDN = total digestible nutrients; NEM = net energy for maintenance; NEG = net energy for body gain; NEL = net energy for lactation; ME = metabolizable energy; DE = digestible energy; CP = crude protein; ME_n = nitrogen-corrected metabolizable energy.

- the reliability of the available economic data
- the crops grown and the sustainable practices used
- the type of animal husbandry employed
- farm size
- erosion values relative to the rest of the watershed.

Each farm grew corn (conventional and alternative), which is the predominant crop in the Saint-Esprit area and provides the highest net income. Each farm was also allowed to grow hay (alfalfa) because it is efficient in abating erosion. The remaining crops (conventional and alternative) were selected according to animal nutrient requirements. Data input on farming practices, number of fields, farm size and net incomes are listed in Table 1 for the three farms.

Each of the tested alternative farming practices was designed to reduce soil erosion. One can distinguish two types of practice: reduced-till or no-till and green manure. Reduced-till and no-till leave more than 30% of residues on the topsoil after preparation of the seedbed, and thus reduce erosion. This objective is reached with most tillage practices except plowing. Green manuring, the practice of plowing down a growing crop, provides organic fertilizer and reduces the risk of erosion by providing more organic matter to the soil.

THE MODEL

A programming model was chosen to compare the impacts of erosion abatement practices on the profitability of individual farms with that of the whole watershed. The objective of this model is to maximize the sum of field net incomes, derived from crop budgets, subject to three types of constraints:

- singleness of field use
- animal nutrient requirements
- erosion.

Given the interest in singleness of field use, it was decided that a MILP model run on LINGO[1] would be most suitable for this analysis.

Farmers may purchase nutrients from the Rest of the World (ROW) to satisfy animal needs. Inputs are purchased from ROW at the same price used to estimate income in crop budgets. Since soybeans are fed to animals as soybean meal, the extrusion cost was added to the purchase price. No constraint was imposed on what crops should be grown. An erosion constraint was applied at the farm and watershed levels to permit comparison of its economic impact at these levels and to study distributional effects between producers. One model was built for each of three farms (Farms A, B and C), and a fourth to represent the watershed was defined as the summation of the three others.[2] The four models were built using the same types of constraints, decision variables and coefficients.

The model used crop budgets and erosion data obtained and/or calculated at the field level, respecting proprietary boundaries and the cropping plans of the farmers. The unit of analysis replicating the real world in the model[3] was therefore single fields. This is why MILP was used.

The following assumptions were explicitly made:

- the crops grown are used on-farm and are grown to satisfy animal nutrient requirements, unless the particular crop cannot be fed to an animal (i.e., hay to swine and poultry, or sold to ROW)
- prices remain constant throughout the year both for product sales and purchased inputs
- the three farms are assumed to be representative of the Saint-Esprit watershed as a whole[4]
- the watershed is the sum of the three farms in all respects
- no new technologies are used on these farms
- transportation costs are not explicitly included because exchanges with ROW are extremely limited.

MATHEMATICAL MODEL

The **objective function** is written as follows:

$$\text{Max } \Sigma\, aX_{ijk} - \Sigma\, eZR_{ip} \qquad (1)$$

where:
X = a field activity (0/1 variable)
a = the field level net income ($)
i = the farm code
j = the field number
k = the crop/practice code
ZR = crop p sold by ROW (rest of the world) to farm i (real variable)
p = the crop code
e = the purchased input price ($/t).

Constraints

There are three sets of constraints. The first set forces the model to choose only **one use out of five for a given field**. There are as many constraints of this type as there are fields for a given farm model (i.e., 15 for model A, 8 for model B, 16 for model C and 39 for the watershed model). This is summarized mathematically as follows:

$$\Sigma X_k = 1 \text{ for given } i \text{ and } j \tag{2}$$

where:
X = a field activity (0/1)
i = the farm code
j = the field number
k = the crop/practice code.

The second set of constraints forces the model to satisfy **animal nutrient requirements**. These constraints account for the nutrients provided by crops grown on-farm and by purchased inputs from ROW. The number of constraints of this type depends on the type of animal production. There are 10 constraints of this type for model A, 5 for model B, 4 for model C and 19 for the watershed model. This may be mathematically summarized as follows:

$$\Sigma b_m X_{ijk} + \Sigma d_m ZR_{ip} \geq B_m \tag{3}$$

where:
X = a field activity (0/1)
i = the farm code
j = the field number
k = the crop/practice code
b_m = the field contribution to satisfying animal needs in nutrient m
ZR = crop 1 sold by ROW to farm i (real)
p = the crop code
d_m = the crop contribution to satisfying animal needs in nutrient m
B_m = the animal nutrient requirement in element m.

The third set of constraints forces the model to satisfy the **erosion constraint**. There is only one constraint of this type for a given model, including the watershed model. This may be mathematically summarized as follows:

$$\Sigma gX_{ijk} \leq C \tag{4}$$

where:
X = a field activity (0/1)
i = the farm code
j = the field number
k = the crop/practice code
g = the field contribution to erosion
C = the erosion target.

It should be noted that the models focus on erosion control assuming the number and species of animal produced on each farm remain unchanged. This again identifies the models as being short-run in nature.

DATA AND METHODS

Crop Budgets

Economic data were collected at the farm level for the year 1995, at which time the farmers had begun on-farm trials of alternative practices. Budgets were created using additional data from MAPAQ and assuming constant returns to scale. Additional information on the agricultural situation within the watershed was also obtained from project reports. When relevant costs had been omitted from the producer's budgets, they were estimated from secondary sources, e.g., Comité de Références Économiques en Agriculture du Québec (CREAQ 1996, 1994a, 1994b, 1991) budgets. Crops used on the farm were attributed a value equal to the selling price to ROW. When yields from conventional and alternative farming practices were not available for a given crop, they were assumed to be the same. Thus, the conventional and alternative approaches could sometimes be compared only on the basis of costs. Income from Assurance Stabilisation du Revenu Agricole (ASRA, government revenue insurance program) was not taken into account.

Crop operation costs were split into labor and fuel costs. Farmers were asked to record the time taken to perform each crop operation and to note which tractor was used for that operation, in order to permit inference of labor and fuel costs. Since most alternative farming practices required special equipment, fixed costs were calculated using a machinery inventory that recorded the purchase date and value. Although some machinery purchases were subsidized by the project, those items were recorded at their market price in the crop budgets to eliminate bias.[5]

Animal Nutrient Requirements Data

Animal nutrient requirements were estimated from three sources:

- herd inventories for Farms A, B and C
- Comité de Références Économiques en Agriculture du Québec (CREAQ) data
- National Research Council (NRC) data.

Inventories provided data on animal species for a given herd and for the year 1995. "Life cycles" were derived for the year 1995; that is, the different phases that a given animal species would go through for that year. Nutrient requirements were then estimated for each animal species and, consequently, for the whole herd. It should be understood that these estimates were sometimes based on diets and dietary energy concentrations provided by NRC. Since crops grown by selected farmers may not be exactly the same, it is acknowledged that values generated in this fashion may be different from those actually required. However, as stated by NRC (1994, 61): "From a nutritional point of view, there is no 'best' diet formula in terms of ingredients that are used. Ingredients should, therefore, be selected on the basis of availability, price and the quality of the nutrients they contain."

In 1995, Farm A was predominantly a dairy farm (48 cows and 30 heifers), Farm B was predominantly in swine production (12 gilts, 135 sows, 2,686 piglets and three adult boars) and Farm C specialized in poultry production (25,530 immature chickens and 25,030 laying hens). Nutrient requirements for these animal productions are listed in Table 1. The farmers bought pre-mixed feeds from ROW to satisfy requirements in macro-minerals. It was decided not to account for these elements explicitly because no data were available on the ability of the farms to satisfy these requirements themselves. NRC data (1994, 1988a, 1988b) were used to estimate the nutritional value of the crops grown by Farms A, B and C.

Erosion Data

Erosion is defined as the movement of soil by water, wind and gravity. It occurs in all regions of Canada under a wide range of land uses and creates problems on and off the farm (Wall et al 1997). The on-farm impact of topsoil loss is long-term loss of productivity. Off-farm impacts include: sediment deposits, bacteria from organic matter, nutrients and pesticides in surface water. This has a negative impact on water quality and an economic consequence on surface water use (Wall et al 1997). Quantitative methods to predict erosion have not been developed for specific Canadian conditions; however, the Universal Soil Loss Equation (USLE) is a field scale model developed in the United States. There has been limited use of USLE in Canada because the information required to determine soil erosion rates has not been available (Wall et al 1997). The Revised USLE (RUSLE) was developed for interim use until the development of a new generation of soil erosion process models. The RUSLE For Application in Canada (RUSLEFAC) has been prepared to provide information pertinent to Canadian conditions.

The purpose of the RUSLEFAC is “to predict the long-term average annual rate of soil erosion for various land management practices in association with an area’s rainfall pattern, specified soil type and topography” (Wall et al 1997, 1.4). “There are several general conditions, unique to any site, which affect erosion by water. These are: climate; soil; topography; vegetation or crop; land use practices. Each of the conditions is represented by a different factor in the USLE or RUSLE” (Wall et al 1997, 1.5), as follows:

$$A = R * K * L * S * C * P \tag{5}$$

where:
A = the estimated potential long-term average annual soil loss (t/ha) per year
R = the rainfall and runoff erositivity factor (MJ.mm/ha/h)[6]
K = the soil erodibility factor (t.h/MJ/mm)
L, S = the slope length (in metres) and steepness (dimentionless) factors
C = the cropping-management factor[7] (dimensionless)
P = the support practice factor[8] (dimensionless).

Erosion values were calculated by a two-stage process tied to the selection of watershed farmers (Figure 1). Differences between the two sets of erosion values were limited to the L and S factors only. The first set was calculated using the proposed RUSLEFAC table. Results showed that the three selected farms were representative of the watershed in terms of erosion. The analysis also showed that the L and S factor values were biased due to field shapes (long and narrow) and lengths often exceeding the maximum applicable in the formula.[9] A modified RUSELFAC method was therefore used to obtain more accurate L and S factors for the three farms.

Data needed to calculate the two sets of erosion values were extracted from a SPANS/GIS database that was developed for the Saint-Esprit watershed project (Mousavizadeh et al 1995). Data layers include public domain and site-specific information. The public domain information consists of cadaster, hydrography, watershed boundary, road, land use, soil information, elevation points and topographic contour lines, slope and land ownership. The site-specific information includes farm plans, soil fertility, fertilizer, manure and pesticide applications and crop yield data. A specific data set was generated[10] from this database to calculate the erosion factors. A basemap of the watershed was created, featuring areas of the watershed with the fol-

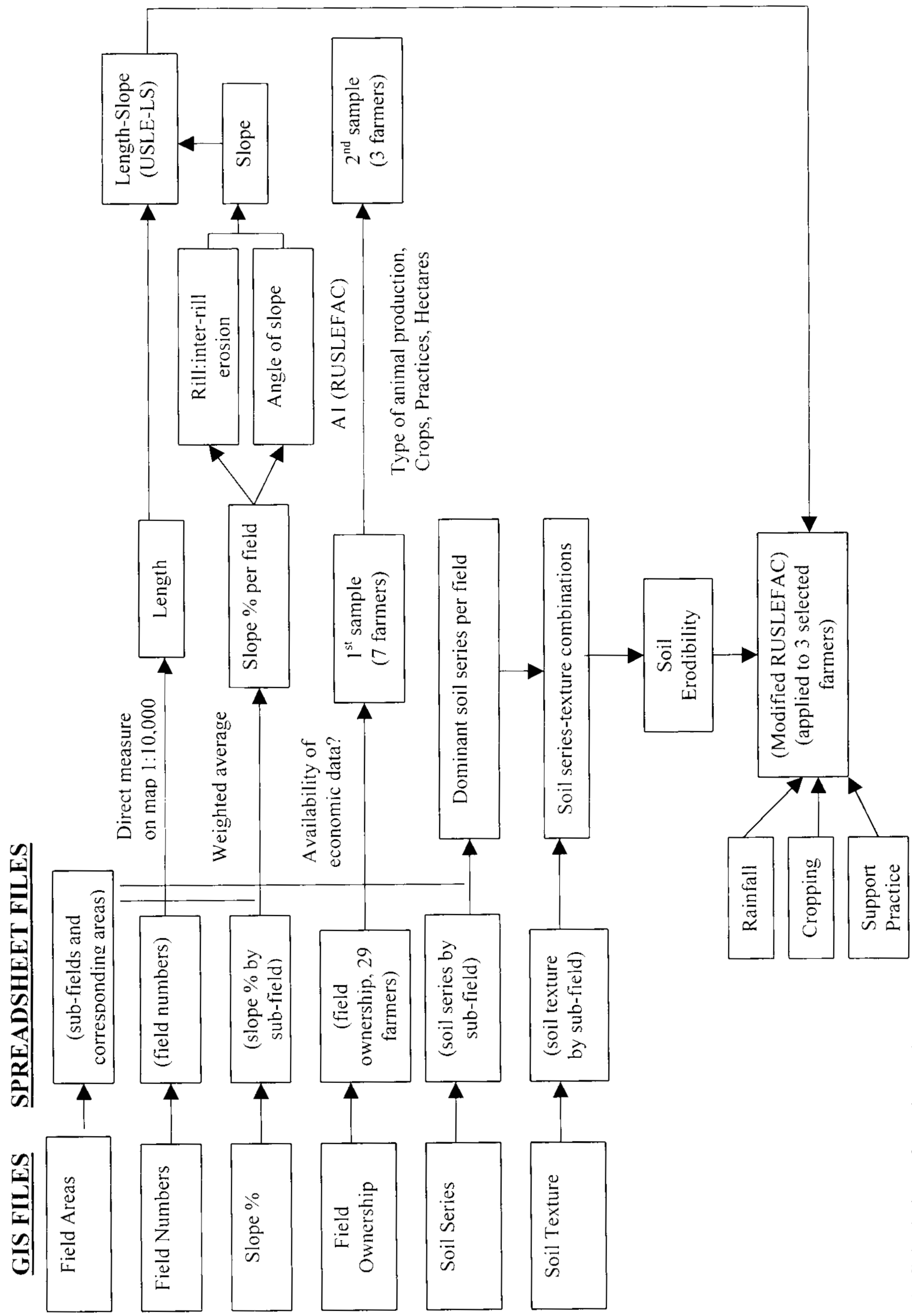


Figure 1. Calculation of erosion values

lowing land uses: grains, vegetables and hay. Other land uses (e.g., forest, residential, pasture and any other unspecified use) were removed. The following data were made available by overlaying on a sub-field basis: slope percentage, soil texture, soil series, area, field number and ownership. The tabular data were exported into a spreadsheet format and recombined for each field.

The *R* factor was determined by locating the area of interest on the isoerodent map indicating annual *R* values for Ontario and Quebec (Wall et al 1997). Since the *K* factor represents the inherent erodibility of a soil type, a separate K value was determined for the "predominant" soil series and soil texture for each field on the basis of sub-area field size in the map unit. Soil erodibility values for common surface textures were used (Wall et al 1997) because information was limited for this watershed. Generalized *C* values for Quebec were used (Wall et al 1997) according to farmers' crops and tillage practices. The *P* factor reflects the erosion control effectiveness of support practices, such as cross slope cultivation, contour farming, strip cropping and terracing, used to reduce the amount and rate of runoff water (Wall et al 1997). Since none of these support practices was used in the watershed, *P* was set equal to 1 in the RUSLEFAC.

For moderately consolidated soil conditions, including row-cropped agricultural land, with little to moderate cover and where rill and inter-rill erosion processes are of similar importance, Wall et al (1997) recommended that a table giving *L* and *S* factors as a function of slope length and slope percentage be used. The majority of the fields in the area are long and narrow in the direction perpendicular to streams (see note 9). The slope length of each individual field on farms A to C was measured manually on the cadastral map (1:10,000). A second set of more precise *L* and *S* factor values was obtained from the original USLE equation for a uniform slope, which is based on the slope length of the site, the angle of the slope and a coefficient related to the ratio of rill to inter-rill erosion describing the nature of the erosion process (Wall et al 1997).

The modified RUSLEFAC calculations showed that Farms A, B and C were representative of the rest of the watershed in terms of percentages of fields in a given erosion class. Modified RUSLEFAC calculations for Farms A, B and C yielded the following estimates of the average erosion value per hectare weighted by field area using corn grain with conventional tillage for comparison: 4.36 t/ha/y for Farm A, 4.11 t/ha/y for Farm B and 4.40 t/ha/y for Farm C. These values fell in the very low erosion class (< 6 t/ha/y), and soils in this class had very slight to no erosion potential (Wall et al 1997). However, some individual fields had erosion values in the low (6–11 t/ha/y, about 17%) to moderate (11–22 t/ha/y, about 2%) erosion classes. Nevertheless, long-term productivity should be sustainable if average management practices are used.

RESULTS AND POLICY IMPLICATIONS

The four models described in the previous section were run with two erosion scenarios:

- base case with no erosion constraint
- a series of estimates with increasing erosion constraints.

The farm and watershed models were run 20 times, using erosion values ranging from the lowest to the highest per hectare in increments of 250 kg/ha. The lowest erosion value per hectare for a given farm was reached when the cropping plan was 100% hay. The cost of complying with the erosion constraint was estimated through changes in net income (the objective function value).

Choice variables of interest for the analysis were: erosion per hectare, net income per hectare, conventional corn hectares (on plowed land), corn hectares produced using alternative cultivation techniques and hay hectares. Barley was not used at all because it is a supplier of energy like corn, but provides much lower net incomes for both the conventional and the alternative practices. Soybean was rarely used because it is usually cheaper to buy soybean/protein from ROW rather than cultivate it. This held as long as access to higher net income corn was possible. Percentages of hectares in conventional corn, alternative corn and hay were calculated for each farm and the watershed in total. The following relationships were analyzed: net income as a function of erosion, corn and hay hectares as a function of erosion, and the difference in net income between farm and watershed levels. Finally, results obtained from simulations of the watershed model were decomposed and recomposed for each farm. It was therefore possible to study what happens at the farm level when the erosion target value is set at the watershed level.

Base Case — No Erosion Constraint

The binding constraint in each of the four models was the crude protein requirement. Erosion was calculated by subtracting the slack value of the constraint from its right-hand side. In the base case scenario, Farm C had the highest net income ($1,086/ha) and the highest erosion value (4,751 kg/ha). Farm B values were $700/ha and 4,272 kg/ha, while Farm A had the lowest income and lowest erosion ($495/ha and 3,806 kg/ha). For the watershed, the model yielded the following results: $883/ha and 4,448 kg/ha. Conventional corn (i.e., corn on plowed land for Farms B and C and reduced-till corn for Farm A) was selected on 100% of the farm hectares for Farms A and B and 94% of Farm C's hectares.

Objective Function Value as a Function of Erosion

The relationship between net income per hectare and soil erosion value per hectare for the three individual farm models and for the watershed model is shown in Figure 2. Note that the shapes of the curves are similar. They are fairly straight up to 2,000 kg/ha and then fall rapidly. The watershed curve is closer to that for Farm C. This is due to the greater weight in terms of land area for Farm C (60% of the watershed hectares). The watershed curve intersects that of Farm C at a soil erosion value of 1,250 kg/ha. Farm A's curve does not fall as quickly as the others because it has the lowest erosion values per hectare, and the erosion constraint is not binding for soil erosion values less than 3,806 kg/ha. Also, Farm A has the smallest difference between conventional corn and hay net incomes ($533/ha versus $743/ha for Farm B and $1,009/ha for Farm C). As a consequence, Farm A's net income per hectare cannot fall as dramatically as it does for the two other farms when conventional corn is gradually replaced with lower net income crops.

It was proposed that increasing the erosion constraint would reduce the amount of erosion generated from agricultural production. As can be seen in Table 2, the farm operations in the watershed could adjust their production decisions to satisfy a policy objective of decreasing the amount of soil erosion in the watershed. Table 2 shows the estimated decrease in profits for the erosion constraint analyzed. For example, for an erosion target of 3,250 kg/ha, (i.e., a reduction in soil loss of 1,501 kg/ha from the baseline solution), the costs are $9/ha to Farm A, $123/ha to Farm B and $31/ha to Farm C and $23/ha to the watershed as a whole. Net income becomes negative for erosion values of less than 500 kg/ha, as seen in Figure 2

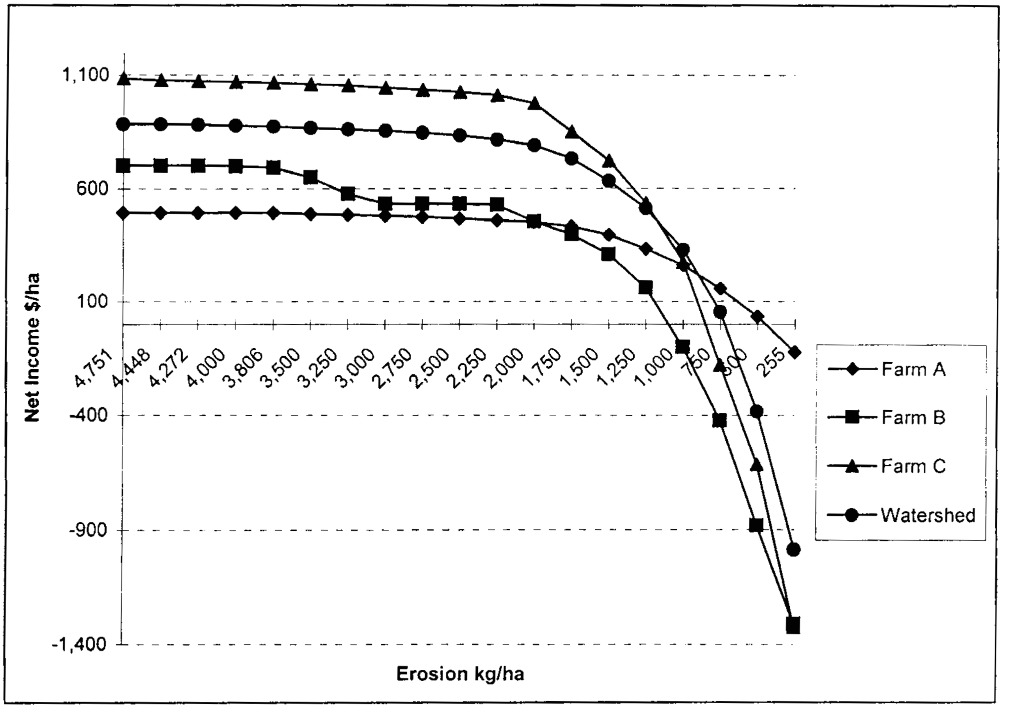


Figure 2. Net income as a function of erosion

(explanation provided in the next section). Finally, Figure 2 shows that net income curves become steeper as the erosion constraint increases, indicating that the marginal cost of complying with the environmental constraint increases. The explanation for this increase is the substitution of alternative corn with hay. Hay is the only crop that can satisfy an increasingly severe erosion constraint but this results in the lowest net income per hectare. Furthermore, more animal inputs must be purchased from ROW to fulfil energy and protein needs if hay replaces corn, thus further reducing net income.

Cropping Patterns as a Function of Erosion

Figure 3 shows the relationship between the percentage of hectares in conventional corn, alternative corn and hay and erosion for the watershed. It is possible to distinguish two phases in the cropping pattern evolution as the erosion constraint increases. In the first phase, the proportion of total hectares in conventional corn decreases continuously to zero from about 100%, the proportion of total hectares in alternative corn increases continuously from zero to about 100%, and the proportion of total hectares in hay is constant and equal to zero. In the second phase, the proportion of total hectares in conventional corn is constant and equal to zero, the proportion of total hectares in alternative corn decreases continuously from about 100% to zero, and the proportion of total hectares in hay increases continuously from zero to 100%.

Table 2. Costs for farms of reducing erosion, farm and watershed levels[a]

Erosion	Lost profits A FAM[b]	Lost profits A WM[c]	Lost profits B FBM[b]	Lost profits B WM	Lost profits C FCM[b]	Lost profits C WM	Lost profits FABCM[d]	Lost profits ABC, WM[e]
(kg/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)	($/ha)
4751	0	0	0	0	0	0	0	0
4272	0	9	0	2	12	0	7	2
3806	0	13	8	3	19	12	12	11
3250	9	16	123	4	31	31	40	23
2750	18	33	167	6	50	50	60	39
2250	33	61	171	15	75	85	80	68
1750	61	189	301	254	236	111	204	152
1250	163	471	539	399	548	320	453	369
750	338	616	1122	930	1263	887	1017	828
255	616	616	2010	2010	2409	2335	1913	1869
238	616	616	2010	2010	n.f.[f]	n.f.	n.f.	n.f.

[a]For reasons of conciseness, only half of scenario results are shown.
[b]FAM = Farm A Model; FBM = Farm B Model; FCM = Farm C Model; erosion target value set at the farm level.
[c]WM = Watershed Model; erosion target value set at the watershed level.
[d]Weighted average of lost profits per hectare for Farms A, B, C. Values obtained from Farm A Model, Farm B Model and Farm C Model.
[e]Weighted average of lost profits per hectare for Farms A, B, C. Values obtained from the Watershed Model.
[f]n.f. = not feasible. The erosion constraint cannot be satisfied even with 100% of the land being allocated to hay (the crop with lowest erosion value).

The explanation for this change in cropping patterns is as follows. Conventional corn is chosen in the first phase because it provides the highest net income. Alternative corn gradually replaces it because it provides the second highest net income while abating soil loss to a certain extent. Hay is not used because it has the lowest net income. The erosion constraint is not large enough during this phase to force hay into the solution. In the second phase, alternative corn is gradually replaced by hay to satisfy the increasing erosion constraint. At this point, most if not all animal nutrients are purchased from ROW. In this situation, net incomes from crop production are decreasing and the costs of purchased inputs are increasing. This results in a negative net income for the highest erosion constraints.

Watershed versus Farm Scale

Results from the watershed model were decomposed and recomposed at the farm level in terms of net income, erosion and cropping patterns. This was done to assess the consequences of imposing target values for erosion at the farm and watershed levels. Figure 4 shows the difference in net income per hectare for each farm when the erosion target value is set at:

- the watershed level
- at the farm level.

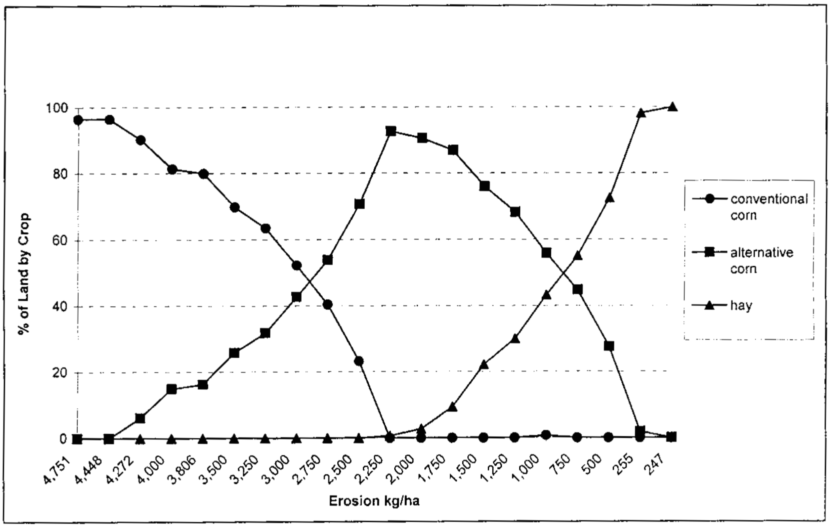
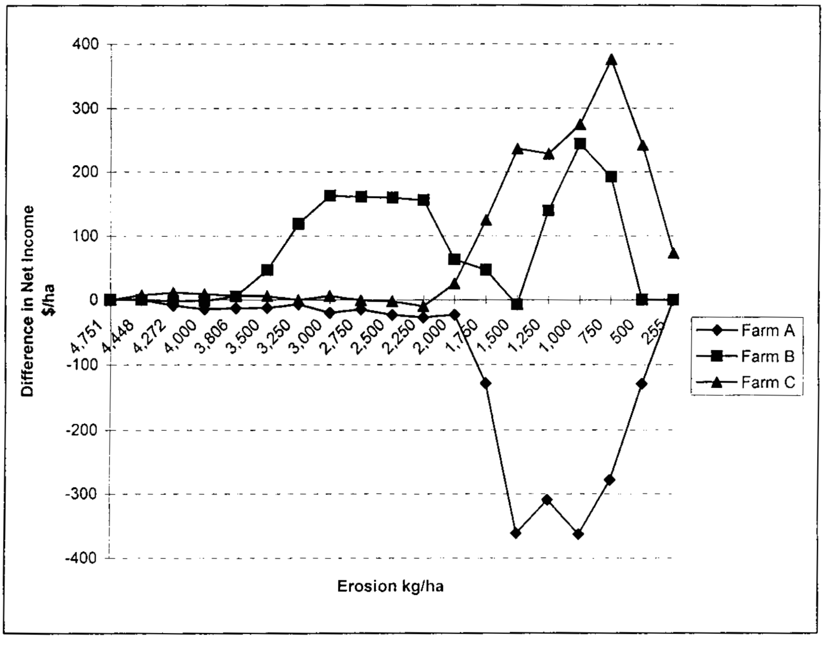


Figure 3. Watershed: Corn and hay hectares as a function of erosion



Net income/ha values obtained from the Watershed Model (WM) simulations minus net income/ha values obtained from the Farm Model simulations.

Figure 4. Farms A, B and C: Difference in net income per hectare of watershed model versus individual farm models

Three regions can be distinguished. In the first region — 4,751 kg/ha (i.e., maximum erosion for Farm C) to 3,806 kg/ha (i.e., maximum erosion for Farm A) — there is no major effect of setting the target erosion at the watershed level. This is evidenced by the fact that the curves stay close to zero. The second region stretches from 3,806 kg/ha to 2,000 kg/ha. Here, Farm B's net income is higher with an erosion target value set at the watershed level (the curve is above the zero line). In the third region (2,000 kg/ha to 255 kg/ha; i.e., minimum erosion for Farm C), Farms B and C are better off with the erosion target value set at the watershed level, whereas Farm A is worse off.

If the difference between the watershed and the individual farm model solutions were plotted against the percentage of hectares of crops other than hay, the curves would mimic those in Figure 4. The decision on where to grow hay in the whole watershed drives the observed differences in net income per hectare. The watershed model results in a higher percentage of area cropped to hay in Farm A than does the single model for Farm A. The explanation is as follows.

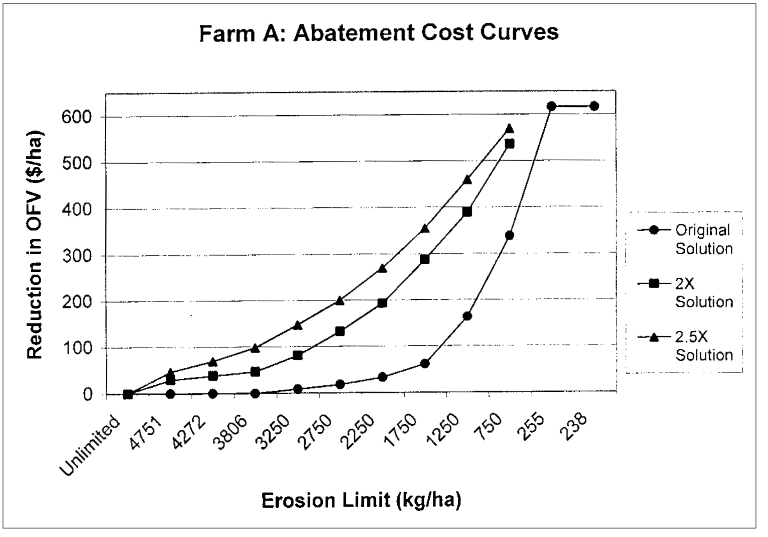
Net incomes from conventional or alternative corn production increase from Farm A to Farm C. For Farm A, net income for conventional and alternative corn is \$600/ha and \$634/ha, respectively. Net incomes for Farm B are \$840/ha and \$844/ha, whereas they are \$1,042/ha and \$1,110/ha for Farm C. The average difference between the watershed and the individual farm net income per hectare also increases from Farm A to Farm C: –\$91/ha for Farm A, \$78/ha for Farm B and \$85/ha for Farm C. Since the watershed model maximizes the sum of Farms A, B, C net incomes, it first chooses to grow conventional corn on each farm. The model then decides where to grow alternative corn or hay to satisfy the increasing erosion constraint. The choice is clearly to do that where conventional corn net incomes are lower, thus minimizing the economic loss of the watershed as a whole. Thus, in a watershed with an implemented erosion reduction policy and reasonably homogeneous susceptibility to erosion, farms with higher net incomes will be better off if the erosion target value is set at the watershed level, while farms with lower net incomes will be worse off.

Sensitivity Analysis

Figures 5, 6, 7 and 8 illustrate the impact of increasing the field level erosion values on the objective function value (OFV) for the three farm models and the watershed model. The figures show the abatement cost curve for the original solution for each model. This curve is derived by solving the appropriate model for each erosion threshold. As the erosion threshold is decreased, greater efforts must be made to apply abatement measures by the producer. The erosion values per field reflect the results of solving the RUSLEFAC model for each field. Thus, the appropriate slope and length of each field was taken into account along with the prevailing soil type for the field in question.

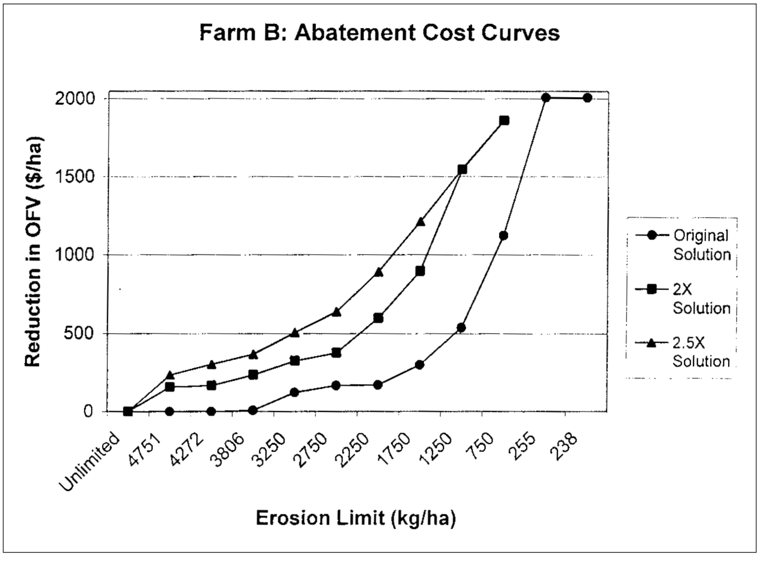
The abatement cost curves identified in these figures as 2X Solution and 2.5X Solution were derived as follows. The base case field level erosion values were increased by a factor of 2 (and then by a factor of 2.5) to approximate different slope, length and soil type scenarios. The models were then run again using these new erosion estimates to produce data for these figures.

The models are quite responsive to changes in the RUSLEFAC erosion values set at the field level. Figure 5 indicates that the original solution resulted in a reduction of \$33/ha in the OFV of Farm A for an erosion constraint of 2250 kg/ha. When the field erosion values were



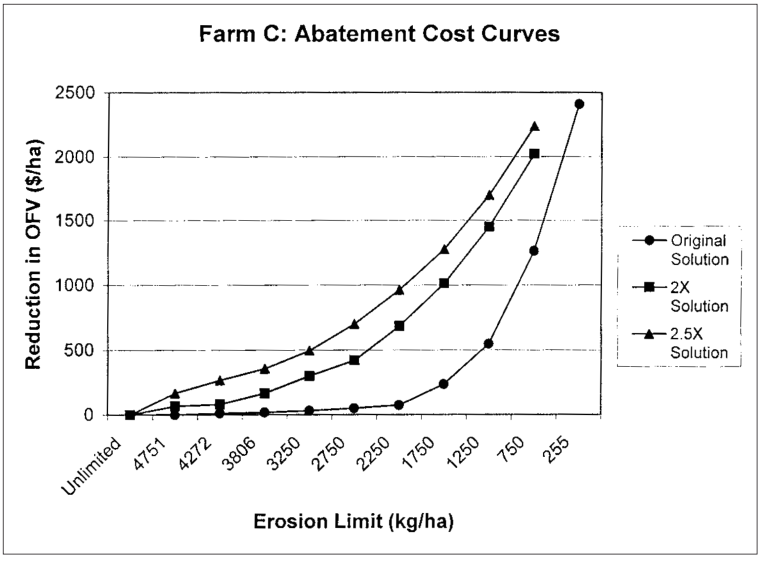
NB: Neither the 2X nor the 2.5X solution shows any reduction of OFV for erosion limits less than 750 kg/ha. With erosion limits less than 750 kg/ha the solutions were infeasible.

Figure 5. Abatement cost curves for Farm A



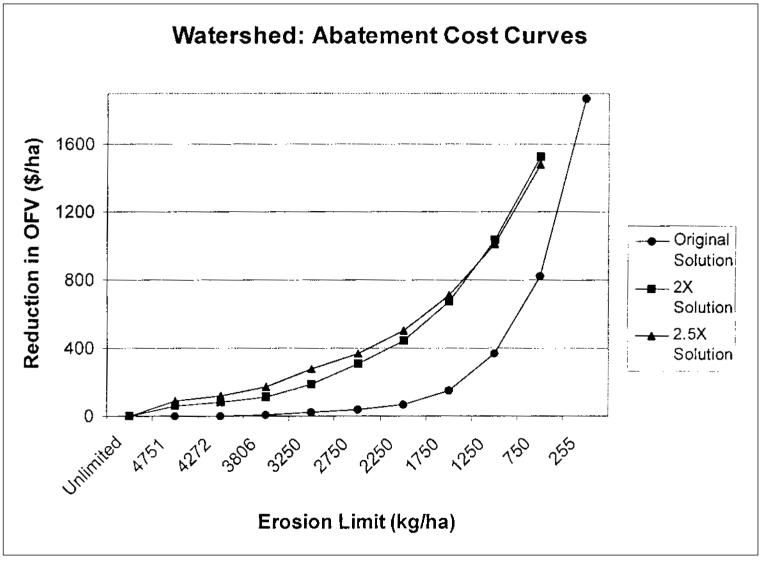
NB: Neither the 2X nor the 2.5X solution shows any reduction of OFV for erosion limits less than 750 kg/ha. With erosion limits less than 750 kg/ha the solutions were infeasible.

Figure 6. Abatement cost curves for Farm B



NB: Neither the 2X nor the 2.5X solution shows any reduction of OFV for erosion limits less than 750 kg/ha. With erosion limits less than 750 kg/ha the solutions were infeasible.

Figure 7. Abatement cost curves for Farm C



NB: Neither the 2X nor the 2.5X solution shows any reduction of OFV for erosion limits less than 750 kg/ha. With erosion limits less than 750 kg/ha the solutions were infeasible.

Figure 8. Abatement cost curves for watershed

doubled and increased by a factor of 2.5, the OFV dropped by $193/ha and $270/ha, respectively. These reductions in the OFV are 485% and 718% (2.5 times base case). The behavior for Farm B is similar; however, the reductions are much greater (note difference in y-axis scale in Figure 6). In percentage terms, Farm C (Figure 7) suffers the greatest percentage reductions in the OFV/ha, particularly at the higher end of the erosion limit scale (least restrictive). At lower erosion limits, the reductions in OFV/ha of Farm C were closer to those of Farm B and the watershed model.

Equity Issues and Policy Implications

Table 2 provides the estimated costs of reducing soil erosion for each farm and for the watershed. Thus, if an erosion reduction policy were implemented in the Saint-Esprit watershed and the erosion target value set at 2,750 kg/ha for each farm, it would cost Farms A, B and C $18/ha, $167/ha and $50/ha, respectively. If an erosion reduction policy were implemented at the Saint-Esprit watershed level and the erosion target value set at 2,750 kg/ha for the whole watershed, it would cost: $33/ha, $6/ha and $50/ha respectively for Farms A, B and C.

For Farm A, the estimated cost of reducing soil erosion with the target set for the watershed is always greater than or equal to that set at the farm level. For Farm B, watershed costs are greater than individual farm costs at 4,272 kg/ha. However, after this, the estimated cost of reducing soil erosion with the erosion target value set at the farm level is always greater than or equal to that set at the watershed level. For Farm C, except for a soil erosion value of 2,250 kg/ha, the estimated cost of reducing soil erosion with the erosion target value set at the farm level is always greater than or equal to that set at the watershed level.

The two right-most columns in Table 2 estimate the opportunity cost per hectare at the watershed level and a weighted average of the opportunity cost for the three individual farms. The estimates show that the opportunity cost is lower when the required erosion target is set at the watershed level. This can be explained by the fact that when an erosion target is set at the watershed level, the model has more room to maneuver to allocate crops to fields; that is, it does so in a more efficient (less costly) manner.

Policy makers could implement a standard for erosion or subsidize producers to decrease erosion. Applied to the watershed, the Quebec Ministry of the Environment could fix a standard corresponding to a certain level of erosion or soil loss per hectare (e.g., 2,750 kg/ha) for each farm or for the watershed. Farmers or the watershed as a whole polluting beyond this standard would be charged a penalty (e.g., lump-sum fine or fines per unit of erosion beyond that permitted under the standard). On the other hand, once the baseline level of effluents is established (e.g., 4,751 kg/ha), the Ministry could subsidize each farmer or the watershed as a whole for reductions in soil loss. This could, however, attract more producers into the watershed and increase the total amount of pollution generated (Baumol and Oates1988).

Sergenson (1998) and Bystrom and Bromley (1998) have proposed new policy designs for nonpoint pollution control for agriculture. Both of these designs attempted to minimize the transaction costs associated with the pollution control policy. Sergenson (1998) integrated both voluntary and mandatory aspects into her design. The voluntary aspect is a subsidy with mandatory controls if specific quality goals are not met. The Bystrom and Bromley (1998) policy was based on a watershed scale and included a trading scheme that allowed producers to trade abatement effort between one another with collective penalties if target levels were violated.

CONCLUSION

This study shows that implementing an erosion constraint:

- reduces the amount of soil loss generated from agricultural production
- forces cropping patterns and farming practices to change
- reduces profits.

Also, in a given watershed with comparable average soil losses per hectare across farms, farms with higher net incomes would be better off if the erosion target value were set at the watershed level, while farms with lower net incomes would be worse off. If a subsidy or a regulation approach were used, the least cost approach would be to set the erosion target value at the watershed level.

A sensitivity analysis was undertaken to estimate the impact on opportunity cost as field level erosion values are changed with an increasing soil erosion constraint. The abatement cost curves were quite responsive to changes in field level erosion values as estimated by RUSLEFAC. This implies that the cost of erosion abatement would be substantially higher for agricultural lands that were more susceptible to erosion, i.e., steep slope, field length and/or soil type.

There are several contributions of this study. First, it used data extracted from a GIS database and recombined at the field level in order to calculate erosion values on a field basis. Second, it used a modified RUSLEFAC method to calculate erosion values. This was done because of the Canadian context of the study and the field layout, which was the result of the former French land use. Third, MILP models were built to study the effect of an increasing erosion constraint and distributional issues, both at the farm and the watershed levels. Fourth, animal nutrient requirements are taken into account. Finally, even though a different methodology was used, conclusions are comparable with those of other studies. In particular, it is concluded that farmers' costs increase when forced to comply to more stringent erosion constraints.

This study has several limitations. First, the number of field activities was limited. An increase in this number would permit one to run models with more conventional and alternative practices for a given field, more fields for a given farm, and more farms within a given watershed, allowing for more complex problems and distributional issues. Also, off-farm benefits of reducing erosion have not been taken into account. Quantitative economic studies of off-farm benefits of reducing nonpoint source pollution are rather limited, but such studies could be used by a government agency to set tax rates or subsidy levels or pollution permit prices. Third, crop sales between producers could be developed. Transportation costs would have to be taken into account and these potential sources of trade could be studied both from an economic and an environmental point of view. Finally, the study reports the results of a short-term analysis. The development of a multiperiod framework, such as presented by Miranowski (1984), incorporating GIS at the field level would allow producers in the analysis to make appropriate changes in their production plans over time.

NOTES

[1]LINGO version 6.0 by Lindo Systems Inc. Chicago, Illinois. 1999.

[2]This summing of the three farms into the "watershed" model is used to investigate distributional questions. Therefore, the use of the term "watershed" does not imply that all farms in the watershed are represented by this model. Rather, the model represents an aggegation of three farms (A, B and C) within the watershed.

[3]Field size and other physical characteristics of the fields were not allowed to be altered in the study. Thus, the analysis is short-run in nature.
[4]The farms were to a degree self-selected as few of the 29 participating farmers were willing to collect the economic data. However, the farms used for this economic analysis were reasonably representative of the watershed farmers involved in the production of the same commodities. The "representativeness" implies that the species and size (animal units or hectares) of commodities produced on these farms are typical of other watershed farmers. However, these farmers do not control all of the land in the watershed nor do they produce all of the commodities produced in the watershed.
[5]Subsidization of the equipment might encourage farmers to use the sustainable technique employing the equipment whereas they might not have used the technique in the absence of the subsidization. A group of the farmers involved in the project purchased the equipment using a subsidy from the project. Thus they were interested in the sustainable technique, but whether the subsidization was required to "cement" the choice of technique was not determined.
[6]MJ stands for megajoule.
[7]"The *C* factor is used to determine the relative effectiveness of soil and crop management systems in terms of preventing or reducing soil loss" (Wall et al 1997, 1.32).
[8]"The *P* factor accounts for the erosion control effectiveness of support practices. . . . The *P* factor reflects the effect of practices that will reduce the amount and rate of runoff and thus reduce the amount of erosion" (Wall et al 1997, 1.43).
[9]Field shape in Quebec is quite different from that observed in other parts of Canada, e.g., the prairie provinces. Due to the historic reliance on water transportation, fields tend to be very elongated in Quebec with the narrow end adjoining the waterway. This design allowed for maximum access to the waterway by the most people.
[10]Data generated by M. Mousavizadeh, Department of Agricultural and Biosystems Engineering, McGill University.

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