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

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Abstract

The Saint-Esprit watershed project was initiated to address the issue of nonpoint source agricultural pollution and relies on the adoption of sustainable practices tested on-farm by willing farmers. To study the economic impact of an increasing erosion constraint at the farm and the watershed scales, four Mixed Integer Linear Programming (MILP) models, corresponding to three selected farms and the watershed, were built. The models maximize the sum of field net margins subject to singleness of field use, animal nutrient requirements, and erosion.

Scenario results show that increasing the erosion constraint: (1) reduces soil loss from agricultural production; (2) forces cropping patterns and farming practices to change; (3) reduces profits; and (4) induces marginal and average costs to increase at an increasing rate. Also, with comparable average soil losses per hectare, farms with lower net margins would be worse off if the erosion target was set at the watershed level.

Résumé

Le projet du bassin versant Saint-Esprit a été initié pour traiter le problème de la pollution diffuse d'origine agricole. Il repose sur l'adoption de pratiques durables testées sur les exploitations par des producteurs volontaires. Pour étudier l'impact économique d'une contrainte érosive croissante à l'échelle de l'exploitation et du bassin versant, quatre modèles de Programmation Linéaire Entière Mixte (PLEM), correspondant à trois exploitations sélectionnées et au bassin versant, ont été construits. Les modèles maximisent la somme des marges nettes par champ soumise à l'unicité de l'utilisation du champ, aux besoins alimentaires des animaux, et de l'érosion.

Les résultats des scénarios montrent qu'une augmentation de la contrainte érosive: (1) réduit les pertes de sol issues de la production agricole; (2) force les assolements et les pratiques agricoles à changer; (3) réduit les profits; et (4) entraîne une augmentation des coûts marginaux et moyens à un taux croissant. Aussi, avec des pertes de sol moyennes par hectare comparables, les exploitations avec des marges nettes plus faibles seraient dans une plus mauvaise situation si la valeur érosive cible était fixée au niveau du bassin versant.

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Chapter 1 Introduction

1.1 Problem Statement

The Saint-Esprit small stream, which drains the watershed of the same name, is very polluted, with high levels of pesticides and heavy loads of sediments, nitrates and phosphates being found in the water (Papineau 1993). This pollution has been related to agricultural production which is the main activity in this area located North of Montreal (Quebec, Canada). The farming practices are known to be conventional, i.e. they rely on high amounts of pesticides and fertilizers and intensive machinery use.

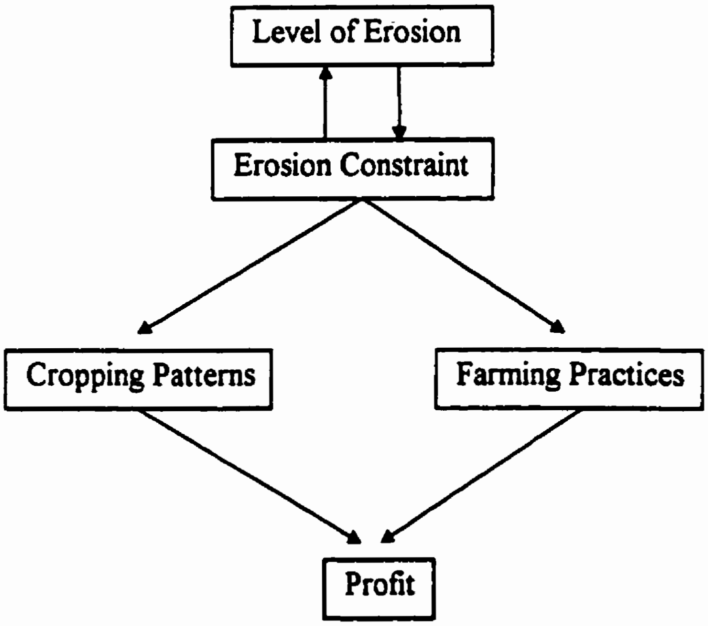
Upon request from the agriculture society of Saint-Jacques-de-Montcalm, the Quebec Ministry of Agriculture, Fisheries and Food (MAPAQ) initiated a water resources management project. The objective of this project is to reduce the amount of agricultural non-point pollution and improve water quality at the outlet of the Saint-Esprit watershed. It relies on the adoption of sustainable farming practices by farmers willing to get involved in the project. These farming practices are known to reduce the amounts of pollutants because they rely on a reduction in use of synthetic fertilizers and pesticides. They also tend to reduce erosion by using special pieces of equipment and fewer machinery passings and by leaving more residues on the topsoil. Refined definitions of conventional and sustainable farming practices will be given in chapter 2. Prior to the establishment of the project, few sustainable practices were being used, but farmers were aware of the existing techniques and opened to them.

These practices may have an economic cost to farmers adopting them, and there are few studies indicating what these costs may be. Therefore, this study aims at determining the cost of implementing environmental constraints, both at the farm and the watershed levels. This study is focused on the issue of erosion. If adopting sustainable practices proved to decrease profits, this information would then be helpful to answer distributional questions: should the erosion target be set at the farm or the watershed level, i.e. should each farmer be constrained to a certain amount of erosion or should the overall watershed be constrained, regardless of each farmer's situation? In this case, what would be the consequences for the farmers and how should these potential costs be shared among them?

1.2 Hypotheses

The hypotheses tested in this study are illustrated in Figure 1.1.

Figure 1.1 Hypothetized effects of an erosion constraint



In other words, the study tests the following hypotheses both at the farm and the watershed levels: (1) implementing an erosion constraint reduces the amount of erosion generated from agricultural production; (2) implementing an erosion constraint forces cropping patterns and farming practices to change; and (3) changes in cropping patterns and farming practices reduce profits. As a result of testing these hypotheses, one should be able to draw some conclusions concerning the tradeoff between lost profits and decreased soil erosion.

1.3 Objectives

The general objective of this study is to determine the cost of implementing an erosion constraint both at the farm and the watershed levels. The specific objectives of this study are:

(1) To select farmers according to the physical characteristics of their fields, the sustainable farming practices they adopted and the available economic data for these farms.

(2) To build two types of models: one at the watershed level, the other at the farm level.

(3) To run scenarios based on an increasing erosion constraint and test for the above hypotheses.

(4) By comparing changes in profits and farming practices and cropping patterns, to conclude on distributional aspects involved in the implementation of an erosion constraint.

1.4 General Methodology and Organization of the Study

The general methodology of this study is related to the specific objectives mentioned above and is based on five steps:

(1) A collection of bibliographical data on sustainable farming practices and methods to assess the economics of sustainable agriculture.

(2) A sampling of a few watershed farmers. The sampling was made on the basis of farming practices, availability of economic data and physical characteristics of the fields. The latter was assessed by analyzing watershed soil and slope data with a Geographic Information System (GIS). Erosion estimates for each field were derived using the fields' physical characteristics, farming practices and cropping patterns on the land.

(3) The development of two types of MILP (Mixed Integer Linear Programming) models: one for the watershed and one for each selected farm. The objective function of these models is to maximize profits, subject to three types of

constraints: an erosion constraint; a set of animal nutrient requirement constraints; and a set of constraints related to field use.

(4) The simulation of numerous scenarios. The base case is a simulation where no environmental constraint is implemented, i.e. where profit maximization is only constrained by satisfying animal nutrient constraints. Subsequent scenarios are based on the implementation of an increasing erosion constraint, i.e. farmers and the watershed have to respect increasingly limited erosion loads.

(5) The results of this "what-if" analysis show the evolution of profits, cropping patterns and farming practices across selected farms and the watershed, as a function of the erosion constraint. By comparing these results, some conclusions can be drawn concerning where is the best level to implement the environmental constraint (i.e., at the farm or the watershed level).

The main contributions of this research lie in the fact that several models were built at two different scales to study the same issue of economic costs of implementing an erosion constraint in a given watershed. Erosion estimates are derived from GIS information and used within the economic models. Step 1 is dealt with in chapter 2. Steps 2, 3 and 4 are developed in chapter 3. Results of the analysis are presented in chapter 4. A conclusion chapter summarizes the study and makes proposition for further research.

Chapter 2 Literature Review

"Agriculture is both a cause of major environmental and ecological loss as well as a major potential beneficiary from the conservation of living things and their life-support systems. Thus it is a central concern in the economics of environmental conservation" (Tisdell 1991, 178). This review of literature first describes the impact of agriculture on water quality. Sources and impacts of agricultural pollutants are presented, as well as the rise of the notion of "sustainable" agriculture as opposed to "conventional" agriculture. Then sustainable agriculture is defined. Techniques used, and conditions necessary to achieve sustainability are presented, as well as empirical factors affecting the adoption of sustainable practices. Then, the economics of sustainable agriculture and erosion are studied. Research methodologies and results are presented, distinguishing the budgeting approach from the mathematical modeling one. Finally, Geographic Information System (GIS) applications related to agricultural water quality management are introduced.

2.1 Influence of Agriculture on Water Quality

2.1.1 Agriculture and Its Link to Water Quality

According to Young and Burton (1992), the environment provides four types of services: material inputs into the production process, an assimilative waste sink for the by-products of production and consumption, essential life support services, and "existence values" unrelated to any economic valuation of it. As the result of the plant, soil, climate and human interactions, agriculture clearly uses the environment for its activity. Libby and Boggess (1990, 11) outlined agriculture's role in water pollution. "First, the generation of residuals is an unavoidable by-product of production. [...]. Second, the composition and the timing of agricultural wasteflows can be modified by changing crop mixes, by changing production practices such as input substitution and timing of applications, or by developing new technologies that alter the output/waste ratio. [...]. Third, the production processes affect the spatial and temporal dimensions of water outflows, which in turn affect the delivery and transport of the potential loadings." Water transports pollutants to agriculture and from agriculture into receiving water bodies via four processes: rainfall, surface runoff, percolation/leaching, and irrigation/evaporation (Libby and Boggess 1990).

2.1.2 Sources of Agricultural Pollutants

Farm wastes can be grouped into six categories (Libby and Boggess 1990): soil sediments, nutrients, pesticides, mineral salts, heavy metals, and disease organisms. Soil sediments come from soil erosion which is a natural process, but accelerated by the cultivation of land. Nutrients, in particular nitrogen, phosphorus, and potassium, are commonly applied to crops as fertilizers. They become pollutants when they are in excess of crop uptake. Pesticides, which include herbicides, fungicides, insecticides and nematicides, are used to inhibit growth of organisms that otherwise would decrease crop yields. Mineral salts come from the natural dissolution of rocks and soils and remain in the soil after the plants uptake or water evaporation. Finally, livestock production processes generate heavy metals (lead, zinc, mercury, arsenic), disease organisms (coliform bacteria, viruses) and nutrients.

Pollutants are often classified by point source and nonpoint source origins (Libby and Boggess 1990). Point source pollutants are those that can be traced to a precise source defined as a "discernable, confined, and discrete conveyance" (Libby and Boggess 1990, 13). On the other hand, nonpoint sources encompass a large area and thus are difficult to trace back to a precise source. According to Headworth (1993), point sources of agricultural pollution are not very common, contrary to nonpoint sources ones.

In general, water pollutants (especially fertilizers and pesticides) are originally useful for agricultural production. As stated before, they become pollutants only when they are in excess of crop uptake and are carried away by water. For instance, the use of inorganic nitrogen fertilizers increased eleven-fold between 1950 and 1980 (150% from 1965 to 1984) (Lee and Nielsen 1987). Since the increase in nitrogen fertilizer costs due to the energy crisis in 1973, excessive applications of nitrogen have decreased. "However, [...] typically about 20-30% of the applied fertilizer nitrogen still leaches out as nitrate [...]" (Bouwer and Bowman 1989, 161). On the other hand, there was a sharp rise in the agricultural use of pesticides, nearly tripling from 1965 to 1984 (Lee and Nielsen 1987). Thus it is not surprising that "Agricultural applications of fertilizers and pesticides are being increasingly recognized as significant sources of ground water pollution" (Canter 1987, 153).

2.1.3 Impacts of Agricultural Pollution

Impacts of agricultural pollution can be divided into onsite effects on agricultural productivity and offsite damages incurred by other users of surface waters and groundwater aquifers. These effects lie at two levels: an environmental level and an economic one. At the level of the farm, losses of nutrients, soil sediments and pesticides result in lower productivity and yields, thus reducing efficiency and increasing costs. Concerns about the offsite effects of agricultural pollution are also important since health and environmental problems may affect many people downstream. Moreover, because of the slow movement of groundwater in many areas, as well as the slow degradation of many chemicals, contamination can persist for years, even centuries (Lee and Nielsen 1987). According to Bouwer and Bowman (1989, 162): "Now the problem [of pesticide pollution in groundwater] is widespread. A recent Environmental Protection Agency report shows that about 50 pesticides have been detected in groundwater samples from about 30 states. As a result, thousands of drinking water wells have been closed. Potential health effects of pesticides in humans include cancer, male sterility and other clinical and subclinical effects". Moreover, agricultural chemical contamination could affect 53.8 million people in the United States; and, in order to avoid this contamination, monitoring costs could reach US$ 1.36 billion (Lee and Nielsen 1987).

2.1.4 From "Conventional" to "Sustainable" Agriculture

Concern about the sustainability of modern agricultural systems has emerged as an important question to be addressed. Why so? Ruttan (1994, 212) gave three reasons. First, "unprecedented demands that growth of population and income are imposing on agricultural systems. [...] second [...] the sources of future productivity growth are not as apparent as we move toward the early years of the 21st century as they were a quarter century ago. [...] third [...] the environmental spillover from agricultural and industrial intensification". As Tisdell (1991, 168) stated: "while non-sustainability of economic activities is not invariably connected with negative environmental spillover or externalities, in practice they frequently go hand in hand".

According to Schaller (1993, 90), environmental and health problems associated with conventional farming raised interest in the idea of sustainability. These problems include the following: "(1) Contamination of ground and surface water from agricultural chemicals and sediments; (2) Hazards to human and animal health from pesticides and feed additives; (3) Adverse effects of agricultural chemicals on food safety and quality; (4) Loss of the generic diversity in plants and animals [...]; (5) Destruction of wildlife, bees, and beneficial insects by pesticides; (6) Growing pest resistance to pesticides [...]; (7) Reduced soil productivity due to soil erosion, compaction, and loss of organic matter; (8) Over-reliance on non-renewable resources; (9) Health and safety risks incurred by farm workers who apply potentially harmful chemicals". Edwards (1989) added a number of economic problems caused by conventional agriculture: overproduction of crops, increased costs of energy-based inputs and decreased farm incomes. Batie and Taylor (1989, 128) also listed a series of problems associated with conventional agriculture: "too concentrated in ownership; too reliant on technology, petroleum-based inputs, and credit; too specialized and ecologically unsound; and too dependent on government subsidies". Finally, Kiley-Worthington (1981) broadened the problems linked to modern high-input agriculture by dividing them into biological, resource utilization (including energy), economic, social, political and ethical.

2.2 Sustainable Agriculture

2.2.1 What Is Sustainable Agriculture?

Ikerd (1993a) argued that sustainable and conventional agriculture were more different in terms of their farming philosophy than in farming practices. The latter is fundamentally an industrial development model which views farms as factories and considers fields, plants and animals as production units. On the contrary, sustainable agriculture is based on a holistic model of development which views production units as organisms. These organisms consist of many complex interrelated suborganisms, all of which have physical, biological, and social limits. Therefore, sustainability is a system concept. Ruttan (1994) and Schaller (1993) reviewed some of the terms which have been used to emphasize different dimensions of sustainability: biodynamic, organic, biological, ecological, farming systems, appropriate technology, regenerative, reduced-input, low-input, alternative agriculture. Then followed definitions in technical and economic terms, in ecological terms and finally in terms of physical resources and community values. For example, Batie and Taylor (1991) presented a technological perspective on alternative agriculture and provided definitional distinctions between low-input, organic, sustainable and conventional agriculture.

In connection with this, Youngberg, Schaller and Merrigan (1993) stressed the importance of terms used to describe non-conventional agriculture in order to get scientific and political legitimacy. Indeed it had to fight the negative symbolism of being a "primitive, backward, nonproductive, unscientific technology suitable only for the nostalgic and disaffected back-to-the-landers of the 1970s" (Youngberg, Schaller and Merrigan 1993, 298). On the contrary, Ikerd (1990, 20) argued sustainable agriculture gained from synergism: "the productivity of an integrated system can be greater than the sum of the products of the individual system components". Furthermore, resource conservation, protection of the environment and farming in partnership with nature would enhance, not reduce, global food production (Schaller 1993).

The most used definition of sustainability is that adopted by the Brundtland Commission: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, 43). Allen et al. (1991, 37) proposed an extended definition: "a sustainable agriculture is one that equitably balances concerns of environmental soundness, economic viability, and social justice among all sectors of society". However, "the concept of agricultural sustainability does not lend itself to precise definition, partly because it implies a way of thinking as well as of using farming pratices, and because the latter cannot be specified as final answers" (Schaller 1993, 89). The terms "alternative" and "sustainable" will be used interchangeably for the rest of the study.

2.2.2 Techniques Used

Batie and Taylor (1989) argued that farmers could and did adopt some low-input agricultural practices without necessarily adopting the more holistic, whole system approach of alternative agriculture. This is why the differences between conventional agriculture and alternative agriculture span a continuum of farming practices, from conventional through low-input to organic. In order to reduce production costs, soil erosion and pollution by agrichemicals, several techniques are emphasized (Edwards 1989, 25): "legume rotations; use of waste organic matter as well as that from animals and crops; integrated pest management; pest and disease forecasting; biological and cultural pest control; living mulches and mechanical weed control; conservation tillage; specialized innovative cultural techniques, including intercropping, strip cropping, undersowing, trap crops, and double-row cropping". The combination of these techniques has to be based on a good understanding of the nature of interactions between fertilizers, pesticides, cultivations and rotations that influence crop yields and farm income.

2.2.3 Conditions for Sustainability

These are alternative views as to what criteria should be used to assess sustainability. Young and Burton (1992) and Tisdell (1991) suggested the criterion of resilience at the agro-ecosystem level. Resilience is the ability of a system to maintain its structure in the face of external changes. Tisdell (1991) would also consider the level, the degree of variability and the sustainability of yields; as well as their impact on the distribution of income. Allen et al. (1991) would use a different set of factors at different scales: agronomic factors at the field level, microeconomic factors at the farm level, ecological factors at the regional level, and macroeconomics factors at the national and international levels. Stockle et al. (1994) proposed a framework using nine attributes, scored and weighted according to the judgment of the evaluating team: profitability, productivity, soil, water and air quality, energy efficiency, fish and wildlife habitat, quality of life, and social acceptance. Kiley-Worthington (1981) distinguished seven requirements: self-sustainability, diversification, smallness of unit size, maximization of the net yield per unit area, economic viability, on-farm processing of farm products and direct sale to local consumers, and aesthetic and ethical acceptability. Finally, Ikerd, Devino and Traiyongwanich (1996) assessed sustainability of a conventional and an alternative farming system with three sets of criteria: environmental (natural resource conservation and environmental protection), economic (farm profitability), and social responsibility (employment opportunities in the community and use of community resources).

Among all of the factors previously mentioned, economic sustainability is a critical issue. Schaller (1993) considered profitability of sustainable farming as critical as the adequacy of food production. Tradeoffs between, on one hand, resource conservation and environmental soundness and, on the other hand, productivity and competitiveness are the key in the search for sustainable agricultural systems. "A system must be profitable in the long run or it cannot be sustained. A system must be sustainable or it cannot be profitable in the long run" (Ikerd 1990, 18).

2.2.4 Factors Affecting the Adoption of Sustainable Practices

Factors that affect adoption of technologies on farming systems include the farmers' "opportunity sets" (Batie and Taylor 1989, 131). "That is, farmers make choices within "opportunity sets", and the current "opportunity sets" are conditioned by farm programs, environmental constraints, credit and tax policies, and integrated contracts and leases, as well as by available research on alternative agricultural and conventional practices". Camboni and Napier (1993) analysed data from 371 farms in Ohio to assess how attitudes, personal characteristics and farm structure factors influence use of soil conservation practices at the farm level. Their findings were that farm structure variables, such as annual acreage farmed or tractor size, were the best predictors of adoption of farming pratices while personal characteristics were not very important. Ervin and Ervin (1982, 291) conducted a similar study in Missouri and concluded that "economic factors play a more important role in determining conservation effort than for [soil conservation] practice numbers".

On the other hand, Feather and Amacher (1994) showed that adoption of sustainable practices depended on the knowledge of a demonstration program and the success of this program depended on improved practices being economically appealing as well as environmentally sound. This is why educational programs, such as LISA (Low-Input/Sustainable Agriculture), were implemented in the United States (Liebman 1992). However, these results are contradicted by Gould, Saupe and Klemme (1989) who found that perception of soil erosion was a significant determinant of conservation tillage adoption. Rahm and Huffman (1984, 405) concluded that "the probability of adopting reduced-tillage in corn enterprises differs widely across farms and depends on soil characteristics, cropping systems, and size of farming operation". Finally, Stonehouse (1994) listed four sets of factors affecting the adoption and use of soil conservation practices in Canada. These factors are broadly classified into technical, social, economic, and institutional, and interact among themselves in ways that may influence conservation decisions.

Another important factor is communication between the university and the farmer. However, it traditionally has just been from the university to the farmer, and farmers' research priorities and recovery of information from farmers have not been very important to researchers (Shore Auburn and Baker 1992). For example, Walter (1993) asked farmers about validity cues they used to evaluate reports of field-scale research. He concluded more information should be included about the system being studied, such as its costs and risks, along with data on the research methods used. This may explain the popularity of Practical Farmers of Iowa. This organization was founded in 1985 to help farmers generate and share information on profitable, environmentally sound farming methods through on-farm research trials (Rosmann 1994). "Research conducted by farmers on their own farms can be more directly applicable to other farmers' conditions than experiment station research, and therefore can reduce the risk of an incorrect decision" (Ikerd 1993b).

2.3 Agricultural Economic Sustainability: Methodologies and Results

2.3.1 Economic Sustainability as a Debate

Economic sustainability is defined as providing enough income to maintain all those working on the farm in a way similar to others in society, and covering the farm's maintenance costs (Kiley-Worthington 1981). "The profitability of sustainable versus conventional farming is often the most contentious issue encountered when the subject of sustainability is discussed" (Schaller 1993, 94). This is partly because studies of the profitability of alternative farming systems are limited (Batie and Taylor 1989). Although there is wide disagreement as to what system is more profitable, there is anecdotal evidence of individual successful alternative farming systems. Individual profitability may result from good management as well as employing fewer purchased inputs. Disparities may also result from on-farm unmeasured benefits such as less vulnerability to drought, nutrient convervation, better seasonal distribution of inputs (Batie and Taylor 1989). Knowledge of how ecological agriculture compares economically with conventional practices is still very incomplete (Lockeretz 1989a). Reasons range from the definition of "ecological agriculture" to the assumptions regarding agricultural subsidies and price differentials, the scale of application, the importance of the farmer's management ability in the results and the viewpoint from which the economic comparison is made (society, farmers, future generations). As a conclusion, Roberts and Swinton (1996) reviewed economic methods used in 58 recent studies to compare alternative crop production systems. They concluded that "most economic studies of crop production focus exclusively on profitability, and incorporate neither environmental criteria nor the dynamic characteristics inherent in alternative systems" (Roberts and Swinton 1996, 10).

2.3.2 The Budgeting Approach

2.3.2.1 "Regular" Accounting

Enterprise budgets are a very common method to compare profitability by focusing on the costs and returns of alternative systems. Budgets may be derived from farm surveys or for a representative farm. Weersink et al. (1992) compared the costs of three conservation tillage systems -chisel plow, ridge-till, no-till- to a conventional moldboard plow system for hypothetical corn-soybeans farms in Southern Ontario, differentiated by farm size and soil type. Input costs were either computed or based on actual levels of use and current market prices. Total costs per hectare were calculated, mainly showing that labor costs could be reduced up to 61% annually with the reduced tillage systems. Wollenhaupt and Blase (1990) developed crop budgets to estimate the economic impact of conservation compliance on northern Missouri farms. They computed income over variable costs and then distinguished labor, machinery and return to land for practices that met a given soil erosion goal. The budgets showed an economic advantage for soybeans over corn, wheat, and forages, regardless of the price scenario. Lockeretz (1989b) extended the analysis to include estimates of each production system's contribution to the local economy, both directly through farmers' payments for labor and interest, and indirectly through the payrolls and benefits of enterprises serving farmers. His results implied that under the conventional system the local economy would capture a smaller share of the total productive value of the agricultural resources.

Experiment station trials are also widely used. For example, Smolik, Dobbs and Rickerl (1995) conducted a two-phase on-farm and experiment station trials study. Their economic analysis included net income over all costs except land, labor and management. Analysing also agronomic and ecological factors, they concluded that alternative systems were more sustainable in South Dakota than conventional and reduced-till systems. Heilman, Hickman and Taylor (1991) used a randomized complete block design with four replications and treatments of conventional versus wing-chisel plow. They based their analysis on the difference between variable costs of traditional and conservation production practices and showed that even though incomes did not differ significantly, environmental benefits were higher in the wing-chisel tillage system than in the conventional one. Ott and Hargrove (1989) tested two factors -choice of winter cover crop and amount of fertilizer applied- with several treatments. Their finding was that legume cover crops increased both average corn yield and yield variance and proposed an optimal combination of the two factors considering a farmer's position on risk. Jolly, Edwards and Erbach (1983) studied farm-level risks and returns for corn-soybeans rotations under a conventional moldboard plow system and three conservation tillage systems. They computed, after total operating costs and total production costs, returns to land and management and showed that short-run economic criteria favored conventional tillage systems and could inhibit the adoption of conservation tillage. Finally, Ess et al. (1994) used the criterion of energy savings along with a budgeting approach to compare the costs of growing corn for silage using manufactured nitrogen-fertilizer or nitrogen-fixing legume cover crops. They concluded that even though net income was statistically equivalent in both practices, cover-crop treatments used about 50% as much energy per hectare as the conventional practice.

2.3.2.2 "Natural Resource" Accounting

"When changes in natural resource assets are ignored, resource degradation is encouraged, if not guaranteed" (Faeth 1993a, 162). As a consequense, Faeth (1993a and 1993b) presented a natural resource accounting framework including soil depreciation and off-site costs to estimate the profitability and sustainability of conventional and sustainable agriculture. Soil depreciation was estimated from a model computing the economic impacts of soil productivity changes due to soil erosion and changes in soil structure. These economic impacts were subtracted from gross operating margin to get net farm operating income and further net farm income. Off-site costs, obtained from the literature, were subtracted from net operating income to determine the net economic value. The profitability of conventional versus sustainable agriculture could be assessed using this framework with different rotations and policy scenarios.

2.3.3 The Mathematical Modeling Approach

2.3.3.1 Linear Programming and Derivations

The mathematical modeling approach consists of building a model of predictive costs or returns of adopting a sustainable practice and then comparing these with estimates from conventional practices. Linear Programming (LP) is a mathematical technique for optimizing an objective within a set of constraints. Most of the time crop budgets are the building blocks of LP, be they gross or net margins. LP allows one to run scenarios, perform "what-if" analyses, and study the sensitivity of a model to changes in a given variable or a given constraint.

Russell and Fraser (1995) used an LP model and data from a farm survey to predict the combination of crop enterprises which would maximize the gross margin generated by the arable enterprise while taking account of the limits imposed by land availability and other factors. The results showed that a permanent (as opposed to rotational) set-aside combined with a reduction of up to 45% in fertilizer use produced no more than a 6% reduction in gross margins. Heimlich and Ogg (1982) also used an LP model to analyze soil-erosion reduction strategies while holding pesticide loadings constant. Their findings were that reductions in pesticide exposure were compatible with high levels of erosion control. However, shifts in cropping patterns and resource use were necessary to achieve greater reductions at relatively low cost. Turvey and Weersink (1991) used a two-period LP model with a corn soybeans rotation under either conventional or no-till management practices. The objective was to maximize profits (gross margins) subject to an increasing erosion constraint. Erosion data were derived from a simulation model using the Universal Soil Loss Equation (USLE). The results indicated that extensive marginal and average cost increases would be borne by farmers. Stonehouse and Bohl (1993) used a multi-period linear programming model to assess the economic on-farm consequences of soil conservation policies in southwestern Ontario. Results showed that regulatory limits to soil erosion and taxation of eroded soil would impose significant financial difficulties on farmers. However, subsidizing the cost of conservation tillage equipment or the cost of producing crops such as alfalfa would be more appealing for farmers.

Xu, Prato and Ma (1995) used a multi-objective programming model to generate efficient combination of net returns, soil erosion and nitrate available for leaching. Net returns were calculated for six farming systems based on actual case study farm data in north-central Missouri; soil erosion was calculated for four predominant soils using USLE; and nitrate available for leaching was computed using a specific computer program. The results indicated there were tradeoffs between farm income and soil erosion and between farm income and nitrate available for leaching. Therefore, both economic and environmental objectives should be considered simultaneously in evaluating farming systems. A multi-objective programming model as well as a simulation model were used by Fernandez-Santos, Zekri and Casimiro Herruzo (1993) to link environmental and economic data and assess on-farm costs of reducing nitrogen pollution. Results indicated that the adoption of alternative practices needed to be accompanied by targeting subsidies because of the potential considerable economic losses for farmers. Finally, Lopez-Pereira et al. (1994) used Discrete Stochastic Programming to determine the potential farm-level income effects of the soil-conservation and seed-fertilizer technologies. Results showed that if policy-actions reduced the risk of low prices due to high production, then adoption of the improved technologies would be profitable for small-scale farmers.

One of the assumptions of LP (see section 3.5.3) is divisibility, i.e., decision variables are continuous and can take any fractional value (Turban and Meredith 1985). However, real-world decision variables often must be integers (Eppen, Gould and Schmidt 1993). For example, decisions regarding the number of airplanes to build or where to locate a warehouse clearly cannot take fractional values. An LP model with the additional characteristic that some or all of the decision variables are required to take on integer values is called an Integer LP (ILP) model. A problem in which all of the decision variables are required to be integers is an all-integer LP. A problem in which only some of the variables are restricted to integer values and others can assume nonnegative fractional numbers is referred to as a Mixed Integer Linear Program (MILP). A problem in which the integer variables are restricted to the values 0 or 1 is called a binary, or 0-1, integer linear program (Eppen, Gould and Schmidt 1993).

2.3.3.2 Other Methods of Mathematical Modeling

Taylor and Young (1985) used a breakeven equation to equalize farm income under a conventional and a no-till systems. The model predicted yields in the long-run (50 years) and incorporated the yield-depressing impact of soil erosion (using USLE), as well as the yield-enhancing effects of technical progress. Results showed that the level of price support, cost-sharing and soil loss taxes needed to equalize income would increase as the topsoil depth is smaller and/or the farm planning horizon is longer. Johnson, Adams and Perry (1991) integrated plant simulation, hydrologic and economic models of farm-level processes to study on-farm costs of strategies to reduce nitrate groundwater pollution. Their findings were that changes in timing and application rates of nitrogen reduced nitrate pollution in groundwater with little loss in profits. But once such practices were adopted, further reductions in nitrates could be achieved only at increasing costs to producers. Chang et al. (1994) used a multi-commodity agricultural sector model to study the regional and national economic impacts of erosion management measures in coastal drainage basins. The analysis concluded that a reduction of $42 million in net returns to croplands would result because of a decrease in land farmed, a substitution of lower profit crops, and the use of more expensive erosion control methods. Finally, Rendleman (1991) used a general equilibrium model to assess the effect of three ways to reduce farm chemicals on gross and net farm income. Results showed that a chemical use tax and farm sales restrictions imposed on input suppliers reduced net income because of rising costs. Only input restriction in chemicals held the potential for raising net farm income.

2.4 Applications of GIS to Agricultural Water Quality Management

2.4.1 General Facts about GIS

Although many definitions of Geographic Information Systems (GIS) have been proposed, the most commonly used is: "a system for capturing, storing, checking, (GIS) integrating, manipulating, analyzing and displaying data which are spatially referenced to the Earth. This is normally considered to involve a spatially referenced computer database and appropriate applications software" (Association for Geographic Information 1997, 13). GIS deal with spatial objects, which are delimited geographic areas, with a number of different kinds of associated attributes or characteristics. Three types of spatial objects exist: points, lines, and polygons. GIS also deal with data structures. Two broad types of data structures exist. The first structure, raster, is a cellular organization of spatial data, where a value for the parameter of interest is developed for every cell in the matrix. The other structure is a vector, where a vector is a quantity with a starting coordinate, and an associated displacement and direction.

GIS are used because it is a powerful tool for handling spatial data. According to Aronoff (1989, 43): "The ability to manipulate the spatial data and corresponding attribute information and to integrate different types of data in a single analysis and at high speed are unmatched by any manual methods. The ability to perform complex spatial analyses rapidly provides a quantitative as well as a qualitative advantage." GIS deal with layers of information constituted as spatial objects that have two characteristics: a spatial one (the coordinates of the object in the layer) and a non-spatial one (the parameter of interest in the layer or attribute). Star and Estes (1990) and Aronoff (1989) distinguished the following GIS functions: data acquisition (input), pre-processing, data management, manipulation and analysis, and product generation.

2.4.2 GIS and Agricultural Water Quality Management

One of the roots of GIS development is a concern for balancing competing uses of environmental resources. Hence GIS were first designed for small scale work. However, with the availability of more precise data and the ever increasing data processing capabilities of computers, there is a growing concern for using GIS at larger scales (Taupier and Willis 1994). Interest for agricultural applications of GIS also find their origin in environmental problems associated with conventional agriculture. These applications may address such issues as irrigation, land use and suitability, yield prediction or soil and water conservation. GIS may be used as a data provider and/or as a tool for analyzing spatially referenced problems.

The DRASTIC (Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity of the aquifer) method is used to detect and predict changes in groundwater quality resulting from the effects of various land use activities. DRASTIC parameters are multiplied by their respective weight and summed to get a final rating. Using classes, it is possible to target most sensitive areas for action (Evans and Myers 1990). Cully Hession and Shanholtz (1988) used a pollution density index derived from USLE with a GIS to estimate potential sediment loading to streams from agricultural land. Estimates were used to target cost-share monies in a drainage basin. Similarly, Mellerowicz et al. (1994) integrated data from a soil survey, land use inventory, property ownership, digital elevation data and climatic atlases in a GIS to generate USLE factor values. Then USLE was used to calculate predicted annual soil loss rates. Results consisted of a characterization of the spatial distribution of the risk of soil erosion by water on agricultural land within a watershed.

Recent models tend to provide a better integration of economic and environmental dimensions of water quality management. Prato and Wu (1995) developed a watershed-scale model for evaluating economic and water quality effects of various farming systems by considering spatial variation and stochasticity in key parameters. A GIS provided the basic spatial input parameters required for the agricultural nonpoint source pollution model which simulated surface water quality. Water quality indicators from this model were merged with economic data in a constrained optimization model. The study concluded that tradeoffs existed between improvement in water quality and maintenance of watershed net returns. Imposing water quality constraints reduced total acreage in cropping activities that were detrimental to water quality and those changes were costly.

2.5 Conclusion

This chapter first described the influence of agriculture on water quality, since water transports pollutants to agriculture and from agriculture into receiving water bodies. Soil sediments, nutrients, pesticides, mineral salts, heavy metals, and disease organisms may constitute nonpoint sources of agricultural pollution. Impacts of agricultural pollutants can be divided into onsite and offsite effects, both at the environmental and the economic levels. These problems often have been associated with modern, high input "conventional" agriculture. Hence the rise of "sustainable" agriculture. Many definitions of sustainable agriculture exist. The most common would be agriculture "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, 43). Actually, sustainable agriculture draws both on a farming philosophy and a set of farming practices. Criteria to assess sustainability were presented, where economic sustainability is obviously a critical one. Factors affecting the adoption of sustainable agriculture ranged from farm structure variables to the perception of an on-farm environmental problem. On-farm research can help improve the adoption rate of alternative farming practices.

Although few people would not agree that sustainable must be profitable, ways to measure economic sustainability often is a contentious issue. Different methodologies used to evaluate the economics of erosion and sustainable agriculture were reviewed. Enterprise budgeting and mathematical modeling, in particular linear programming, were emphasized. Finally, GIS and its application to agricultural water quality management were introduced. It is acknowledged that more effort is needed to better integrate environmental and economic dimensions of alternative farming systems to assess their profitability, environmental impact and stability. The model being developed by Bockstael et al. (1995) is such an attempt, where ecological and economic modeling are being integrated in order to assess and analyze agricultural policy options.

Chapter 3 Methodology

Mixed Integer Linear Programming (MILP) was used to assess the costs of implementing an erosion constraint at the farm and the watershed levels. This program is based on three types of data: crop budgets, animal nutrient requirements data, and erosion data. Before explaining how these data were obtained, the Saint-Esprit area and the watershed project are presented.

3.1 The Watershed Project and the Saint-Esprit Area

3.1.1 The Watershed Project

This section is derived from Enright et al. (1996). Increasingly, the issue of agricultural impacts on water quality in Quebec is focusing on nonpoint source pollution. MAPAQ has tried to address this issue by developing programs and extension material to promote soil and water conservation as well as the adoption of Best Management Practices (BMPs). Two watershed pilot projects were initiated in Quebec, under the Drainage Basin Management Program, with funding provided by the Canada-Quebec Entente on Sustainable Agriculture. The Ruisseau Saint-Esprit is one of these projects. The objectives of the project were to: (1) support the actions of the watershed farming community to improve integrated water management and environmental quality; (2) develop technological expertise in integrated water management within individual agricultural drainage basins; (3) accumulate knowledge on agricultural technology and the processes that cause contamination of surface waters; and (4) develop an intervention strategy applicable to other small watersheds in Quebec with similar environmental problems.

The structure of the project is based upon a multidisciplinary team composed of a legally constituted farmers' group, scientists, agro-economists, and an agronomist who is the link between all parties involved in the project. General activities that have to be undertaken are set out by the Drainage Basin Management Program, but the selection of specific activities and priorities and the way funds are allocated are left up to the farmers involved in the project. Also, farmers receive one-on-one technical support from the agronomist, as well as financial support, to accelerate the adoption of BMPs. The project uses a paired watershed approach. A control and an intervention (Saint-Esprit) watershed are defined, and water quality parameters are measured at the outlet of each watershed. There are 52 farmers on the Saint-Esprit basin, of which 29 participated. These accounted for about 90% of the agricultural area. The evolution of water quality on the control watershed can be compared with that on the intervention watershed.

McGill University is the scientific partner in the Saint-Esprit watershed project and was assigned four tasks: (1) define and characterize the environmental problems related to agricultural activities on the watershed and suggest remedial actions; (2) monitor discharge and water quality at the outlet of the two watersheds and analyze the data as a function of the agricultural activities; (3) develop a methodology and associated tools for targeting conservation activities and assessing the potential impacts of conservation practices; and (4) assess the economic impacts of the soil and water conservation projects implemented at the farm and watershed scales.

3.1.2 The Saint-Esprit Area

This section is derived from Enright et al. (1995). The conditions described below were those prevailing in the Saint-Esprit basin in the period 1993-94, prior to the adoption of conservation practices. The Saint-Esprit watershed has a rolling topography. Globally, the difference in elevation from the outlet and the top of the basin is 40 meters. Most of the land has slopes from 0 to 3%. The land with slopes greater than 5% is stony and under forested cover. With respect to soils, there are twenty-one identified soil series within the boundaries of the watershed. About 50% of the total area has light soils (coarse sand to silt loam). Soil samples showed an average organic matter content of 4.21%. More than 64% of the land in the basin is cultivated. Hay and pasture account for 25% of the cultivated area. Corn is the major annual crop, followed by other cereals and vegetables. Fifty-five percent of the annual crops are grown on heavy textured soils and 38% on light textured soils. The animal density in the basin is 0.8 animal units per hectare, which is below the carrying capacity of the area as estimated by the Ministry of Environment. Of the nineteen farms with animals in the basin, nine are dairy farms; the others are swine, beef cattle and poultry farms.

There were no water quality data available on this particular watershed, although it has been shown that the L'Assomption River, and several of its tributaries, of which Saint-Esprit is one, were polluted by agricultural sources, mainly animal production. Since animal production in the study area is not as intensive as in other areas of the L'Assomption basin, it is thought that in the Saint-Esprit watershed the primary impact on water quality is due to the production of annual crops, such as corn, cereals and vegetables. With respect to erosion only, the combination of rolling topography, intensive cultivation and light textured soils on a large area of the basin indicates a risk of erosion. Indeed the soil is left bare for long periods of time and the amount of residues left at cultivation is minimal, especially for fields used for vegetable production. Cultivation in close proximity to ditches creates an instability problem of the ditch banks and thus a source of sediments in the water.

3.2 Practices and Crop Budgets

3.2.1 Data Collection Methodology

Since on-farm trials of alternative farming practices were performed by farmers, economic data were primarily collected at the farm level. Additional information on the agricultural situation of the watershed were obtained from Léger, Lemay and Gaudet (1995) and Dissart et al. (1996). When obvious costs had been omitted from the producer's budgets then these costs were estimated using a number of secondary sources, e.g. Comité de Références Économiques en Agriculture du Québec (CREAQ) budgets. Therefore, the resulting crop budgets are directly linked to the quality of the data which were collected by farmers themselves or during interviews. Economic data refer to the year 1995. When prices were from a different year, they were updated with the farm input price index computed by Statistics Canada. Detailed crop budgets are presented in Appendix 1 in Canadian dollars per hectare.

Revenue estimates were obtained by multiplying the crop yield by its selling price. When crop production was to be used on-farm, it was assumed to have the same selling price. When differentiated yields for conventional and alternative farming practices were not available, the same yield was assumed. In this case the two practices are only comparable on the basis of costs. Income from Assurance Stabilisation du Revenu Agricole (ASRA) was not taken into account for several reasons. First, it cannot really be considered as a production income, i.e. originating from the sale of a crop. Second, there is a temporal difference between the year the crop is grown and the year the corresponding ASRA is paid for. Third, amounts paid do not necessarily reflect production quantity and quality. Fourth, this information was not available on a systematic basis for every farmer.

Several categories of variable costs were distinguished: inputs, services, and crop operations. Inputs are those products used before or during the growing season, i.e. seeds, pesticides, and fertilizers. Services performed on a flat rate ("à forfait") were counted in the service category. Costs associated with other services, i.e. crop insurance, Commission Santé et Sécurité au Travail were not taken into account for the same reasons as ASRA's. Crop operation costs were split into labor and fuel costs. Operator wage was assumed to be equal to $10 per hour. Employee and employer wages were assumed to be the same, since time associated with operation management was not recorded. Farmers were asked to record the duration associated with every crop operation and what tractor was used for that operation. Labor and fuel costs were inferred from this information. When available, machinery repair costs were taken into account.

Since most alternative farming practices required the use of special pieces of equipment, fixed costs were calculated using a machinery inventory that recorded the purchase date and value. Depreciation charges were calculated with the straight-line method, using the formula (Boehlje and Eidman 1984, 61):

$$\text{depreciation per year} = \frac{\text{purchase cost - salvage value}}{\text{years of useful life}}$$

The number of years of useful life was assumed to be 10 years for all machinery. The salvage value was estimated by multiplying the purchase cost by a coefficient related to machinery type. These coefficients were as follows (Boehlje and Eidman 1984, 141): 29.5% for wheel tractors, and stationary power units; 18.9% for combines, cotton pickers, and SP windrowers; 16.5% for balers, blowers, forage harvesters, and SP sprayers; 17.7% for all other field machines. Depreciation per hectare was obtained by dividing by the total farm hectares. Although some machinery purchases were subsidized by the project, those items were counted at their market price in final crop budgets so as not to bias alternative practices profitability.

3.2.2 Selection of Farmers

There was a two-stage selection process for watershed farmers to be included in the model. The first stage was based on the availability of economic data. Data were available for only 7 producers out of 29 in the watershed. The second stage of the selection process was based on five criteria: (1) the reliability of the available economic data, (2) the crops grown and the tested sustainable practices, (3) the type of animal husbandry, (4) hectarage, and (5) erosion values relative to the rest of the watershed. Two out of the seven remaining producers had economic data for the year 1994 only. As data from this year were of a much lesser quality than 1995 data, these two producers were not selected. Of the five remaining producers, one grew vegetables only. If incorporated in the model, there could not have been substitution between crops when implementing increasing erosion constraints for that farm. Since another producer also grew vegetables, the former was not selected. The four remaining producers were characterized as follows: one with grain, hay and dairy production; one with vegetable, grain and hog production; one with grain and egg production; the last one with grain and broiler production. The first two were selected because they had representative crop and animal productions in Quebec in general and the Saint-Esprit watershed in particular. The remaining two farms were similar in terms of production types. But the last one was 88 hectares smaller than the third one and was not selected.

Erosion values were computed for every farm field in the watershed. Results showed the three selected farms were representative of the rest of the watershed in terms of erosion values. For the rest of the study, these farms will be referred to as Farm A, Farm B, and Farm C. Characteristics of Farms A, B and C are presented in Table 3.1. Since forested, residential, pasture and unknown use areas were excluded from the analysis, these values do not correspond to total farm and watershed areas but to crop cultivated (including hay) areas only.

Table 3.1 Farms A, B and C: hectarage and number of fields

	Farm A	Farm B	Farm C
Hectarage (ha)	53.29	33.58	134.17
% of watershed hectarage	4.57	2.88	11.50
Number of fields	21	13	25
% of watershed fields	4.54	2.81	5.41

3.2.3 Alternative Farming Practices and Crop Budgets

Because of software limitations (see section 3.5), every farm was allowed to grow a total of five combinations of crops and farming practices only. Each farm grew corn (conventional and alternative farming practices) which is the predominant crop in the Saint-Esprit area and presents the highest net margins. Each farm was also allowed to grow hay (alfalfa) because it is very efficient from the viewpoint of erosion reduction. The last crop (conventional and alternative farming practices) was selected according to the necessity of satisfying animal nutrient requirements.

Each of the tested alternative farming practices was aimed at reducing soil erosion. One can distinguish two types: 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. Residues left on the topsoil are recognized as a way to protect soil against erosion. This objective is reached with most tillage practices except plowing. Reduced-till is done with such equipment as a chisel, a hoe, a cultivator, or a harrow. Green manure consists of sowing a crop right after the previous one (main crop) has been harvested. During the fall seedbed preparation for the next main crop, that crop is buried and becomes a green manure. Before the next main crop is sown, the future green manure protects the soil against erosion. After it is buried, it provides more organic matter to the soil which increases protection against erosion. Finally, once buried, it becomes an organic fertilizer and provides nutrients to the next main crop. Simplified crop budgets for each practice and farm included in the model are presented in Tables 3.2, 3.3 and 3.4.

Table 3.2 Simplified crop budgets for Farm A

Practice (/ha)	BC[1]	BG[1]	CR[1]	CN[1]	H[1]
Yield (kg)	3,500	3,500	7,534	7,027	5,594
Income ($)	553.00	553.00	1,318.45	1,229.72	373.77
Variable costs ($)	(393.87)	(413.50)	(626.19)	(570.91)	(196.94)
Fixed costs ($)	(53.89)	(53.89)	(58.49)	(58.49)	(76.07)
Net margin ($)	105.24	85.61	633.77	600.32	100.76

[1] BC: conventional barley; BG: green manure barley; CR: corn reduced-till; CN: corn no-till; H: hay

For information on data and estimation sources and assumptions, see Appendix 1

Table 3.3 Simplified crop budgets for Farm B

Practice (/ha)	CP[1]	CR[1]	SP[1]	SN[1]	H[1]
Yield (kg)	9,630	9,442	3,100	2,676	5,594
Income ($)	1,685.25	1,652.35	1004.40	867.02	373.77
Variable costs ($)	(732.37)	(702.28)	(583.93)	(564.28)	(196.94)
Fixed costs ($)	(109.23)	(109.23)	(109.26)	(129.09)	(76.07)
Net margin ($)	843.65	840.84	311.21	173.65	100.76

[1] CP: corn plow; CR: corn reduced-till; SP: soybeans plow; SN: soybeans no-till; H: hay

For information on data and estimation sources and assumptions, see Appendix 1

Table 3.4 Simplified crop budgets for Farm C

Practice (/ha)	SP[1]	SN[1]	CP[1]	CN[1]	H[1]
Yield (kg)	3,900	3,366	9,286	8,492	5,594
Income ($)	1,263.60	1,090.58	1,625.05	1,486.10	373.77
Variable costs ($)	(483.22)	(456.75)	(410.38)	(339.22)	(196.94)
Fixed costs ($)	(86.24)	(90.25)	(104.78)	(104.78)	(76.07)
Net margin ($)	694.14	543.58	1,109.89	1,042.10	100.76

[1] SP: soybeans plow; SN: soybeans no-till; CP: corn plow; CN: corn no-till; H: hay

For information on data and estimation sources and assumptions, see Appendix 1

3.2.4 Discussion of Economic Data

Data were not of excellent quality and several estimations had to be made (see Appendix 1). According to farmers' data, only Farm A produced hay to feed to its dairy cattle. But growing hay reduces erosion by so much that it was decided to allow Farms B and C to grow it also. It was assumed Farms B and C would produce hay with the same net margin as Farm A. With respect to barley, yields for the conventional and the alternative practices were the same. This is because there was no yield differentiation at harvest and no other data were available for this farm and for any other farm in the watershed. However, the type of fertilizer used in the two practices was different, reflecting the contribution of green manure.

With respect to corn, only Farm C was allowed to switch from corn plow to no-till. This is because Farm C presented the highest erosion values. On the other hand, Farm A was already using a reduced-till practice on a regular (conventional) basis. Farm B was allowed to switch from corn plow to reduced-till. Farms A, B, and C grew conventional corn and some alternative corn but not aimed at reducing soil erosion. Budgets were created using some data from MAPAQ and applying a proportionality rule. For alternative soybeans budgets, a no-till adapted sower replaced the conventional one in fixed costs. Crop operations costs were changed accordingly. Changes in yields were estimated from MAPAQ data.

3.3 Animal Nutrient Data

3.3.1 General Considerations

Animal nutrient requirements were estimated from three sources: (1) herd inventories for Farms A, B, C; (2) Comité de Références Économiques en Agriculture du Québec (CREAQ) data; and (3) National Research Council (NRC) data. Inventories provided data on animal types for a given herd and for the year 1995. "Life cycles" were derived for the year 1995, i.e. the different phases which a given animal type would go through for that year. Nutrient requirements were then estimated for each animal type and consequently for the whole herd. It should be understood that these estimates are sometimes based on diets and dietary energy concentrations provided by NRC. Since crops grown by selected farmers may not be exactly the same, values given below should be taken as less than accurate estimates. Moreover, as NRC (1994, 61) stated: "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". Farm A had dairy cattle, Farm B produced swine and Farm C immature chickens and laying hens. Nutrient estimates varied from one animal production to another, but in general included energy, protein and macro minerals. Nutritional values of the crops grown by the three farms can be found in section 3.3.5.

3.3.2 Farm A

Farm A had dairy cattle with the following characteristics:

(1) 48 cows. The average weight was 650kg and they produced 9,050kg of milk per year, 29.5 kg of milk per day, with 4% milk fat. Their yearly life cycle was 307 days of lactation and 58 dry days. Insufficient data were available to take account of live weight variations during lactation.

(2) 30 heifers. The average weight was 100kg at the beginning of the year, with a weight gain of 0.6kg per day. By the end of the year a heifer weighed 319kg, was about 16 months old and was not bred (CREAQ 1994b). Their yearly life cycle was 365 days of growth.

The following elements were retained to estimate the dairy cattle nutrient requirements. Dry Matter Intake (DMI), which "is an important criterion when formulating diets, especially for high yielding cows" (NRC 1988b, 2). "The use of the [Total Digestible Nutrients] TDN unit is retained [...] because many of the available data both for the energy requirements of animals and for the value of feeds are reported as TDN" (NRC 1988b, 6). "[...] One feed value [Net Energy for Lactation] (NEL) expresses the requirements for maintenance, pregnancy, milk production and live weight change" (NRC 1988b, 6). Other considered energy requirements were Metabolisable Energy (ME) and Digestible Energy (DE) for both cows and heifers; and Net Energy for body Gain (NEG) and Net Energy for Maintenance (NEM) for heifers only. The [Degraded Intake Protein] DIP and [Undegraded Intake Protein] UIP system, based on absorbed protein (AP) was not used to estimate the nutrient requirements of dairy cattle because "the lack of extensive data on the undegradability of protein in feeds limits the use of the absorbed protein (AP) system in this instance" (NRC 1988b, 15). Other considered nutrients were Calcium (Ca) and Phosphorus (P). Table 3.5 shows the dairy cattle nutrient requirements.

Table 3.5 Farm A, dairy cattle nutrient requirements

Element	Heifers[1]	Cows[2]	Total herd
Dry Matter Intake (kg)	45,502	381,498[3]	427,000
Total Digestible Nutrients (kg)	30,482	223,057	253,539
Net Energy for Maintenance (Mcal)	46,821	0	46,821
Net Energy for body Gain (Mcal)	17,309	0	17,309
Net Energy for Lactation (Mcal)	0	510,745	510,745
Metabolisable Energy (Mcal)	115,221	854,965	970,186
Digestible Energy (Mcal)	134,335	982,972	1,117,307
Crude Protein (kg)	6,336	48,549	54,885
Calcium (kg)	217	1,898	2,115
Phosphorus (kg)	141	1,213	1,354

[1] based on NRC (1988b), Table 6-2

[2] based on NRC (1988b), Table 6-3

[3] DMI estimation for cows based on NRC (1988b), Table 6-1

3.3.3 Farm B

Farm B had swines with the following characteristics:

(1) 12 gilts, purchased at two months old and first bred at eight months (CREAQ 1991). They weighed 124.74kg at mating and, once bred, their nutrient requirements were identical to sows' (CREAQ 1994a). Their yearly life cycle was 183 days of growth, then 114 days of gestation, then 23 days of lactation, then 12 days of reconditioning, and 33 days of gestation again.

(2) 135 sows, weighing 160kg at mating and 185kg at postfarrowing. Each sow produced 19.2 weaned pigs/year. Their yearly life cycle was 114 days of gestation (CREAQ 1994a), then 23 days of lactation, then 12 days of reconditioning (CREAQ 1994a); there were 2.44 cycles per year.

(3) 2,686 piglets were born on the farm. They grew from 1 to 16.33kg in 61 days. They were sold at 2 months old. Their yearly life cycle was 61 days of growth.

(4) 3 adult boars were kept on the farm and weighed 162.5kg each. Their yearly life cycle was 365 days of maintenance.

The following elements were retained for the swine nutrient requirements. "[...] DE is preferable in describing the energy requirements of swine and the energy content of swine feeds because DE is more easily and precisely determined than ME. Also, DE values are available for most of the commonly used feeds" (NRC 1988a, 2). Crude fiber content requirements were not taken into account because "[...] utilization of crude fiber by nonruminants has been shown to vary considerably [...]" (NRC 1988a, 5). Other nutrients included in the analysis were Crude Protein (CP), Calcium (Ca) and total Phosphorus (P). Table 3.6 shows the swine nutrient requirements.

Table 3.6 Farm B, swine nutrient requirements

Element	Gilts[1]	Sows[2]	Piglets[3]	Ad. boars[4]	Total herd
Digestible Energy (Mcal)	35,822	414,245	337,227	6,899	794,192
Metabolisable Energy (Mcal)	34,444	397,576	322,132	6,680	760,832
Crude Protein (kg)	1,382	15,120	19,003	250	35,756
Calcium (kg)	66	921	737	16	1,740
Phosphorus, total (kg)	53	737	621	12	1,424

[1] based on NRC (1988a), Tables 5-2, 5-3, 5-6, 5-7; estimation of ME using the NRC formula ME = DE / 100 * (96 - [.202 * % of crude protein]) (NRC 1988a)

[2] based on NRC (1988a), Tables 5-3, 5-6, 5-7; estimation of ME using the NRC formula ME = DE / 100 * (96 - [.202 * % of crude protein]) (NRC 1988a)

[3] based on NRC (1988a), Table 5-2

[4] based on NRC (1988a), Table 5-4

3.3.4 Farm C

Farm C raised immature chickens and laying hens with the following characteristics:

(1) 25,530 immature chickens per year. These were replacement animals for laying hens, grown from 1 day to 18 weeks. They started laying eggs at 20 weeks old. Their yearly life cycle was 18 weeks of growth.

(2) 25,030 laying hens per year. They entered the building at 18 weeks old and 1.315kg. They started laying eggs at 20 weeks old, remained 50 weeks in production and weighed 1.814kg. They were given a daily ration of 110g/hen with a dietary concentration of 2900 kcal/kg in nitrogen-corrected metabolisable energy. The assumed rate of egg production was 90%. Their yearly life cycle was 2 weeks of growth and 50 weeks of production.

The following elements were retained for the poultry nutrient requirements. Since "Birds excrete feces and urine together via a cloaca, [...] it is difficult to separate the feces and measure digestibility. As a consequence, DE values are not generally employed in poultry feed formulation" (NRC 1994, 4). "A correction for nitrogen retained in the body is usually applied to yield a corrected-nitrogen ME (ME_n) value. ME_n [...] is the most common measure of available energy used in formulation of poultry feeds" (NRC 1994, 4). Net Energy (NE) was not retained because "there is no absolute NE value for each feedstuff" (NRC 1994, 4). Other considered nutrients were Crude Protein (CP), nonphytate Phosphorus (npP) and Calcium (Ca) which is particularly important since "the onset of egg production creates a need for more calcium to make the eggshell" (NRC 1994, 25). Table 3.7 shows the poultry nutrient requirements.

Table 3.7 Farm C, poultry nutrient requirements

Element	Immature chickens[1]	Laying hens[2]	Total flock
N-corrected Metab. Energy (Mcal)	533,564	2,794,600	3,328,164
Crude Protein (kg)	29,998	131,408	161,405
Calcium (kg)	1,827	28,472	30,298
nonphytate Phosphorus (kg)	627	2,190	2,817

[1] based on NRC (1994), Tables 2-1 (white-egg-laying strains) and 2-2 (white-egg-laying strains)

[2] based on NRC (1994), Tables 2-3 and 2-4 (white-egg-layers)

3.3.5 Nutritional Value of Crops Grown by Farms A, B and C

Table 3.8 provides the nutritional values of the crops grown by Farms A, B, and C. The unit of measure is given for each nutritional element for each crop. As nutritional values for corn grain, dent yellow, were not available for dairy cattle, equivalent nutritional values for corn grain, cracked, were used to complement the data.

Table 3.8 Nutritional value of crops grown by Farms A, B and C

Element	Unit	Barley[1]	Corn[2]	Hay[3]	Soybeans[4]
International Feed number[5]		4-00-549	4-02-935 4-20-698	1-00-063	5-04-612
Dry Matter	kg/t	887	887	900	900
Total Digestible Nutrients	kg/t	840	800	580	870
Digestible Energy	Mcal/t	3,410	3,530	2,560	3,760
Metabolisable Energy	Mcal/t	3,165	3,270	2,130	3,403
N-corrected Metab. Energy	Mcal/t	2,640	3,350	n/a	2,440
Net Energy for Maintenance	Mcal/t	2,060	1,940	1,240	2,160
Net Energy for body Gain	Mcal/t	1,400	1,300	680	1,480
Net Energy for Lactation	Mcal/t	1,940	1,840	1,300	2,010
Crude Protein	kg/t	120	90	170	507
Calcium	kg/t	0.4	0.3	14.1	2.7
Phosphorus	kg/t	3.6	2.8	2.4	6.5
nonphytate Phosphorus	kg/t	1.7	0.8	n/a[6]	2.2

Sources: NRC (1994, 1988a, 1988b)

[1] Barley, grain

[2] 4-02-935: Corn, dent yellow, grain; 4-20-698: Corn, grain, cracked

[3] Alfalfa, hay, sun-cured, midbloom

[4] Soybean seeds, dehulled, meal solvent extracted

[5] First digit is class of feed: 1, dry forages and roughages; 4, energy feeds; 5, protein supplements; the other five digits are the International Feed Number.

[6] n/a: not available

3.4 Erosion Data

3.4.1 GIS Data

A SPANS/GIS database was developed for the Saint-Esprit watershed project (Mousavizadeh et al. 1995). Data layers accommodate both public domain and site specific information. The public domain information consists of cadastre, hydrography, watershed boundary, road, land use, soil information, elevation points and topographic contour line, slope, and land ownership. The site specific information is farm plans, soil fertility, fertilizer, manure and pesticide applications, and crop yield data. From this database a specific set of data was generated by Mohammad Mousavizadeh (Department of Agricultural and Biosystems Engineering, McGill University) for erosion calculation purposes. First of all a basemap of the watershed was created, only featuring areas of the watershed with the following land uses: grains, vegetables, and hay. The other land uses (i.e., forest, residential, pasture, unknown use) were removed in the resulting basemap. By performing appropriate overlaying operations, the following data were made available on a sub-field basis: slope percent, soil texture, soil series, area, field number, ownership, and 1995 land use. Those various tabular data were exported into a spreadsheet format and recombined for each field. Field boundary, cultivated area, hydrography, soil texture, soil series and slope maps are in Appendix 3.

3.4.2 RUSLEFAC

Erosion is defined as the movement of soil by water and wind. It occurs in all regions of Canada under a wide range of land uses. It is a widespread environmental challenge facing Canadians today (Wall et al. 1997). Erosion causes both on-farm and off-farm problems for agriculture in Canada. On-farm impacts of erosion concern not only the immediate loss of topsoil from Canadian cropland, but also a long-term loss of productivity. Off-farm impacts include: sediment, bacteria from organic matter, nutrients and pesticides in surface water. This has a negative impact on water quality and has an economic consequence on surface water use (Wall et al. 1997). Quantitative methods to predict erosion have not been developed for specific Canadian conditions.

The Universal Soil Loss Equation (USLE) is a field scale model which was developed in the United States. Use of USLE in Canada has been limited since much of the information required to determine soil erosion rates has not been available (Wall et al. 1997). The Revised USLE (RUSLE) was developed as an interim improvement on the USLE before a new generation of soil erosion process models can be estimated. Until now, the RUSLE soil loss equation has not been tested or modified for use in Canada (Wall et al. 1997). The RUSLE For Application in Canada (RUSLEFAC) has been prepared to provide information pertinent to Canadian conditions in order to use the RUSLE in Canada.

The purpose of the RUSLEFAC is "to predict the longterm 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:

$$A = R * K * L * S * C * P$$

where:

A is the estimated potential, long term average annual soil loss (t/ha) per year

R is the rainfall factor (MJ.mm/ha/h)

K is the soil erodibility factor (t.h/MJ/mm)

L and S are the slope length and steepness factors, respectively (dimensionless)

C is the cropping-management factor (dimensionless)

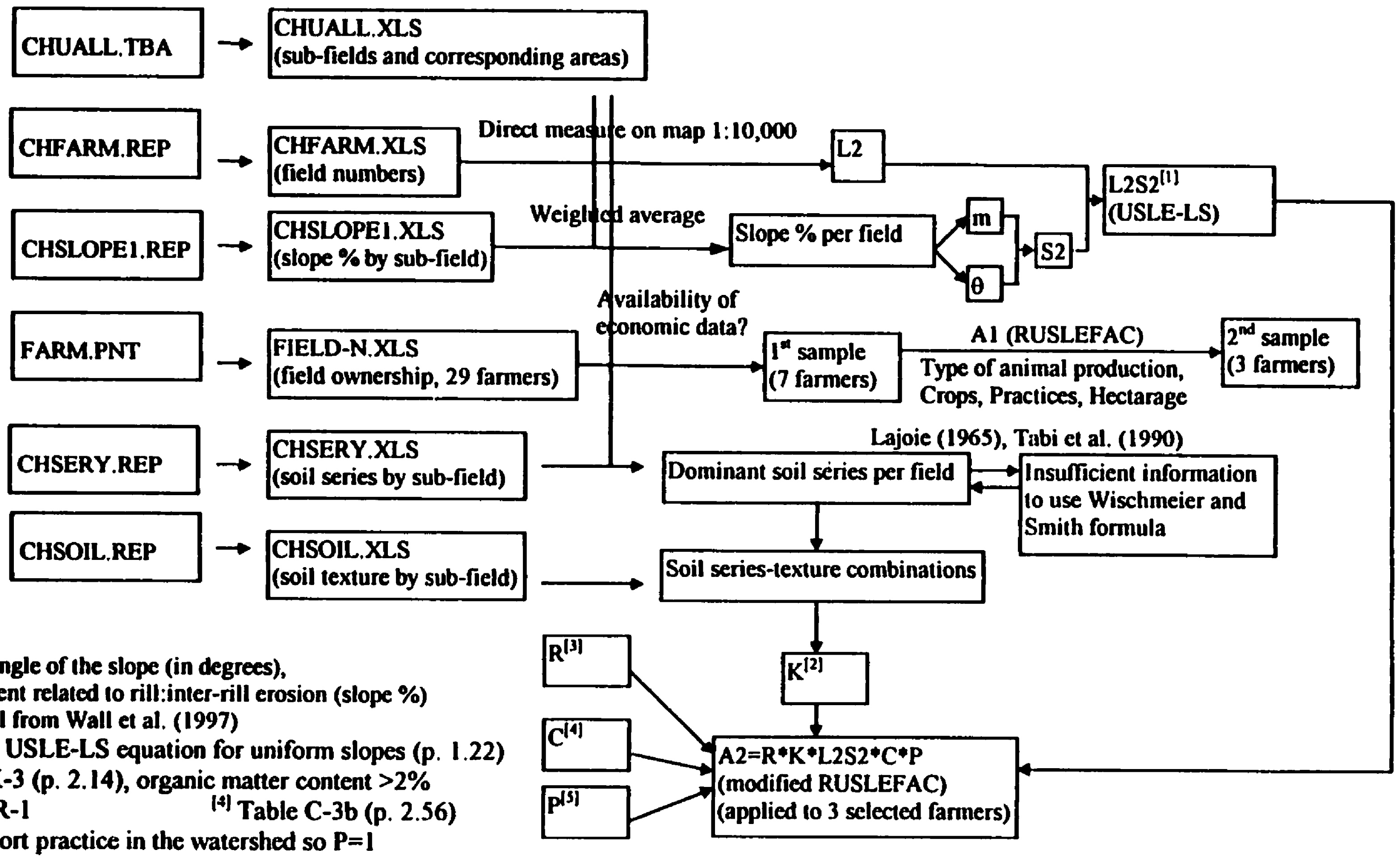
P is the support practice factor (dimensionless)

Calculation of erosion values was a two-stage process tied to the selection of watershed farmers. Differences between the two sets of erosion values were limited to the LS factors only. The first set was calculated using the proposed RUSLEFAC table for these factors. Results showed the three selected farms were representative of the watershed in terms of erosion values. The analysis also showed LS factor values were biased due to field shapes which are long and narrow. Consequently, a different method was used to calculate more accurate LS factor values for the three selected farms only. Thus, a second set of more precise erosion values was calculated using a "modified" RUSLEFAC method for these farms. The methodology used to calculate the two sets of erosion values and the farm selection process is described in Figure 3.1 and explained below.

3.4.3 R Factor

R is the rainfall and runoff erositivity index required to predict erosion by water using the USLE. It was determined by: (1) locating the area of interest (Eastern Canada in this case) on the isoerodent map indicating annual R values for Ontario and Quebec (Wall et al. 1997, 2.4); and (2) extrapolating the area of Saint-Jacques-de-Montcalm relatively to R factor contours. This generated a value applicable to all fields: 1,312.50 MJ.mm/ha/h.

Figure 3.1 Calculation of erosion values and selection of farmers



Notes: θ: angle of the slope (in degrees),
m: coefficient related to rill:inter-rill erosion (slope %)
Sources: all from Wall et al. (1997)
[1] original USLE-LS equation for uniform slopes (p. 1.22)
[2] Table K-3 (p. 2.14), organic matter content >2%
[3] Figure R-1 [4] Table C-3b (p. 2.56)
[5] no support practice in the watershed so P=1

3.4.4 K Factor

The soil erodibility factor (K) represents the rate of soil loss per unit area as measured on a 3.7*22m plot (Wall et al. 1997). "K is a quantitative measure of a soil's inherent susceptibility/resistance to erosion and the soil's influence on runoff amount and rate" (Wall et al. 1997, 1.16). The spreadsheet field information file was exhaustive since records were available for every sub-area within a given field corresponding to a soil series and/or soil texture. However, according to Wall et al. (1997, 1.20), "a separate K value should be determined for each soil series associated with the map unit, or for the "predominant" soil series in the unit. Do not average the K values, as a combined value will not represent the inherent erodibility of any soil type and will produce misleading results". For this reason, a "predominant" soil series and soil texture were determined for each field on the basis of sub-area hectarage. To get as precise information as possible for each field, it was decided to calculate a K value for a specific soil using the equation (Wall et al. 1997):

$$100\,K = 2.1\,M^{1.14}\,(10^{-4})\,(12 - a) + 3.25\,(b - 2) + 2.5\,(c - 3)$$

where:

M = (% silt + % very fine sand) * (100 - % clay)

a is % organic matter, b is the soil structure code used in soil classification

c is the profile permeability class

Two sources on soil information were available for the Saint-Esprit watershed: Lajoie (1965) and Tabi et al. (1990). Although containing more information than Lajoie (1965) on the physical and chemical properties of the soil series in the given area, Tabi et al. (1990) did not provide information on very fine sand. Very fine sand corresponds to particles with a diameter in the range 0.10-0.05mm (Agriculture Canada Expert Committee on Soil Survey 1987) and Tabi et al. (1990) only has information about particles 2-1mm diameter and more. Information about percent clay, percent sand, percent silt and percent organic matter was not available for every series in the watershed. Hence it was not possible to use the soil erodibility monograph proposed by Wall et al. (1997). Thus soil erodibility values for common surface textures were used. This table (Wall et al. 1997, 2.14) provides K factor values for different textural classes as a function of organic matter content. Therefore each soil series in the watershed was associated with one or two soil textures. Each textural class was converted to a "readable" soil texture (i.e., listed in Wall et al. 1997) on the basis of a comparison between the spreadsheet analysis, Lajoie (1965) and Tabi et al. (1990). Resulting values are presented in Table 3.9.

Table 3.9 Soil series, textures and K factor values in the Saint-Esprit watershed

Soil series	Associated texture[1]	"Readable" texture[2]	K value[3]
Alluvium (Auh)	clay to clay loam	clay loam	0.037
Alluvium (Aul)	fine and v. f. sandy loam	fine sandy loam	0.022
Aston (An)	loamy sand	loamy sand	0.005
Aston (An)	sand	sand	0.001
Baudette (Bd)	silt loam to silty clay loam	silty clay loam	0.04
Belle-Riviere (Br)	sandy loam	sandy loam	0.016
Chicot (C)	fine and very fine sandy loam	fine sandy loam	0.022
Dalhousie (D)	clay loam	clay loam	0.037
Joliette (Jo)	sand	sand	0.001
Laplaine (Lp)	clay	clay	0.028
Péningue (Pg)	sand	sand	0.001
Perrot (P)	sandy loam	sandy loam	0.016
Soulanges (S)	fine and very fine sandy loam	fine sandy loam	0.022
St-Bernard (Bn)	loam to sandy loam	loam	0.038
St-Bernard (Bn)	loam	loam	0.038
St-Bernard (Bns)	sandy loam	sandy loam	0.016
St-Laurent (Lr)	clay	clay	0.028
St-Laurent (Lrl)	clay loam	clay loam	0.037
Ste-Rosalie (R)	clay	clay	0.028
Ste-Rosalie (R)	clay to clay loam	clay	0.028
Ste-Rosalie (Rl)	clay loam	clay loam	0.037
Ste-Rosalie (Rs)	sandy clay	sandy clay loam	0.026
St-Urbain (U)	clay loam	clay loam	0.037
St-Urbain (U)	silty clay loam	silty clay loam	0.04

[1] from spreadsheet analysis, according to biggest sub-area acreage
[2] from a spreadsheet analysis, Lajoie (1965) and Tabi et al. (1990) comparison
[3] from Wall et al. (1997, 2.14); the organic matter content was assumed to be >2% since every soil series listed in Tabi et al. (1990) presented such a value

3.4.5 LS Factor

The slope factor "accounts for the effects of slope angle and length on erosion. [...] The LS factor represents a ratio of soil loss under the given conditions to that at a site with the "standard" slope steepness of 9% and slope length of 22.13m" (Wall et al. 1997, 1.22). The original equation 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 which describes the nature of the erosion process. Tables have been developed "to provide a simple and rapid means of solving the equation for slopes from 0.2 to 20% and slope lengths from 2 to 300m" (Wall et al. 1997, 1.23). 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 (not applicable to thawing soils), Wall et al. (1997) recommend the use of this table.

Sixteen classes of slope corresponding to classes used in Wall et al. (1997) were developed from the GIS data: <0.2%, 0.2-0.5%, 0.5-1.0%, 1-2%, 2-3%, 3-4%, 4-5%, 5-6%, 6-8%, 8-10%, 10-12%, 12-14%, 14-16%, 16-20%, 20-25%, 25-30%. These classes were converted to numerical values by taking the mid-point value of the interval. Using field sub-area slope values, a weighted average slope was then calculated for each field. In order to be able to read LS values in the table provided, these values were converted back into the same classes.

The square root of the area was taken as the field slope length. However, assuming square fields is wrong. The French seigneurial system, which was used in Quebec, allocated land on the principle that every field had to have access to water (for transportation purposes). As a result, the majority of the fields are perpendicular to streams and fields tend to be long and narrow. Thus, for the LS factor, the slope length is the length of the field. However, there is no way to determine how much a field is longer than it is wider. For this reason, the square root of the field area was systematically adjusted to the upper class limit. Slope lengths greater than 300m, which is the upper limit length in the LS table, were set to equal 300m. The resulting combinations of slope values and slope lengths were used to determine the first set of LS factor values.

Once Farms A, B, and C were selected, it was much easier (59 versus 462 fields) to measure each field slope length manually on the cadastral map (1:10,000). The second set of LS factor values were calculated using the original USLE equation for a uniform slope (Wall et al. 1997):

$$LS = (\lambda / 22.13)^m * (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065)$$

where:

λ is the slope length of the site (metres)

θ is the angle of the slope (in degrees)

m is a coefficient related to the ratio of rill to inter-rill erosion, and is equal to: 0.5 for slopes of 5% or more, 0.4 for slopes of 3.5 to 4.5%, 0.3 for slopes of 1 to 3%, and 0.2 for slopes of less than 1% (all slopes being estimated to the nearest ½%)

Using this formula it was possible to calculate a second set of LS factor values that had more precise slope lengths (instead of an interval) and slope lengths greater than 300m. These values were used with other factor values to calculate a second set of "modified" RUSLEFAC erosion values for Farms A, B, and C.

3.4.6 C Factor

"The C factor is used to determine the relative effectiveness of soil and crop management systems in terms of preventing or reducing soil loss. A C value is a ratio comparing the soil eroded under a specific crop and management system to continuous fallow conditions" (Wall et al. 1997, 1.32). Wall et al. (1997) produced tables of appropriate C values for specific crops. In order to do so, they state that the following information is required: location, crop or vegetation type, previous crop, tillage. A table with C values based on these information requirements is presented for the Great Lakes/St. Lawrence region. However, many values are missing for Quebec and the existing ones often do not reflect practices adopted by farmers in the Saint-Esprit area. Hence generalized C values for Quebec were used (Wall et al. 1997), according to farmers' crops and tillage practices.

Table 3.10 Generalized C values for Quebec applicable to the Saint-Esprit area

Crop	Conventional till	Conservation till	No-till
Spring grain	0.41	0.36	0.15
Fall grain	0.27	0.22	n/a[1]
Corn (grain)	0.37	0.32	0.15
Soybeans	0.46	0.40	0.28
Hay (alfalfa)	0.02	0.02	0.02
Vegetables	0.56	0.42	n/a[1]

[1] not applicable

Source: Table C-3b (Wall et al. 1997, 2.56)

3.4.7 P Factor

"The P factor accounts for the erosion control effectiveness of support practices. P supports the cover and management factor. The P factor reflects the effect of practices that will reduce the amount and rate of runoff water by modifying the flow pattern, grade, or direction of surface runoff and thus reduce the amount of erosion. [...]. The most commonly used supporting cropland practices are: cross slope cultivation, contour farming, strip cropping, and terracing." (Wall et al. 1997, 1.43). In accordance with Wall et al. (1997), since none on these support practices were used in the watershed, P was set equal to 1 in the RUSLEFAC.

3.4.8 Resulting Erosion Values

A qualitative ranking system was developed based on soil loss tolerance rates (Wall et al. 1997). Five erosion classes were identified: very low (<6t/ha/y), low (6-11t/ha/y), moderate (11-22t/ha/y), high (22-33t/ha/y) and severe

(>33t/ha/y). Analysis of erosion values calculated for each field in the watershed using the RUSLEFAC method are presented in Table 3.11. These values correspond to corn grain with conventional tillage.

Table 3.11 Erosion classes for Farms A, B, C and RUSLEFAC method

Soil erosion class	Farm A	Farm B	Farm C	A+B+C
1 Very low[1]	81 (87)	77 (87)	84 (87)	81 (87)
2 Low	19 (11)	15 (11)	16 (11)	17 (11)
3 Moderate	0 (2)	8 (2)	0 (2)	2 (2)
4 High	0 (0)	0 (0)	0 (0)	0 (0)
5 Severe	0 (0)	0 (0)	0 (0)	0 (0)

[1] % of fields on the farm (% of fields in the watershed) in a given erosion class

According to Wall et al. (1997), soils in class 1 have very slight to no erosion potential. Minimal erosion problems should occur if good conservation methods are used. Long-term sustainable productivity should be maintainable under average management practices. However, the tolerable soil loss limit may be exceeded for soils that are shallow, low in organic matter, of poor structure or previously eroded. For class 2, low to moderate soil losses will occur without the use of crop rotations and cross slope farming (Wall et al 1997). For class 3, moderate to high soil losses will occur unless conservation measures such as conservation tillage, contour cropping and grass waterways are used (Wall et al. 1997). It is interesting to note that percentages of fields in a given erosion class for Farms A, B, C were representative of the rest of the watershed. This contributes to justify the selection of these three farms. Modified RUSLEFAC calculations for Farms A, B and C yielded the following results (Table 3.12) with the same conditions (corn grain with a conventional tillage).

Table 3.12 Erosion classes for Farms A, B, C and modified RUSLEFAC method

Soil erosion class	Farm A	Farm B	Farm C	A+B+C
1 Very low[1]	90 (81)	77 (77)	76 (84)	81 (81)
2 Low	10 (19)	15 (15)	24 (16)	17 (17)
3 Moderate	0	18 (8)	0	2 (2)
4 High	0	0	0	0
5 Severe	0	0	0	0

[1] % of fields on the farm in a given erosion class; figures between parentheses are those calculated with the RUSLEFAC method

There is no particular difference between the two methods as far as erosion classes are concerned. Percentage of fields in a given erosion class are the same for Farm B, while Farm A gains more fields in the very low class and Farm C gains more fields in the low class. Estimates of the average erosion value per hectare weighted by field area are presented in Table 3.13.

Table 3.13 Weighted average erosion per hectare

Method		Farm A	Farm B	Farm C	A+B+C
	Hectarage (ha)	53	34	134	221
RUSLEFAC	Total erosion (t)	171	143	466	780
RUSLEFAC	Weighted average (t/ha)	3.21	4.26	3.47	3.53
Mod. RUSLEFAC	Total erosion (t)	232	138	590	960
Mod. RUSLEFAC	Weighted average (t/ha)	4.36	4.11	4.40	4.34

Changing the LS factor calculation increased total erosion for Farms A and C while reducing it for Farm B. Farm B was the most sensitive farm to erosion problems and is now the least. Farm C now has the highest average erosion value per hectare, followed by Farm A. However, the average erosion value per hectare for the three farms fall into the very low erosion class. Therefore, erosion problems do not seem to be a widespread problem at the watershed level but rather a localized issue, at the field level.

3.5 The Model

3.5.1 Overview of the Model

The model used to assess the costs of placing an erosion constraint on the farms or the watershed is a Mixed Integer Linear Program (MILP). The objective is to maximize the sum of field net margins, derived from crop budgets, subject to three types of constraints: (1) singleness of field use, (2) animal nutrient requirements, and (3) erosion. Farmers may purchase nutrients from the Rest Of the World (ROW) to satisfy animal needs. No constraint was imposed as to what crops should be grown. To assess the impact of the erosion constraint on the farm and the watershed levels, and to study distributional effects between producers, if the erosion constraint was to be imposed at the watershed versus the farm scale, four models were built: one for each of the three Farms A, B, and C; and one for the watershed. The four models were built using the same types of constraints, decision variables and coefficients. The watershed model is simply the summation of the three others. Resulting models are presented in Appendix 2.

3.5.2 Justification for Use of Single-Period MILP Model

The starting points of this study are crop budgets and erosion data both obtained and/or calculated on a field level, respecting proprietary boundaries. Therefore, the analysis should also be made at the field level. Moreover, when farmers decide to grow a certain crop with a certain practice, they also make their decision on a field-by-field basis, thus developing a cropping plan. Hence using a field as the unit of analysis is a means of replicating the real-world problems for the modeler. Thus, data related to net margins and erosion values were calculated at the field level. Animal nutrient requirements were calculated at the farm level. The model replicates the farmer's decision-making process to allocate land to a certain use given his objective of maximizing his profits (net returns) while satisfying constraints related to animal nutrient requirements and soil loss.

The model investigates the farmer's single period decision regarding (1) profit maximization, (2) satisfaction of animal nutrient requirements, and (3) satisfaction of an erosion constraint. One of the reasons why producers often do not adopt alternative farming practices is the negative impact these practices may have on the short-term farm profits. It is acknowledged that soil loss and the remedial soil conservation practices used to repair these losses have an impact on long-term profits through changes in the productivity of the soil. Farmers often think of production decisions in terms of short-term tradeoffs. Therefore, a single period MILP was used to estimate the short-term impacts of an erosion constraint on farm profits for the year 1995.

3.5.3 Assumptions

The applicability of LP is limited by several assumptions. As in all mathematical models, assumptions are made to reduce the complex real-world problems into a simplified form. These major assumptions are (Turban and Meredith 1985): (1) certainty of data, (2) linearity of objective function, (3) linearity of constraints, (4) nonnegativity of decision variables, (5) additivity of activities, (5) divisibility of variables, and (6) independence of coefficients. Since this model used MILP, divisibility could not be assumed: most of the variables were restricted to whole numbers and thus were indivisible.

To minimize uncertainty regarding the reliability of the results, additional assumptions were made. First, unless it cannot be fed to an animal (i.e., hay to swine and poultry, sold to ROW), crops are used on-farm and grown to satisfy animal nutrient requirements. Second, prices remain constant throughout the year both for product sales and purchased inputs. Third, the watershed model is constituted by the sum of the three farms which are assumed representativity of the Saint-Esprit watershed as a whole. Fourth, there is no adoption of new technology.

Finally, fifth, because exchanges with ROW are extremely limited, there are no transportation costs.

3.5.4 Objective Function

The objective function maximizes the sum of field net margins for one of the three selected farms in the Saint-Esprit watershed or for the watershed, and allows for purchasing feed inputs from ROW. Purchased inputs from ROW are real variables respecting the divisibility assumption. 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, extrusion cost was added to the purchase price. Field use is represented by a dummy (0/1) variable. Since there are five potential uses for each field, the number of required dummy variables for a given model is five times the number of fields for the considered farm or for the watershed. But the version of LINDO used dated back to 1985 and was limited to a maximum of 200 dummy variables. With 59 fields currently in the watershed, and a need for 59*5 = 295 dummies, it would not have been possible to run the model. Consequently the number of fields was reduced so that about 90% of the original hectarage was covered (Table 3.14). Fields were sorted by descending hectarage and selected for further model building purposes up to a cumulative percent area of 90%. Animal nutrient requirements were reduced accordingly.

Table 3.14 Final hectarages and field numbers

	Farm A	Farm B	Farm C	A+B+C
Old field number	21	13	25	59
New field number	15	8	16	39
Old hectarage	53.29	33.58	134.17	221.04
New hectarage	47.77	30.26	119.13	197.16
% of original hectarage	89.64	90.11	88.79	89.20

In mathematical terms, the objective function is summarized as follows:

$$\text{Max } \Sigma\, \alpha X_{ijk} - \Sigma\, \varepsilon ZR_{il}$$

where:

X is a field activity (0/1 variable)

α is the field net margin ($)

i is the farm code

j is the field number

k is the crop/practice code

ZR is crop l sold by ROW to farm i (real variable)

l is the crop code

ε is the purchased input price ($/t)

Objective function elements for the four models are presented in Table 3.15.

Table 3.15 Elements of the objective function for the four models

Elements	Farm A	Farm B	Farm C	A+B+C
i	A	B	C	A, B, C
j	1 to 15	1 to 8	1 to 16	39
k[1]	BC, BG, CR, CN, H	CP, CR, SP, SN, H	SP, SN, CP, CN, H	BC, BG, CP, CR, CN, SP, SN, H
Number of X	5*15 = 75	5*8 = 40	5*16 = 80	195
l[2]	B, C, H	C, S	C, S	same as A, B, C
Number of ZR	3	2	2	7

[1] CP: corn plow; CR: corn reduced-till; SP: soybeans plow; SN: soybeans no-till; H: hay; BC: conventional barley; BG: green manure barley; CN: corn no-till

[2] B: barley; C: corn; H: hay; S: soybeans

3.5.5 Constraints

3.5.5.1 One Field, One Production

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

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

where:

X is a field activity (0/1)

i is the farm code, j is the field number, k is the crop/practice code

3.5.5.2 Animal Nutrient Requirements

Table 3.16 Summary of animal nutrient requirements

	Farm A	Farm B	Farm C	A+B+C
Production	dairy (D)	swine (S)	poultry (P)	D, S, P
Nutrients[1]	DMI, TDN, DE, ME, NEM, NEG, NEL, CP, Ca, P	DE, ME, CP, Ca, P	ME_n, CP, Ca, npP	same as A, B, C
From ROW[2]	B, C, H	C, S	C, S	same as A, B, C

[1] 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: Metabolisable Energy; DE: Digestible Energy; CP: Crude Protein; Ca: Calcium; P: Phosphorus; ME_n: nitrogen-corrected Metabolisable Energy; npP: nonphytate Phosphorus

[2] B: barley; C: corn; H: hay; S: soybeans

The second set of constraints forces the model to satisfy animal nutrient requirements. Animal nutrient requirements are summarized in Table 3.16. These constraints take account of nutrients provided by crops grown on-farm and by purchased inputs from ROW. For a given model, the number of constraints of this type depends on the type of animal production. Hence 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 is mathematically summarized as follows:

$$\Sigma\ \beta X_{ijk} + \Sigma\ \delta ZR_{il} >= B_m$$

where:

X is a field activity (0/1)

i is the farm code, j is the field number, k is the crop/practice code

β is the field contribution to satisfying animal needs in nutrient m

ZR is crop l sold by ROW to farm i (real), l is the crop code

δ is the crop contribution to satisfying animal needs in nutrient m

B_m is the animal nutrient requirement in element m

3.5.5.3 Erosion

The third set of constraints forces the model to satisfy the erosion constraint. For a given model, there is only one constraint of this type. Hence there is 1 constraint of this type for models A, B, and C, and there is 1 constraint of this type for the watershed model. This is mathematically summarized as follows:

$$\Sigma\ \gamma X_{ijk} <= C$$

where:

X is a field activity (0/1)

i is the farm code, j is the field number, k is the crop/practice code

γ is the field contribution to erosion, C is the erosion target

3.5.6 General Framework of the Models

The general framework of the four models is summarized in Table 3.17.

Table 3.17 General framework of the models

Row identification and number of constraints for each model	Field activities X	ROW Inputs ZR	RHS
Objective function	α	$-\varepsilon$	Max
One field, one production: 15 for A, 8 for B, 16 for C, 39 for W	1		= 1
Animal nutrient requirements: 10 for A, 5 for B, 4 for C, 19 for W	β	δ	$>= B_m$
Erosion: 1 for A, B, C, W	γ		<= C

3.6 Conclusion

Mixed Integer Linear Programming (MILP) was used to assess the costs of implementing an erosion constraint at the farm and the watershed levels. This program was based on three types of data: crop budgets, animal nutrient requirements data, and erosion data.

The Saint-Esprit watershed project was one of the projects initiated to address the issue of agricultural nonpoint source pollution in Quebec. It was based on a multidisciplinary effort of farmers, university people and an agronomist. The project used a paired watershed (control and intervention) approach. On the intervention watershed, farmers received technical and financial support to accelerate the adoption of Best Management Practices (BMPs). Most of the activities taking place on the basin were agricultural, especially annual crops with a predominance of corn. The combination of rolling topography, intensive cultivation and light texture soils on a large area of the basin indicated a risk for erosion.

Economic data originated from on-farm trials of alternative farming practices. Most data were collected by the farmers themselves. Crop budgets were established for the year 1995 and net margins were calculated. There was a two-stage selection of farmers based on the availability of economic data, the crops grown and the tested sustainable practices, the type of animal production, hectarage, and erosion values for that farm. Thus, three farms were selected: A, B, and C. The alternative farming practices tested were green manure on barley, reduced-till and no-till on corn, and no-till soybeans. Each farm was allowed to grow hay which is very efficient from the standpoint of erosion reduction. Data were not of excellent quality and several estimated values had to be made.

Animal nutrient requirements data were estimated from published references and herd inventories of Farms A, B, and C. The latter were respectively a dairy, a swine and a poultry farm. Life cycles for the year 1995 were estimated for each animal type in a given animal production. These cycles were used to estimate annual total nutrient requirements for each animal type and further for each farm. These estimates should be taken as approximations only. The estimated nutrients depended on the type of animal production, but in general included energy, protein, calcium and phosphorus. Finally nutritional values of crops grown on-farm were estimated.

Erosion data were estimated for the Saint-Esprit watershed using a GIS database. Slope percent, soil texture, soil series, area, field number, ownership, and 1995 land use were combined on a field basis. There was a two-stage process for the erosion value calculation. The RUSLEFAC method was used to calculate a first set of erosion values for the whole watershed. It was observed that the three selected farms were representative of the rest of the watershed. A second set of erosion values were calculated for these three farms, using a modified RUSLEFAC method based on a more accurate estimation of the LS factor. The resulting erosion values showed that Farm C presented the highest average erosion value per hectare. However, this value was less than 6t/ha/y and fell into the very low erosion class. Therefore, erosion problems did not seem to be a widespread problem at the watershed level but rather a localized issue, at the field level.

The model used to assess the costs of an erosion constraint was a Mixed Integer Linear Program (MILP). The objective function maximized the sum of field net margins subject to three types of constraints: (1) singleness of field use, (2) animal nutrient requirements, and (3) erosion. Field activities were 0/1 variables. Farmers could purchase nutrients from ROW to satisfy animal needs. To assess the impact of the erosion constraint at the farm and the watershed levels, and to study distributional effects between producers if the erosion constraint was to be imposed at the watershed versus the farm level, four models were built: one for each of the three Farms A, B, and C; and one for the watershed which simply was the summation of the three others. The four models were built using the same types of constraints, decision variables and coefficients. Because of software limitations, total hectarage and animal nutrient requirements were reduced to about 90% of their original values, hence reducing the number of field activities.

Chapter 4 Results and Discussion

4.1 Introduction

4.1.1 Solving Formulation Problems and Data Adjustments

The four models described in the previous chapter were run in the following manner: (1) a base case scenario was estimated, where no erosion constraint was applied; and (2) a series of scenarios were estimated with an increasing erosion constraint. The base case scenario for the four models yielded a negative value for the objective function. Nutrient requirements in calcium and phosphorus were so high, relative to each farm hectarage, that inputs from ROW had to be purchased in great quantities. Feed grown on-farm could not satisfy animal nutrient requirements in macrominerals. This is actually not surprising since farmers usually buy premixes from ROW to satisfy requirements in macro and micro minerals. Since no data were available on the percentage requirements in calcium and phosphorus to be satisfied with feed grown on-farm, it was decided to remove constraints related to these two nutrients (including nonphytate phosphorus for poultry). Once removed, the next binding constraint was the crude protein nutrient requirement.

The method used by LINDO to solve IP and MILP models is the branch and bound algorithm. "Branch and bound [...] is a general approach to problem solving, an approach that must be adapted to a specific setting. The general idea is to partition the set of all feasible solutions to a given problem into smaller and nonoverlapping subsets. Bounds on the value of the best solution in each subset are then computed. Then the branch-and-bound algorithm cleverly allows one to eliminate certain subsets for consideration. In this way one is said to *partially* (as opposed to completely) *enumerate* all of the possible feasible solutions" (Eppen, Gould and Schmidt 1993, 351). In practice, LINDO uses a default number of pivots and branches to solve the model. If unsuccessful, LINDO asks for how many more pivots or branches to be allowed. This can be done a few times, but not indefinitely.

Thus, the base case scenario for Farm C (poultry production) proved to be not solvable, at least within reasonable time limits. This seemed to be linked to difficult tradeoffs: (1) requirements in crude protein were high and difficult to satisfy; but they could be by either (2) growing more soybeans with a lower net margin than corn; or (3) purchasing expensive soybeans from ROW while growing more profitable corn. MILP models can be difficult to solve, even with an apparently easy formulation. As (1) LINDO could not solve Farm C's base case scenario while no erosion constraint was applied; (2) solving more constrained problems was even more difficult; (3) a strong need in crude protein was the cause of the problem; and (4) poultry needs in protein were partially satisfied with premixes but no data were available on the extent to which these premixes were used, it was decided to reduce this requirement to 75% of its original value (lesser reductions yielded the same nonsolvability result).

4.1.2 Parameters of Interest

Sensitivity analysis is not possible with MILP: "The solution to an ILP does not contain sensitivity information. [...] an ILP does not include information that is equivalent to the dual price and cost sensitivity information in an LP" (Eppen, Gould and Schmidt 1993, 361). In LINDO, IP solution reports include reduced costs and dual prices but they are "essentially meaningless to the casual user and therefore should be disregarded" (Schrage 1987, 32). However, the cost of complying with environmental constraints could be estimated in several ways: (1) changes in Objective Function Value (OFV), (2) marginal costs of compliance, and (3) average costs of compliance.

Parameters of interest for the analysis were: erosion per hectare, objective function value per hectare, conventional corn hectarage, alternative corn hectarage, hay hectarage. Barley proved to be not used at all and soybeans only marginally. From these parameters, marginal and average costs were calculated, as well as percent hectarage for each farm and the watershed in conventional corn, alternative corn and hay. Results are displayed using tables and figures for the following relationships: OFV as a function of erosion, corn and hay hectarages as a function of erosion, marginal and average costs as a function of erosion, marginal and average costs and hay hectarage as a function of erosion, difference in OFV between farm and watershed levels. Finally, results obtained from simulations of the watershed model were decomposed and recomposed for each farm. Thus, it was possible to study what happens at the farm level when the erosion target value is set at the watershed level.

4.2 Base Case Scenario

The base case scenario corresponds to the model solved with no erosion constraint. For each of the four models, the binding constraint was the crude protein requirement. Erosion was calculated by subtracting the slack value of the constraint from its RHS.

Table 4.1 Base case scenario

Parameter	Unit	Farm A, FAM[1]	Farm B, FBM[1]	Farm C, FCM[1]	Watershed, WM[1]
Erosion	kg/ha	3,806	4,272	4,751	4,448
OFV	$/ha	495	700	1,086	883
Conventional corn	% hectarage	100	100	94	96
Alternative corn	% hectarage	0	0	0	0
Hay	% hectarage	0	0	0	0

[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; WM: Watershed Model

Farm C presents both the highest OFV per hectare and the highest erosion value per hectare (Table 4.1). Then follows Farm B, then Farm A. Conventional corn (i.e., plow corn for Farms B and C and reduced-till corn for Farm A) is selected on 100% of the farm hectarage for Farms A and B and 94% of Farm C's hectarage. For Farm C, in order to satisfy the crude protein requirement, growing some soybeans is less detrimental to OFV than purchasing it from ROW.

4.3 Subsequent Scenarios

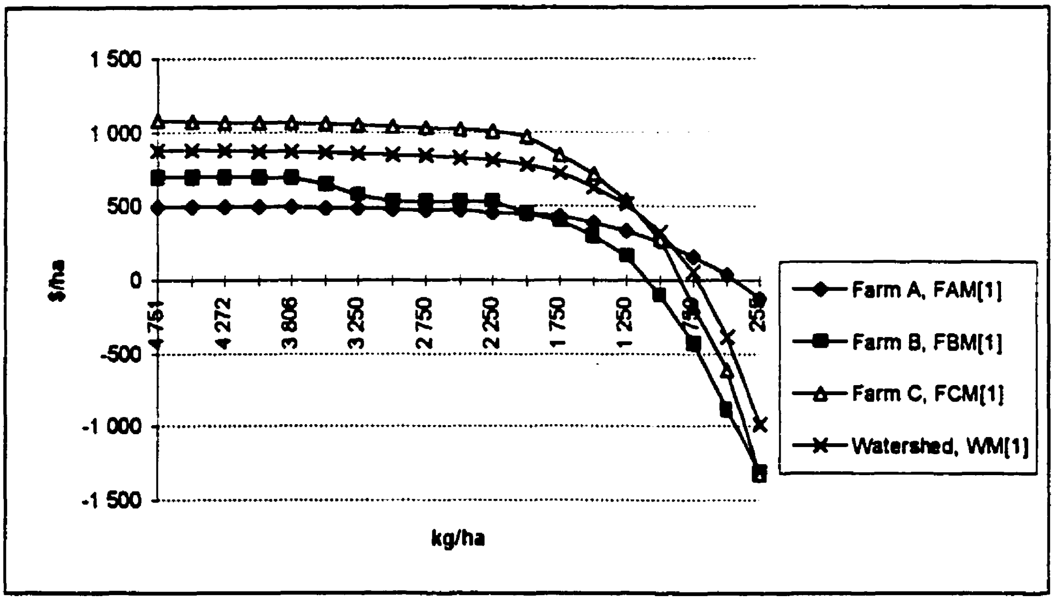
4.3.1 Introduction

Twenty two scenarios were computed for every farm and the watershed model, from the highest erosion value per hectare (4,751kg/ha for Farm C) to the lowest erosion value per hectare (231kg/ha for Farm B). The lowest erosion value per hectare was reached, for a given farm, when the cropping plan was 100% hay. Scenarios were computed for each farm's maximum and minimum erosion value per hectare. Between extremes, scenarios were computed for every reduction of 250kg/ha of the erosion constraint. Hence scenarios were computed for the following erosion per hectare values: 4,751; 4,448; 4,272; 4,000; 3,806; 3,500; 3,250; 3,000; 2,750; 2,500; 2,250; 2,000; 1,750; 1,500; 1,250; 1,000; 750; 500; 255; 247; 238; 231. For conciseness reasons, tables presented below display values for odd scenarios (i.e., from 1 to 21) only.

4.3.2 Objective Function Value as a Function of Erosion

Figure 4.1 shows the relationship between OFV per hectare and soil erosion value per hectare for the three individual farm models and for the watershed model. Note that the shapes of the curves are similar. They are fairly straight up to 2,000kg/ha, and then fall drastically. For erosion values of less than 500kg/ha and less, OFV becomes negative (explanation provided in the next section). The watershed curve is closer to Farm C's. This is because Farm C hectarage represents more than 60% of the watershed hectarage and thus has a greater weight in the watershed model scenario results. The watershed curve intersects Farm C's for a soil erosion value of 1,250kg/ha.

Figure 4.1 OFV as a function of erosion



[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; WM: Watershed Model

Farm A curve does not fall as quickly as the other curves for two reasons. First, Farm A presents the lowest erosion values per hectare and the erosion constraint is not binding for soil erosion values less than 3,806kg/ha. Second, Farm A has the smallest difference between conventional corn and hay net margins (533$ versus 743$ for Farm B and 1,009$ for Farm C). As a consequence, OFV/ha for Farm A cannot fall as drastically as it does for the two other farms when conventional corn is gradually replaced with lower net margin crops.

Table 4.2 shows the relationship between the cost of reducing erosion per hectare, measured in lost OFV from its maximum value, and the soil loss reduction per hectare, measured in lost erosion from its maximum value. In chapter 1 it was hypothesized that increasing the erosion constraint would reduce the amount of erosion generated from agricultural production. This hypothesis was not rejected.

As can be seen by Table 4.2, 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 4.2 Cost of reducing erosion

Erosion value kg/ha	Soil loss reduction kg/ha	OFV reduction ($/ha) Farm A, FAM[1]	Farm B, FBM[1]	Farm C, FCM[1]	Watershed, WM[1]
4,751	0	0	0	0	0
4,272	479	0	0	12	2
3,806	945	0	8	19	11
3,250	1,501	9	123	31	23
2,750	2,001	18	167	50	39
2,250	2,501	33	171	75	68
1,750	3,001	61	301	236	152
1,250	3,501	163	539	548	369
750	4,001	338	1,122	1,263	828
255	4,496	616	2,010	2,409	1,869
238	4,513	616	2,010	n.f.[2]	n.f.

[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; WM: Watershed Model

[2] n.f.: not feasible

In chapter 1 it was hypothesized that implementing an erosion constraint would reduce profits. This hypothesis was not rejected. Table 4.2 provides the estimated decrease in profits for the erosion constraints analyzed. For example, for an erosion target of 3,250kg/ha, i.e. a reduction in soil loss of 1,501kg/ha from the baseline solution, it would cost Farm A 9$/ha, Farm B 123$/ha, Farm C 31$/ha, and the watershed 23$/ha to reach this objective. It can be seen from Table 4.2 that increasing the erosion constraint reduces profits at an increasing rate.

4.3.3 Cropping Patterns as a Function of Erosion

Table 4.3 Cropping patterns as a function of erosion (% hectarage)

Erosion	Farm A, FAM[1]			Farm B, FBM[1]			Farm C, FCM[1]			Watersh., WM[1]		
kg/ha	c.c.[2]	a.c.[2]	h[2]	c.c.	a.c.	h	c.c.	a.c.	h	c.c.	a.c.	h
4,751	100	0	0	100	0	0	94	0	0	96	0	0
4,272	100	0	0	100	0	0	82	11	0	90	6	0
3,806	100	0	0	45	55	0	73	20	0	80	16	0
3,250	82	18	0	18	64	5	59	33	0	63	32	0
2,750	64	36	0	88	0	12	38	53	0	40	54	0
2,250	35	65	0	61	27	12	10	79	0	0	93	1
1,750	0	97	3	0	67	18	0	94	6	0	87	9
1,250	0	77	23	37	24	39	3	73	24	0	68	30
750	0	47	53	5	32	63	6	41	53	0	45	55
255	0	0	100	0	0	100	0	0	100	0	2	98
238	0	0	100	0	0	100	n.f.[3]	n.f.	n.f.	n.f.	n.f.	n.f.

[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; WM: Watershed Model

[2] c.c.: conventional corn; a.c.: alternative corn; h: hay

[3] n.f.: not feasible

Table 4.3 shows cropping patterns as a function of erosion, displaying percent hectarage in conventional corn, alternative corn and hay for Farms A, B, C and the watershed. From 4,751kg/ha to 3,806kg/ha of soil erosion, Farm A cropping plan is 100% conventional corn. From 3,250kg/ha to 2,250kg/ha of soil erosion, the proportion of conventional corn decreases gradually from 82% to 35% while the proportion of alternative corn increases gradually from 18% to

65%. At 1,750kg/ha of soil erosion, (1) the proportion of conventional corn reaches 0% and keeps this value for further increases in the erosion constraint; (2) the proportion of alternative corn reaches a maximum of 97%; and (3) the proportion of hay is 3%, the first nonzero value. From 1,750kg/ha to 255kg/ha of soil erosion, the proportion of alternative corn decreases gradually from 97% to 0% and the proportion of hay increases gradually from 3% to 100%.

These changes in cropping patterns for Farms B and C and the watershed are similar to Farm A, however, the turning points vary. For Farms B and C and for the watershed, percent values do not always add up to 100% because farm operations sometimes grow soybeans in addition to corn. Not feasible values correspond to scenarios where the erosion constraint cannot be satisfied even with a 100% hay cropping plan.

Figure 4.2 Watershed: corn and hay hectarages as a function of erosion

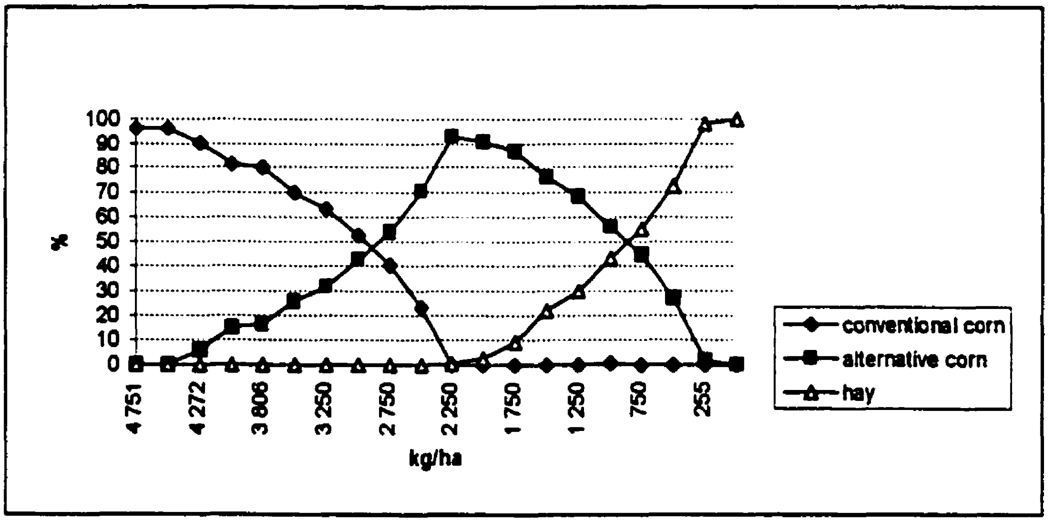


Figure 4.2 shows the relationship between percent hectarage in conventional corn, alternative corn and hay and erosion for the watershed. The graphs for Farms A, B, C, would be similar to the watershed, however, the turning points would vary. In chapter 1 it was hypothesized that implementing an erosion constraint would force cropping patterns and farming practices to change. This

hypothesis was not rejected. From Figure 4.2 it is possible to distinguish two phases in the cropping pattern evolution as the erosion constraint increases. In the first phase, (1) the proportion of conventional corn in total hectarage decreases continuously from about 100% to zero; while (2) the proportion of alternative corn in total hectarage increases continuously from zero to about 100%; while (3) the proportion of hay in total hectarage is constant and equal to zero. In the second phase, (1) the proportion of conventional corn is constant and equal to zero; while (2) the proportion of alternative corn in total hectarage decreases continuously from about 100% to zero; while (3) the proportion of hay in total hectarage increases continuously from zero to 100%. Hence, implementing an erosion constraint does force cropping patterns and farming practices to change.

The explanation for this change in cropping patterns is as follows. In the first phase, conventional corn is first chosen because it provides the highest net margin. Alternative corn gradually replaces it because it provides the second highest margin while allowing for less soil loss. Hay is not used because it has the lowest net margin. During this phase the erosion constraint is not large enough to force hay into the solution. In the second phase, conventional corn remains at zero because it produces too much erosion relative to the erosion constraint. Alternative corn is gradually replaced by hay in order to satisfy the increasing erosion constraint. Hay is the only crop which can achieve very low soil loss levels and is chosen despite its lowest net margin. At this point, most if not all animal nutrients are purchased from ROW. In this situation, net margins from crop production are decreasing and the costs of purchased inputs are increasing. This results in a negative OFV for the highest erosion constraints.

In chapter 1, it was hypothesized that changes in cropping patterns and farming practices that resulted from a soil erosion constraint would reduce profits. Since higher net margin conventional crops were substituted by lower net margin alternative crops as the erosion constraint increased, this hypothesis was accepted. The three hypotheses made in chapter 1 were not rejected. Barley is never used because it is a supplier of energy, like corn, but provides much lower net margins, for both the conventional and the alternative practices. Soybean is rarely used because, although it is a protein supplier and needs in protein are high, it is usually cheaper to buy soybean/protein from ROW rather than cultivate. This holds as long as access to higher net margin corn is possible.

4.3.4 Marginal and Average Costs as a Function of Erosion

Marginal and average costs are, respectively, a measure of the change in cost for a given change in output and a measure of the cost per unit of output. Marginal and average costs are additional ways of estimating the cost of implementing the soil erosion constraint. Marginal and average costs of reducing soil loss were calculated using the following formulas:

$$\text{Marginal cost} = \frac{(OFV_i - OFV_{i-1}) * 1000}{EROS_i - EROS_{i-1}} \quad \text{in \$/t}$$

$$\text{Average cost} = \frac{(OFV_i - OFV_{max}) * 1000}{EROS_i - EROS_{max}} \quad \text{in \$/t}$$

Where:

OFV is objective function value per hectare ($/ha)

EROS is erosion value per hectare (kg/ha)

i refers to a given scenario

Table 4.4 presents relationships between marginal and average costs and erosion for Farms A, B, C and the watershed. Scenario results show that marginal and average costs are always non-negative and, as the erosion constraint increases, marginal and average costs increase at an increasing rate. For example, the change in erosion constraint from 3,250kg/ha to 2,750kg/ha, for the watershed, results in a 62% increase in marginal cost and a 21% increase in average cost. For an erosion constraint change from 2,750kg/ha to 2,250kg/ha, for the same model, there was a 79% increase in marginal cost and a 35% increase in average cost.

Table 4.4 Marginal and average costs ($/t) as a function of erosion

Erosion	Farm A, FAM[1]		Farm B, FBM[1]		Farm C, FCM[1]		Watersh., WM[1]	
kg/ha	m.c.[2]	av.c.[2]	m.c.	av.c.	m.c.	av.c.	m.c.	av.c.
4,751	n/a[3]	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4,272	n/a	n/a	n/a	n/a	22	24	14	14
3,806	n/a	n/a	29	17	21	19	18	17
3,250	14	16	288	119	20	20	24	19
2,750	21	17	n/a	89	30	24	39	23
2,250	28	21	25	84	60	30	70	31
1,750	71	29	234	119	503	79	228	56
1,250	236	63	599	178	830	157	475	115
750	400	110	1,176	316	1,743	315	1,081	224
255	608	173	1,601	497	2,937	536	2,441	445
238	n/a	173	n/a	497	n.f.[4]	n.f.	n.f.	n.f.

[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; WM: Watershed Model

[2] m.c.: marginal cost; av.c.: average cost

[3] n/a: not applicable

[4] n.f.: not feasible

The explanation for this increase is the substitution of alternative corn with hay. Hay is the only crop that can be grown in order to satisfy an increasingly severe erosion constraint. But it presents the lowest net margin per hectare and, in order to fulfill animal needs in energy and protein, inputs have to be purchased from ROW. This contributes to a further OFV reduction, which becomes negative for the lowest erosion values. From section 4.3.2, it can be seen that profits for Farms A, B, C and the watershed decrease at an increasing rate.

There is an apparent anomaly for Farm B and a soil erosion value of 3,250kg/ha. Indeed there is a sharp increase in both marginal and average costs as

Farm B loses 115$/ha from 3,806kg/ha to 3,250kg/ha. This is because of a change in cropping patterns and a substitution of higher net margin crops with lower net margin crops. At a soil erosion value of 3,806kg/ha, the cropping plan is 45% conventional corn and 55% alternative corn. At a soil erosion value of 3,250kg/ha, the proportion of conventional corn has decreased to 18% and the proportion of alternative corn has increased to 64%. But hay has entered the cropping plan (5%) and Farm B also grows 13% of its crop hectarage with soya no-till which has a much lower net margin than corn, be it conventional or alternative.

Figure 4.3 Watershed: marginal, average costs and hay hectarage

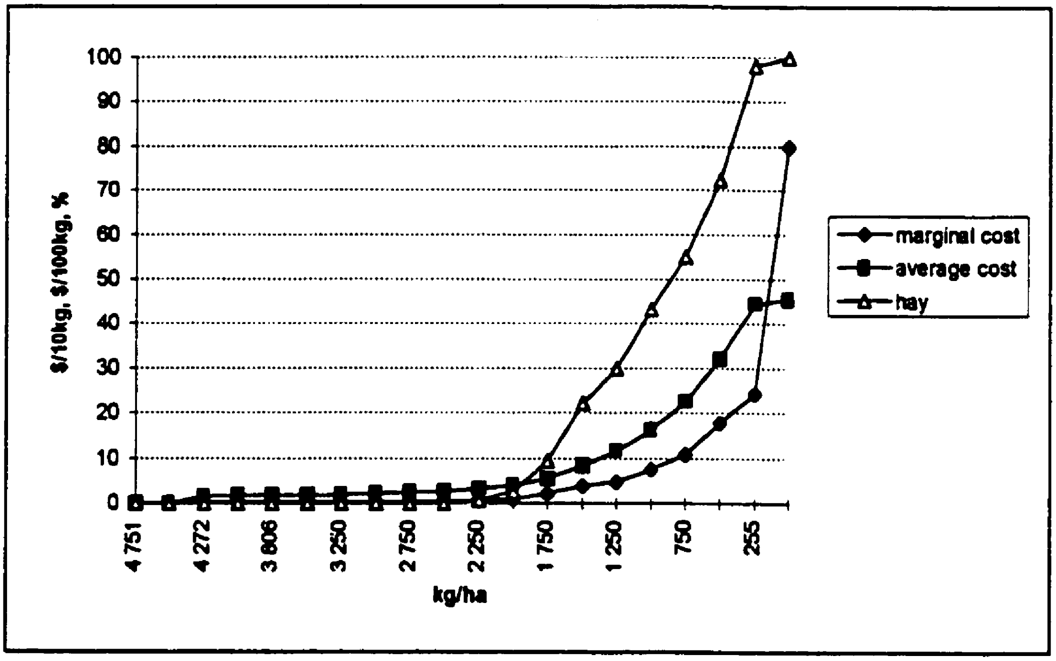
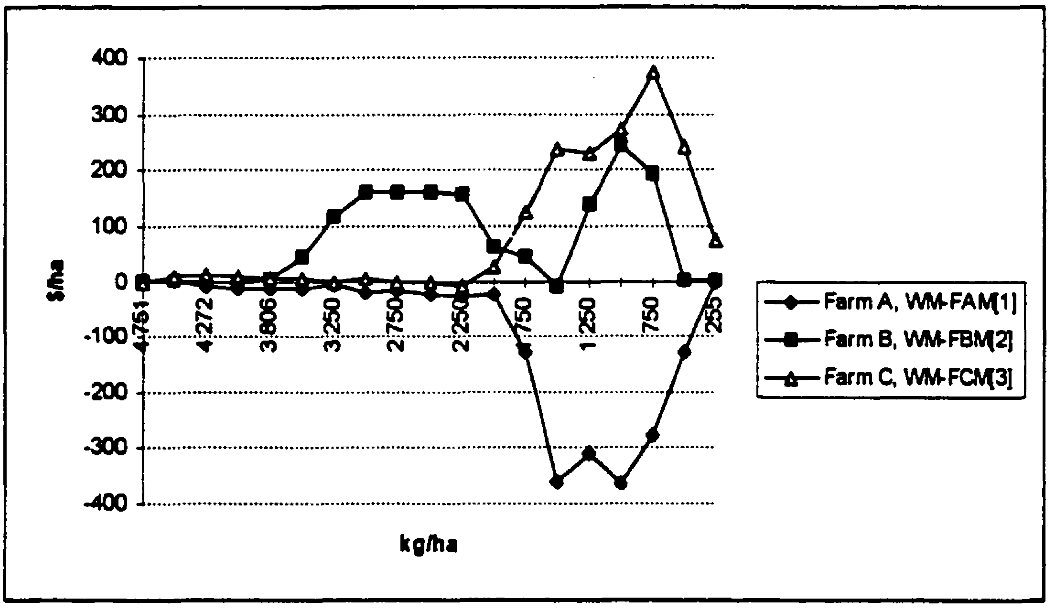


Figure 4.3 shows the relationship between marginal and average costs and hay hectarage and erosion for the watershed. Note that marginal cost values are in $/10kg while average cost values are in $/100kg. Line shapes would be the same for Farm A and for most values calculated for Farms B and C. An average cost curve that is always increasing and below the marginal cost curve "implies that production is displaced from an optimum and efficient farm plan with non-increasing returns to scale to a less than profit maximizing optimum exhibiting

decreasing returns to scale. [...] Decreasing returns to scale in this context implies overall technical and allocative inefficiency with respect to input use (i.e. land) and output (i.e. profits)" (Turvey and Weersink 1991, 679). The increase in marginal and average costs corresponds to the increase in hay hectarage as part of the crop rotation. Although costly in terms of lost profits, growing hay is the only way to satisfy a very severe erosion constraint.

4.3.5 Watershed versus Farm Scale

Figure 4.4 Farms A, B, C: decomposed difference in OFV/ha



[1] OFV/ha values obtained from the Watershed Model (WM) simulations minus OFV/ha values obtained for Farm A Model (FAM) simulations

[2] OFV/ha values obtained from the Watershed Model (WM) simulations minus OFV/ha values obtained for Farm B Model (FBM) simulations

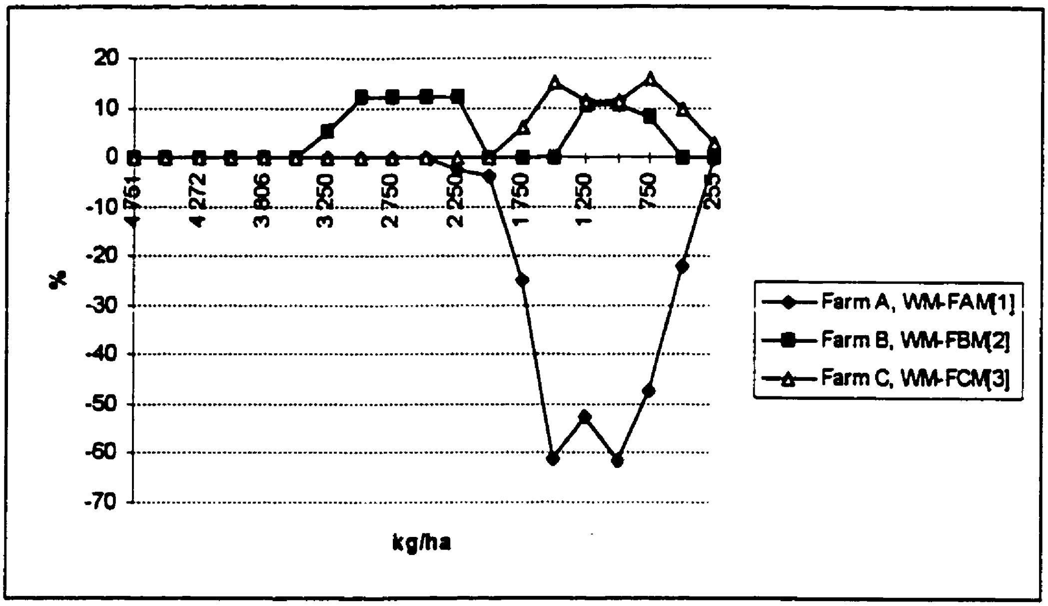
[3] OFV/ha values obtained from the Watershed Model (WM) simulations minus OFV/ha values obtained for Farm C Model (FCM) simulations

In order to assess the consequences for farmers of imposing an erosion target value at the farm level or at the watershed level, results from the watershed model were decomposed and recomposed at the farm level in terms of OFV, erosion and cropping patterns. Figure 4.4 shows the difference in OFV/ha for each farm for the two situations: (1) when the erosion target value is set at the watershed level; and (2) when the erosion target value is set at the farm level.

Three phases can be distinguished. The first phase is from 4,751kg/ha (i.e., maximum erosion for Farm C) to 3,806kg/ha (i.e., maximum erosion for Farm A). During this phase there is no particular difference between the two situations for each farm. The second phase is from 3,806kg/ha to 2,000kg/ha. During this phase, there is still no difference between the two situations for Farms A and C, however, Farm B is better off with an erosion target value set at the watershed level. That is the OFV/ha curve is above the zero line. The third phase is from 2,000kg/ha to 255kg/ha (i.e., minimum erosion for Farm C). During this phase, Farm C and Farm B are in the same situation as Farm B during the second phase, i.e. they are better off with the erosion target value set at the watershed level. On the contrary, Farm A is worse off, with a curve below the zero line. Farms A, B and C lines reach a zero value at an erosion value of 255kg/ha.

Figure 4.5 shows the difference between the watershed and the individual farm model solutions as a percentage of crop hectarage other than hay. The three different phases observed in Figure 4.4 are observed again in Figure 4.5. Therefore, it seems that the decision made at the watershed level as to where to grow hay is responsible for the observed differences in OFV/ha. As can be seen in Figure 4.5, the watershed model places a large amount of Farm A in hay as compared to the single model for Farm A.

Figure 4.5 Farms A, B, C: decomposed difference in crop hectarage other than hay



[1] % hectarage other than hay values obtained from the Watershed Model (WM) minus % hectarage other than hay values obtained from Farm A Model (FAM)

[2] % hectarage other than hay values obtained from the Watershed Model (WM) minus % hectarage other than hay values obtained from Farm B Model (FBM)

[3] % hectarage other than hay values obtained from the Watershed Model (WM) minus % hectarage other than hay values obtained from Farm C Model (FCM)

Table 4.5 shows corn net margins, the average difference in OFV/ha between the watershed and the individual farm model solutions and the average field area for Farms A, B and C. From Table 4.5, it can be seen that corn net margins increase from Farm A to Farm C. Similarly, the average difference between the watershed and the individual farm OFV/ha estimates increases from Farm A to Farm C. Since the watershed model maximizes the sum of Farms A, B, C net margins, it first chooses to grow conventional corn on each farm. Then, the model has to choose where to grow alternative corn or hay in order to satisfy the increasing erosion constraint. It chooses to grow alternative corn or hay where conventional corn net margins are lower so that the watershed can still benefit from higher corn net margins. Thus, in a given watershed where an erosion-reduction policy is implemented and where average soil losses per hectare are comparable from one farm to another, farms with higher net margins will be better off if the erosion target value is set at the watershed level, while farms with lower net margins will be worse off.

Table 4.5 Corn net margins, average decomposed OFV/ha difference and field area

	Farm A	Farm B	Farm C
Corn plow net margin ($/ha)		843.65	1,109.89
Corn reduced-till net margin ($/ha)	633.77	840.84	
Corn no-till net margin ($/ha)	600.32		1,042.10
Average decomposed difference[1] ($/ha)	-91	78	85
Average field area (ha)	3.185	3.782	7.446

[1] Values obtained for each farm from the watershed model simulations minus values obtained for each farm from that farm model simulations

4.4 Discussion

4.4.1 Summary of Findings

The three hypotheses made in chapter 1 were not rejected. First, implementing an erosion constraint reduces the amount of erosion generated from agricultural production. This implies that the baseline scenario of profit maximization produces an amount of soil erosion that can be decreased. Second, implementing an erosion constraint forces cropping patterns and farming practices to change. Crop mix changes from the baseline scenario of profit maximization in order to satisfy the erosion constraint. Third, changes in cropping patterns and farming practices reduce profits. Implementing an erosion constraint decreases the profits from the baseline scenario. From this it can be concluded that implementing an erosion constraint reduces both erosion and profits. There are additional findings. Fourth, as restrictions on soil losses increase, both marginal and average costs increase at an increasing rate and profits decrease at an increasing rate. Fifth, the increase in marginal and average costs corresponds to the increase in hay hectarage. Sixth, in a given watershed with comparable average soil losses per hectare across farms, farms with higher net margins will be better off if the decision to implement the erosion target value is made at the watershed level; farms with lower net margins will be worse off.

4.4.2 Erosion Reduction Costs and Equity Issues

Table 4.6 provides the estimated costs for each farm and the watershed of reducing soil erosion. Thus, if an erosion-reduction policy was implemented in the Saint-Esprit watershed, and the erosion target value set at 2,750kg/ha for each farm, it would cost: 18$/ha, 167$/ha and 50$/ha, respectively, for Farms A, B and C. If an erosion-reduction policy was implemented in the Saint-Esprit watershed, and the erosion target value set at 2,750kg/ha for the whole watershed, it would cost: 33$/ha, 6$/ha and 50$/ha, respectively, for Farms A, B and C.

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

Table 4.6 Costs for farms of reducing erosion, farm and watershed levels

Erosion	Lost profits A		Lost profits B		Lost profits C		Lost profits	Lost profits
	FAM[1]	WM[1]	FBM[1]	WM	FCM[1]	WM	FABCM[2]	ABC, WM[3]
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.[4]	n.f.	n.f.	n.f.

[1] FAM: Farm A Model; FBM: Farm B Model; FCM: Farm C Model; erosion target value set at the farm level. WM: Watershed Model; erosion target value set at the watershed level

[2] 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

[3] weighted average of lost profits per hectare for Farms A, B, C. Values obtained from the Watershed Model

[4] n.f.: not feasible

This raises an equity issue since farmers, although responsible for generating erosion, would be the only ones to bear the costs associated with erosion reduction while society as a whole would benefit from it. Policy makers may consider a combination of a subsidy and a pollution standard. Following Randall's (1987) explanations concerning these two ways of controlling polluting emissions, for each polluting firm, a government agency would determine the maximum permissible amount of pollution, i.e. an effluent standard. The standard indicates that a certain level of abatement must be provided, or the polluter will be considered in violation and charged penalties accordingly. On the other hand, once the baseline level of effluents is established, the agency could subsidize the acting party for reductions in residuals.

Applied to the watershed, this would mean that, for example, the Quebec Ministry of Environment could fix an effluent standard corresponding to a certain level of erosion or soil loss per hectare (e.g., 2,750kg/ha) for each Farm A, B, C, 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 effluent beyond that permitted under the standard). On the other hand, once the baseline level of effluents is established (e.g., 4,751kg/ha), the Ministry could subsidize each farmer or the watershed as a whole for reductions in soil loss. Thus, society and farmers could each bear some of the costs associated with erosion reduction.

The two right-most columns in Table 4.6 estimate the lost profits per hectare at the watershed level and a weighted average of lost profits for the three individual farms. The estimates show that the least amount of money is required to achieve erosion reduction when the 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, i.e. it does it in a more efficient (less costly) manner. But this mode of allocation raises an important equity question within the watershed. Assuming that the watershed would receive a subsidy corresponding to some portion of the profits lost in reducing soil loss, how should this amount be shared among farmers?

Previous analysis showed that an erosion target set at the watershed level would make higher net margin farms better off and lower net margin farms worse off. In other words, farmers who already earn less money because of lower net margins would earn even less money given cropping patterns allocated by the model. Subsidies could be allocated on a per hectare basis but also, according to some redistribution, on a farm basis. Or higher profits made by higher net margin farmers could be redistributed in some way among watershed farmers.

One way to deal with the redistribution issue may be pollution certificates. As explained by Randall (1987), a government agency would determine the total permissible soil losses in a geographic region. This region may be an individual farm or the watershed. Certificates that permit the amount of soil loss resulting in the attainment of the desired water quality would be printed and auctioned for polluters. Each polluter would be permitted a certain amount of soil loss corresponding to the certificates he had purchased and would face prohibitive penalties for excess losses. Income derived from the auction may be viewed as compensation to society for nonpoint source pollution. Should the erosion target be set at the farm level, individual farms would have to pay for lost profits due to changes in cropping patterns plus for the certificates.

However, results of this study show that there are cost savings when the erosion target is set at the watershed level, i.e., lost profits for individual farms are greater when the erosion target is set at the farm level than when it is set at the watershed level. To achieve these cost savings, higher net margin crops are grown on higher net margin farms. But these higher net margin crops are also those which generate more erosion. In this case, producers would benefit from the gains from trade to satisfy the regulation requirement. Higher net margin farms would be better off by producing higher net margin (more polluting) crops after purchasing needed pollution certificates from lower net margin farms. Lower net margin farms would be better off by selling unneeded pollution certificates after growing lower net margin (less polluting) crops. Each farm would be better off from a less costly way of achieving the effluent standard.

One last technical issue is that calculations made for this study are only valid for the three selected farms in this given watershed, i.e. field physical characteristics and farmer cropping decisions generate a unique combination of erosion and economic data in a given watershed. Hence, since every watershed is different and the associated erosion reduction costs are different, "legislators could not legislate across the board abatement controls [...]. One approach may be to identify an average cost of abatement for all farmers and from this establish how much abatement would be required" (Turvey and Weersink 1991, 683). Or, following the discussion on pollution certificates, the government could set a per hectare soil loss standard and let either the watershed or the individual farms deal with it. More generally, to induce enhanced stewardship and sustainability on Canadian farms, "policies should be prescribed on a targeted basis, so that differences among farms and among farmers in terms of conservation needs and effort can be accounted for, and so that prespecified societal goals, such as more effective use of scarce public funds for conservation enhancement, can be more nearly attained" (Stonehouse 1996, 116).

Chapter 5 Conclusion

In this concluding chapter, a summary of the study will first be presented, with its main conclusions. This will be followed by identifying the limitations of this study and recommendations for future research.

5.1 Summary and Conclusions

Nonpoint source agricultural pollution is increasingly recognized as a critical issue in Quebec. Several water management programs have been initiated. One of these programs is the Saint-Esprit watershed project. This project, initiated by the agriculture society of Saint-Jacques-de-Montcalm, relies on the adoption of sustainable practices by willing farmers. Alternatives practices are tested on-farm in order to assess their environmental and economic impacts. Farmers receive financial and technical assistance when they test a practice. The Saint-Eprit watershed is characterized by a rolling topography and light to medium soils, as well as intensive crop production, creating a risk for soil erosion in this area. Consequently, this study focused on the issue of soil erosion.

A literature review first described the influence of agriculture on water quality since water transports pollutants to and from agriculture into receiving water bodies. Soil sediments, excess nutrients and pesticides constitute sources of agricultural pollution. Impacts of this pollution can be divided into onsite and offsite effects, both at the environmental and the economic levels. These problems often have been associated with "conventional" agriculture. As a response, "sustainable" agriculture, which relies both on a philosophy and a set of techniques, should be environmentally sound, economically profitable and socially acceptable. The issue of economic sustainability is a critical one since sustainable must be profitable, although opinions as to how to measure sustainability may differ. Two main methods of studying the economics of erosion and sustainable practices are crop budgets and mathematical modeling, in particular linear programming. Finally, there is a need for a better integration of environmental and economic dimensions of alternative agriculture, which GIS can help with.

As the objective was to study the impact of an erosion constraint on profits, a MILP model was built. This model was based on three types of data: crop budgets, animal nutrient requirements data, and soil erosion data. Economic data were obtained from on-farm trials of alternative practices. Crop budgets were established for the year 1995 and net margins were calculated. A two-stage selection of farmers based on the availability of economic data, the crops grown and the tested sustainable practices, the type of animal production, hectarage, and field erosion values were conducted. Three farmers were selected: A, B, and C. The alternative practices tested were green manure on barley, reduced-till and no-till on corn, and no-till soybeans. Because of its efficiency from the viewpoint of erosion reduction, each farm was also allowed to grow hay. Farms A, B, and C were respectively a dairy, a swine and a poultry farm. Animal nutrient requirements were estimated for the year 1995 from annual life cycles and references. They were estimated for each animal type and for each farm, including energy, protein and macromineral needs. Nutritional values of crops were also estimated.

Erosion data were derived from the Saint-Esprit watershed GIS database. Slope percent, soil texture, soil series, area, field number, ownership, and 1995 land use were combined on a field basis. The RUSLEFAC method was first used to calculate a set of erosion values for the whole watershed. Farms A, B, C, were observed to be representative of the rest of the watershed. A second set of erosion values was calculated for Farms A, B, C only, using a modified RUSLEFAC method based on a more accurate estimation of the LS factor. The resulting average value for each farm was less than 6t/ha/y and fell into the very low erosion class. Therefore erosion problems seemed to be a localized, field level issue.

The model used to assess the costs of an increasing erosion constraint was a MILP whose objective function maximized the sum of field net margins subject to three types of constraints: (1) singleness of field use, (2) animal nutrient requirements, and (3) soil erosion. Field activities were 0/1 variables. Farmers could purchase nutrients from ROW in order to satisfy animal needs. Four models were built to assess the impact of the erosion constraint at the farm and the watershed levels, and to study the distributional effects between producers if the erosion target value was set at the watershed versus the farm scale. The four models were: one for each individual Farm A, B, and C; and one for the watershed which was simply the summation of the three others. These models were built with the same types of constraints, decision variables and coefficients. Software limitations imposed a reduction in the number of field activities.

Twenty-two scenarios were run, from a base case scenario with no erosion constraint to a minimum level of erosion where hay was grown on every field. Results showed that implementing an erosion constraint: (1) reduced the amount of soil loss generated from agricultural production; (2) forced cropping patterns and farming practices to change; (3) and reduced profits. Additional findings were that marginal and average costs associated with erosion reduction increased at an increasing rate. Also, in a given watershed with comparable average soil losses per hectare across farms, farms with higher net margins would be better off if the erosion target value was set at the watershed scale; farms with lower net margins would be worse off.

Since substantial costs associated with erosion reduction would be borne by farmers, several equity issues were raised. Since society as a whole would benefit from a reduction of erosion, how should associated costs be shared between farmers and society? If a subsidy and a regulation approach were used, the least cost subsidizing mode for society would be to set the erosion target value at the watershed level. Since lower net margin farmers would be worse off in this situation, how should the subsidy allocated to the watershed as a whole be shared among watershed farmers? One way to deal with this equity issue would be pollution certificates. To satisfy the regulation requirement, higher net margin farms would grow higher net margin crops after purchasing pollution certificates from lower net margin farms which would grow lower net margin crops.

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, while usually only one regular LP model is used. Fourth, animal nutrient requirements were taken into account. Finally, even though a different methodology was used, results were comparable to other studies, in particular that an increasing erosion constraint could be satisfied only by increasing cost to farmers.

5.2 Limitations of the Study and Recommendations for Future Research

This study has several limitations. As stated in the methodology chapter, the number of 0/1 variables or field activities was limited to 200. Using a more powerful package would permit an increase in the number of field activities. This means that the models could be run with: (1) more conventional and alternative practices for a given field; (2) more fields for a given farm; and (3) more farms within a given watershed. At the limit, several small watersheds could be aggregated as a larger drainage basin, allowing for more complex analyses of distributional issues.

With respect to distributional issues, another limitation of this study is that off-farm benefits of reducing erosion were not taken into account. If this was the case, the question of how costs associated with erosion reduction should be shared between farmers and society would certainly be easier to answer. It usually is easier to provide quantitative estimates of environmental off-farm benefits of reduced pollution. But quantitative economic studies of off-farm benefits of reducing nonpoint source pollution, although existing (for instance, Van Vuuren, Giraldez and Stonehouse 1997), are rather limited. Such studies could be used by a government agency to set tax rates or subsidy levels or pollution certificate prices for policies aimed at reducing agricultural pollution in general and erosion in particular.

Also, this study assumed crops were exclusively grown to be fed to animals or, as is the case for hay on the swine and the poultry farms, exclusively grown to be sold to ROW. With increased field activity capacities, a field could become a location where a crop is produced and that production could have several uses or destinations: either it could be fed to animals on-farm, or it could be sold to ROW, or it could be sold to other producers in the watershed. Trading blocks would then have to be built between farmers and ROW, and transportation costs would have to be taken into account. These potential sources of trade could be studied both from an economic and an environmental point of view. For example, the impact on profits and erosion of a given field use.

Finally, extracting data from the GIS database, recombining it on a field basis and doing calculations on a spreadsheet, then typing MILP models on different software looks rather arduous. With increased GIS modeling capabilities, economic-environmental modellers would benefit from the integration of basic GIS functions and management tools such as LP. A bigger spatially referenced database would be created and updated, and LP would simply be an application of a more powerful GIS.

Limitations of the study are acknowledged. It seems most of the limitations would be removed by increased software capabilities. Therefore, although rather small, the models built for the study could be used without major changes as an interesting management and decision-making tool.

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Appendix 1 Detailed Crop Budgets of Selected Producers

1.1 Farm A, Conventional Barley Budget

● **INCOME**	yield (kg)		**553.00**
grain	3,500		553.00
● **VARIABLE COSTS**			**(393.87)**
- inputs			
barley seeds: windtrop	180 kg		(78.07)
fertilizer: 75-40-45	361 kg		(84.75)
herbicide: buctril-M	1 l		(13.75)
cow manure	4.5 t, on-farm product		(0.00)
- crop operations	fuel ($)	labor (h)	
harrowing (2*)	(3.47)	0.91	(12.57)
spreading	(18.50)	9.69	(115.40)
sowing	(0.87)	0.45	(5.37)
spraying	(0.34)	0.18	(2.14)
- services/other costs			
harvest			(81.82)
● **FIXED COSTS**	purch. Date	purch. value	**(53.89)**
tractor 1	1991	55,000	(34.34)
tractor 2	1982	9,100	(5.68)
tractor 3	1969	4,200	(2.62)
spreader 1	1985	1,500	(1.09)
spreader 2	1977	3,000	(2.19)
sower	1990	5,000	(3.64)
harrow	1975	1,160	(0.85)
sprayer	1987	4,700	(3.48)
● **NET MARGIN**			**105.24**

Sources:
primary data from Farm A

1.2 Farm A, Alternative (Green Manure) Barley Budget

● **INCOME**	yield (kg)		**553.00**
grain	3,500		553.00
● **VARIABLE COSTS**			**(413.50)**
- inputs			
barley seeds: windtrop	180 kg		(78.07)
fertilizer: 60-25-25	207 kg		(74.66)
herbicide: buctril-M	1 l		(13.75)
green manure seeds	60 kg		(15.00)
cow manure	4.5 t, on-farm product		(0.00)
- crop operations	fuel ($)	labor (h)	
barley harrowing (2*)	(3.47)	0.91	(12.57)
spreading	(18.50)	9.69	(115.40)
g.m. sowing	(0.35)	0.18	(2.15)
barley sowing	(0.87)	0.45	(5.37)
g.m. harrowing	(3.47)	0.91	(12.57)
spraying	(0.34)	0.18	(2.14)
- services/other costs			
harvest			(81.82)
● **FIXED COSTS**	purch. Date	purch. value	**(53.89)**
tractor 1	1991	55,000	(34.34)
tractor 2	1982	9,100	(5.68)
tractor 3	1969	4,200	(2.62)
spreader 1	1985	1,500	(1.09)
spreader 2	1977	3,000	(2.19)
sower	1990	5,000	(3.64)
harrow	1975	1,160	(0.85)
sprayer	1987	4,700	(3.48)
● **NET MARGIN**			**85.61**

Sources:
primary data from Farm A

1.3 Farm A, Conventional (Reduced-Till) Corn Budget

● **INCOME**	yield (kg)		**1,318.45**
crop	7,534		1,318.45
● **VARIABLE COSTS**			**(626.19)**
- inputs			
seeds	n/a		(91.89)
fertilizer	781.96 kg		(264.21)
herbicide: bladex	2.5 kg		(15.55)
herbicide: pardner	2 l		(31.56)
- crop operations	fuel ($)	labor (h)	
harrowing	(1.28)	0.33	(4.58)
hoeing	(1.85)	1	(11.85)
sowing	(0.74)	0.39	(4.64)
fertilizer spreading	(0.21)	0.11	(1.31)
herbicide spraying	(0.31)	0.17	(2.01)
field inspection	n/a	0.1	(1)
- services/other costs			
drying			(119.47)
harvesting			(78.12)
● **FIXED COSTS**	purch. date	purch. Value	**(58.49)**
tractor 1	1991	55,000	(34.34)
tractor 2	1982	9,100	(5.68)
tractor 3	1969	4,200	(2.62)
harrow	1975	1,160	(0.85)
sower	1985	5,000	(3.64)
spreader	1977	3,000	(2.19)
sprayer	1987	4,700	(3.48)
hoe	1992	7,800	(5.69)
● **NET MARGIN**			**633.77**

Sources:
primary data from Farm A updated with Statistics Canada (1994 and 1995)

1.4 Farm A, Alternative (No-Till) Corn Budget

● **INCOME**	yield (kg)		**1,229.72**
crop	7,027[1]		1,229.72
● **VARIABLE COSTS**			**(570.91)**
- inputs/crop operations			
seeds	n/a		(91.89)
crop operations, weed control, fertilization[2]			(281.43)
- services/other costs			
drying			(119.47)
harvesting			(78.12)
● **FIXED COSTS**[3]	purch. date	purch. Value	**(58.49)**
● **NET MARGIN**			**600.32**

Sources:
primary data from Farm A updated using Statistics Canada (1994 and 1995)
[1] derived from MAPAQ (1997a)
[2] derived from MAPAQ (1997a); crop operations include a 10.00$/h wage for the operator and every charge related to tractors and machinery; weed control includes input cost as well as spraying and mechanical control charges if any; organic and mineral fertilization is calculated with N=1.05$, P=0.65$ and K=0.55$; these items do not include charges related to seeds, harvesting, drying, management, buildings and land
[3] no data were available for comparison; fixed costs were assumed to be the same as in the case of the conventional farming practice

1.5 Farm B, Conventional (Plow) Corn Budget

● **INCOME**	yield (kg)		**1,685.25**
crop	9,630		1,685.25
● **VARIABLE COSTS**			**(732.37)**
- inputs			
seeds	n/a		(94.56)
fertilizer 1	111.11 kg		(36.22)
fertilizer 2	259.26 kg		(91.26)
fertilizer 3	222.22 kg		(73.33)
nitrates: 32-0-0	334 kg		(108.92)
herbicide 1: ultim	n/a		(7.15)
herbicide 2: aatrex	n/a		(9.26)
herbicide 3: dual	2.59 l		(55.74)
herbicide 4: banvel	n/a		(20.89)
insecticide: DLC	n/a		(2.31)
- crop operations	fuel ($)	labor (h)	
estimation[1]	(15.06)	2.36	(38.66)
- services/other costs			
lubricant			(1.48)
harvesting + drying			(192.59)
● **FIXED COSTS**	purch. date	purch. Value	**(109.23)**
tractor 1	1978	15,000	(13.06)
tractor 2	1995	70,000	(60.97)
tractor 3	1981	20,000	(17.42)
plow	1988	6,000	(6.10)
sower	1986	5,000	(5.08)
spreader	1995	1,980	(2.01)
sprayer	1985	1,000	(1.03)
harrow	1980	3,500	(3.56)
● **NET MARGIN**			**843.65**

Sources:
primary data from Farm B
[1] based on other Saint-Esprit Watershed farmers

1.6 Farm B, Alternative (Reduced-Till) Corn Budget

● **INCOME**	yield (kg)		**1,652.35**
crop	9,442[1]		1,652.35
● **VARIABLE COSTS**			**(702.28)**
- inputs/crop operations			
seeds	n/a		(94.56)
crop operations, weed control, fertilization[2]			(415.13)
- services/other costs			
harvesting + drying			(192.59)
● **FIXED COSTS**[3]	purch. Date	purch. Value	**(109.23)**
● **NET MARGIN**			**840.84**

Sources:
primary data from Farm B
[1] derived from MAPAQ (1997a)
[2] derived from MAPAQ (1997a); crop operations include a 10.00$/h wage for the operator and every charge related to tractors and machinery; weed control includes input cost as well as spraying and mechanical control charges if any; organic and mineral fertilization is calculated with N=1.05$, P=0.65$ and K=0.55$; these items do not include charges related to seeds, harvesting, drying, management, buildings and land
[3] no data were available for comparison; fixed costs were assumed to be the same as in the case of the conventional farming practice

1.7 Farm B, Conventional (Plow) Soybeans Budget

● **INCOME**	yield (kg)		**1004.40**
crop	3,100		1004.40
● **VARIABLE COSTS**			**(583.93)**
- inputs			
seeds	131.04 kg		(120.55)
fertilizer	205.91 kg		(71.04)
herbicide 1: reifen	n/a		(15.72)
herbicide 2: afolan	n/a		(48.52)
herbicide 3: lexone	n/a		(29.20)
inoculator[1]	n/a		(55.98)
- crop operations	fuel ($)	labor (h)	
estimation[1]	(25.80)	2.28	(48.60)
- services/other costs			
harvesting			(56.68)
extrusion			(137.64)[2]
● **FIXED COSTS**	purch. date	purch. Value	**(109.26)**
tractor 1	1978	15,000	(13.06)
tractor 2	1995	70,000	(60.97)
tractor 3	1981	20,000	(17.42)
plow	1988	6,000	(6.10)
sower	1988	7,000	(7.12)
sprayer	1985	1,000	(1.03)
harrow	1980	3,500	(3.56)
● **NET MARGIN**			**311.21**

Sources:
primary data from Farm B
[1] based on primary data from other Saint-Esprit Watershed farmers
[2] (CREAQ 1996, 4) updated with Statistics Canada (1995 and 1996)

1.8 Farm B, Alternative (No-Till) Soybeans Budget

● INCOME	yield (kg)		**867.02**
crop	2,676[1]		867.02
● VARIABLE COSTS			**(564.28)**
- inputs			
seeds	131.04 kg		(120.55)
fertilizer	205.91 kg		(71.04)
herbicide 1: reifen	n/a		(18.77)
herbicide 2: afolan	n/a		(48.52)
herbicide 3: lexone	n/a		(29.20)
inoculator[2]	n/a		(55.98)
- crop operations	fuel ($)	labor (h)	
estimation[3]	(23.83)	2.09	(44.73)
- services/other costs			
harvesting			(56.68)
extrusion			(118.81)[4]
● FIXED COSTS	purch. date	purch. Value	**(129.09)**
tractor 1	1978	15,000	(13.06)
tractor 2	1995	70,000	(60.97)
tractor 3	1981	20,000	(17.42)
sower[5]	1994	32,500	(33.05)
sprayer	1985	1,000	(1.03)
harrow[6]	1980	3,500	(3.56)
● NET MARGIN			**173.65**

Sources:
primary data from Farm B
[1] derived from MAPAQ (1997b)
[2] based on primary data from other Saint-Esprit Watershed farmers
[3] based on primary data from other Saint-Esprit Watershed farmers and on no-till soya practice tested by a Saint-Esprit Watershed farmer
[4] (CREAQ 1996, 4) updated with Statistics Canada (1995 and 1996)
[5] derived from no-till soya practice tested by a Saint-Esprit Watershed farmer
[6] used for mechanical weed control

1.9 Farm C, Conventional (Plow) Soybeans Budget

• **INCOME**	yield (kg)		**1,263.60**
crop	3,900		1,263.60
• **VARIABLE COSTS**			**(483.22)**
- inputs			
seeds: KG41	110 kg		(96.58)
fertilizer	66 kg		(22.97)
herbicide	0.4 l		(60.00)
inoculator: high stick	0.22 kg		(92.67)
- crop operations	fuel ($)	labor (h)	
seedbed preparation	(5.99)	0.51	(11.09)
plowing	(5.99)	0.52	(11.19)
sowing	(1.05)	0.41	(5.15)
fertilizer spreading	(0.25)	0.05	(0.75)
herbicide spraying	(0.20)	0.08	(1)
harvesting	(5.36)	0.33	(8.66)
extrusion			(173.16)[1]
- services/other costs			
• **FIXED COSTS**	purch. Date	purch. Value	**(86.24)**
plow	1991	12,900	(3.54)
sower	1986	5,000	(1.37)
tractor 1	1991	80,480	(18.91)
tractor 2	1986	26,500	(6.23)
tractor 3	1979	9,241	(2.17)
sprayer	1993	8,478	(2.36)
combine	1993	176,450	(47.70)
cultivator	1992	12,960	(3.55)
spreader	1993	1,500	(0.41)
• **NET MARGIN**			**694.14**

Source:
primary data from Farm C
[1] (CREAQ 1996, 4) updated with Statistics Canada (1995 and 1996)

1.10 Farm C, Alternative (No-Till) Soybeans Budget

● **INCOME**	yield (kg)		**1,090.58**
crop	3,366[1]		1,090.58
● **VARIABLE COSTS**			**(456.75)**
- inputs			
seeds: KG41	110 kg		(96.58)
fertilizer	66 kg		(22.97)
herbicide	0.4 l		(71.37)
inoculator: high stick	0.22 kg		(92.67)
- crop operations	fuel ($)	labor (h)	
cultivatorl[2][3]	(4.55)	0.36	(8.15)
sowing	(1.05)	0.41	(5.15)
fertilizer spreading	(0.25)	0.05	(0.75)
herbicide spraying	(0.20)	0.08	(1)
harvesting	(5.36)	0.33	(8.66)
- services/other costs			
extrusion			(149.45)[4]
● **FIXED COSTS**	purch. Date	purch. Value	**(90.25)**
sower[2]	1994	32,500	(8.92)
tractor 1	1991	80,480	(18.91)
tractor 2	1986	26,500	(6.23)
tractor 3	1979	9,241	(2.17)
sprayer	1993	8,478	(2.36)
combine	1993	176,450	(47.70)
cultivator	1992	12,960	(3.55)
spreader	1993	1,500	(0.41)
● **NET MARGIN**			**543.58**

Source:
primary data from Farm C
[1] derived from MAPAQ (1997b)
[2] derived from no-till soya practice tested by a Saint-Esprit Watershed farmer
[3] used for mechanical weed control
[4] (CREAQ 1996, 4) updated with Statistics Canada (1995 and 1996)

1.11 Farm C, Conventional (Plow) Corn Budget

● **INCOME**	yield (kg)		**1,625.05**
crop	9,286		1,625.05
● **VARIABLE COSTS**			**(410.38)**
- inputs			
seeds: pride K15	n/a		(87.94)
fertilizer starter	352.45 kg		(102.46)
nitrates	137 units		(127.54)
herbicide: primextra	6.6 l		(48.18)
- crop operations	fuel ($)	labor (h)	
sowing	(1.06)	0.41	(5.16)
herbicide	(1.05)	0.41	(5.15)
harvesting	(6.59)	0.41	(10.69)
plowing	(5.23)	0.45	(9.73)
cultivating + rolling	(2.87)	0.25	(5.37)
hoeing	(1.66)	0.65	(8.16)
- services/other costs			
● **FIXED COSTS**	purch. Date	purch. Value	**(104.78)**
tractor 1	1991	80,480	(18.91)
tractor 2	1991	41,700	(9.80)
tractor 3	1986	26,500	(6.23)
cultivator	1992	12,960	(3.56)
sower	1984	14,880	(4.08)
combine	1993	176,450	(47.70)
sprayer	1993	8,478	(2.36)
plow 1	1985	7,200	(1.98)
plow 2	1991	12,900	(3.54)
roller	1992	8,300	(2.28)
hoe	1994	15,804	(4.34)
● **NET MARGIN**			**1,109.89**

Source:
primary data from Farm C

1.12 Farm C, Alternative (No-Till) Corn Budget

• INCOME	yield (kg)		**1,486.10**
crop	8,492[1]		1,486.10
• VARIABLE COSTS			**(339.22)**
- inputs/crop operations			
seeds: pride K15	n/a		(87.94)
crop operations, weed control, fertilization[2]			(251.28)
- services/other costs			
• FIXED COSTS[3]	purch. Date	purch. Value	**(104.78)**
• NET MARGIN			**1,042.10**

Source:
primary data from Farm C
[1] derived from MAPAQ (1997a)
[2] derived from MAPAQ (1997a); crop operations include a 10.00$/h wage for the operator and every charge related to tractors and machinery; weed control includes input cost as well as spraying and mechanical control charges if any; organic and mineral fertilization is calculated with N=1.05$, P=0.65$ and K=0.55$; these items do not include charges related to seeds, harvesting, drying, management, buildings and land
[3] no data were available for comparison; fixed costs were assumed to be the same as in the case of the conventional farming practice

1.13 Farms A, B, C, Hay (Alfalfa) Budget

• **INCOME**	yield (kg)		**373.77**
crop	5,594		373.77[1]
• **VARIABLE COSTS**			**(196.94)**
- inputs			
seeds	3.11 kg		(15.92)
fertilizer	296.02 kg		(94.53)
herbicide: cobutox	8.15 l		(18.41)
conservation agent	3.11 kg		(9.27)
- crop operations	fuel ($)	labor (h)	
pressing	(1.48)	0.78	(9.28)
raking	(1.08)	0.58	(6.88)
tossing	(2.23)	0.59	(8.13)
sowing	(1.12)	0.58	(6.92)
reaping	(1.57)	0.82	(9.77)
fertilizer spreading	(0.21)	0.11	(1.31)
herbicide spraying	(0.31)	0.17	(2.01)
field inspection	n/a	0.1	(1)
transportation	(1.26)	0.33	(4.56)
- services/other costs			
string			(8.95)
• **FIXED COSTS**	purch. Date	purch. value	**(76.07)**
tractor 1	1991	55,000	(34.34)
tractor 2	1982	9,100	(5.68)
tractor 3	1969	4,200	(2.62)
press	1989	14,250	(10.39)
sower	1990	5,000	(3.64)
spreader	1977	3,000	(2.19)
reaper	1981	8,000	(5.83)
wagon 1	1982	2,000	(1.46)
wagon 2	1982	2,500	(1.82)
wagon 3	1982	2,500	(1.82)
rake	1986	2,600	(1.89)
sprayer	1987	4,700	(3.48)
tosser	1976	1,250	(0.91)
• **NET MARGIN**			**100.76**

Sources:
primary data from Farm A
[1] hay price from CREAQ (1994b) and Statistics Canada (1993 and 1995)

Appendix 2 Mixed Integer Linear Programming Models

2.1 Farm A Model

MAX 688 XA1BC + 630 XA2BC + 586 XA3BC + 517 XA4BC + 396 XA5BC
+ 347 XA6BC + 277 XA7BC + 259 XA8BC + 256 XA9BC + 229 XA10BC
+ 195 XA11BC + 188 XA12BC + 166 XA13BC + 164 XA14BC + 128 XA15BC
+ 560 XA1BG + 513 XA2BG + 477 XA3BG + 420 XA4BG + 322 XA5BG
+ 283 XA6BG + 225 XA7BG + 211 XA8BG + 208 XA9BG + 187 XA10BG
+ 158 XA11BG + 153 XA12BG + 135 XA13BG + 134 XA14BG + 104 XA15BG
+ 4145 XA1CR + 3796 XA2CR + 3530 XA3CR + 3112 XA4CR + 2383 XA5CR
+ 2091 XA6CR + 1667 XA7CR + 1559 XA8CR + 1540 XA9CR + 1382 XA10CR
+ 1172 XA11CR + 1134 XA12CR + 1001 XA13CR + 989 XA14CR + 773 XA15CR
+ 3926 XA1CN + 3596 XA2CN + 3344 XA3CN + 2948 XA4CN + 2257 XA5CN
+ 1981 XA6CN + 1579 XA7CN + 1477 XA8CN + 1459 XA9CN + 1309 XA10CN
+ 1111 XA11CN + 1075 XA12CN + 949 XA13CN + 936 XA14CN + 732 XA15CN
+ 659 XA1H + 604 XA2H + 561 XA3H + 495 XA4H + 379 XA5H + 333 XA6H
+ 265 XA7H + 248 XA8H + 245 XA9H + 220 XA10H + 186 XA11H + 180 XA12H
+ 159 XA13H + 157 XA14H + 123 XA15H - 158 ZRAB - 175 ZRAC - 67 ZRAH

SUBJECT TO

2) ! one field, one production
XA1BC + XA1BG + XA1CR + XA1CN + XA1H = 1
3) XA2BC + XA2BG + XA2CR + XA2CN + XA2H = 1
4) XA3BC + XA3BG + XA3CR + XA3CN + XA3H = 1
5) XA4BC + XA4BG + XA4CR + XA4CN + XA4H = 1
6) XA5BC + XA5BG + XA5CR + XA5CN + XA5H = 1
7) XA6BC + XA6BG + XA6CR + XA6CN + XA6H = 1
8) XA7BC + XA7BG + XA7CR + XA7CN + XA7H = 1
9) XA8BC + XA8BG + XA8CR + XA8CN + XA8H = 1
10) XA9BC + XA9BG + XA9CR + XA9CN + XA9H = 1
11) XA10BC + XA10BG + XA10CR + XA10CN + XA10H = 1
12) XA11BC + XA11BG + XA11CR + XA11CN + XA11H = 1
13) XA12BC + XA12BG + XA12CR + XA12CN + XA12H = 1
14) XA13BC + XA13BG + XA13CR + XA13CN + XA13H = 1
15) XA14BC + XA14BG + XA14CR + XA14CN + XA14H = 1
16) XA15BC + XA15BG + XA15CR + XA15CN + XA15H = 1
17) ! dairy cattle requirements in DM
20296 XA1BC + 18589 XA2BC + 17286 XA3BC + 15237 XA4BC
+ 11669 XA5BC + 10241 XA6BC + 8162 XA7BC + 7634 XA8BC + 7541 XA9BC
+ 6765 XA10BC + 5741 XA11BC + 5555 XA12BC + 4903 XA13BC + 4841 XA14BC
+ 3786 XA15BC + 20296 XA1BG + 18589 XA2BG + 17286 XA3BG + 15237 XA4BG
+ 11669 XA5BG + 10241 XA6BG + 8162 XA7BG + 7634 XA8BG + 7541 XA9BG
+ 6765 XA10BG + 5741 XA11BG + 5555 XA12BG + 4903 XA13BG + 4841 XA14BG
+ 3786 XA15BG + 43688 XA1CR + 40014 XA2CR + 37208 XA3CR + 32800 XA4CR
+ 25117 XA5CR + 22044 XA6CR + 17569 XA7CR + 16433 XA8CR + 16233 XA9CR
+ 14563 XA10CR + 12358 XA11CR + 11957 XA12CR + 10555 XA13CR
+ 10421 XA14CR + 8150 XA15CR + 40746 XA1CN + 37321 XA2CN + 34704 XA3CN
+ 30592 XA4CN + 23427 XA5CN + 20561 XA6CN + 16386 XA7CN + 15327 XA8CN
+ 15140 XA9CN + 13583 XA10CN + 11527 XA11CN + 11153 XA12CN

+ 9844 XA13CN + 9720 XA14CN + 7601 XA15CN + 32926 XA1H + 30157 XA2H
+ 28043 XA3H + 24720 XA4H + 18930 XA5H + 16614 XA6H + 13241 XA7H
+ 12385 XA8H + 12234 XA9H + 10975 XA10H + 9314 XA11H + 9012 XA12H
+ 7955 XA13H + 7854 XA14H + 6142 XA15H + 887 ZRAB + 887 ZRAC
+ 900 ZRAH >= 382770

18) ! dairy cattle requirements in TDN

19228 XA1BC + 17611 XA2BC + 16376 XA3BC + 14435 XA4BC
+ 11054 XA5BC + 9702 XA6BC + 7732 XA7BC + 7232 XA8BC + 7144 XA9BC
+ 6409 XA10BC + 5439 XA11BC + 5263 XA12BC + 4645 XA13BC + 4586 XA14BC
+ 3587 XA15BC + 19228 XA1BG + 17611 XA2BG + 16376 XA3BG + 14435 XA4BG
+ 11054 XA5BG + 9702 XA6BG + 7732 XA7BG + 7232 XA8BG + 7144 XA9BG
+ 6409 XA10BG + 5439 XA11BG + 5263 XA12BG + 4645 XA13BG + 4586 XA14BG
+ 3587 XA15BG + 39418 XA1CR + 36103 XA2CR + 33572 XA3CR + 29594 XA4CR
+ 22662 XA5CR + 19890 XA6CR + 15852 XA7CR + 14827 XA8CR + 14646 XA9CR
+ 13139 XA10CR + 11150 XA11CR + 10789 XA12CR + 9523 XA13CR
+ 9402 XA14CR + 7353 XA15CR + 36765 XA1CN + 33673 XA2CN + 31312 XA3CN
+ 27602 XA4CN + 21137 XA5CN + 18551 XA6CN + 14785 XA7CN + 13829 XA8CN
+ 13660 XA9CN + 12255 XA10CN + 10400 XA11CN + 10063 XA12CN
+ 8882 XA13CN + 8770 XA14CN + 6858 XA15CN + 21219 XA1H + 19435 XA2H
+ 18072 XA3H + 15931 XA4H + 12199 XA5H + 10707 XA6H + 8533 XA7H
+ 7982 XA8H + 7884 XA9H + 7073 XA10H + 6002 XA11H + 5808 XA12H
+ 5126 XA13H + 5061 XA14H + 3958 XA15H + 840 ZRAB + 800 ZRAC
+ 580 ZRAH >= 227276

19) ! dairy cattle requirements in DE

78055 XA1BC + 71491 XA2BC + 66478 XA3BC + 58601 XA4BC
+ 44876 XA5BC + 39386 XA6BC + 31389 XA7BC + 29360 XA8BC + 29002 XA9BC
+ 26018 XA10BC + 22080 XA11BC + 21364 XA12BC + 18857 XA13BC
+ 18619 XA14BC + 14561 XA15BC + 78055 XA1BG + 71491 XA2BG
+ 66478 XA3BG + 58601 XA4BG + 44876 XA5BG + 39386 XA6BG + 31389 XA7BG
+ 29360 XA8BG + 29002 XA9BG + 26018 XA10BG + 22080 XA11BG
+ 21364 XA12BG + 18857 XA13BG + 18619 XA14BG + 14561 XA15BG
+ 173931 XA1CR + 159304 XA2CR + 148134 XA3CR + 130582 XA4CR
+ 99997 XA5CR + 87764 XA6CR + 69945 XA7CR + 65424 XA8CR + 64626 XA9CR
+ 57977 XA10CR + 49201 XA11CR + 47605 XA12CR + 42020 XA13CR
+ 41488 XA14CR + 32446 XA15CR + 162227 XA1CN + 148584 XA2CN
+ 138166 XA3CN + 121794 XA4CN + 93268 XA5CN + 81858 XA6CN
+ 65238 XA7CN + 61021 XA8CN + 60277 XA9CN + 54076 XA10CN
+ 45890 XA11CN + 44402 XA12CN + 39192 XA13CN + 38696 XA14CN
+ 30262 XA15CN + 93657 XA1H + 85781 XA2H + 79766 XA3H + 70314 XA4H
+ 53848 XA5H + 47258 XA6H + 37663 XA7H + 35229 XA8H + 34799 XA9H
+ 31219 XA10H + 26493 XA11H + 25634 XA12H + 22627 XA13H + 22340 XA14H
+ 17471 XA15H + 3410 ZRAB + 3530 ZRAC + 2560 ZRAH >= 1001572

20) ! dairy cattle requirements in ME

72447 XA1BC + 66354 XA2BC + 61702 XA3BC + 54391 XA4BC
+ 41651 XA5BC + 36556 XA6BC + 29134 XA7BC + 27251 XA8BC + 26918 XA9BC
+ 24149 XA10BC + 20493 XA11BC + 19829 XA12BC + 17502 XA13BC
+ 17281 XA14BC + 13515 XA15BC + 72447 XA1BG + 66354 XA2BG
+ 61702 XA3BG + 54391 XA4BG + 41651 XA5BG + 36556 XA6BG + 29134 XA7BG
+ 27251 XA8BG + 26918 XA9BG + 24149 XA10BG + 20493 XA11BG
+ 19829 XA12BG + 17502 XA13BG + 17281 XA14BG + 13515 XA15BG
+ 161121 XA1CR + 147571 XA2CR + 137224 XA3CR + 120964 XA4CR
+ 92632 XA5CR + 81299 XA6CR + 64793 XA7CR + 60605 XA8CR + 59866 XA9CR
+ 53707 XA10CR + 45577 XA11CR + 44099 XA12CR + 38925 XA13CR
+ 38432 XA14CR + 30056 XA15CR + 150278 XA1CN + 137640 XA2CN

+ 127989 XA3CN + 112823 XA4CN + 86398 XA5CN + 75828 XA6CN
+ 60433 XA7CN + 56527 XA8CN + 55837 XA9CN + 50093 XA10CN
+ 42510 XA11CN + 41131 XA12CN + 36306 XA13CN + 35846 XA14CN
+ 28034 XA15CN + 77926 XA1H + 71372 XA2H + 66368 XA3H + 58504 XA4H
+ 44801 XA5H + 39320 XA6H + 31337 XA7H + 29311 XA8H + 28954 XA9H
+ 25975 XA10H + 22043 XA11H + 21328 XA12H + 18826 XA13H + 18588 XA14H
+ 14537 XA15H + 3165 ZRAB + 3270 ZRAC + 2130 ZRAH >= 869690

21) ! dairy cattle requirements in NEM
47153 XA1BC + 43188 XA2BC + 40160 XA3BC + 35401 XA4BC
+ 27110 XA5BC + 23793 XA6BC + 18962 XA7BC + 17737 XA8BC + 17520 XA9BC
+ 15718 XA10BC + 13339 XA11BC + 12906 XA12BC + 11392 XA13BC
+ 11248 XA14BC + 8796 XA15BC + 47153 XA1BG + 43188 XA2BG + 40160 XA3BG
+ 35401 XA4BG + 27110 XA5BG + 23793 XA6BG + 18962 XA7BG + 17737 XA8BG
+ 17520 XA9BG + 15718 XA10BG + 13339 XA11BG + 12906 XA12BG
+ 11392 XA13BG + 11248 XA14BG + 8796 XA15BG + 95588 XA1CR
+ 87550 XA2CR + 81411 XA3CR + 71764 XA4CR + 54956 XA5CR + 48233 XA6CR
+ 38440 XA7CR + 35955 XA8CR + 35517 XA9CR + 31863 XA10CR
+ 27040 XA11CR + 26163 XA12CR + 23093 XA13CR + 22801 XA14CR
+ 17831 XA15CR + 89156 XA1CN + 81658 XA2CN + 75932 XA3CN + 66935 XA4CN
+ 51258 XA5CN + 44987 XA6CN + 35853 XA7CN + 33536 XA8CN + 33127 XA9CN
+ 29719 XA10CN + 25220 XA11CN + 24402 XA12CN + 21539 XA13CN
+ 21267 XA14CN + 16632 XA15CN + 45365 XA1H + 41550 XA2H + 38637 XA3H
+ 34059 XA4H + 26081 XA5H + 22891 XA6H + 18243 XA7H + 17064 XA8H
+ 16856 XA9H + 15122 XA10H + 12833 XA11H + 12416 XA12H + 10960 XA13H
+ 10821 XA14H + 8463 XA15H + 2060 ZRAB + 1940 ZRAC + 1240 ZRAH
>= 41971

22) ! dairy cattle requirements in NEG
32046 XA1BC + 29351 XA2BC + 27293 XA3BC + 24059 XA4BC
+ 18424 XA5BC + 16170 XA6BC + 12887 XA7BC + 12054 XA8BC + 11907 XA9BC
+ 10682 XA10BC + 9065 XA11BC + 8771 XA12BC + 7742 XA13BC + 7644 XA14BC
+ 5978 XA15BC + 32046 XA1BG + 29351 XA2BG + 27293 XA3BG + 24059 XA4BG
+ 18424 XA5BG + 16170 XA6BG + 12887 XA7BG + 12054 XA8BG + 11907 XA9BG
+ 10682 XA10BG + 9065 XA11BG + 8771 XA12BG + 7742 XA13BG + 7644 XA14BG
+ 5978 XA15BG + 64054 XA1CR + 58667 XA2CR + 54554 XA3CR + 48090 XA4CR
+ 36826 XA5CR + 32321 XA6CR + 25759 XA7CR + 24094 XA8CR + 23800 XA9CR
+ 21351 XA10CR + 18119 XA11CR + 17532 XA12CR + 15475 XA13CR
+ 15279 XA14CR + 11949 XA15CR + 59744 XA1CN + 54719 XA2CN
+ 50883 XA3CN + 44853 XA4CN + 34348 XA5CN + 30146 XA6CN + 24025 XA7CN
+ 22472 XA8CN + 22198 XA9CN + 19915 XA10CN + 16900 XA11CN
+ 16352 XA12CN + 14433 XA13CN + 14251 XA14CN + 11145 XA15CN
+ 24878 XA1H + 22785 XA2H + 21188 XA3H + 18677 XA4H + 14303 XA5H
+ 12553 XA6H + 10004 XA7H + 9358 XA8H + 9244 XA9H + 8293 XA10H
+ 7037 XA11H + 6809 XA12H + 6010 XA13H + 5934 XA14H + 4641 XA15H
+ 1400 ZRAB + 1300 ZRAC + 680 ZRAH >= 15516

23) ! dairy cattle requirements in NEL
44407 XA1BC + 40672 XA2BC + 37820 XA3BC + 33339 XA4BC
+ 25530 XA5BC + 22407 XA6BC + 17858 XA7BC + 16703 XA8BC + 16500 XA9BC
+ 14802 XA10BC + 12562 XA11BC + 12154 XA12BC + 10728 XA13BC
+ 10592 XA14BC + 8284 XA15BC + 44407 XA1BG + 40672 XA2BG + 37820 XA3BG
+ 33339 XA4BG + 25530 XA5BG + 22407 XA6BG + 17858 XA7BG + 16703 XA8BG
+ 16500 XA9BG + 14802 XA10BG + 12562 XA11BG + 12154 XA12BG
+ 10728 XA13BG + 10592 XA14BG + 8284 XA15BG + 90661 XA1CR
+ 83037 XA2CR + 77214 XA3CR + 68065 XA4CR + 52123 XA5CR + 45746 XA6CR
+ 36459 XA7CR + 34102 XA8CR + 33686 XA9CR + 30220 XA10CR

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+ 25646 XA11CR + 24814 XA12CR + 21903 XA13CR + 21626 XA14CR
+ 16912 XA15CR + 84560 XA1CN + 77449 XA2CN + 72018 XA3CN + 63485 XA4CN
+ 48616 XA5CN + 42668 XA6CN + 34005 XA7CN + 31807 XA8CN + 31419 XA9CN
+ 28187 XA10CN + 23920 XA11CN + 23144 XA12CN + 20429 XA13CN
+ 20170 XA14CN + 15774 XA15CN + 47560 XA1H + 43560 XA2H + 40506 XA3H
+ 35707 XA4H + 27343 XA5H + 23998 XA6H + 19126 XA7H + 17890 XA8H
+ 17671 XA9H + 15853 XA10H + 13454 XA11H + 13017 XA12H + 11490 XA13H
+ 11345 XA14H + 8872 XA15H + 1940 ZRAB + 1840 ZRAC + 1300 ZRAH
>=  457840
 24)  ! dairy cattle requirements in CP
      2747 XA1BC + 2516 XA2BC + 2339 XA3BC + 2062 XA4BC + 1579 XA5BC
+ 1386 XA6BC + 1105 XA7BC + 1033 XA8BC + 1021 XA9BC + 916 XA10BC
+ 777 XA11BC + 752 XA12BC + 664 XA13BC + 655 XA14BC + 512 XA15BC
+ 2747 XA1BG + 2516 XA2BG + 2339 XA3BG + 2062 XA4BG + 1579 XA5BG
+ 1386 XA6BG + 1105 XA7BG + 1033 XA8BG + 1021 XA9BG + 916 XA10BG
+ 777 XA11BG + 752 XA12BG + 664 XA13BG + 655 XA14BG + 512 XA15BG
+ 4435 XA1CR + 4062 XA2CR + 3777 XA3CR + 3329 XA4CR + 2550 XA5CR
+ 2238 XA6CR + 1783 XA7CR + 1668 XA8CR + 1648 XA9CR + 1478 XA10CR
+ 1254 XA11CR + 1214 XA12CR + 1071 XA13CR + 1058 XA14CR + 827 XA15CR
+ 4136 XA1CN + 3788 XA2CN + 3523 XA3CN + 3105 XA4CN + 2378 XA5CN
+ 2087 XA6CN + 1663 XA7CN + 1556 XA8CN + 1537 XA9CN + 1379 XA10CN
+ 1170 XA11CN + 1132 XA12CN + 999 XA13CN + 987 XA14CN + 772 XA15CN
+ 6219 XA1H + 5696 XA2H + 5297 XA3H + 4669 XA4H + 3576 XA5H
+ 3138 XA6H + 2501 XA7H + 2339 XA8H + 2311 XA9H + 2073 XA10H
+ 1759 XA11H + 1702 XA12H + 1503 XA13H + 1484 XA14H + 1160 XA15H
+ 120 ZRAB + 90 ZRAC + 170 ZRAH >=  49200
 25)  ! erosion constraint
      18951 XA1BC + 32405 XA2BC + 11546 XA3BC + 10321 XA4BC
+ 18560 XA5BC + 8068 XA6BC + 7702 XA7BC + 10746 XA8BC + 4648 XA9BC
+ 3596 XA10BC + 6717 XA11BC + 6942 XA12BC + 5799 XA13BC + 2371 XA14BC
+ 5023 XA15BC + 15442 XA1BG + 26404 XA2BG + 9408 XA3BG + 8410 XA4BG
+ 15123 XA5BG + 6574 XA6BG + 6275 XA7BG + 8756 XA8BG + 3787 XA9BG
+ 2930 XA10BG + 5473 XA11BG + 5656 XA12BG + 4725 XA13BG + 1932 XA14BG
+ 4093 XA15BG + 22461 XA1CR + 38406 XA2CR + 13685 XA3CR + 12232 XA4CR
+ 21997 XA5CR + 9562 XA6CR + 9128 XA7CR + 12736 XA8CR + 5509 XA9CR
+ 4262 XA10CR + 7961 XA11CR + 8227 XA12CR + 6873 XA13CR + 2811 XA14CR
+ 5953 XA15CR + 10528 XA1CN + 18003 XA2CN + 6415 XA3CN + 5734 XA4CN
+ 10311 XA5CN + 4482 XA6CN + 4279 XA7CN + 5970 XA8CN + 2582 XA9CN
+ 1998 XA10CN + 3732 XA11CN + 3857 XA12CN + 3222 XA13CN + 1317 XA14CN
+ 2790 XA15CN + 1404 XA1H + 2400 XA2H + 855 XA3H + 765 XA4H
+ 1375 XA5H + 598 XA6H + 570 XA7H + 796 XA8H + 344 XA9H + 266 XA10H
+ 498 XA11H + 514 XA12H + 430 XA13H + 176 XA14H + 372 XA15H
<=  577000
END
INTEGER-VARIABLES=    75
```

2.2 Farm B Model

MAX 8200 XB1CP + 3324 XB2CP + 3105 XB3CP + 2792 XB4CP + 2725 XB5CP
+ 2725 XB6CP + 1400 XB7CP + 1257 XB8CP + 8173 XB1CR + 3313 XB2CR
+ 3094 XB3CR + 2783 XB4CR + 2716 XB5CR + 2716 XB6CR + 1396 XB7CR
+ 1253 XB8CR + 3025 XB1SP + 1226 XB2SP + 1145 XB3SP + 1030 XB4SP
+ 1005 XB5SP + 1005 XB6SP + 517 XB7SP + 464 XB8SP + 1688 XB1SN
+ 684 XB2SN + 639 XB3SN + 575 XB4SN + 561 XB5SN + 561 XB6SN
+ 288 XB7SN + 259 XB8SN + 979 XB1H + 397 XB2H + 371 XB3H + 334 XB4H
+ 325 XB5H + 325 XB6H + 167 XB7H + 150 XB8H - 175 ZRBC - 368 ZRBS

SUBJECT TO

2) ! one field, one production
XB1CP + XB1CR + XB1SP + XB1SN + XB1H = 1
3) XB2CP + XB2CR + XB2SP + XB2SN + XB2H = 1
4) XB3CP + XB3CR + XB3SP + XB3SN + XB3H = 1
5) XB4CP + XB4CR + XB4SP + XB4SN + XB4H = 1
6) XB5CP + XB5CR + XB5SP + XB5SN + XB5H = 1
7) XB6CP + XB6CR + XB6SP + XB6SN + XB6H = 1
8) XB7CP + XB7CR + XB7SP + XB7SN + XB7H = 1
9) XB8CP + XB8CR + XB8SP + XB8SN + XB8H = 1
10) ! swine requirements in DE
330421 XB1CP + 133936 XB2CP + 125098 XB3CP + 112520 XB4CP
+ 109800 XB5CP + 109800 XB6CP + 56430 XB7CP + 50651 XB8CP
+ 323970 XB1CR + 131321 XB2CR + 122655 XB3CR + 110323 XB4CR
+ 107657 XB5CR + 107657 XB6CR + 55328 XB7CR + 49662 XB8CR
+ 113296 XB1SP + 45925 XB2SP + 42894 XB3SP + 38581 XB4SP + 37649 XB5SP
+ 37649 XB6SP + 19349 XB7SP + 17367 XB8SP + 97800 XB1SN + 39643 XB2SN
+ 37027 XB3SN + 33304 XB4SN + 32499 XB5SN + 32499 XB6SN + 16703 XB7SN
+ 14992 XB8SN + 3530 ZRBC + 3760 ZRBS >= 715672
11) ! swine requirements in ME
306084 XB1CP + 124071 XB2CP + 115884 XB3CP + 104232 XB4CP
+ 101713 XB5CP + 101713 XB6CP + 52274 XB7CP + 46920 XB8CP
+ 300108 XB1CR + 121649 XB2CR + 113621 XB3CR + 102197 XB4CR
+ 99727 XB5CR + 99727 XB6CR + 51253 XB7CR + 46004 XB8CR + 102524 XB1SP
+ 41558 XB2SP + 38816 XB3SP + 34913 XB4SP + 34069 XB5SP + 34069 XB6SP
+ 17509 XB7SP + 15716 XB8SP + 88501 XB1SN + 35874 XB2SN + 33507 XB3SN
+ 30138 XB4SN + 29409 XB5SN + 29409 XB6SN + 15114 XB7SN + 13567 XB8SN
+ 3270 ZRBC + 3403 ZRBS >= 685610
12) ! swine requirements in CP
8424 XB1CP + 3415 XB2CP + 3189 XB3CP + 2869 XB4CP + 2799 XB5CP
+ 2799 XB6CP + 1439 XB7CP + 1291 XB8CP + 8260 XB1CR + 3348 XB2CR
+ 3127 XB3CR + 2813 XB4CR + 2745 XB5CR + 2745 XB6CR + 1411 XB7CR
+ 1266 XB8CR + 15277 XB1SP + 6192 XB2SP + 5784 XB3SP + 5202 XB4SP
+ 5077 XB5SP + 5077 XB6SP + 2609 XB7SP + 2342 XB8SP + 13187 XB1SN
+ 5346 XB2SN + 4993 XB3SN + 4491 XB4SN + 4382 XB5SN + 4382 XB6SN
+ 2252 XB7SN + 2022 XB8SN + 90 ZRBC + 507 ZRBS >= 32221
13) ! erosion constraint
15634 XB1CP + 7645 XB2CP + 59639 XB3CP + 9163 XB4CP
+ 16303 XB5CP + 7874 XB6CP + 10661 XB7CP + 2360 XB8CP + 13522 XB1CR
+ 6612 XB2CR + 51580 XB3CR + 7924 XB4CR + 14100 XB5CR + 6810 XB6CR
+ 9220 XB7CR + 2041 XB8CR + 19437 XB1SP + 9505 XB2SP + 74146 XB3SP
+ 11391 XB4SP + 20268 XB5SP + 9790 XB6SP + 13254 XB7SP + 2935 XB8SP

+ 11831 XB1SN + 5786 XB2SN + 45132 XB3SN + 6934 XB4SN + 12337 XB5SN
+ 5959 XB6SN + 8068 XB7SN + 1786 XB8SN + 845 XB1H + 413 XB2H
+ 3224 XB3H + 495 XB4H + 881 XB5H + 426 XB6H + 576 XB7H + 128 XB8H
<= 594000
END
INTEGER-VARIABLES= 40

2.3 Farm C Model

MAX 13244 XC1SP + 10044 XC2SP + 8253 XC3SP + 6206 XC4SP + 5109 XC5SP
+ 4998 XC6SP + 4852 XC7SP + 4359 XC8SP + 4283 XC9SP + 4012 XC10SP
+ 3762 XC11SP + 3304 XC12SP + 2617 XC13SP + 2575 XC14SP + 2568 XC15SP
+ 2506 XC16SP + 10372 XC1SN + 7866 XC2SN + 6463 XC3SN + 4860 XC4SN
+ 4001 XC5SN + 3914 XC6SN + 3800 XC7SN + 3414 XC8SN + 3354 XC9SN
+ 3142 XC10SN + 2946 XC11SN + 2587 XC12SN + 2049 XC13SN + 2017 XC14SN
+ 2011 XC15SN + 1962 XC16SN + 21177 XC1CP + 16060 XC2CP + 13197 XC3CP
+ 9922 XC4CP + 8169 XC5CP + 7991 XC6CP + 7758 XC7CP + 6970 XC8CP
+ 6848 XC9CP + 6415 XC10CP + 6016 XC11CP + 5283 XC12CP + 4184 XC13CP
+ 4118 XC14CP + 4107 XC15CP + 4007 XC16CP + 19883 XC1CN + 15079 XC2CN
+ 12391 XC3CN + 9316 XC4CN + 7670 XC5CN + 7503 XC6CN + 7284 XC7CN
+ 6544 XC8CN + 6430 XC9CN + 6023 XC10CN + 5648 XC11CN + 4960 XC12CN
+ 3929 XC13CN + 3866 XC14CN + 3856 XC15CN + 3762 XC16CN + 1923 XC1H
+ 1458 XC2H + 1198 XC3H + 901 XC4H + 742 XC5H + 725 XC6H + 704 XC7H
+ 633 XC8H + 622 XC9H + 582 XC10H + 546 XC11H + 480 XC12H + 380 XC13H
+ 374 XC14H + 373 XC15H + 364 XC16H - 368 ZRCS - 175 ZRCC
SUBJECT TO
2) ! one field, one production
XC1SP + XC1SN + XC1CP + XC1CN + XC1H = 1
3) XC2SP + XC2SN + XC2CP + XC2CN + XC2H = 1
4) XC3SP + XC3SN + XC3CP + XC3CN + XC3H = 1
5) XC4SP + XC4SN + XC4CP + XC4CN + XC4H = 1
6) XC5SP + XC5SN + XC5CP + XC5CN + XC5H = 1
7) XC6SP + XC6SN + XC6CP + XC6CN + XC6H = 1
8) XC7SP + XC7SN + XC7CP + XC7CN + XC7H = 1
9) XC8SP + XC8SN + XC8CP + XC8CN + XC8H = 1
10) XC9SP + XC9SN + XC9CP + XC9CN + XC9H = 1
11) XC10SP + XC10SN + XC10CP + XC10CN + XC10H = 1
12) XC11SP + XC11SN + XC11CP + XC11CN + XC11H = 1
13) XC12SP + XC12SN + XC12CP + XC12CN + XC12H = 1
14) XC13SP + XC13SN + XC13CP + XC13CN + XC13H = 1
15) XC14SP + XC14SN + XC14CP + XC14CN + XC14H = 1
16) XC15SP + XC15SN + XC15CP + XC15CN + XC15H = 1
17) XC16SP + XC16SN + XC16CP + XC16CN + XC16H = 1
18) ! poultry requirements in MEn
181565 XC1SP + 137697 XC2SP + 113145 XC3SP + 85073 XC4SP
+ 70038 XC5SP + 68515 XC6SP + 66517 XC7SP + 59760 XC8SP + 58714 XC9SP
+ 55002 XC10SP + 51577 XC11SP + 45296 XC12SP + 35875 XC13SP
+ 35304 XC14SP + 35209 XC15SP + 34353 XC16SP + 156705 XC1SN
+ 118843 XC2SN + 97653 XC3SN + 73425 XC4SN + 60448 XC5SN + 59134 XC6SN

+ 57409 XC7SN + 51578 XC8SN + 50674 XC9SN + 47471 XC10SN
+ 44515 XC11SN + 39094 XC12SN + 30963 XC13SN + 30470 XC14SN
+ 30388 XC15SN + 29649 XC16SN + 593543 XC1CP + 450134 XC2CP
+ 369875 XC3CP + 278106 XC4CP + 228956 XC5CP + 223978 XC6CP
+ 217446 XC7CP + 195359 XC8CP + 191937 XC9CP + 179805 XC10CP
+ 168606 XC11CP + 148075 XC12CP + 117278 XC13CP + 115411 XC14CP
+ 115100 XC15CP + 112300 XC16CP + 542792 XC1CN + 411645 XC2CN
+ 338249 XC3CN + 254327 XC4CN + 209379 XC5CN + 204827 XC6CN
+ 198853 XC7CN + 178655 XC8CN + 175525 XC9CN + 164431 XC10CN
+ 154189 XC11CN + 135413 XC12CN + 107250 XC13CN + 105543 XC14CN
+ 105258 XC15CN + 102698 XC16CN + 2440 ZRCS + 3350 ZRCC
>= 2955088
19) ! poultry requirements in CP
37727 XC1SP + 28612 XC2SP + 23510 XC3SP + 17677 XC4SP
+ 14553 XC5SP + 14237 XC6SP + 13821 XC7SP + 12417 XC8SP + 12200 XC9SP
+ 11429 XC10SP + 10717 XC11SP + 9412 XC12SP + 7454 XC13SP
+ 7336 XC14SP + 7316 XC15SP + 7138 XC16SP + 32561 XC1SN + 24694 XC2SN
+ 20291 XC3SN + 15257 XC4SN + 12560 XC5SN + 12287 XC6SN + 11929 XC7SN
+ 10717 XC8SN + 10529 XC9SN + 9864 XC10SN + 9250 XC11SN + 8123 XC12SN
+ 6434 XC13SN + 6331 XC14SN + 6314 XC15SN + 6161 XC16SN + 15946 XC1CP
+ 12093 XC2CP + 9937 XC3CP + 7472 XC4CP + 6151 XC5CP + 6017 XC6CP
+ 5842 XC7CP + 5248 XC8CP + 5157 XC9CP + 4831 XC10CP + 4530 XC11CP
+ 3978 XC12CP + 3151 XC13CP + 3101 XC14CP + 3092 XC15CP + 3017 XC16CP
+ 14582 XC1CN + 11059 XC2CN + 9087 XC3CN + 6833 XC4CN + 5625 XC5CN
+ 5503 XC6CN + 5342 XC7CN + 4800 XC8CN + 4716 XC9CN + 4418 XC10CN
+ 4142 XC11CN + 3638 XC12CN + 2881 XC13CN + 2835 XC14CN + 2828 XC15CN
+ 2759 XC16CN + 507 ZRCS + 90 ZRCC >= 107484
20) ! erosion constraint
97839 XC1SP + 163489 XC2SP + 39578 XC3SP + 42371 XC4SP
+ 69694 XC5SP + 58710 XC6SP + 22241 XC7SP + 52299 XC8SP + 22011 XC9SP
+ 19658 XC10SP + 41337 XC11SP + 15153 XC12SP + 10964 XC13SP
+ 7835 XC14SP + 31177 XC15SP + 3883 XC16SP + 59554 XC1SN + 99515 XC2SN
+ 24091 XC3SN + 25791 XC4SN + 42422 XC5SN + 35736 XC6SN + 13538 XC7SN
+ 31834 XC8SN + 13398 XC9SN + 11966 XC10SN + 25162 XC11SN
+ 9224 XC12SN + 6673 XC13SN + 4769 XC14SN + 18977 XC15SN + 2364 XC16SN
+ 78697 XC1CP + 131502 XC2CP + 31834 XC3CP + 34081 XC4CP + 56058 XC5CP
+ 47223 XC6CP + 17889 XC7CP + 42066 XC8CP + 17704 XC9CP + 15812 XC10CP
+ 33249 XC11CP + 12188 XC12CP + 8818 XC13CP + 6302 XC14CP
+ 25077 XC15CP + 3123 XC16CP + 31904 XC1CN + 53312 XC2CN + 12906 XC3CN
+ 13817 XC4CN + 22726 XC5CN + 19144 XC6CN + 7252 XC7CN + 17054 XC8CN
+ 7177 XC9CN + 6410 XC10CN + 13479 XC11CN + 4941 XC12CN + 3575 XC13CN
+ 2555 XC14CN + 10166 XC15CN + 1266 XC16CN + 4254 XC1H + 7108 XC2H
+ 1721 XC3H + 1842 XC4H + 3030 XC5H + 2553 XC6H + 967 XC7H + 2274 XC8H
+ 957 XC9H + 855 XC10H + 1797 XC11H + 659 XC12H + 477 XC13H
+ 341 XC14H + 1356 XC15H + 169 XC16H <= 2616000
END
INTEGER-VARIABLES= 80

2.4 Watershed Model

MAX 688 XA1BC + 630 XA2BC + 586 XA3BC + 517 XA4BC + 396 XA5BC
+ 347 XA6BC + 277 XA7BC + 259 XA8BC + 256 XA9BC + 229 XA10BC
+ 195 XA11BC + 188 XA12BC + 166 XA13BC + 164 XA14BC + 128 XA15BC
+ 560 XA1BG + 513 XA2BG + 477 XA3BG + 420 XA4BG + 322 XA5BG
+ 283 XA6BG + 225 XA7BG + 211 XA8BG + 208 XA9BG + 187 XA10BG
+ 158 XA11BG + 153 XA12BG + 135 XA13BG + 134 XA14BG + 104 XA15BG
+ 4145 XA1CR + 3796 XA2CR + 3530 XA3CR + 3112 XA4CR + 2383 XA5CR
+ 2091 XA6CR + 1667 XA7CR + 1559 XA8CR + 1540 XA9CR + 1382 XA10CR
+ 1172 XA11CR + 1134 XA12CR + 1001 XA13CR + 989 XA14CR + 773 XA15CR
+ 3926 XA1CN + 3596 XA2CN + 3344 XA3CN + 2948 XA4CN + 2257 XA5CN
+ 1981 XA6CN + 1579 XA7CN + 1477 XA8CN + 1459 XA9CN + 1309 XA10CN
+ 1111 XA11CN + 1075 XA12CN + 949 XA13CN + 936 XA14CN + 732 XA15CN
+ 659 XA1H + 604 XA2H + 561 XA3H + 495 XA4H + 379 XA5H + 333 XA6H
+ 265 XA7H + 248 XA8H + 245 XA9H + 220 XA10H + 186 XA11H + 180 XA12H
+ 159 XA13H + 157 XA14H + 123 XA15H + 8200 XB1CP + 3324 XB2CP
+ 3105 XB3CP + 2792 XB4CP + 2725 XB5CP + 2725 XB6CP + 1400 XB7CP
+ 1257 XB8CP + 8173 XB1CR + 3313 XB2CR + 3094 XB3CR + 2783 XB4CR
+ 2716 XB5CR + 2716 XB6CR + 1396 XB7CR + 1253 XB8CR + 3025 XB1SP
+ 1226 XB2SP + 1145 XB3SP + 1030 XB4SP + 1005 XB5SP + 1005 XB6SP
+ 517 XB7SP + 464 XB8SP + 1688 XB1SN + 684 XB2SN + 639 XB3SN
+ 575 XB4SN + 561 XB5SN + 561 XB6SN + 288 XB7SN + 259 XB8SN + 979 XB1H
+ 397 XB2H + 371 XB3H + 334 XB4H + 325 XB5H + 325 XB6H + 167 XB7H
+ 150 XB8H + 13244 XC1SP + 10044 XC2SP + 8253 XC3SP + 6206 XC4SP
+ 5109 XC5SP + 4998 XC6SP + 4852 XC7SP + 4359 XC8SP + 4283 XC9SP
+ 4012 XC10SP + 3762 XC11SP + 3304 XC12SP + 2617 XC13SP + 2575 XC14SP
+ 2568 XC15SP + 2506 XC16SP + 10372 XC1SN + 7866 XC2SN + 6463 XC3SN
+ 4860 XC4SN + 4001 XC5SN + 3914 XC6SN + 3800 XC7SN + 3414 XC8SN
+ 3354 XC9SN + 3142 XC10SN + 2946 XC11SN + 2587 XC12SN + 2049 XC13SN
+ 2017 XC14SN + 2011 XC15SN + 1962 XC16SN + 21177 XC1CP + 16060 XC2CP
+ 13197 XC3CP + 9922 XC4CP + 8169 XC5CP + 7991 XC6CP + 7758 XC7CP
+ 6970 XC8CP + 6848 XC9CP + 6415 XC10CP + 6016 XC11CP + 5283 XC12CP
+ 4184 XC13CP + 4118 XC14CP + 4107 XC15CP + 4007 XC16CP + 19883 XC1CN
+ 15079 XC2CN + 12391 XC3CN + 9316 XC4CN + 7670 XC5CN + 7503 XC6CN
+ 7284 XC7CN + 6544 XC8CN + 6430 XC9CN + 6023 XC10CN + 5648 XC11CN
+ 4960 XC12CN + 3929 XC13CN + 3866 XC14CN + 3856 XC15CN + 3762 XC16CN
+ 1923 XC1H + 1458 XC2H + 1198 XC3H + 901 XC4H + 742 XC5H + 725 XC6H
+ 704 XC7H + 633 XC8H + 622 XC9H + 582 XC10H + 546 XC11H + 480 XC12H
+ 380 XC13H + 374 XC14H + 373 XC15H + 364 XC16H - 158 ZRAB - 175 ZRAC
- 67 ZRAH - 175 ZRBC - 368 ZRBS - 368 ZRCS - 175 ZRCC

SUBJECT TO

2) ! one field, one production
XA1BC + XA1BG + XA1CR + XA1CN + XA1H = 1
3) XA2BC + XA2BG + XA2CR + XA2CN + XA2H = 1
4) XA3BC + XA3BG + XA3CR + XA3CN + XA3H = 1
5) XA4BC + XA4BG + XA4CR + XA4CN + XA4H = 1
6) XA5BC + XA5BG + XA5CR + XA5CN + XA5H = 1
7) XA6BC + XA6BG + XA6CR + XA6CN + XA6H = 1
8) XA7BC + XA7BG + XA7CR + XA7CN + XA7H = 1
9) XA8BC + XA8BG + XA8CR + XA8CN + XA8H = 1
10) XA9BC + XA9BG + XA9CR + XA9CN + XA9H = 1

11) XA10BC + XA10BG + XA10CR + XA10CN + XA10H = 1
12) XA11BC + XA11BG + XA11CR + XA11CN + XA11H = 1
13) XA12BC + XA12BG + XA12CR + XA12CN + XA12H = 1
14) XA13BC + XA13BG + XA13CR + XA13CN + XA13H = 1
15) XA14BC + XA14BG + XA14CR + XA14CN + XA14H = 1
16) XA15BC + XA15BG + XA15CR + XA15CN + XA15H = 1
17) XB1CP + XB1CR + XB1SP + XB1SN + XB1H = 1
18) XB2CP + XB2CR + XB2SP + XB2SN + XB2H = 1
19) XB3CP + XB3CR + XB3SP + XB3SN + XB3H = 1
20) XB4CP + XB4CR + XB4SP + XB4SN + XB4H = 1
21) XB5CP + XB5CR + XB5SP + XB5SN + XB5H = 1
22) XB6CP + XB6CR + XB6SP + XB6SN + XB6H = 1
23) XB7CP + XB7CR + XB7SP + XB7SN + XB7H = 1
24) XB8CP + XB8CR + XB8SP + XB8SN + XB8H = 1
25) XC1SP + XC1SN + XC1CP + XC1CN + XC1H = 1
26) XC2SP + XC2SN + XC2CP + XC2CN + XC2H = 1
27) XC3SP + XC3SN + XC3CP + XC3CN + XC3H = 1
28) XC4SP + XC4SN + XC4CP + XC4CN + XC4H = 1
29) XC5SP + XC5SN + XC5CP + XC5CN + XC5H = 1
30) XC6SP + XC6SN + XC6CP + XC6CN + XC6H = 1
31) XC7SP + XC7SN + XC7CP + XC7CN + XC7H = 1
32) XC8SP + XC8SN + XC8CP + XC8CN + XC8H = 1
33) XC9SP + XC9SN + XC9CP + XC9CN + XC9H = 1
34) XC10SP + XC10SN + XC10CP + XC10CN + XC10H = 1
35) XC11SP + XC11SN + XC11CP + XC11CN + XC11H = 1
36) XC12SP + XC12SN + XC12CP + XC12CN + XC12H = 1
37) XC13SP + XC13SN + XC13CP + XC13CN + XC13H = 1
38) XC14SP + XC14SN + XC14CP + XC14CN + XC14H = 1
39) XC15SP + XC15SN + XC15CP + XC15CN + XC15H = 1
40) XC16SP + XC16SN + XC16CP + XC16CN + XC16H = 1
41) ! dairy cattle requirements in DM
20296 XA1BC + 18589 XA2BC + 17286 XA3BC + 15237 XA4BC
+ 11669 XA5BC + 10241 XA6BC + 8162 XA7BC + 7634 XA8BC + 7541 XA9BC
+ 6765 XA10BC + 5741 XA11BC + 5555 XA12BC + 4903 XA13BC + 4841 XA14BC
+ 3786 XA15BC + 20296 XA1BG + 18589 XA2BG + 17286 XA3BG + 15237 XA4BG
+ 11669 XA5BG + 10241 XA6BG + 8162 XA7BG + 7634 XA8BG + 7541 XA9BG
+ 6765 XA10BG + 5741 XA11BG + 5555 XA12BG + 4903 XA13BG + 4841 XA14BG
+ 3786 XA15BG + 43688 XA1CR + 40014 XA2CR + 37208 XA3CR + 32800 XA4CR
+ 25117 XA5CR + 22044 XA6CR + 17569 XA7CR + 16433 XA8CR + 16233 XA9CR
+ 14563 XA10CR + 12358 XA11CR + 11957 XA12CR + 10555 XA13CR
+ 10421 XA14CR + 8150 XA15CR + 40746 XA1CN + 37321 XA2CN + 34704 XA3CN
+ 30592 XA4CN + 23427 XA5CN + 20561 XA6CN + 16386 XA7CN + 15327 XA8CN
+ 15140 XA9CN + 13583 XA10CN + 11527 XA11CN + 11153 XA12CN
+ 9844 XA13CN + 9720 XA14CN + 7601 XA15CN + 32926 XA1H + 30157 XA2H
+ 28043 XA3H + 24720 XA4H + 18930 XA5H + 16614 XA6H + 13241 XA7H
+ 12385 XA8H + 12234 XA9H + 10975 XA10H + 9314 XA11H + 9012 XA12H
+ 7955 XA13H + 7854 XA14H + 6142 XA15H + 887 ZRAB + 887 ZRAC
+ 900 ZRAH >= 382770
42) ! dairy cattle requirements in TDN
19228 XA1BC + 17611 XA2BC + 16376 XA3BC + 14435 XA4BC
+ 11054 XA5BC + 9702 XA6BC + 7732 XA7BC + 7232 XA8BC + 7144 XA9BC
+ 6409 XA10BC + 5439 XA11BC + 5263 XA12BC + 4645 XA13BC + 4586 XA14BC
+ 3587 XA15BC + 19228 XA1BG + 17611 XA2BG + 16376 XA3BG + 14435 XA4BG
+ 11054 XA5BG + 9702 XA6BG + 7732 XA7BG + 7232 XA8BG + 7144 XA9BG

+ 6409 XA10BG + 5439 XA11BG + 5263 XA12BG + 4645 XA13BG + 4586 XA14BG
+ 3587 XA15BG + 39418 XA1CR + 36103 XA2CR + 33572 XA3CR + 29594 XA4CR
+ 22662 XA5CR + 19890 XA6CR + 15852 XA7CR + 14827 XA8CR + 14646 XA9CR
+ 13139 XA10CR + 11150 XA11CR + 10789 XA12CR + 9523 XA13CR
+ 9402 XA14CR + 7353 XA15CR + 36765 XA1CN + 33673 XA2CN + 31312 XA3CN
+ 27602 XA4CN + 21137 XA5CN + 18551 XA6CN + 14785 XA7CN + 13829 XA8CN
+ 13660 XA9CN + 12255 XA10CN + 10400 XA11CN + 10063 XA12CN
+ 8882 XA13CN + 8770 XA14CN + 6858 XA15CN + 21219 XA1H + 19435 XA2H
+ 18072 XA3H + 15931 XA4H + 12199 XA5H + 10707 XA6H + 8533 XA7H
+ 7982 XA8H + 7884 XA9H + 7073 XA10H + 6002 XA11H + 5808 XA12H
+ 5126 XA13H + 5061 XA14H + 3958 XA15H + 840 ZRAB + 800 ZRAC
+ 580 ZRAH >= 227276

43) ! dairy cattle requirements in DE

78055 XA1BC + 71491 XA2BC + 66478 XA3BC + 58601 XA4BC
+ 44876 XA5BC + 39386 XA6BC + 31389 XA7BC + 29360 XA8BC + 29002 XA9BC
+ 26018 XA10BC + 22080 XA11BC + 21364 XA12BC + 18857 XA13BC
+ 18619 XA14BC + 14561 XA15BC + 78055 XA1BG + 71491 XA2BG
+ 66478 XA3BG + 58601 XA4BG + 44876 XA5BG + 39386 XA6BG + 31389 XA7BG
+ 29360 XA8BG + 29002 XA9BG + 26018 XA10BG + 22080 XA11BG
+ 21364 XA12BG + 18857 XA13BG + 18619 XA14BG + 14561 XA15BG
+ 173931 XA1CR + 159304 XA2CR + 148134 XA3CR + 130582 XA4CR
+ 99997 XA5CR + 87764 XA6CR + 69945 XA7CR + 65424 XA8CR + 64626 XA9CR
+ 57977 XA10CR + 49201 XA11CR + 47605 XA12CR + 42020 XA13CR
+ 41488 XA14CR + 32446 XA15CR + 162227 XA1CN + 148584 XA2CN
+ 138166 XA3CN + 121794 XA4CN + 93268 XA5CN + 81858 XA6CN
+ 65238 XA7CN + 61021 XA8CN + 60277 XA9CN + 54076 XA10CN
+ 45890 XA11CN + 44402 XA12CN + 39192 XA13CN + 38696 XA14CN
+ 30262 XA15CN + 93657 XA1H + 85781 XA2H + 79766 XA3H + 70314 XA4H
+ 53848 XA5H + 47258 XA6H + 37663 XA7H + 35229 XA8H + 34799 XA9H
+ 31219 XA10H + 26493 XA11H + 25634 XA12H + 22627 XA13H + 22340 XA14H
+ 17471 XA15H + 3410 ZRAB + 3530 ZRAC + 2560 ZRAH >= 1001572

44) ! dairy cattle requirements in ME

72447 XA1BC + 66354 XA2BC + 61702 XA3BC + 54391 XA4BC
+ 41651 XA5BC + 36556 XA6BC + 29134 XA7BC + 27251 XA8BC + 26918 XA9BC
+ 24149 XA10BC + 20493 XA11BC + 19829 XA12BC + 17502 XA13BC
+ 17281 XA14BC + 13515 XA15BC + 72447 XA1BG + 66354 XA2BG
+ 61702 XA3BG + 54391 XA4BG + 41651 XA5BG + 36556 XA6BG + 29134 XA7BG
+ 27251 XA8BG + 26918 XA9BG + 24149 XA10BG + 20493 XA11BG
+ 19829 XA12BG + 17502 XA13BG + 17281 XA14BG + 13515 XA15BG
+ 161121 XA1CR + 147571 XA2CR + 137224 XA3CR + 120964 XA4CR
+ 92632 XA5CR + 81299 XA6CR + 64793 XA7CR + 60605 XA8CR + 59866 XA9CR
+ 53707 XA10CR + 45577 XA11CR + 44099 XA12CR + 38925 XA13CR
+ 38432 XA14CR + 30056 XA15CR + 150278 XA1CN + 137640 XA2CN
+ 127989 XA3CN + 112823 XA4CN + 86398 XA5CN + 75828 XA6CN
+ 60433 XA7CN + 56527 XA8CN + 55837 XA9CN + 50093 XA10CN
+ 42510 XA11CN + 41131 XA12CN + 36306 XA13CN + 35846 XA14CN
+ 28034 XA15CN + 77926 XA1H + 71372 XA2H + 66368 XA3H + 58504 XA4H
+ 44801 XA5H + 39320 XA6H + 31337 XA7H + 29311 XA8H + 28954 XA9H
+ 25975 XA10H + 22043 XA11H + 21328 XA12H + 18826 XA13H + 18588 XA14H
+ 14537 XA15H + 3165 ZRAB + 3270 ZRAC + 2130 ZRAH >= 869690

45) ! dairy cattle requirements in NEM

47153 XA1BC + 43188 XA2BC + 40160 XA3BC + 35401 XA4BC
+ 27110 XA5BC + 23793 XA6BC + 18962 XA7BC + 17737 XA8BC + 17520 XA9BC
+ 15718 XA10BC + 13339 XA11BC + 12906 XA12BC + 11392 XA13BC

+ 11248 XA14BC + 8796 XA15BC + 47153 XA1BG + 43188 XA2BG + 40160 XA3BG
+ 35401 XA4BG + 27110 XA5BG + 23793 XA6BG + 18962 XA7BG + 17737 XA8BG
+ 17520 XA9BG + 15718 XA10BG + 13339 XA11BG + 12906 XA12BG
+ 11392 XA13BG + 11248 XA14BG + 8796 XA15BG + 95588 XA1CR
+ 87550 XA2CR + 81411 XA3CR + 71764 XA4CR + 54956 XA5CR + 48233 XA6CR
+ 38440 XA7CR + 35955 XA8CR + 35517 XA9CR + 31863 XA10CR
+ 27040 XA11CR + 26163 XA12CR + 23093 XA13CR + 22801 XA14CR
+ 17831 XA15CR + 89156 XA1CN + 81658 XA2CN + 75932 XA3CN + 66935 XA4CN
+ 51258 XA5CN + 44987 XA6CN + 35853 XA7CN + 33536 XA8CN + 33127 XA9CN
+ 29719 XA10CN + 25220 XA11CN + 24402 XA12CN + 21539 XA13CN
+ 21267 XA14CN + 16632 XA15CN + 45365 XA1H + 41550 XA2H + 38637 XA3H
+ 34059 XA4H + 26081 XA5H + 22891 XA6H + 18243 XA7H + 17064 XA8H
+ 16856 XA9H + 15122 XA10H + 12833 XA11H + 12416 XA12H + 10960 XA13H
+ 10821 XA14H + 8463 XA15H + 2060 ZRAB + 1940 ZRAC + 1240 ZRAH
>= 41971

46) ! dairy cattle requirements in NEG

32046 XA1BC + 29351 XA2BC + 27293 XA3BC + 24059 XA4BC
+ 18424 XA5BC + 16170 XA6BC + 12887 XA7BC + 12054 XA8BC + 11907 XA9BC
+ 10682 XA10BC + 9065 XA11BC + 8771 XA12BC + 7742 XA13BC + 7644 XA14BC
+ 5978 XA15BC + 32046 XA1BG + 29351 XA2BG + 27293 XA3BG + 24059 XA4BG
+ 18424 XA5BG + 16170 XA6BG + 12887 XA7BG + 12054 XA8BG + 11907 XA9BG
+ 10682 XA10BG + 9065 XA11BG + 8771 XA12BG + 7742 XA13BG + 7644 XA14BG
+ 5978 XA15BG + 64054 XA1CR + 58667 XA2CR + 54554 XA3CR + 48090 XA4CR
+ 36826 XA5CR + 32321 XA6CR + 25759 XA7CR + 24094 XA8CR + 23800 XA9CR
+ 21351 XA10CR + 18119 XA11CR + 17532 XA12CR + 15475 XA13CR
+ 15279 XA14CR + 11949 XA15CR + 59744 XA1CN + 54719 XA2CN
+ 50883 XA3CN + 44853 XA4CN + 34348 XA5CN + 30146 XA6CN + 24025 XA7CN
+ 22472 XA8CN + 22198 XA9CN + 19915 XA10CN + 16900 XA11CN
+ 16352 XA12CN + 14433 XA13CN + 14251 XA14CN + 11145 XA15CN
+ 24878 XA1H + 22785 XA2H + 21188 XA3H + 18677 XA4H + 14303 XA5H
+ 12553 XA6H + 10004 XA7H + 9358 XA8H + 9244 XA9H + 8293 XA10H
+ 7037 XA11H + 6809 XA12H + 6010 XA13H + 5934 XA14H + 4641 XA15H
+ 1400 ZRAB + 1300 ZRAC + 680 ZRAH >= 15516

47) ! dairy cattle requirements in NEL

44407 XA1BC + 40672 XA2BC + 37820 XA3BC + 33339 XA4BC
+ 25530 XA5BC + 22407 XA6BC + 17858 XA7BC + 16703 XA8BC + 16500 XA9BC
+ 14802 XA10BC + 12562 XA11BC + 12154 XA12BC + 10728 XA13BC
+ 10592 XA14BC + 8284 XA15BC + 44407 XA1BG + 40672 XA2BG + 37820 XA3BG
+ 33339 XA4BG + 25530 XA5BG + 22407 XA6BG + 17858 XA7BG + 16703 XA8BG
+ 16500 XA9BG + 14802 XA10BG + 12562 XA11BG + 12154 XA12BG
+ 10728 XA13BG + 10592 XA14BG + 8284 XA15BG + 90661 XA1CR
+ 83037 XA2CR + 77214 XA3CR + 68065 XA4CR + 52123 XA5CR + 45746 XA6CR
+ 36459 XA7CR + 34102 XA8CR + 33686 XA9CR + 30220 XA10CR
+ 25646 XA11CR + 24814 XA12CR + 21903 XA13CR + 21626 XA14CR
+ 16912 XA15CR + 84560 XA1CN + 77449 XA2CN + 72018 XA3CN + 63485 XA4CN
+ 48616 XA5CN + 42668 XA6CN + 34005 XA7CN + 31807 XA8CN + 31419 XA9CN
+ 28187 XA10CN + 23920 XA11CN + 23144 XA12CN + 20429 XA13CN
+ 20170 XA14CN + 15774 XA15CN + 47560 XA1H + 43560 XA2H + 40506 XA3H
+ 35707 XA4H + 27343 XA5H + 23998 XA6H + 19126 XA7H + 17890 XA8H
+ 17671 XA9H + 15853 XA10H + 13454 XA11H + 13017 XA12H + 11490 XA13H
+ 11345 XA14H + 8872 XA15H + 1940 ZRAB + 1840 ZRAC + 1300 ZRAH
>= 457840

48) ! dairy cattle requirements in CP

2747 XA1BC + 2516 XA2BC + 2339 XA3BC + 2062 XA4BC + 1579 XA5BC

+ 1386 XA6BC + 1105 XA7BC + 1033 XA8BC + 1021 XA9BC + 916 XA10BC
+ 777 XA11BC + 752 XA12BC + 664 XA13BC + 655 XA14BC + 512 XA15BC
+ 2747 XA1BG + 2516 XA2BG + 2339 XA3BG + 2062 XA4BG + 1579 XA5BG
+ 1386 XA6BG + 1105 XA7BG + 1033 XA8BG + 1021 XA9BG + 916 XA10BG
+ 777 XA11BG + 752 XA12BG + 664 XA13BG + 655 XA14BG + 512 XA15BG
+ 4435 XA1CR + 4062 XA2CR + 3777 XA3CR + 3329 XA4CR + 2550 XA5CR
+ 2238 XA6CR + 1783 XA7CR + 1668 XA8CR + 1648 XA9CR + 1478 XA10CR
+ 1254 XA11CR + 1214 XA12CR + 1071 XA13CR + 1058 XA14CR + 827 XA15CR
+ 4136 XA1CN + 3788 XA2CN + 3523 XA3CN + 3105 XA4CN + 2378 XA5CN
+ 2087 XA6CN + 1663 XA7CN + 1556 XA8CN + 1537 XA9CN + 1379 XA10CN
+ 1170 XA11CN + 1132 XA12CN + 999 XA13CN + 987 XA14CN + 772 XA15CN
+ 6219 XA1H + 5696 XA2H + 5297 XA3H + 4669 XA4H + 3576 XA5H
+ 3138 XA6H + 2501 XA7H + 2339 XA8H + 2311 XA9H + 2073 XA10H
+ 1759 XA11H + 1702 XA12H + 1503 XA13H + 1484 XA14H + 1160 XA15H
+ 120 ZRAB + 90 ZRAC + 170 ZRAH >= 49200

49) ! swine requirements in DE
330421 XB1CP + 133936 XB2CP + 125098 XB3CP + 112520 XB4CP
+ 109800 XB5CP + 109800 XB6CP + 56430 XB7CP + 50651 XB8CP
+ 323970 XB1CR + 131321 XB2CR + 122655 XB3CR + 110323 XB4CR
+ 107657 XB5CR + 107657 XB6CR + 55328 XB7CR + 49662 XB8CR
+ 113296 XB1SP + 45925 XB2SP + 42894 XB3SP + 38581 XB4SP + 37649 XB5SP
+ 37649 XB6SP + 19349 XB7SP + 17367 XB8SP + 97800 XB1SN + 39643 XB2SN
+ 37027 XB3SN + 33304 XB4SN + 32499 XB5SN + 32499 XB6SN + 16703 XB7SN
+ 14992 XB8SN + 3530 ZRBC + 3760 ZRBS >= 715672

50) ! swine requirements in ME
306084 XB1CP + 124071 XB2CP + 115884 XB3CP + 104232 XB4CP
+ 101713 XB5CP + 101713 XB6CP + 52274 XB7CP + 46920 XB8CP
+ 300108 XB1CR + 121649 XB2CR + 113621 XB3CR + 102197 XB4CR
+ 99727 XB5CR + 99727 XB6CR + 51253 XB7CR + 46004 XB8CR + 102524 XB1SP
+ 41558 XB2SP + 38816 XB3SP + 34913 XB4SP + 34069 XB5SP + 34069 XB6SP
+ 17509 XB7SP + 15716 XB8SP + 88501 XB1SN + 35874 XB2SN + 33507 XB3SN
+ 30138 XB4SN + 29409 XB5SN + 29409 XB6SN + 15114 XB7SN + 13567 XB8SN
+ 3270 ZRBC + 3403 ZRBS >= 685610

51) ! swine requirements in CP
8424 XB1CP + 3415 XB2CP + 3189 XB3CP + 2869 XB4CP + 2799 XB5CP
+ 2799 XB6CP + 1439 XB7CP + 1291 XB8CP + 8260 XB1CR + 3348 XB2CR
+ 3127 XB3CR + 2813 XB4CR + 2745 XB5CR + 2745 XB6CR + 1411 XB7CR
+ 1266 XB8CR + 15277 XB1SP + 6192 XB2SP + 5784 XB3SP + 5202 XB4SP
+ 5077 XB5SP + 5077 XB6SP + 2609 XB7SP + 2342 XB8SP + 13187 XB1SN
+ 5346 XB2SN + 4993 XB3SN + 4491 XB4SN + 4382 XB5SN + 4382 XB6SN
+ 2252 XB7SN + 2022 XB8SN + 90 ZRBC + 507 ZRBS >= 32221

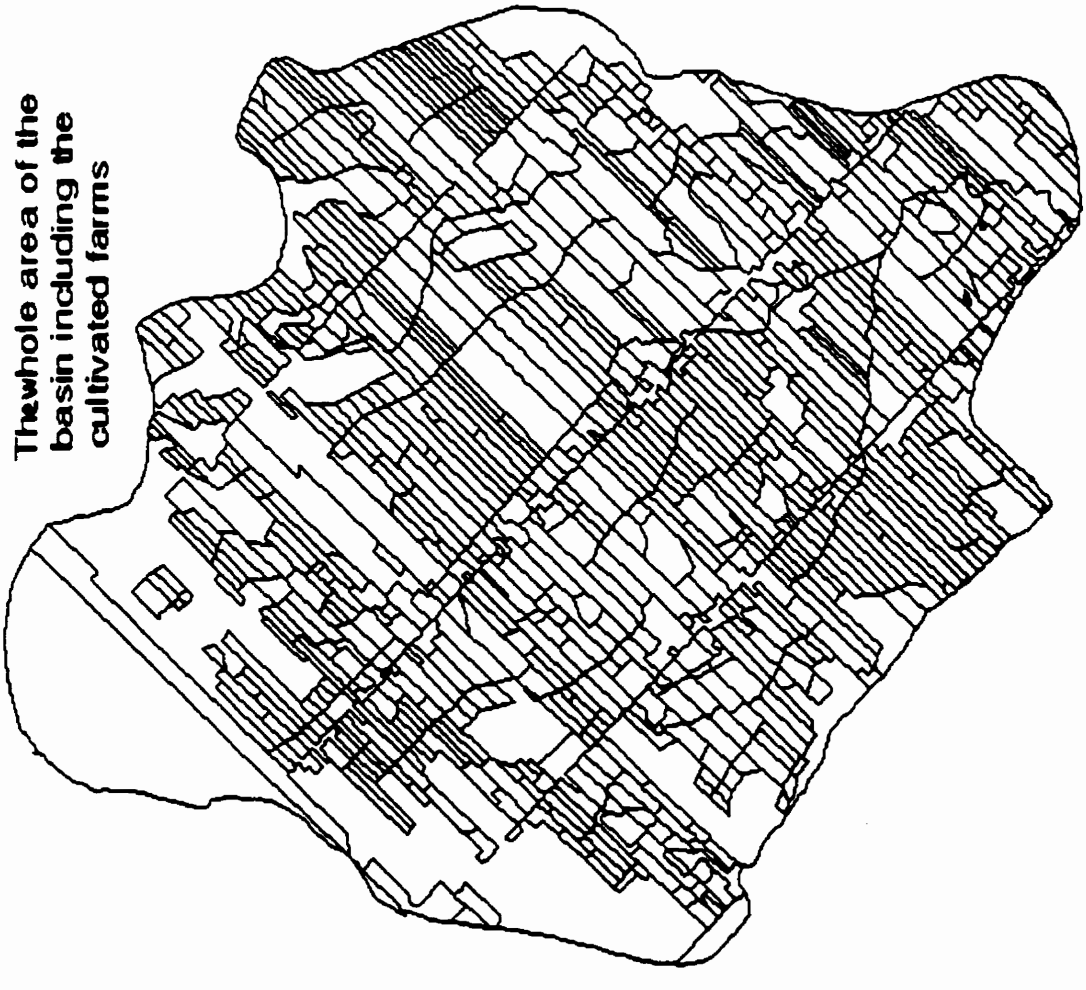
52) ! poultry requirements in MEn
181565 XC1SP + 137697 XC2SP + 113145 XC3SP + 85073 XC4SP
+ 70038 XC5SP + 68515 XC6SP + 66517 XC7SP + 59760 XC8SP + 58714 XC9SP
+ 55002 XC10SP + 51577 XC11SP + 45296 XC12SP + 35875 XC13SP
+ 35304 XC14SP + 35209 XC15SP + 34353 XC16SP + 156705 XC1SN
+ 118843 XC2SN + 97653 XC3SN + 73425 XC4SN + 60448 XC5SN + 59134 XC6SN
+ 57409 XC7SN + 51578 XC8SN + 50674 XC9SN + 47471 XC10SN
+ 44515 XC11SN + 39094 XC12SN + 30963 XC13SN + 30470 XC14SN
+ 30388 XC15SN + 29649 XC16SN + 593543 XC1CP + 450134 XC2CP
+ 369875 XC3CP + 278106 XC4CP + 228956 XC5CP + 223978 XC6CP
+ 217446 XC7CP + 195359 XC8CP + 191937 XC9CP + 179805 XC10CP
+ 168606 XC11CP + 148075 XC12CP + 117278 XC13CP + 115411 XC14CP
+ 15100 XC15CP + 112300 XC16CP + 542792 XC1CN + 411645 XC2CN

+ 338249 XC3CN + 254327 XC4CN + 209379 XC5CN + 204827 XC6CN
+ 198853 XC7CN + 178655 XC8CN + 175525 XC9CN + 164431 XC10CN
+ 154189 XC11CN + 135413 XC12CN + 107250 XC13CN + 105543 XC14CN
+ 105258 XC15CN + 102698 XC16CN + 2440 ZRCS + 3350 ZRCC
>= 2955088
53) ! poultry requirements in CP
37727 XC1SP + 28612 XC2SP + 23510 XC3SP + 17677 XC4SP
+ 14553 XC5SP + 14237 XC6SP + 13821 XC7SP + 12417 XC8SP + 12200 XC9SP
+ 11429 XC10SP + 10717 XC11SP + 9412 XC12SP + 7454 XC13SP
+ 7336 XC14SP + 7316 XC15SP + 7138 XC16SP + 32561 XC1SN + 24694 XC2SN
+ 20291 XC3SN + 15257 XC4SN + 12560 XC5SN + 12287 XC6SN + 11929 XC7SN
+ 10717 XC8SN + 10529 XC9SN + 9864 XC10SN + 9250 XC11SN + 8123 XC12SN
+ 6434 XC13SN + 6331 XC14SN + 6314 XC15SN + 6161 XC16SN + 15946 XC1CP
+ 12093 XC2CP + 9937 XC3CP + 7472 XC4CP + 6151 XC5CP + 6017 XC6CP
+ 5842 XC7CP + 5248 XC8CP + 5157 XC9CP + 4831 XC10CP + 4530 XC11CP
+ 3978 XC12CP + 3151 XC13CP + 3101 XC14CP + 3092 XC15CP + 3017 XC16CP
+ 14582 XC1CN + 11059 XC2CN + 9087 XC3CN + 6833 XC4CN + 5625 XC5CN
+ 5503 XC6CN + 5342 XC7CN + 4800 XC8CN + 4716 XC9CN + 4418 XC10CN
+ 4142 XC11CN + 3638 XC12CN + 2881 XC13CN + 2835 XC14CN + 2828 XC15CN
+ 2759 XC16CN + 507 ZRCS + 90 ZRCC >= 107484
54) ! erosion constraint
18951 XA1BC + 32405 XA2BC + 11546 XA3BC + 10321 XA4BC
+ 18560 XA5BC + 8068 XA6BC + 7702 XA7BC + 10746 XA8BC + 4648 XA9BC
+ 3596 XA10BC + 6717 XA11BC + 6942 XA12BC + 5799 XA13BC + 2371 XA14BC
+ 5023 XA15BC + 15442 XA1BG + 26404 XA2BG + 9408 XA3BG + 8410 XA4BG
+ 15123 XA5BG + 6574 XA6BG + 6275 XA7BG + 8756 XA8BG + 3787 XA9BG
+ 2930 XA10BG + 5473 XA11BG + 5656 XA12BG + 4725 XA13BG + 1932 XA14BG
+ 4093 XA15BG + 22461 XA1CR + 38406 XA2CR + 13685 XA3CR + 12232 XA4CR
+ 21997 XA5CR + 9562 XA6CR + 9128 XA7CR + 12736 XA8CR + 5509 XA9CR
+ 4262 XA10CR + 7961 XA11CR + 8227 XA12CR + 6873 XA13CR + 2811 XA14CR
+ 5953 XA15CR + 10528 XA1CN + 18003 XA2CN + 6415 XA3CN + 5734 XA4CN
+ 10311 XA5CN + 4482 XA6CN + 4279 XA7CN + 5970 XA8CN + 2582 XA9CN
+ 1998 XA10CN + 3732 XA11CN + 3857 XA12CN + 3222 XA13CN + 1317 XA14CN
+ 2790 XA15CN + 1404 XA1H + 2400 XA2H + 855 XA3H + 765 XA4H
+ 1375 XA5H + 598 XA6H + 570 XA7H + 796 XA8H + 344 XA9H + 266 XA10H
+ 498 XA11H + 514 XA12H + 430 XA13H + 176 XA14H + 372 XA15H
+ 15634 XB1CP + 7645 XB2CP + 59639 XB3CP + 9163 XB4CP + 16303 XB5CP
+ 7874 XB6CP + 10661 XB7CP + 2360 XB8CP + 13522 XB1CR + 6612 XB2CR
+ 51580 XB3CR + 7924 XB4CR + 14100 XB5CR + 6810 XB6CR + 9220 XB7CR
+ 2041 XB8CR + 19437 XB1SP + 9505 XB2SP + 74146 XB3SP + 11391 XB4SP
+ 20268 XB5SP + 9790 XB6SP + 13254 XB7SP + 2935 XB8SP + 11831 XB1SN
+ 5786 XB2SN + 45132 XB3SN + 6934 XB4SN + 12337 XB5SN + 5959 XB6SN
+ 8068 XB7SN + 1786 XB8SN + 845 XB1H + 413 XB2H + 3224 XB3H + 495 XB4H
+ 881 XB5H + 426 XB6H + 576 XB7H + 128 XB8H + 97839 XC1SP
+ 163489 XC2SP + 39578 XC3SP + 42371 XC4SP + 69694 XC5SP + 58710 XC6SP
+ 22241 XC7SP + 52299 XC8SP + 22011 XC9SP + 19658 XC10SP
+ 41337 XC11SP + 15153 XC12SP + 10964 XC13SP + 7835 XC14SP
+ 31177 XC15SP + 3883 XC16SP + 59554 XC1SN + 99515 XC2SN + 24091 XC3SN
+ 25791 XC4SN + 42422 XC5SN + 35736 XC6SN + 13538 XC7SN + 31834 XC8SN
+ 13398 XC9SN + 11966 XC10SN + 25162 XC11SN + 9224 XC12SN
+ 6673 XC13SN + 4769 XC14SN + 18977 XC15SN + 2364 XC16SN + 78697 XC1CP
+ 131502 XC2CP + 31834 XC3CP + 34081 XC4CP + 56058 XC5CP + 47223 XC6CP
+ 17889 XC7CP + 42066 XC8CP + 17704 XC9CP + 15812 XC10CP
+ 33249 XC11CP + 12188 XC12CP + 8818 XC13CP + 6302 XC14CP

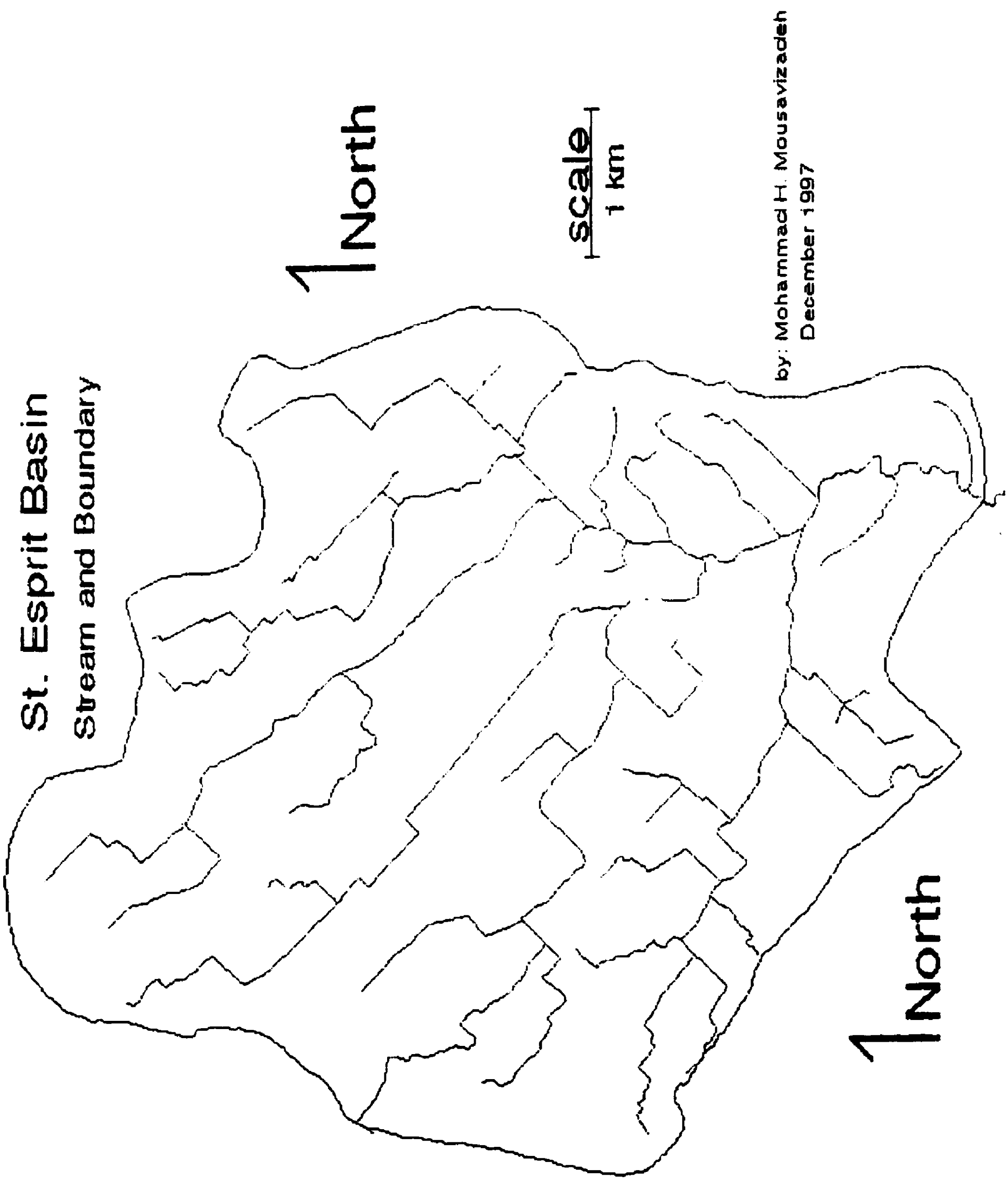
+ 25077 XC15CP + 3123 XC16CP + 31904 XC1CN + 53312 XC2CN + 12906 XC3CN
+ 13817 XC4CN + 22726 XC5CN + 19144 XC6CN + 7252 XC7CN + 17054 XC8CN
+ 7177 XC9CN + 6410 XC10CN + 13479 XC11CN + 4941 XC12CN + 3575 XC13CN
+ 2555 XC14CN + 10166 XC15CN + 1266 XC16CN + 4254 XC1H + 7108 XC2H
+ 1721 XC3H + 1842 XC4H + 3030 XC5H + 2553 XC6H + 967 XC7H + 2274 XC8H
+ 957 XC9H + 855 XC10H + 1797 XC11H + 659 XC12H + 477 XC13H
+ 341 XC14H + 1356 XC15H + 169 XC16H <= 3787000
END
INTEGER-VARIABLES= 195

Appendix 3 Watershed Maps

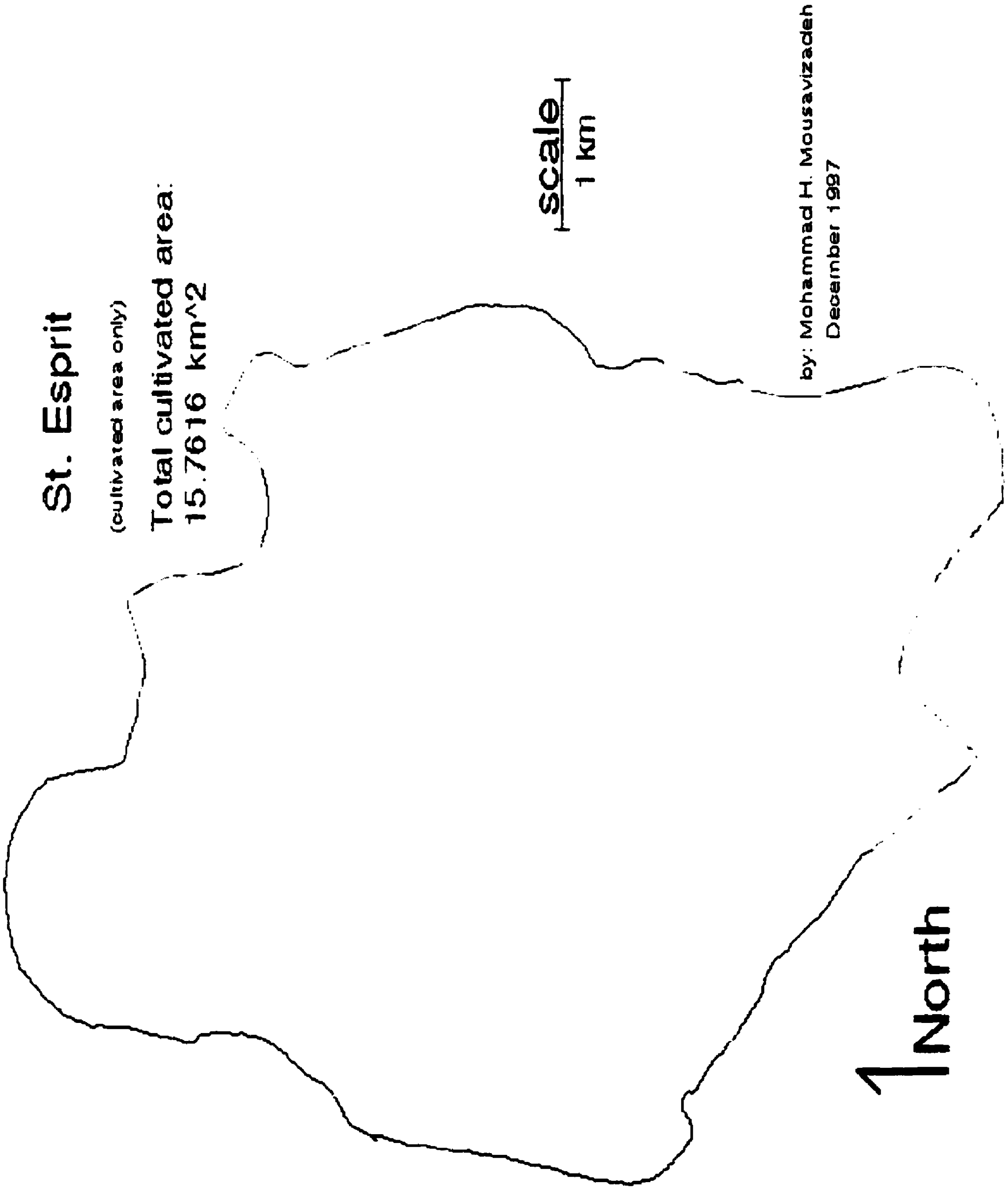
3.1 Field Boundary



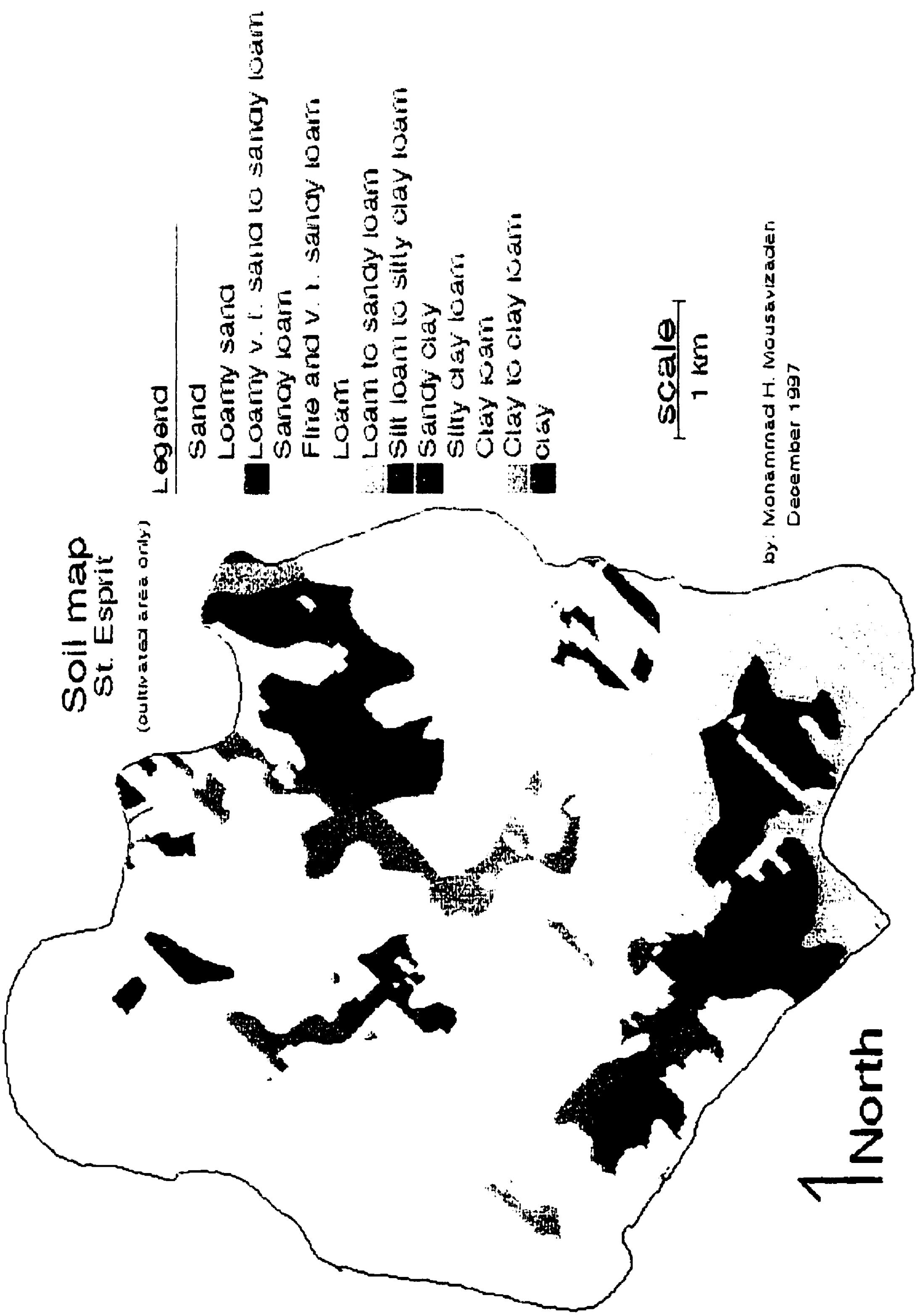
3.2 Hydrography



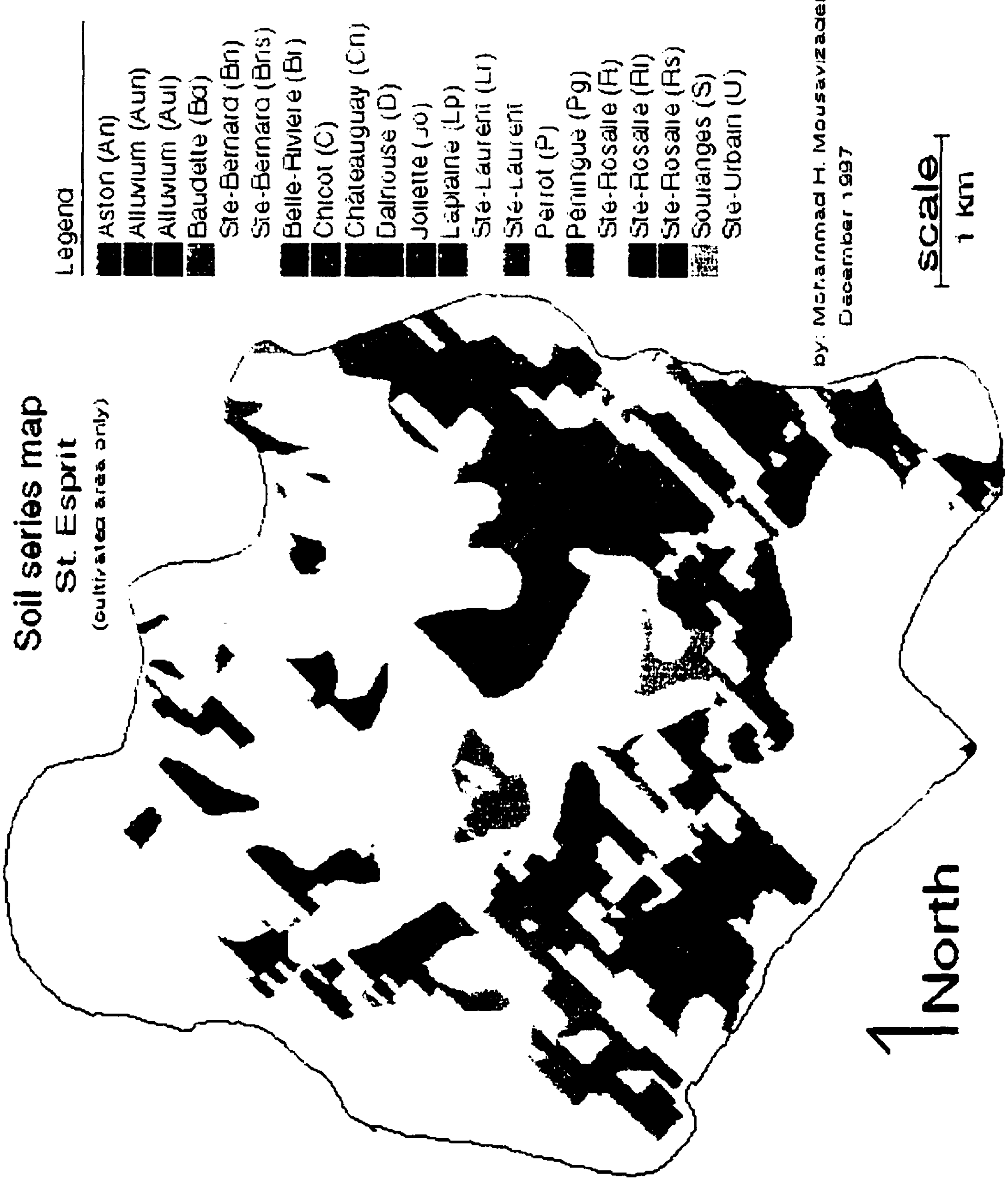
3.3 Cultivated Area



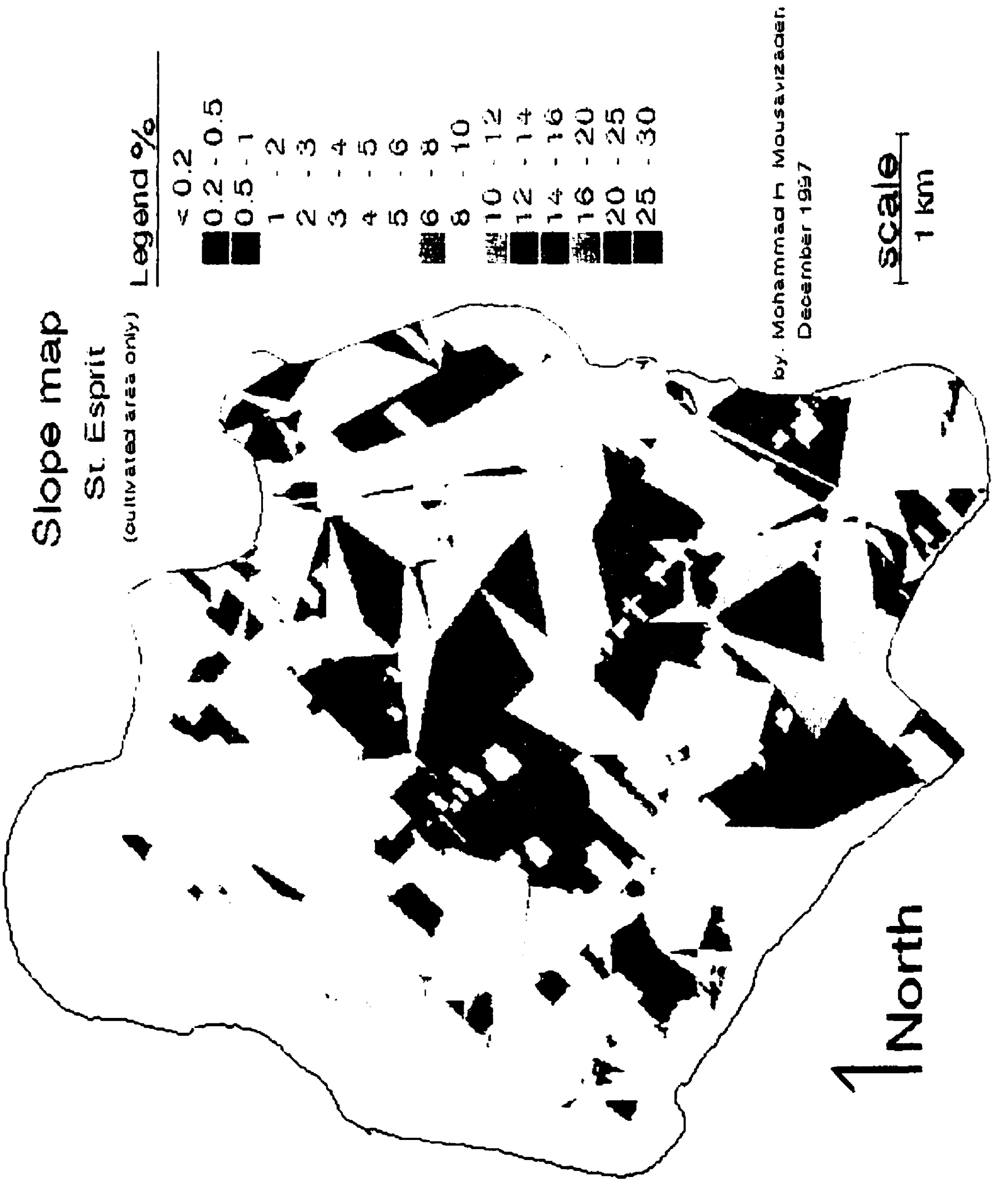
3.4 Soil Texture



3.5 Soil Series



3.6 Slope


Slope map
St. Esprit
(cultivated area only)
Legend %
< 0.2
0.2 - 0.5
0.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16 - 20
20 - 25
25 - 30
by. Mohammad h. Mousavizadeh
December 1997
scale
1 km
North