Exploring options for sustainable development of vegetable farms in South Uruguay

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Exploring options for sustainable development of vegetable farms in South Uruguay

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Abstract

Sustainable development of vegetable farms in South Uruguay requires development of farming systems that contribute to an increase of farmer's income to socially acceptable levels, to reduction of soil erosion and to improved physical and biological soil fertility.
To aid the development of innovative farming systems we propose the use of model-based explorations for strategic re-design of the farming system. Current methodology of model-based and future-oriented land use studies is not able to take into account simultaneously temporal interactions (i.e., interaction among crops in a rotation) and spatial heterogeneity (i.e., differences in characteristics between or within fields on a farm). Particularly in the context of vegetable farming in Uruguay, model-based land use studies should be able to take into account heterogeneity in time and space as well as long-term consequences of various farming systems on the environment. This study develops a method with that specific capability and applies it to explore options for more sustainable vegetable farms in the Canelón Grande micro-watershed in South Uruguay. We focussed on agronomic and economic productivity and on the long-term effects of land use options on soil erosion and fertility. The method was divided in two main steps. In the first step we designed and quantitatively evaluated a large set of land use systems (crop rotations) at the field scale. A computer program (ROTAT) was developed to create all feasible crop rotations based on a list of crops and following well-defined agronomic rules. In the second step we designed farm systems by optimally allocating crop rotations to different fields of the farm as a function of the resource availability of the farm and the priorities given to different objectives using a mixed-integer linear programming model (SmartFarmer). Applied to 7 existing farms with different resource availability, the model suggested that decreasing the area of vegetable crops by introducing long crop rotations with pastures and green manure during the inter-crop periods, and integrating beef-cattle production into the farm systems is a better strategy in most cases than current farmer's practice, which is more oriented to increasing the area of vegetables and specializing their farm systems. The study demonstrated that possibilities for development for almost half of the vegetable farms in this region depends upon changes in the resource endowment at the farm level, either by access to more land, by increase in the irrigated area or both. This study brings explorative land use studies to the context of real farms and the conditions in which they have to operate, by developing a tool with the potential to contribute to farmers' strategic thinking about their own farms.

Keywords: land use system, modeling, farming system, future-oriented studies, vegetables, Uruguay

A el abuelo Juan, el abuelo Julio, el tío Luis y Mariana

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Chapter 1

General Introduction

1 General Introduction

1.1 Vegetable production in Uruguay

Vegetable production is the third agricultural activity in importance in Uruguay, after beef cattle and dairy production, in terms of the number of farms and the number of permanent and temporary workers (DIEA, 2001). In 2000, 5121 farms occupying an area of 83,000 ha and growing 21,500 ha of vegetable crops had vegetable production as main source of income. These farms employed more than 14,000 permanent workers and 257,000 days of hired labor. Estimated yearly production of vegetable products is around 330,000 tons (DIEA-PREDEG, 1999). Most of this production is sold on the internal market. Trade flows are only minor, i.e., from 1996 to 2000 Uruguay exported 2,200 tons of vegetable products per year while importing 28,000 tons. Around 70% of the area with vegetable crops is located in the South of the country in a radius of 70 km around Montevideo, the capital city (Figure 1.1).

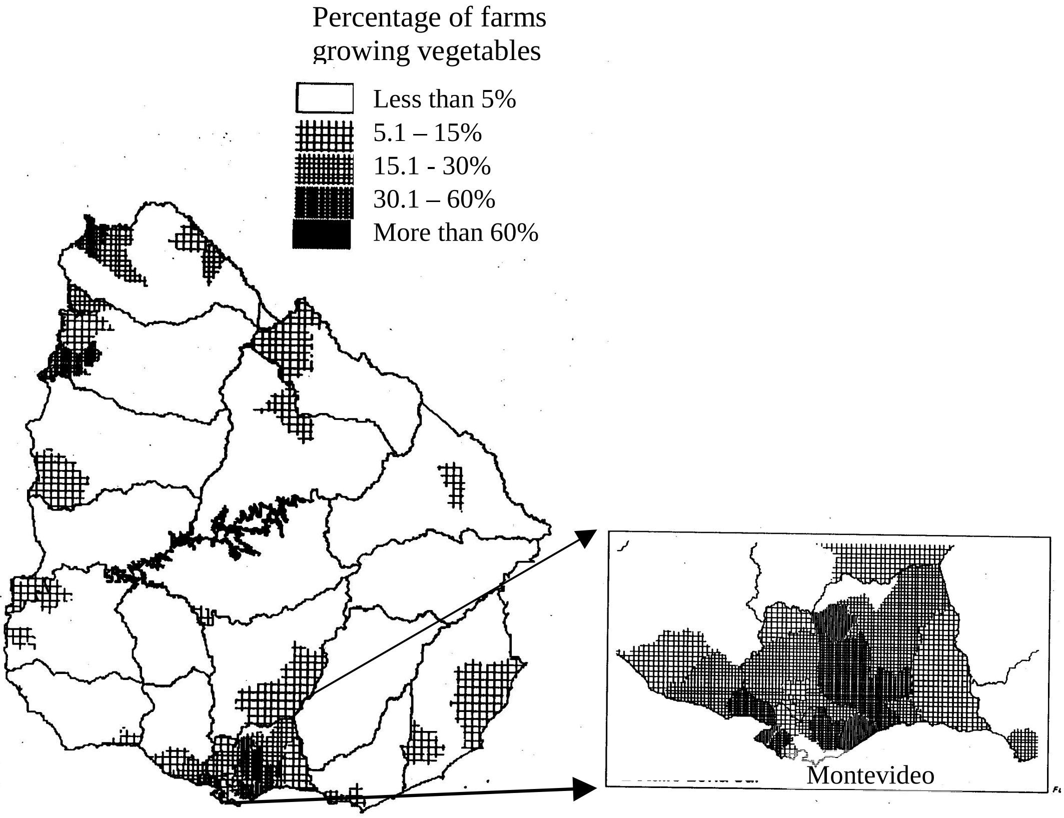

Figure 1.1. Location of vegetable production in Uruguay (Source: DIEA, 2001)

From 1990 to 1998, production of vegetable crops increased by 24%, crop yields increased by 29% while the area of vegetable crops decreased by 9% (DIEA-PREDEG, 1999). Market de-regulation and liberalization of regional trade resulted in a 114% increase in imports of fruits and vegetables from 1990 to 1997 (JUNAGRA, 1999). As a result of increased production and imports the average price of fruits and vegetables decreased by 34% from 1992 to 2001 (Figure 1.2). Vegetable farmers suffered from the decrease of prices and from competition from imported goods. The number of farms specialized in vegetable production decreased by 20% in 10 years (DIEA, 2001). Vegetable growers had to produce more, cheaper and better quality products to stay in business. A farmer in 1996 had to produce either 75% more sweet pepper, 60% more sweet potato or 72% more squash to maintain the same income level as in 1991 (PRONAPPA, 1997).

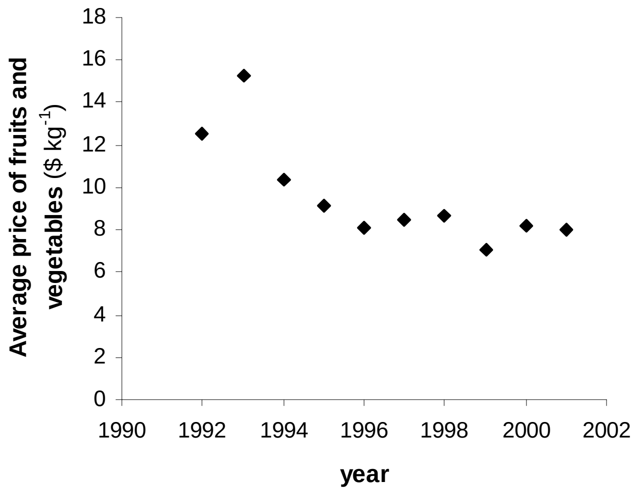

Figure 1.2. Average price of fruits and vegetables at the Montevideo wholesale market for the period 1992-2001 ($ kg^{-1}) in constant prices (base year 1992) (CAMM, 2002).

In order to increase production, farmers intensified and specialized their farm systems. They increased the area with vegetable crops by shortening the fallow periods. The use of chemical crop protectants, imported seeds and irrigation also increased (Aldabe, L., 2002). These changes in the production systems put more pressure on already deteriorated soils and on limiting farm resources. Experts and farmers perceive physical and biological soil fertility as an important yield-limiting factor in most vegetable crops (Carmona et al, 1993; García and Reyes, 1999; Peñalva and Calegari, 2000; Klerkx, 2002). Consequently, sustainable development for vegetable farms in South Uruguay requires the development of farm systems that contribute to an increase of farmers' income to socially acceptable levels, to a reduction of soil erosion and to an improved physical and biological soil fertility.

1.2 Model-based explorative land use studies

The need for re-design of agricultural production systems is not exclusive for the vegetable production sector of Uruguay. Causes may differ, but all over the world there is a struggle for sustainable development of agriculture (Pretty, 1995; Altieri et al., 1995; Rabbinge, 1994). Sustainable development implies that the productive capacity of the resource base has to be maintained to guarantee stable or increasing production in the future. Sustainability may be interpreted as the degree to which a set of objectives in different domains e.g. economics, environment, landscape, and equity is satisfied. The relative importance of sometimes conflicting objectives varies with the valuation by different stakeholder groups, and the set as well as the valuation may vary over time (Norman and Douglas, 1994; Jansen et al., 1995). Sustainability of farming systems thus can be seen as a social construct (Röling, 1997) shaped by negotiation or political debate (WRR, 1995). A role of science is to feed the debate with information on alternative farming systems and their performance in terms of the set of sustainability objectives (Van Ittersum et al., 1998; Ten Berge et al., 2000).

Interactive prototyping, participatory approaches and dynamic simulation of production processes using computer models are important scientific approaches developed to contribute to the design and implementation of innovative farming systems. The prototyping approach is a methodical way of designing, testing, improving and disseminating prototypes of integrated and ecological arable farming systems developed and applied in The Netherlands and other European countries. This procedure has 5 steps: making a hierarchy of objectives, linking the objectives to parameters to quantify them, designing a theoretical prototype and farming methods, testing the prototype on pilot farms and finally disseminating the prototype by pilot groups (Vereijken, 1997). Participatory approaches are a set of methods, which emphasize the involvement of stakeholders in the designing process. They aim to get insight in the choices that stakeholders make under changing conditions. The innovation of farming systems and management practices is seen as a learning process. Participatory Rural Appraisal (Mukherjee, 1993) and Praxeology (Deugd et al., 1998) are two types of participatory studies. The potential of dynamic simulation of production processes using computer models to contribute to improved farm management was envisaged from the early 1960’s (McCown, 2002). Starting by simulating potential crop growth (De Wit, 1978), in 3 decades models grew along with the knowledge on biophysical processes, software engineering and computer capabilities. Currently a wide variety of simulation models exists addressing agricultural problems at different aggregation levels (i.e. crop, field, farm and region) and different time horizons (i.e., single growing season, crop rotation, long-term fate of soil resources) (Kropff et al., 2001). However, the main applications of these models have been in the area of research and education, while its potential to influence the decision making of farming systems managers is still largely unrealized (Keating and McCown, 2001; Van Ittersum et al., 2003).

In the systematic development of farming systems four phases may be distinguished: diagnosis, design, testing and improvement and dissemination (Rossing et al., 1997a). In the diagnosis phase stakeholders' views are identified and translated into a set of objectives and parameters to enable their evaluation, main problems caused by current farm systems are assessed, and available production resources are quantified. The results of the diagnosis phase guide the design phase. In the design phase, knowledge from different disciplines and from farmers' experience is integrated and synthesized to higher integration levels to create new theoretical production systems (Hengsdijk and Van Ittersum, 2002). In the third step, the operational feasibility, economic benefits and ecological performance of these new theoretical prototypes are tested and evaluated in pilot farms. Diagnosis of performance of the new systems allows a new cycle of design and testing as in the 'Prototyping approach' (Vereijken, 1997). In the fourth step, those prototypes considered satisfactory are disseminated through pilot groups of farms. Since very few theoretical prototypes can be tested in practice and testing takes many years, the design phase becomes critical. Three important qualities are required from the design method. The first one is the ability to create a great number of alternatives (ideally all feasible ones) which comply with the designing criteria derived from the data obtained and goals agreed upon in the diagnosis phase. The second quality is the ability to quantitatively evaluate and compare 'a priori' the created alternatives in terms of the degree of achievement of pre-defined objectives. The third quality is the clear presentation of requirements and consequences of the alternatives to promote discussion among stakeholders about change.

Simulation of production processes using comprehensive systems models can contribute to the design phase by generating and quantitatively evaluating a large number of alternatives. During the last decade, powerful biophysical simulation tools have been developed at the cropping system level such as DSSAT (Jones et al., 2003) and APSIM (Keating et al., 2003), which allow the prediction of the consequences of management actions and strategies on crop yields and long-term fate of soil resources under variable weather conditions. The APSIM simulator was successfully used within the farming community of Northeast Australia by combining the principles of the participatory approaches in simulation-aided discussions about management between farmers and their advisers in the frame of the FARMSCAPE approach (Carberry et al., 2002). Cropping systems simulation models are very useful for a detailed analysis of a limited number of crop rotations, focussing on temporal dynamics of water, nutrients and soil physical properties. However, this type of models does not design crop rotations but the crop sequence is given as input to the model. Also, current cropping systems models are not particularly suited to evaluate a large number of crop rotations, neither do they take into account the effect of cropping frequency due to soil borne pests and diseases.

Model-based explorative land use studies may contribute to cropping or farming systems development by presenting a quantified set of alternatives that result from different priorities for sustainability objectives, thus revealing consequences of following different development pathways. Explorative land use studies can address different hierarchical levels: field, farm, (supra) region and different time horizons (e.g. Rabbinge et al., 1994; Penning de Vries et al, 1995; Van Rheenen, 1995; Habekotté and Schans, 1996; Rossing et al., 1997b). Explorative farm modeling is a method that integrates component knowledge at crop and animal level, stakeholder objectives and external variables to outline the consequences of strategic choices at the farm scale and hence support strategic thinking during the design of new farming systems (Ten Berge et al., 2000). The integrating method generally used in model-based explorative land use studies is optimization modeling. The optimization technique used in many of these studies is linear programming (LP), which enables capitalizing on extensive experience with this optimization approach in the field of economics (de Wit et al., 1988; Veeneklaas, 1990; Wossink, 1993; Hardaker et al., 1997). However other optimization approaches have been used such as dynamic programming (Stott et al., 1996) and global search algorithms (Mayer et al., 1999).

Farm systems are heterogeneous in time and space. Temporal heterogeneity is a result of the interaction among crops in a rotation with respect to resource availability and resource quality, as a function of weather variability. The combination of crop species, the frequency of each crop, the crop sequence and the inter-crop activities influence the yielding ability of each crop, the amount of inputs required to realize a given yield level and the long-term processes that affect soil fertility (Struik and Bonciarelli, 1997). However, many explorative studies do not consider temporal interactions when designing land use systems (Hengsdijk and Van Ittersum, 2002). Heterogeneity in space results from differences in characteristics between or within fields on a farm. Methodology developed in previous model-based explorative land-use studies at the farm level is not able to take into account simultaneously temporal interactions and spatial heterogeneity. Particularly in the context of vegetable farming in Uruguay, model-based land use studies should be able to take into account heterogeneity in time and space as well as long-term consequences of various farming systems on the environment.

1.3 Objective of the study

This study aims at exploring options for improvement of vegetable farmers' income in the Canelón Grande micro-watershed in South Uruguay, while soil erosion is reduced and physical and biological soil fertility is improved. Since the potential space for solution of problems related to the sustainability of a farm in a given environment is limited by the resource availability of the farm, this study provides insight in the influence of farm resource endowment on the potential room for sustainable development of vegetable farms in this region.

In order to achieve this aim in the context of the vegetable farms of Canelón Grande, this study develops an explorative farm modeling method to be applied in situations where climate allows year-round cropping and spatial heterogeneity within the farms is important. Transparency during design of production activities is emphasized to reduce the risk of overlooking important alternatives. The method developed is targeted at supporting the design phase of a systematic process of developing production systems at farm level.

1.4 Outline of thesis

Chapter 2 describes the study area and the main problems threatening sustainability of farming systems, and introduces the method developed to explore options for sustainable development of vegetable farms in Canelón Grande.

In Chapter 3, a procedure, made operational in a software tool, is presented to generate all agronomically feasible crop rotations, given a set of agronomic rules representing expert knowledge in a quantitative and transparent manner. Method and tool are illustrated with a case study from the Netherlands. The usefulness of the approach for generating crop sequences for subsequent use in linear programming models as well as its direct applicability in the design of crop rotations is discussed.

In Chapter 4, the approach adopted to design and evaluate a wide variety of production activities (crop rotations) for Canelón Grande is presented. The usefulness of this approach as an ex-ante evaluation of new systems is illustrated with a case study from Canelón Grande.

The room for improvement of farmers' income at reduced soil erosion and improved physical and biological soil fertility is explored in Chapter 5. Using an interactive multiple goal linear programming model, farm systems were re-designed for 7 vegetable farms in Canelón Grande. The chapter discusses the potential degree of achievement of different sustainability objectives and the main changes proposed for the current farm systems.

In Chapter 6, the explorative farm modeling method is used to gain insight in the influence of farm resource endowment, i.e. land, labor, irrigation and machinery, on possibilities for sustainable development. The impact of farm resource endowment on farm resource use efficiency and on possibilities for sustainable development of vegetable farms in Canelón Grande is discussed.

Chapter 7 discusses the contribution made by this study to improve the methodology of model-based and future-oriented land use studies and to reveal future options for vegetable farms in Canelón Grande. The chapter suggests the manner in which the explorative farm modeling method would contribute to a systematic process of farm research and development and provides an agenda for future research.

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Chapter 2

General description of the study area and overview of the research approach

2 General description of the study area and overview of the research approach

ABSTRACT

This chapter describes the Canelón Grande watershed and presents an overview of the approach developed to explore options for sustainable development of vegetable farms in this region. In Canelón Grande climate allows year round cropping, 81% of the land is suitable for arable crops and 54% of the farms have vegetable production as main source of income. Main problems threatening sustainability are decreasing farmers' income and deteriorated physical and biological soil fertility. Means proposed to overcome these problems are agronomically sound crop rotations, inter-crop practices to reduce soil erosion and increase soil organic matter content, mixed production systems and optimal farm resource allocation. The approach presented supports the design phase of a systematic process of developing production systems at the farm level with a time horizon of 1-5 years. We divided the method in two steps. The first step was conducted at the field scale and resulted in 336,128 production activities i.e., combinations of crop rotations and production technologies completely specified by their inputs and outputs. The second step was conducted at the farm scale and resulted in optimal farming systems designed by allocating production activities to different land units on the farm as a function of the resource availability and the priorities given to different objectives, using a multiple goal linear programming model.

2.1 Description of Canelón Grande watershed

2.1.1 Climate

Canelón Grande is situated in the South of Uruguay (34º 25' S and 56º 15' E), 50 km to the North of Montevideo (Figure 2.1). It is a smoothly hilly area with an altitude between 13 and 67 m above sea level. The average temperature is 16 ºC and the average annual rainfall is 1100 mm (Table 2.1). Light frosts occur from the end of May till the end of September. There is risk of water deficit from October till March and water surplus from May till August. Climate allows year round cropping and 81% of the area is suitable for arable crops.

2.1.2 Soils

The dominant soil types in Canelón Grande are Typic Hapluderts, Typic Argiudols and Abruptic Argiaquols. Their main limitations for agricultural use are high erosion risk and difficulties for tillage due to their heavy textures (Table 2.2). The region is located in one of the most eroded areas of the country. In 1992, 45% of the area had lost between 25 to 75% of the top horizon (Carmona et al., 1993). The content of organic matter in the top horizon of these soil types under undisturbed conditions (natural pastures) varies between 4.5 and 6.5%

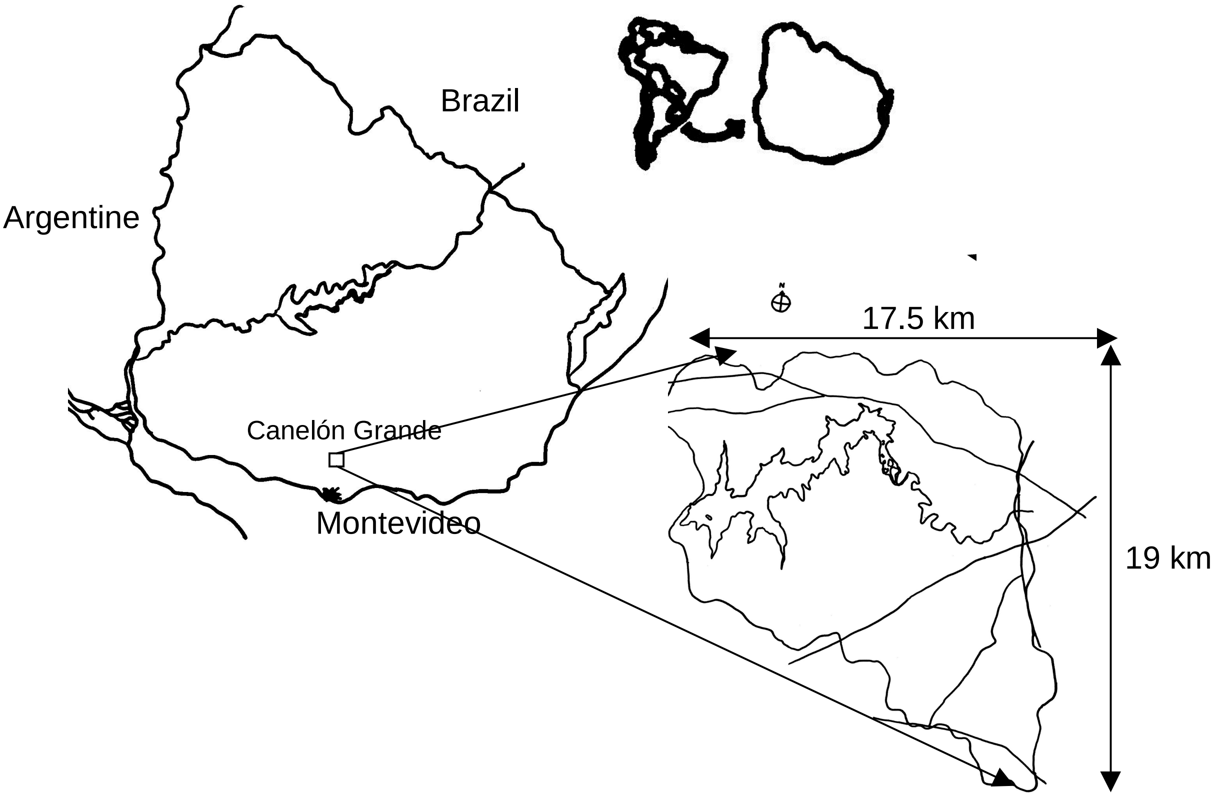

Figure 2.1 Location of Canelón Grande

Table 2.1. Average climate data for Canelón Grande calculated based on daily data from 1989 to 1999 from Las Brujas research station (34º 40' 02'' S, 56º 20' 01'' W, 32 m above sea level), located 25 km Southwest from the study region (Furest, 2000).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
T Max (ºC)	28.7	27.4	26.4	22.3	19.0	15.4	14.7	17.7	18.2	21.7	24.4	27.5
T Min (ºC)	16.5	16.3	15.4	12.4	8.9	6.3	5.2	6.6	7.7	10.5	12.9	15.2
Relative Humidity (%)	69.9	73.0	74.8	79.7	81.0	80.9	79.9	77.0	74.2	73.3	71.6	69.7
Daily global radiation (MJ m^{-2} d^{-1})	23.4	19.7	16.4	10.7	8.2	6.3	6.9	9.9	13.4	17.2	21.4	23.1
Rainfall (mm $month^{-1}$)	94	98	92	144	80	76	72	54	73	106	129	116
Evaporation from water surface (mm $month^{-1}$)	223	165	149	88	65	50	53	75	102	142	174	217
Wind speed (m s^{-1})	2.0	1.8	1.7	1.7	2.7	2.3	1.8	1.9	2.1	2.1	2.1	2.1

(Durán, 1998). Presently, under vegetable cropping they have between 2 to 3% of organic matter. The conditions for crop growth have deteriorated due to crust formation, lowered water-holding capacity and reduced gaseous exchange (Therzaghi and Sganga, 1998). Farms in this region usually own land with more than one soil type with different topographic position, risk of erosion and suitability for crop growth.

Table 2.2 Characteristics of main soil types suitable for agriculture in Canelón Grande.

Soil Type	Share of total area (%)	Horizons thickness (cm)	Water holding capacity (mm 10^{-1} cm^{-1})	Topsoil			Slope gradient (%)	Infiltration rate (cm h^{-1})
				Texture	Clay (%)	Organic matter (%)		
1 Typical Hapluderts	31	A_1 18	13.2	Clay	45	2.0-3.0	2.5-4.5	0.50
		A_2 28	8.5					
		B_{21} 17	6.3					
		B_{22} 25	4.1					
2 Typical Argiudolls	28	Ap 14	15.8	Silty clay loam	35	1.7-2.5	3.0-4.5	4.20
		B_{1t} 10	18.4					
		B_{2t} 42	17.1					
		B_{3Ca} 24	16.5					
3 Abruptic Argiaquolls	22	A 20	18.3	Silty clay loam	28	2.5-3.5	1.0-1.5	0.12
		B_{21t} 20	16.7					
		B_{22t} 30	16.1					
		B_3 20	15.2					

2.1.3 Farm resource endowment

There are 280 farms in Canelón Grande, 47% and 87% are smaller than 10 and 50 ha, respectively and 150 have vegetable production as main source of income (DIEA, 2000 unpublished). The average size of vegetable farms is 17.2 ha. In a sample of 26 vegetable farmers, 69% of their land was in ownership and 31% rented (Klerkx, 2002). There are 317 tractors in the region, 93% are more than 7 years old and 55% and 92% have 50 and 85 HP or less, respectively. Almost 80% of the farms have basic tools for soil tillage and 50% of the farms have access to a tractor-mounted sprayer (DIEA, 2000 unpublished). In 2000, 56 farms irrigated 239 ha of vegetable crops, which represented 37% of vegetable farms and 9% of the area with vegetable crops. The average family size is 4.1 members (Klerkx, 2002). The average number of permanent workers per farm is 3.0 and the farmers and their families deliver 84% of the permanent labor. The average amount of temporary labor hired is 350 man-hours per farm per year (DIEA, 2000 unpublished).

Almost all households in Canelón Grande had electricity and 65% of them had telephone service in 2000. Roads and communication infrastructure allow transport of products and supplies all year round. Farmers with regular assistance from a technical advisor were only 29% (DIEA 2000, unpublished) and members of farmers' associations or cooperatives were 26% (Carmona et al., 1993). The highest formal educational level of most farmers is primary school, while 23 % of farmers' wives attended or completed secondary school.

2.1.4 Vegetable farming systems

Main vegetable crops grown in Canelón Grande, according to the planted area, are squash, onion, garlic, potato, sweet potato and sweet maize. There is a smaller area of carrots, sweet pepper and tomato (DIEA 2000, unpublished). Squash, onion and garlic are grown in 61, 56 and 53% of the vegetable farms, respectively. Almost 88% of the farmers grow 3 to 6 different crops. The majority of farmers grows the same crop on the same field sequentially and only 12% intentionally plant certain crops in a succession. Well-defined crop rotations do not exist (Aldabe pers. com.; Klerkx, 2002).

After harvest, most farmers perform soil tillage and leave the soil bare until preparations for the next crop starts. Only 27% of the farmers occasionally grow a green-manure crop during the inter-crop periods (Klerkx, 2002). The use of organic manure is important only in some crops such as sweet pepper and tomato, which are grown in small areas. Almost 75% of the vegetable farmers apply some kind of erosion control measure but very few recognize the importance of soil cover to decrease soil erosion.

More than 90% of vegetable farmers use chemical fertilizers for most of their crops. However, only 45 and 20% of the farmers use chemical fertilizers for sweet potato and sweet maize, respectively. Almost all farmers use herbicides, fungicides and insecticides for their vegetable crops. Use of herbicides is low in squash, and less than 20% of the farmers use chemical crop protectants for sweet potato and sweet maize (Klerkx, 2002; Aldabe pers. com.).

Almost 83% of the farms in Canelón Grande have some animals (DIEA, 2000 unpublished). Most vegetable farms (77%) have few animals for domestic consumption of milk and meat and 15% of them have cattle as a secondary source of income. The average number of animals amongst farmers with cattle is 9 (Klerkx, 2002).

Most frequent commercialization channel is the sale through a middleman to the Montevideo’s wholesale market. The middleman charges to the farmer the transportation costs and 15% commission. Other important commercialization channels are direct sales at the farm to a wholesaler and direct sale at the Montevideo’s wholesale market with own or rented transportation (DIEA-PREDEG, 1999; Klerkx, 2002).

2.1.5 Farmers’ perceptions of their systems

The data presented here were gathered through interviews with 26 vegetable farmers of Canelón Grande during April and May 2001 (Klerkx, 2002), which represented 17% of the vegetable farms in the region. All farmers declared that they make plans about what crop to grow and where to plant it, but almost 80% only plan 1 year ahead. Most farmers have preference for a more specialized farming system, focussing on few different crops. Main reasons mentioned to specialize their farm systems were the difficulty to manage a large number of crops and the commercial advantage of selling a larger volume of fewer products. Reasons mentioned by the minority of farmers preferring a more diversified system were the security against crop failure or low product prices. Only one mentioned the possibility of crop rotation.

Farmers declared that the main reason to change their farm systems is to continue farming (DIEA-PREDEG, 1999). They associate the concept of ‘sustainability’ to economic perseverance and enterprise stability (75%). When asked about the main problems that they perceive in nature in their surroundings most answers were related to climate. Only 15 and 7% mentioned pollution by residues of agro-chemicals and soil erosion, respectively. However, 88% of farmers perceive the presence of soil erosion on their farms and mentioned construction of terraces and soil tillage in short tracks as the main control measures applied.

Almost half of the farmers declared that crop yields have increased over the past years, while 35% said that yields decreased on their farms. Main reasons mentioned for yield increase were improvement of their knowledge, application of irrigation and improvement of nutrient supply. The main reason mentioned for yield decrease was deteriorated soil quality. Most farmers think that yields could increase in the near future if some deficiencies are solved, such as low resource availability (i.e. lack of irrigation equipment, machinery, good quality seeds, fertilizers) and poor soil quality.

2.2 Main changes during the last 10 years

From 1992 to 2002, the price at the Montevideo's wholesale market showed a decreasing trend for the main vegetable products cultivated in Canelon Grande except for onion (Figure 2.2). In the period 1997 – 2001, the imports of these products represented between 30 to 58% of the total imports of vegetable products. Farmers' response to this trend was to increase the area with vegetables in an effort to maintain their income. The number of vegetable farmers and the area occupied by their farms in Canelón Grande did not change from 1990 to 2000, but the area with vegetables increased by 23% (DIEA, 2000 unpublished). The average area with vegetable crops per farm increased from 6.5 to 8.3 ha in the same period. Growing more vegetables in the same area was only possible by decreasing fallow periods and increasing cropping frequencies of the same crops. The average area of onion, squash and garlic per farm increased by 112, 31 and 27%, respectively (DIEA, 1994; DIEA 2000 unpublished). Most farmers decreased the number of crops grown. Potato, wheat and a local variety of squash were the crops most frequently dropped from the cropping systems (Klerkx, 2002).

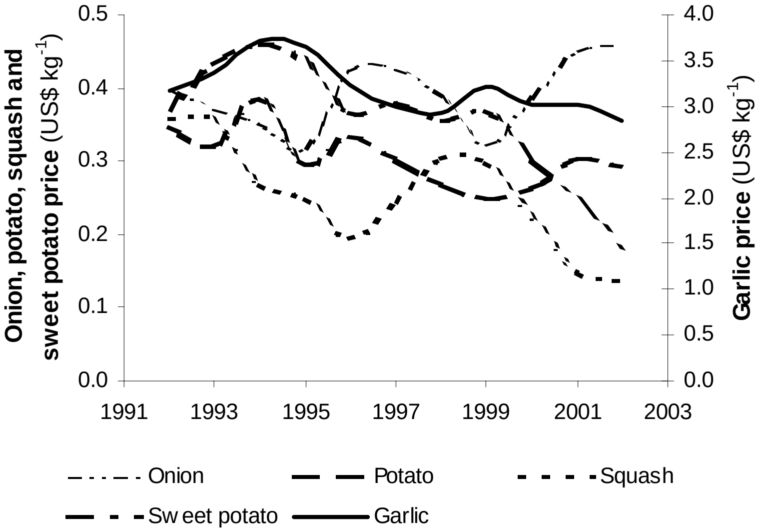

Figure 2.2. Evolution of prices of the main vegetable products of Canelón Grande at the Montevideo wholesale market from 1992 to 2002. Elaborated with data from JUNAGRA (2002).

The use of chemical crop protectants, chemical fertilizers, irrigation and technical assistance increased in this region from 1990 to 2000 (DIEA, 1994; DIEA 2000 unpublished; Klerkx, 2002), as well as did crop yields (DIEA-PREDEG, 1999; Klerkx, 2002). However, main practices regarding soil tillage and soil conservation remained unchanged. Because most recent data available on incidence of soil erosion in Canelón Grande are from 1992 (Carmona et al., 1993), we have no hard data to state how much the situation with respect to soil quality has deteriorated during the last 10 years. We estimated soil erosion and soil organic matter loss per year for 7 farms in the region to be between 9.1 to 15.5 Mg ha^{-1} and 118 to 332 kg ha^{-1}, respectively (Chapter 5). Puentes (1981) defined tolerance levels of 5 to 7 Mg ha^{-1} for erosion in soil types with similar characteristics. According to our calculations and in line with farmers' and experts' opinion, soil quality has deteriorated during the last 10 years.

2.3 Means proposed to overcome sustainability problems in Canelón Grande

During the last 20 years many research projects with different aims have been carried out in Uruguay to solve different problems related to vegetable production systems, such as, reduction of soil erosion, physical and biological soil fertility improvement, irrigation techniques, measures to control weeds, pests and diseases, and breeding of varieties adapted to local environment (i.e., García and Clerici, 1996; Galván et al., 1997; García and Reyes, 1999; Docampo and García, 1999; Zaccari and Sollier, 1999; Durán, 2000). However, the task of integrating the knowledge generated in different areas into new, improved and applicable farming systems, to a large extent, has been left in the hands of the farmers themselves. In this study, a method to integrate this knowledge into theoretical farm systems that can be discussed with farmers and other stakeholders before being tested on pilot farms is developed. The main means proposed to overcome the sustainability problems described for the vegetable production systems in Canelón Grande are:

At the field scale,

- *Crop rotations* to improve crop yields by reducing soil-borne pests and diseases, to reduce soil erosion by including in the rotation crops giving good soil cover and avoiding excessive inter-crop periods, and to reduce input requirements and improve resource use efficiency.
- *Inter-crop practices* to reduce soil erosion and increase soil organic matter by applying organic manure, or growing green manure crops and forage crops.

At the farm scale,

- *Mixed production systems* to increase resource use efficiency and make the inclusion of grass and legumes pastures in the rotation more attractive. Cattle will use as fodder residues from crops such as sweet maize and sweet potato. Pastures will reduce soil erosion and N requirements, increase soil organic matter, and reduce the frequency of vegetable crops.

- *Optimal farm resource allocation* to increase farm income and resource use efficiency, and to achieve the targets of a given set of social and environmental objectives, by selecting the optimal combination of production activities for each farm.

2.4 Methods

During systematic development of farming systems four phases may be distinguished: diagnosis, design, testing and improvement and dissemination (Rossing et al., 1997). The method presented here supports the design phase of a systematic process of production systems development at farm level. We did not deal with the testing and improvement, and dissemination phases. Main objectives of the diagnosis phase are the identification of stakeholders’ views, the translation of these views into a set of objectives and parameters to enable their evaluation, the identification of main problems caused by current farm systems, and the quantification of production resources. The results of the diagnosis phase guide the design phase. Three main sources of information supported the diagnosis phase in our study: unpublished data of on-farm-surveys performed by the Faculty of Agronomy from 1993 to 2000 in vegetables farms of Canelón Grande (Aldabe pers. com.), the bio-physical and socio-economic diagnosis of the Canelón Grande micro-shed performed by FAO project TCP/URU/2252 (Carmona et al., 1993), and the Agriculture Census (DIEA, 1994; 2001). To check and upgrade the data from these sources and gain further insight on farmers' views about their farming systems we performed a farm survey interviewing 26 vegetable farms of Canelón Grande (Klerkx, 2002).

2.4.1 Time horizon

The time horizon affects choices about economic and social factors, production techniques and constraints related to current infrastructure. For this study a time horizon of 1-5 years was assumed, implying that we combined crops currently grown in the region and techniques experimentally tested, but not widespread adopted by farmers. Design criteria and constraints at the farm level were based on current farm resource endowment. Prices of products and inputs were estimated based on trends of the last 10 years, though the method easily allows investigation of alternative prices. However, the effect of proposed farming systems on soil erosion and soil organic matter was estimated for a much longer time horizon (Chapter 4).

2.4.2 Field scale design

A general overview of the design method developed to explore options for sustainable development of vegetable farms in Canelón Grande is provided in Figure 2.3. We divided the design method in two main steps. The first step is conducted at the field level and the second at the farm scale. At the field level we started by selecting a list of crops suitable to be grown in each of the three main soil types found in Canelón Grande. We only selected crops currently grown in the region, in line with our objective of demonstrating opportunities for farmers that may be implemented within 1-5 years. Next we combined these crops into all feasible crop rotations for each of the 3 soil types following well-defined agronomic rules using a computer program (ROTAT) created for this purpose (Chapter 3 - Dogliotti et al., 2003a). Each crop rotation could be grown with four different types of inter-crop activities: fallow, fallow plus animal manure, green manure crops and forage crops. Each crop could be managed with different production techniques resulting in different requirements of labor, capital and inputs, different gross margin and different emissions to the environment. We defined production technologies based on current resource endowment of farms in the region. We distinguished two levels of mechanization and two levels of crop protection, and crops could be irrigated or rain fed. The first step of the design method resulted in 336,128 production activities, i.e. combinations of crop rotations and production technologies, at the field level. For each of these production activities we quantified variables related to their economic performance (gross margin), resource requirement (labor, external inputs, irrigation) and impact on the environment (soil erosion, soil organic matter change, N surplus, environmental exposure to pesticides). The procedure followed and the design criteria used to design and quantify inputs and outputs of production activities at the field level was future-oriented and target-oriented, i.e., technically efficient sets of inputs needed to realize a yield target were identified rather than current input-output relationships. The procedures are detailed in Chapter 4 (Dogliotti et al., 2003b).

2.4.3 Farm scale design

In the second step we designed farming systems by optimally allocating production activities to different land units on the farm as a function of the resource availability and the priorities given to different objectives using multiple goal linear programming (MGLP). We created a MGLP model named SmartFarmer able to optimally allocate production activities to different land units of a farm differing in soil quality to maximize or minimize different objective functions and subject to constraints at the farm scale. We wrote, compiled and solved the

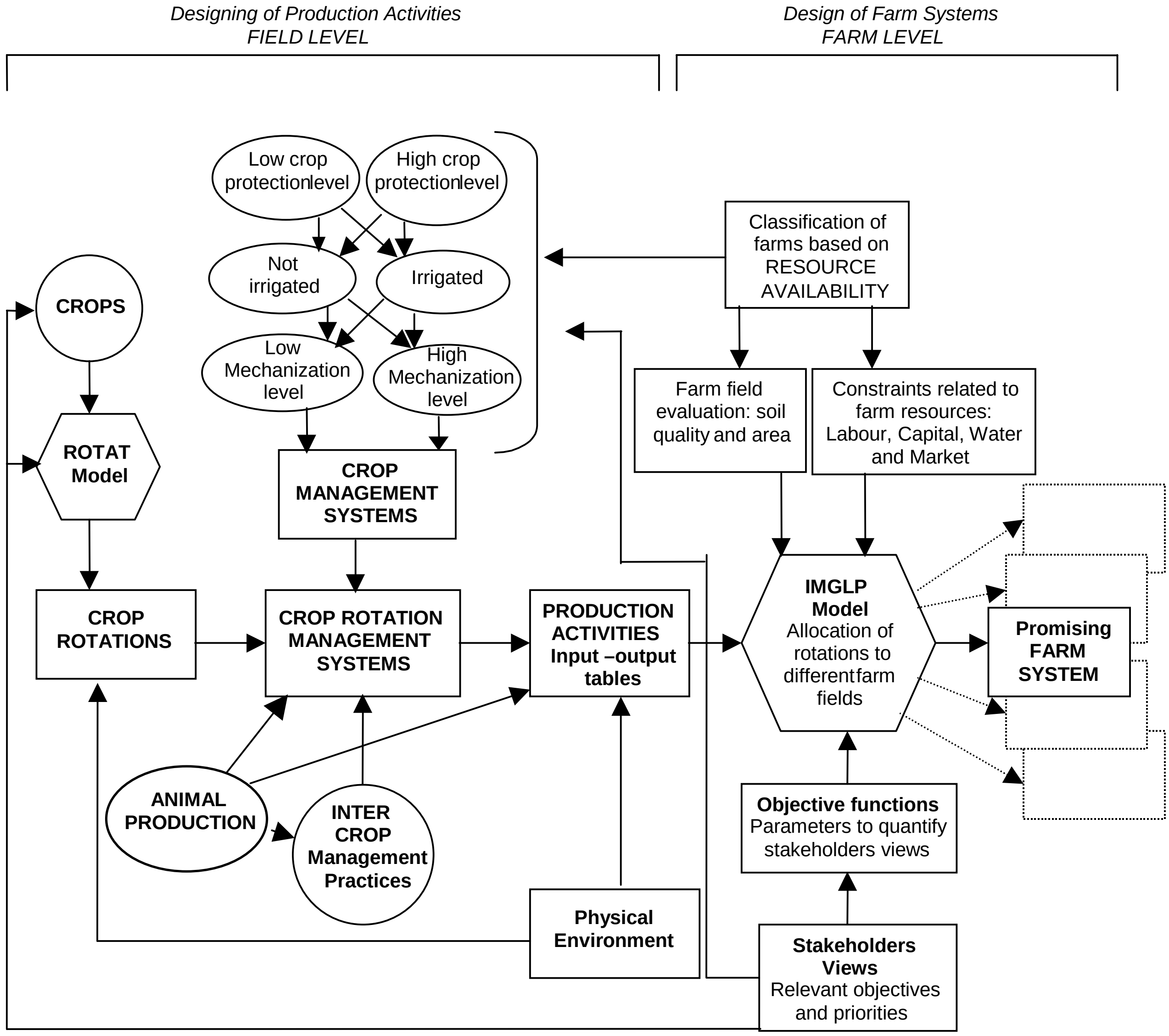

Figure 2.3 General overview of the design method developed to explore options for sustainable development of vegetable farms in Canelón Grande.

model using XPRESS-MP (Dash Optimization Ltd.). The MGLP model had 7 objective functions: farm gross margin, family income, capital requirement, soil erosion, soil organic matter rate, N surplus and environmental exposure to pesticides. Besides the objective functions, that may be used as constraints once target levels have been defined, the model has other constraints that describe the farm’s resources, the desired complexity of the system and the farmer’s preferences. The constraints related to farm resource availability include area of each soil type suitable for cropping, maximum amount of labor available per year, maximum amount of labor available for each of the 24 periods of half a month in a year, and maximum irrigated area. Constraints related to the desired complexity of the farming system and farmer’s preferences include maximum number of production activities per land unit, maximum number of different crops per farm, minimum plot area and maximum and minimum area for each crop. A plot is the unit into which a field has to be divided to carry out a rotation, i.e. the plot area of a 4 ha field with an 8 year rotation is 0.5 ha, assuming each crop of the rotation to be grown every year. We defined an animal production activity at the farm level with the purpose of exploring the potential contribution of mixed systems to the sustainability of farming systems in the region. Based on current farmer practices, we defined the animal production activity as the raising of beef cattle from 150 to 420 kg body weight using mainly on-farm-produced forage. The number of animals in a farm is constrained by the amount of energy and protein produced and labor availability. Smart Farmer model and settings used in this study are described in detail in Chapter 5.

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Chapter 3

ROTAT, a tool for systematically generating crop rotations

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3 ROTAT, a tool for systematically generating crop rotations

ABSTRACT

This chapter reports part of a methodology for a model-based exploration of land use motivated by the lack of sustainability of small farming systems in southern Uruguay. Explorative land use studies aim to gain insight in future possibilities for agricultural development. They support strategic thinking during the design of new farming systems. The crop rotation plays a central role in a farming system and represents a logical starting point in the design process. The combination and sequence of crop species determine characteristics of farming systems such as crop yields, soil erosion, occurrence of soil-borne pests, diseases and weeds, and dynamics of nitrogen and labor. Here, we present a software tool called ROTAT, designed for generating crop rotations based on agronomic criteria in a transparent manner. The program combines crops from a predefined list to generate all possible rotations. The full factorial number of possible combinations of crops is limited by a number of filters controlled by the user. These filters are designed to eliminate crop successions that are agronomically unfeasible and for farm-specific reasons not practical or desirable. The filters represent expert knowledge in a quantitative and explicit way. The use of this computer programme as a stand-alone tool in the process of designing crop rotations is illustrated with a published case study from an ecological pilot farm in Flevoland (The Netherlands). Using this software we were able to design 840 rotations based on the same crops and designing criteria that were used for the example farm. Many of these rotations might be interesting alternatives to the one actually implemented. Coupled with a sound procedure to evaluate the performance of such a large number of rotations 'a priori', ROTAT can reduce the risk of ignoring promising options and the arbitrariness present in previous studies dealing with design of rotations. The usefulness of ROTAT for designing production activities in explorative land use studies based on linear programming is discussed.

3.1 Introduction

Negative side effects of current farming systems on the environment and the landscape, along with lack of social and economic equity for farmers call for redesign of current farming systems in different parts of the world (Altieri et al., 1995; Pretty, 1995; Vandermeer et al., 1998; Pannell, 2001). The study reported in this chapter was prompted by concern over high erosion rates, declining biological soil fertility and decreasing farm income in a vegetable and fruit producing area in southern Uruguay (Carmona et al., 1993). Such concern is often summarized as 'lack of sustainability' of farming systems. Sustainability may thus be interpreted as the degree to which a set of objectives in different domains – e.g. economics, environment, landscape, and equity – is satisfied. The objectives are usually at least partially conflicting, their relative importance varies with the valuation by different stakeholder groups, and the set as well as the valuation may vary over time (Jansen et al., 1995; Norman and Douglas, 1994). Sustainability of farming systems thus is also a social construct (Röling, 1997) and is shaped by negotiation or political debate (WRR, 1995). The role of science is to feed the debate with information on alternative farming systems and their performance in terms of the set of sustainability objectives. This chapter describes part of the methodology that we developed to support design of sustainable smallholder farming systems in southern Uruguay.

Explorative land use studies represent an approach which aims to combine knowledge of biophysical processes underlying agricultural production, stakeholder objectives and external variables to reveal the 'window of opportunities' from an economic-agronomic viewpoint (van Ittersum et al., 1998). The aim of model-based exploration at the farm level is to support strategic thinking of farmers and other stakeholders during re-design of the farm. Such re-design may be seen as a phase in a 'prototyping' process (Vereijken, 1997). The first step in this process is diagnostic, and involves identification and analysis of problems in current systems. It also includes assessment of each of the stakeholders' objectives to arrive at a set of objectives that defines sustainability. In the next step, systems are re-designed to better meet the overall set of objectives. In addition to current agricultural practices, experimental practices are considered in order to create unexpected options for sustainability. In the third step, the operational feasibility, economic benefits and ecological performance of the proposed options are assessed by implementation and testing at actual farms. Diagnosis of performance of the re-designed system completes the learning cycle and paves the way for a next round of re-design and testing. Model-based explorations are thus part and parcel of a systematic approach to development of farming systems.

The model component of explorative land use studies may be based on linear programming (LP), which enables capitalizing on extensive experience with this optimization approach in the field of economics (de Wit et al., 1988; Veeneklaas, 1990; Hardaker et al., 1997), or on other optimization approaches such as dynamic programming (Stott et al., 1996) and global search algorithms (Mayer et al., 1999). Studies ideally address different hierarchical levels: field, farm, and (supra)region, as well as different time horizons (e.g. Rabbinge et al., 1994; Penning de Vries et al, 1995; Van Rheenen, 1995; Habekotté and Schans, 1996). In our research groups we have used interactive multiple goal linear programming for farm level studies for generating alternative farming systems (Rossing et al., 1997a; Makowski et al., 2000; Ten Berge et al., 2000).

Explorative land use studies should have skill in capturing on-farm heterogeneity in time and space. Temporal heterogeneity is a result of the interaction among crops in a rotation with respect to resource availability and resource quality, as a function of weather variability. For example, crop species composition and crop sequence affect the dynamics of nitrogen and labor, as well as occurrence of soil-borne pests, diseases and weeds. Heterogeneity in space results from differences in characteristics between or within fields on a farm. When heterogeneity in space can be ignored, the power of LP can be used to optimize temporal interactions, i.e. to generate those sequences of crops (including inter-crop activities) that optimize one or more objective functions. We found two examples in the literature. El-Nazer and McCarl (1986) developed an LP rotation model for an arable farming system in Oregon, using individual crops and their relation to the crops grown in three preceding years as activities (variables) in the model. Parameters in their model were derived using regression analysis of historical cropping records. This approach does not allow for novel activities for which, by definition, historical data do not exist. As a consequence, results are biased by prevailing farmer practices and can not be used for design purposes. In an LP model for flower bulb and arable farming systems in the Netherlands, Rossing et al. (1997b) and Ten Berge et al. (2000) designed land use activities as the combination of crop species, previous crop, cropping frequency, nitrogen management as well as crop protection regime. Similar to El-Nazer and McCarl (1986), model parameters referred to individual crops, but here they were calculated using production ecological concepts and experimental data rather than farm data (Van Ittersum and Rabbinge, 1997). They described this approach as target-oriented, with activities based on best technical means. In both case studies, the authors assumed homogeneity in space. Both the Oregon and the Dutch case studies used a static model typically applicable for agro-ecological zones with periodic alternation of growing seasons in which one or two crops are grown, and crop-less winter periods that synchronize production cycles.

Conditions where climate allows year-round cropping or where spatial heterogeneity is important, present a methodological challenge because linear programming approaches based on single annual activities do not take these aspects into account. One solution is to define activities in terms of explicit crop rotations and use the LP model to select optimal combinations of activities for the various spatial units in the system. The approach has been used extensively in economic literature, following its introduction by Hildreth and Reiter in 1949 (cited in El-Nazer and McCarl, 1986), and has more recently also been used in studies in which land use is explored from an agronomic perspective (e.g. WRR, 1992). Explicit generation of rotations limits the choice for the LP model to those combinations that the modeler develops. This methodological step should be transparent because it has a major impact on results by constraining the potential solution space of the LP model. In the literature, however, the factorial number of combinations is commonly reduced to a feasible number of rotations by invoking ‘expert knowledge’, which introduces an undesirable element of arbitrariness.

This chapter addresses the problem of how to define explicit crop sequences in a transparent and inter-subjective manner. We present a method that uses agronomic ‘filters’ to reduce the full factorial set of potential crop sequences. These filters represent expert knowledge in a quantitative and transparent manner, and may be subjected to sensitivity analyses. The method is made operational in a software tool called ROTAT. Method and tool are applied to a case study from the Netherlands (Vereijken, 1997). The illustration demonstrates the usefulness of the approach for generating crop sequences for subsequent use in linear programming models as well as its direct applicability in the design of crop rotations.

3.2 ROTAT: a tool for generating crop rotations based on explicit criteria

Crop rotation plays a central role in the development of sustainable farming systems (Vereijken, 1995; Struik and Bonciarelli, 1997). This is because the yielding ability of each crop and the quantity and type of inputs required to realize a given yield level in a particular environment depend not only on the management of each crop, but also on the long term effects on physical, chemical and biological soil fertility by the crop rotation. These effects are primarily determined by the combination of crop species, the frequency of each crop, the sequence of crops and the activities during the inter-crop periods. A crop rotation or a combination of crop rotations on a farm causes a rather fixed pattern in requirements of production resources: labor, water, machinery, storage facilities, etc. and in cash flows.

In principle, all crops that may be grown in a particular production environment can be combined into different cropping sequences. Not all of these combinations are agronomically feasible, but even the total number of feasible combinations may be huge. Expert knowledge is often invoked to select a subset of rotations, but this inherently introduces arbitrariness and the risk of overlooking important alternatives.

ROTAT is a computer program developed to make the procedure of designing crop rotations more transparent and objective. Settings in the current study limit the number of crops to 30 and the number of crop rotations to a maximum of 250,000. The program combines crops from a predefined list to generate all possible different rotations. The maximum number of feasible combinations of crops is limited by a number of filters or rules controlled by the user. For example, starting with 8 crops and allowing 1 crop per year, ROTAT generates 71,824 rotations varying from 1 to 6 years in duration if no limitations are imposed to the combinatorial process except for the removal of duplicates (e.g. BCA and CAB are equal to ABC) and multiples (e.g. ABCABC is equivalent to ABC). If the maximum rotation length is increased to 7 years the number of rotations exceeds 250,000.

The filters eliminate in early stages those crop successions that do not make sense from an agronomic point of view and that are, for farm-specific reasons, not practical or desirable. They are based on expert knowledge capturing the timing of the crop growth periods in the growing season, restrictions on agronomically undesirable sequences and crop frequencies, and restrictions on the complexity of the farm system. The user can parameterize ROTAT for any situation by controlling these filters through input parameters that describe timing constraints, sequence and frequency constraints and farm-specific feasibility and applicability.

3.2.1 Timing constraints

- *Sowing and harvesting dates*: for each crop the sowing and harvesting dates should be provided. In case of crops with a prolonged harvesting period (such as sweet pepper or tomato) the harvesting date is the date of the last harvest. If a crop can be grown in, for example, two different periods of the year, then it is treated as two different crops.
- *Minimum inter-crop period*: The minimum inter-crop period is the shortest period required for proper soil preparation after the harvest of the crop, to be able to sow a following crop. This period depends on the amount of residues and weeds left by the crop and on expected temperature and rain during that particular period.

3.2.2 Sequence and frequency constraints

- *Restrictions on crop successions:* the succession of subsequent crops can be controlled by defining “not allowed” successions, whenever a certain crop cannot be followed by another crop. With this function we can avoid crop successions with negative effects on physical, chemical and biological soil quality. We can also avoid excessively long or short inter-crop periods. This parameter is complementary to the minimum inter-crop period. For example, late onion crops in Canelón Grande are harvested around January 20th while autumn potato crops are sown around February 1st. The minimum inter-crop period for late onion is 30 days (normal soil tillage). However, oats as green manure or as forage crop can be sown 15 days after late onion harvest with minimum tillage. In order to take into account the differences in soil tillage requirements, the minimum inter-crop period of late onion can be set in 14 days and the succession “late onion – autumn potato” can be defined as not allowed.
- *Maximum frequency of each crop in the rotation, maximum frequency of groups of related crops and minimum period before repeating cultivation of a crop:* high cropping frequency of a single crop or a group of crops sensitive to the same soil-borne diseases results in a strong increase in the prevalence of soil-borne pathogens and then in the need for crop protectants (Abawi and Widmer, 2000). The frequency of a crop or related crops in a rotation can also affect the seed bank of weeds (Doucet et al., 1999). A high frequency of crops with low soil cover or with below-ground-harvestable organs can negatively affect soil structure and increase soil erosion (Edwards et al., 1998). To avoid these types of problems the program allows the user to set the maximum average frequency of each crop and of any group of crops, and the minimum time period before repeating cultivation of a crop. The average frequency of crop X in a rotation is calculated by the ratio of the number of times the crop is sown in the rotation (N_X), multiplied by a correction factor (CF_X) that takes into account the growth period (L_X, days) of the crop, and the rotation length (L_{ROT}, years):

Average Frequency Crop X = $N_X * CF_X / L_{ROT}$,
with $CF_X = \text{Round}(L_X / 365)$ for $L_X > 365$ and $CF_X = 1$ for $L_X \leq 365$,
where Round is a function that rounds to the nearest integer.

The average frequency of a group of crops is calculated by adding the individual average frequencies of the crops belonging to the group. If a crop such as potato has a maximum average frequency of 0.25, it can be grown only once in a 4-year rotation and cannot be grown in a rotation shorter than 4 years. However, it does not mean that there always will be three years between two potato crops. For example, potatoes grown in year 1 and year 3 of an 8 year rotation will have an average cropping frequency of 0.25, although the second crop is grown only two years after the first. To implement cropping frequency as a minimum time interval between crops, we need an additional parameter: *the minimum time period before repeating cultivation of a crop*. To effectuate a period of at least 4 years between two subsequent potato crops, this parameter should be set to 4 for potato.

3.2.3 Farm-specific feasibility and applicability

- *Maximum length of the rotation in years:* The program will generate all rotations with a length less than or equal to the maximum rotation length. In practice, the rotation length will be equal to or a multiple of the number of plots or fields required to implement the rotation growing all crops every year. The value of this parameter should be determined by taking into account the desired complexity of the rotation and the minimum field area.
- *Maximum number of different crops per rotation**:*** This parameter prevents the program from creating any rotation with the number of different crops larger than the given parameter value. The specific value depends on the type of crops in the region, the farmer's planning and management skills, the degree of specialization of the system, the degree of market or self-consumption orientation, and possible other factors.
- *Maximum number of main crops and maximum number of secondary crops per rotation**:*** These two parameters are optional. Farmers commonly give priority to particular crops when they take decisions about the amount of resources assigned to each crop. These crops are typically the ones generating a large part of the farmer's income and are denoted here as `main crops'. The user can choose to classify potential crops for a rotation as main crops, secondary crops and no preference crops. The maximum number of crops selected from the first two categories allowed in a rotation needs to be specified. This is another filter to control the complexity of the resulting rotation to fit the capability, resources and interests of the farmer.

By using the ROTAT procedure the process of generating crop rotations becomes transparent and inter-subjective. Decisions taken during the process of designing crop rotations have to be made explicit, and are therefore amenable to sensitivity analysis. It should be noted that ROTAT focuses on generating crop rotations. The evaluation, comprising calculation of inputs and outputs, which is also part of the design process, is carried out externally to ROTAT.

3.2.4 Application: Prototyping a Dutch organic arable farming system

To illustrate the potential contribution of ROTAT to the process of designing crop rotations, we used a case study of the 10 pilot farms in Flevoland (The Netherlands), reported by Vereijken (1997). This author proposed a procedure to design and test prototypes for integrated and ecological arable farming systems. This procedure has 5 steps: making a hierarchy of objectives, linking the objectives to parameters to quantify them, designing a theoretical prototype and farming methods, testing the prototype on pilot farms and finally disseminating the prototype by pilot groups. The multi-functional crop rotation plays a central role in the theoretical prototype and Vereijken (1997) proposed a method to design this rotation for ecological arable farming systems. First, candidate crops are listed in diminishing order of marketability and profitability. Secondly, all crops are characterized by their potential role in the rotation using expert-based quantitative ratings of biological, physical and chemical characteristics (Table 3.1). The biological characteristics represent crop species and membership of genetically and phytopathologically similar crop groups. The physical characteristics used are the period of soil cover by the crop and the effect of the crop on soil structure calculated by adding together the rating on crop rooting density and the rating on effect of the crop on soil compaction. The chemical characteristics used are N uptake and N transfer by the crop to the following one (see footnotes of Table 3.2 for detailed explanation of biological, physical and chemical ratings). Finally, the rotation is drafted based on the following procedure (for ecological arable farming systems): fill the first place in the rotation with the first crop on the list, then fill the subsequent places trying to preserve biological soil fertility by limiting the share per crop species to ≤ 0.167 and the share per crop group to ≤ 0.33, preserve physical soil fertility by consistently scheduling a crop with a high rating of soil cover or effect on soil structure after a crop with a low rating, maintain chemical soil fertility and reduce N loss to the environment by scheduling a crop with a high rating of N transfer before a crop with a high rating of N uptake and a crop with a low rating of N transfer before a crop with low N uptake. The N need of a crop was defined as the N uptake by the crop minus the N transfer by the previous crop. Finally, inspect the result to ensure that the crop rotation is feasible in terms of harvest time, crop residues and volunteers from preceding crops (Vereijken 1997).

Table 3.1. Selection of crops and physical, chemical and economic ratings used to design a multifunctional crop rotation for pilot farm No. 6 in Flevoland (based on Table 3 from Vereijken, 1997 and on Anon., 1998).

	Biological		**Physical**				**Chemical**		**Economic**	
No.	**Species**	**Group** (a)	**Cover** (b)	**Rooting** (c)	**Compaction** (d)	**Structure** (c + d)	**N uptake** (e)	**N transfer** (f)	**Gross margin** (ε ha^{-1} yr^{-1}) (h)	**Labor** (h ha^{-1} yr^{-1})
1	Carrot	Umbel.	-2	1	-4	-3	4	1	11361	415.0
2	Potato	Solan.	-2	1	-2	-1	5	2	5020	40.5
3	Onion	Lil.	-4	1	-2	-1	4	1	8783	137.0
4	Celeriac	Umbel.	-2	1	-4	-3	4	1	5494	664.0
5	Sugar Beet	Chen.	-2	1	-4	-3	5	1	2448	124.0
6	Pea, bean**	Leg.	-2	2	-1	1	0	2	1784	49.0
7	Wheat	Gram.	-2	3	-1	2	4	1	1363	16.5
8	Grass-clover	Gram/Leg	0	3	-1	2	2	2	828	26.5

The original table of Vereijken (1997) also included barley and oats. Since these crops were not selected in the rotation designed for pilot farm 6, we did not include them.
* * Gross margin and labor is average of data for green peas and beans

For footnotes a-h, see Table 3.2

Table 3.2 Multifunctional crop rotation for pilot farm nº6 in Flevoland (based on Table 4 from Vereijken, 1997 and on Anon., 1998).

Block No.	**Crop No.**	**Species**	**Group** (a)	**Cover** (b)	**Structure** (c + d)	**N need** (g)	**Gross margin** (ε.ha^{-1}.yr^{-1}) (h)	**Labor** (h.ha^{-1}.yr^{-1})
I	1	Carrot	Umbel.	-2	-3	3	11361	415.0
II	6	Pea, bean	Leg.	-2	1	-1	1784	49.0
III	2	Potato	Solan.	-2	-1	3	5020	40.5
IV	8	Grass-clover	Gram/Leg	0	2	0	828	26.5
V	3	Onion	Lil.	-4	-1	2	8783	137.0
VI	7	Wheat	Gram.	-2	2	3	1363	16.5
VII	5	Sugar Beet	Chen.	-2	-3	4	2448	124.0
VIII	6	Pea, bean	Leg.	-2	1	-1	1784	49.0
IX	2	Potato	Solan.	-2	-1	3	5020	40.5
X	8	Grassclover	Gram/Leg	0	2	0	828	26.5
XI	4	Celeriac	Umbel.	-2	-3	2	5494	664.0
XII	7	Wheat	Gram.	-2	2	3	1363	16.5
Length (years)**:** 12			**Average:**	-1.833	-0.167	1.75	3842	134.0

(a) Genetically and phytopathologically related groups,

(b) No cover in autumn and winter = -4, no cover in autumn or winter = -2, all others = 0 (green manure crops included).

(c) Cereals, grasses and Lucerne = 3, root, bulb and tuber crops = 1, all others = 2 (green manure crops included)

(d) Compaction by mowing in summer = -1, and autumn =-2, lifting in summer = -2, and in autumn =-4.

(e) N uptake by crop from soil reserves: legumes = 0. All other crops: 25-50 kg/ha = 1, 50-100 kg/ha = 2, 100-150 kg/ha = 3, 150-200 kg/ha = 4, etc. (Nuptake = Nproduct + N crop residues).

(f) N transfer is the expected net contribution of N to subsequent crop, based on N residues in the soil after harvest, N mineralization from crop residues and N losses by leaching and denitrification. N transfer < 50 kg/ha = 1, 50-100 kg/ha = 2, 100-150 kg/ha = 3.

(g) N need (block x) = N uptake (block x) – N transfer (block x – 1). N need is net N input to be provided by manure or N fertilizer.

(h) Gross margin = (marketable yield * price) – variable costs.

We illustrated the use of ROTAT for designing crop rotations by applying it to ‘pilot farm No. 6’ as described by Vereijken (1997). The list of crops and the ratings for the various parameters are presented in Table 3.1. The rotation that was designed by Vereijken is presented in Table 3.2. Based on the same crop list, we used ROTAT to generate all possible crop rotations for that farm. We used rules identical to those used by Vereijken (1997). The maximum rotation length was set to 12 years, the maximum average frequency of each crop in the rotation was set to 0.167 (1:6 years) and the minimum time period before repeating cultivation of a crop was set to 6 years. The share per crop group was limited to a maximum of 0.334 (1:3 years). Successions of crops 1 to 5, 6 and 8, and 7 and 8 (see Table 3.1) were not allowed, hence the model was forced to schedule crops with a beneficial effect on soil structure after crops with a detrimental effect and to select successive crops from different groups. In contrast to Vereijken (1997), we used gross margin of the rotation per ha per year and labor requirement per ha per year to compare the crop rotations once they were created, while he used a heuristic approach by selecting the most profitable crop first. Rotations generated by ROTAT were evaluated by calculating average values per ha per year for all characteristics (i.e. frequencies of crop species and groups, soil cover and structure, N need, gross margin and labor) using a spread-sheet program.

3.3 Results

Following the design rules by Vereijken (1997), ROTAT generated 840 rotations. The best and worst values obtained for each characteristic are shown in Table 3.3, along with the results of Vereijken (1997) for pilot farm No. 6. Absolute differences for soil fertility characteristics are small as a result of the scoring system. All rotations had a length of 6 or 12 years and included 6 or 8 different crops. There was no rotation achieving better results than Vereijken (1997) for all characteristics simultaneously, but 12 rotations showed the same performance in soil cover, soil structure and N need and better results for gross margin and labor (Table 3.4). Identical performance for all characteristics was found in 71 rotations that differed from the one implemented on pilot farm No. 6 not in crop choice but in the order of the crops. If a poorer value in soil cover is accepted, we can choose from 12 rotations with better values for soil structure, N need, gross margin and labor. Furthermore, we found 12 rotations that achieved better results in soil cover, N need and gross margin while having worse values in soil structure and labor (Table 3.4). Compared to the rotation on pilot farm No. 6, 24 rotations performed better in N need and gross margin while being equal in soil cover and soil structure, and worse in labor.

Table 3.3. Performance per individual characteristic of the crop rotation designed by Vereijken (1997) for pilot farm No. 6 and of the set of 840 rotations generated by ROTAT using the same design rules. For ROTAT generated rotations, best and worst results are shown for each characteristic.

	Cover	**Structure**	**N need**	**Gross margin** ($€ ha^{-1} yr^{-1}$)	**Labor** ($h ha^{-1} yr^{-1}$)
Vereijken (1997): Rotation on pilot farm 6, Flevoland	-1.83	-0.167	1.75	3,842	134
ROTAT: Best results	-1.67	0.000	1.67	4,940	66
ROTAT: Worst results	-2.00	-0.667	1.83	2,823	218

3.4 Discussion

ROTAT is a computer program that has been developed to systematically and reproducibly generate crop rotations. It may be used as a stand-alone tool in farming systems design processes and as an instrument in explorative land use studies that use Linear Programming. The usefulness of ROTAT as a stand-alone tool has been illustrated in this chapter. Based on the same list of crops and rules used by Vereijken (1997), we were able to design not one but 840 crop rotations. After evaluation using the semi-quantitative parameters proposed by Vereijken (1997), 12 of the rotations showed better performance in two characteristics and equal performance for the other characteristics compared to the one designed for pilot farm nº6. In total, 71 rotations exhibited a performance equal to pilot farm No. 6, but with different crop sequences. Moreover, crop rotations were found with fewer crops and which were shorter and therefore may be more feasible or desirable for some farmers. Whether or not all these rotations perform better or equal than the rotation actually implemented on the pilot farm needs a more extensive quantitative and empirical evaluation, taking into account e.g. soil fertility and soil-borne-diseases. The results, however, demonstrate the usefulness of ROTAT for generating large numbers of theoretical prototypes based on existing knowledge before further evaluating and subsequently testing them in practice. This complements the 'Prototyping Approach' proposed by Vereijken (1997) for designing and testing ecological and integrated arable farming systems, and reduces the risk of ignoring promising options. Moreover, at the time when the theoretical prototype is discussed with the farmer, the discussion may benefit from presentation of variants similar in performance characteristics but differing in crop ensemble, proportion of particular crops in the rotation, distribution of labor requirements during the year, etc.

Table 3.4. Performance, compared to pilot farm No. 6 and in absolute terms, number of rotations and example for subsets of rotations selected from the total of 840 crop rotations generated by ROTAT based on Vereijken (1997) design criteria for pilot farm No. 6. Performance compared to pilot farm No. 6 is indicated as equal (=), poorer (-) or better (+).

Performance[a] compared to pilot farm No. 6		**Number of rotations**	**Example**	**Cover**	**Structure**	**N need**	**Gross margin** (ε ha^{-1} yr^{-1})	**Labor** (h ha^{-1} yr^{-1})
soil cover soil structure N need gross margin labor	= = = = =	72	Carrot-Pea-Potato-Grassclover-Onion-Wheat-SugBeet-Pea-Potato-Grassclover-Celeriac-Wheat	-1.83	-0.167	1.75	3,842	134
soil cover soil structure N need gross margin labor	= = = + +	12	Carrot-Grassclover-Potato-Wheat-Onion- Pea/bean-Carrot-Grassclover-SugBeet-Wheat-Potato- Pea/bean	-1.83	-0.167	1.75	4,334	113
soil cover soil structure N need gross margin labor	- + + + +	12	Carrot-Wheat-Potato-Grassclover-Onion- Pea/bean	-2.00	0.000	1.67	4,862	114
soil cover soil structure N need gross margin labor	+ - + + -	12	Carrot- Pea/bean-Celeriac-Grassclover-Potato-Wheat	-1.67	-0.333	1.67	4,313	202
soil cover soil structure N need gross margin labor	= = + + -	24	Carrot-Grassclover-Potato-Wheat-Celeriac-Pea/bean-Carrot-Grassclover-Onion-Wheat-Potato- Pea/bean	-1.83	-0.167	1.67	4,587	158

[a] Performance compared to pilot farm no. 6 is indicated as equal (=), poorer (-) or better (+).

As far as we know, this is the first study that describes a transparent method of generating crop rotations. Smith and Glendining (1996) mention that a component of the SUNDIAL model is under development that has a similar purpose. However, their approach seems to be linked to the set of crops parameterized in SUNDIAL, it schedules one crop per year, generated rotations are all of the same duration and all eligible crops are included in all rotations.

The crop rotations generated by ROTAT constitute basic information for designing production activities (Van Ittersum and Rabbinge, 1997). These production activities are input for a multi-objective linear programming model, which combines land use alternatives with the aim of exploring options for sustainable development at the farm or regional scale. The contribution of ROTAT to this process is to increase the choices for the LP model, by increasing its potential solution space, and to reduce the arbitrariness present in previous studies when reducing the factorial number of combinations to a computationally feasible set of rotations.

The program creates all the crop rotations that can be generated within the limits imposed by the user through a set of explicit definition criteria or filters. The filters required by the program are based on agronomic principles and farmer-specific constraints and objectives. Important decisions about the characteristics of the production systems that we aim to improve are made explicit through those filters. For example, by imposing short rotation duration, few crops and high crop frequencies ROTAT generates crop rotations that are more specialized, easier to manage and more dependent on external inputs such as crop protectants and fertilizers than longer rotations with a larger number of crops and lower crop frequencies. The consequences of different design rules can be evaluated, provided we have the tools to quantify performance of the rotations, in terms of their inputs and outputs. Here, we used semi-quantitative expert rules proposed by Vereijken (1997) to quantify a limited set of inputs and outputs.

Information requirement in a more comprehensive case study would involve inputs such as labor, machinery, storage facilities, water for irrigation, capital to buy external inputs, fertilizers and pesticides, as well as, desired and undesired outputs such as crop yields, gross margin, soil loss due to erosion and N loss to the environment. Such a task requires the use of additional tools, such as static and dynamic models and a database to store the data and aggregate from the crop to the crop rotation scale. The application of ROTAT combined with evaluation tools in an LP model based explorative land use study for sustainable smallholder farming systems in southern Uruguay will be presented in the next chapter.

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Chapter 4

Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay

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4 Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay

ABSTRACT

Rapid changes in the social and economic environment in which agriculture is developing together with the deterioration of the natural resource base threatens sustainability of farm systems in many areas of the world. For vegetable farms in South Uruguay, survival in the long term depends upon the development of production systems able to reduce soil erosion, maintain or improve physical and biological soil fertility, and increase farmer’s income to socially acceptable levels. We propose a model-based explorative land use study to support the re-orientation of vegetable production systems in South Uruguay. In this chapter we present a new method to quantitatively integrate agricultural, environmental and socio-economic aspects of agricultural land use based on explicit design objectives. We describe the method followed to design and evaluate a wide variety of land use activities for Canelón Grande (South Uruguay) and we illustrate the usefulness of this approach in an *ex-ante* evaluation of new farming systems using data from 25 farms in this region. Land use activities resulted from systematic combination of crops and inter-crop activities into crop rotations, different crop management techniques (i.e. mechanization, irrigation and crop protection) and animal production. We identified and quantified *all* possible rotations and estimated inputs and outputs at crop rotation scale, explicitly considering interactions among crops. Relevant inputs and outputs (i.e., soil erosion, balance of soil organic matter and nutrients, environmental impact of pesticides, labor and machinery requirements, and economic performance) of each land use activity were quantified using different quantitative methods and following the target-oriented approach. By applying the methodology presented in this chapter we were able to design and evaluate 336,128 land use activities suitable for the different soil types in Canelón Grande and for farms with different availability of resources, i.e. land, labor, soil quality, capital and water for irrigation. After theoretical evaluation, a large subset of these land use activities showed promise for reducing soil erosion, maintaining soil organic matter content of the soil and increasing farmer’s income, allowing improvement of current farming systems in the region and providing a widely diverse set of strategic options for farmers in the region to choose from. This method can be used as a stand-alone tool to explore options at the field and farm scale or to generate input for optimization models to explore options at the farm or regional scale.

4.1 Introduction

During the past 20 years, the conditions under which the vegetable production sector in Uruguay developed, changed rapidly from a highly protected internal market to a free market situation. Small farmers, suppliers of the internal market, were the most affected by the increased competition from imported goods (PRONAPPA, 1997). A vegetable grower in 1996 had to produce either 75% more sweet pepper, 60% more sweet potato or 72 % more squash to maintain the same income level as in 1991 (PRONAPPA, 1997). To cope with this market change and maintain the same family income, farmers had to produce more, cheaper and better quality products. They faced the challenge by intensifying and specializing their production systems, putting more pressure on already deteriorated soils and on limiting farm resources. The survival of this production sector in the long term depends on the development of sustainable production systems able to reduce soil erosion, maintain or improve physical and biological soil fertility, and increase farmers family income to socially acceptable levels. To explore opportunities for sustainable development for vegetable production farms in Uruguay we selected the Canelón Grande micro-watershed, a region where 60% of the farms are smaller than 20 ha and the main source of income is vegetable production.

The prototyping approach (Vereijken, 1997) currently represents an important research method for systematic development of innovative farming systems in The Netherlands and other European countries (Wijnands, 1999). This approach has 5 main steps: making a hierarchy of objectives, linking the objectives to parameters to quantify them, designing a theoretical prototype and farming methods, testing the prototype on experimental farms or on commercial farms and finally disseminating the prototype by pilot groups (Vereijken, 1997). One limitation of the prototyping process is that only a few production systems can be tested empirically in the field. Consequently, during the step in which the theoretical prototype is designed, several feasible alternative production systems are arbitrarily discarded introducing the risk of overlooking promising options. In this chapter we present a new method to quantitatively integrate agricultural, environmental and socio-economic aspects of agricultural land use based on explicit objectives. This method can support the design phase of the prototyping approach through the designing and quantitative evaluation of a large number of theoretical production systems before testing them in practice. This method can be used as a stand-alone tool to explore options at the field scale or to generate input for optimization models to explore options at the farm or regional scale.

The study is divided in two main steps. In the first step we design and evaluate a large set of land use systems at the field scale. In the second step we design farm systems by optimally allocating land use systems to different fields of the farm as a function of the resource availability of the farm and the priorities given to different objectives using multiple goal linear programming (de Wit et al., 1988). This chapter addresses the first step of the study.

We focussed on strategic farm management, i.e. re-design of the farm system, rather than on changes in a particular production technique, and on the long-term effects of land use options on soil erosion and fertility and short term effects on farm income. The objectives, being in this study reduction of soil erosion, improvement of physical and biological soil fertility and increase of farmers' family income, directed the designing process (Hengsdijk and Van Ittersum, 2002). We designed alternative land use systems taking into account not only the main objectives but also the main differences in farm resource availability present in the region. A land use system or production activity is defined as a combination of land use type and physical environment completely specified by its inputs and outputs (Van Ittersum and Rabbinge, 1997). In this study, a production activity is the result of the combination of different crops and inter-crop activities in a rotation, together with the production techniques used to grow each crop and the physical environment given by the soil type. Alternative production activities, which result from the design process, should be better than current ones in at least one of the defined objectives. It is important in an explorative study to have a wide range of alternatives to choose from, because any relevant production activity excluded in this phase will limit the potential solution in the optimization phase.

The main means proposed to overcome the sustainability problems described for the vegetable production systems are:

- *Crop rotations* to improve crop yields, reduce soil erosion and input requirements, and improve resource use and farm income.
- *Inter-crop practices* to reduce soil erosion and increase soil organic matter.
- *Mixed production systems* to increase resource use efficiency and make the inclusion of pastures in the rotation more attractive. Pastures will reduce soil erosion and N requirements, and increase soil organic matter.
- *Optimal farm resource allocation* to increase farm income and resource use efficiency.

In this chapter, we describe the method followed to design and evaluate a wide variety of production activities for Canelón Grande (Sections 2 and 3). Using data from 25 existing vegetable farms in this region we illustrate the usefulness of this approach as an *ex-ante* evaluation of new systems and we analyze the effect of farm size and labor availability on gross margin and family income (Section 4). Finally we discuss the application of this method as a systematic and transparent way of generating a wide range of alternatives at the field scale to be combined at the farm scale using linear programming (Section 5).

4.2 Designing of production activities

4.2.1 The physical environment

Canelón Grande is situated at 34º 25’ S latitude and it has an average altitude of 44 m above sea level. The average temperature is 16 ºC and the average annual rainfall is 1041 mm. For the purpose of this study the soils in the region were grouped into three soil types according to their topographic position, susceptibility to erosion and physical characteristics. Soil type 1 is a typical hapludert with 45 % clay (clay loam) and 2 –3 % organic matter in the top horizon, a slope gradient between 2.5 – 4.5 % and low to moderate degree of erosion present. Soil type 2 is a typical argiudoll with 35 % clay (silty clay loam) and 1.7 –2.5 % organic matter in the top horizon, a slope gradient between 3 – 4.5 % and moderate to severe degree of erosion present. Soil type 3 is an abruptic argiaquoll with 28 % clay (silty clay loam) and 2.5 –3.5 % organic matter in the top horizon, a slope gradient between 1 – 1.5 % and low soil erosion. Almost 80% of the area are suitable for arable crops and the main limitations of soils for agricultural use are workability, erosion risk and drainage.

4.2.2 Time horizon

The time horizon affects choices concerning economic and social factors, production techniques and constraints related to current infrastructure. For this study we assumed a time horizon of 1-5 years. Consequently we combined crops and techniques currently in use in the country, but not widespread. Their intelligent combination results in innovative land use systems. We based the exploration on the current availability of farm resources (capital, machinery, water for irrigation, land and labor). Prices of products and inputs were estimated based on trends of the last 10 years. We explored the effect of land use systems on soil fertility and soil loss due to erosion in the long term (40 years).

4.2.3 Designing of crop rotations

We selected crops based on the main crops currently grown in the region under study. Summer and winter crops were included to spread labor requirements, land use and family income over the year. We ensured diversity in genetically and phytopathologically related crop groups and variability in requirements of labor, machinery and external inputs. The same crop species, but grown in different periods of the year were considered as different crops. Following expert knowledge and farmer practice, we established the suitability of each soil type for the cultivation of the selected crops. A list of crops possible to be grown on each soil type was created and used it as the basis for the designing of the crop rotations for each of the three soil groups identified.

We developed a computer program named ROTAT to systematically and reproducibly generate all possible crop rotations from a list of crops. In this program, the full factorial number of possible combination of crops is limited by a number of rules eliminating those crop successions that do not make sense from an agronomic point of view. These rules are given by a set of input parameters controlled by the user (Dogliotti et al., 2003).

The list of crops and the input parameters selected to generate all feasible crop rotations for each soil type using ROTAT are summarized in Table 4.1. A number of successions of crops were not allowed to avoid negative effects on biological soil quality or long inter-crop periods. Successions of the same crop were not allowed in any case, as well as of crops from the same botanical family. The maximum frequency of each crop in a rotation and the maximum frequency of groups of related crops varied from 1 in 2 to 1 in 4 years and the minimum period before repeating cultivation of a crop varied from 2 to 4 years (Tables 4.1 and 4.2).

The complexity of a rotation is determined by its length and by the number of different crops grown. The rotation length is equal to the number of plots or fields required to implement the rotation, when all crops are grown every year. Long rotations reduce the area of each field making farm management more complex. However, the maximum rotation length should be set long enough to ensure that low frequencies of the same crop or crop groups can be achieved. In this study the maximum rotation length was set to 8 years on soil types 1 and 2, and to 9 years on soil type 3. With this rotation length a 4 years grass-legume pasture can be grown with a maximum frequency of 0.5, while the rest of the crops can be grown with

Table 4.1. List of selected crops, main constraints used by ROTAT for the generation of crop rotations, suitable soil types for each crop and levels of irrigation, mechanization and crop protection used for each crop for the designing of crop production techniques. For explanation see text.

Crop	**Sowing date**	**Growth period** (days)	**Min intercrop period** (days)	**Max freq.** (#.yr^{-1}) (1)	**Min period before repetition** (yr.)	**Sequence constraints** (2) **Number of the next crop**													**Soil type** (3)	**Irrigation level** (4)	**Mech. Level** (5)	**Crop prot level** (5)	**Nr. of prod. Tech.**
						1	2	3	4	5	6	7	8	9	10	11	12	13					
1. Garlic	Jun-1	187	15	1/3	3	X_1	X_2	X_2	0	0	0	0	0	0	0	0	—	0	1	I, R	H, L	H, L	8
2. Onion early	Jul-10	138	15	1/3	3	X_2	X_1	X_1	0	0	0	0	0	0	0	0	—	0	1, 2	I, R	H, L	H, L	8
3. Onion late	Sept-1	136	15	1/3	3	X_2	X_1	X_1	X_3	0	0	0	0	0	0	0	—	0	1, 2	I, R	H, L	H, L	8
4. Potato	Feb-1	114	90	1/4	4	X_3	X_3	0	X_1	0	0	0	0	X_2	0	X_3	—	0	1	I, R	H	H, L	4
5. Sweet potato early	Oct-15	120	30	1/3	3	0	0	0	X_3	X_1	X_1	0	0	0	0	0	—	0	1, 2	I, R	H, L	H, L	8
6. Sweet potato	Oct-15	151	60	1/3	3	X_3	0	0	0	X_1	X_1	0	0	0	0	X_3	—	X_3	1, 2	I, R	H, L	H, L	8
7. Sweet maize	Oct-15	120	30	1/2	2	0	0	0	X_3	0	0	X_1	X_1	0	0	X_2	0	0	1, 2, 3	I, R	H, L	H, L	8
8. Sweet maize late	Dec-22	115	60	1/2	2	X_3	0	0	0	0	0	X_1	X_1	0	0	X_2	0	X_3	1, 2, 3	I, R	H, L	H, L	8
9. Sweet pepper	Nov-1	165	60	1/4	4	0	0	0	X_2	0	0	0	0	X_1	X_4	X_3	0	X_3	1, 2, 3	I	H, L	H, L	4
10. Squash	Nov-1	195	90	1/3	3	0	X_3	0	0	0	0	0	0	X_4	X_1	X_3	0	0	1, 2, 3	R	H	H, L	2
11. Wheat	May-15	204	60	1/2	2	0	0	0	X_3	0	0	X_2	X_2	0	0	X_1	—	0	1, 2	R	H	H, L	2
12. Sudan grass	Nov-1	120	30	1/2	2	—	—	—	—	—	—	0	0	0	0	—	X_1	0	3	R	H, L	L	2
13. Pasture	Apr-1	1310	60	1/2	4	0	0	0	0	0	0	0	0	0	0	0	0	X_1	1, 2, 3	R	H, L	L	2

(1) The frequency of crop X in a rotation is calculated by the ratio of the number of times the crop is sown in the rotation (N_X), and the rotation length (L_{ROT}, years) multiplied by a correction factor (CF_X) that takes into account the growth period (L_X, days) of the crop: Frequency Crop X = $N_X * CF_X / L_{ROT}$, with CF_X = Round (L_X / 365) for $L_X > 365$ and $CF_X = 1$ for $L_X \leq 365$

(Round is a function that rounds to the nearest integer).

(2) Sequence constraints: 0 = the sequence is allowed; X_1 = not allowed because same species; X_2 = not allowed because same botanical family; X_3 = not allowed because inter-crop period > 10 months; X_4 = not allowed because important soil borne diseases are shared; — = combination does not occur.

(3) 1 = typical hapludert; 2 = typical argiudoll 2; 3 = abruptic argiaquoll.

(4) Irrigation level: I = irrigated; R = rain fed

(5) Mechanization or crop protection level: H = high; L = low

frequencies from 1 in 2 or 3 years to 1 in 8 years. Various factors influence the number of different crops grown by a farmer, among them his preference for either security or profit maximization, his planning and management skills, his relation with the market and characteristics of the market itself. More than 80% of the farmers in the region grow between 3-6 crops (Klerkx, 2002), consequently the maximum number of different crops per rotation was set at 6 crops.

Table 4.2. Maximum frequency of groups of related crops and minimum period in years between crops of the same group.

	Group of crops	**Max. frequency**	**Min. period** (years)	**Remarks**
1	Garlic, onion early, onion late	1/3	2.5	Same botanical family, share of soil borne diseases
2	Sweet potato early, sweet potato late	1/3	3.0	Same species
3	Sweet maize early, sweet maize late	1/2	1.5	Same species
4	Potato, sweet pepper	1/3	3.0	Same botanical family, share of soil borne diseases
5	Garlic, onion early, onion late, sweet potato early, sweet potato late, potato	1/2	0	Higher frequencies of tuber, root and bulb crops have negative effect on soil structure
6	Sweet pepper, squash	1/3	3.0	Severe problems in the region with *Phytophtora capsici*

4.2.4 Designing of inter-crop activities

The inter-crop activities were defined with the aim of reducing soil erosion, mainly by keeping the soil covered as much as possible, and raising soil organic matter content by significantly increasing the input of organic C to the soil. Four types of inter-crop activities were designed and combined with the crop rotations in such a way that each rotation can be grown using each type of inter-crop activity:

- *Fallow*: the soil is ploughed a few weeks after harvest of a crop. No other activity is carried out until the start of the secondary tillage 6 – 9 weeks before the sowing of the next crop. This option represents current farming practice;
- *Fallow plus manure*: chicken bed (chicken manure and rice husk), that is available from poultry farms in the region, is applied two months before the sowing of a crop. Experimental data from the region show high response of crop yields to chicken bed application on soils with deteriorated structure after many years of agriculture (García and Reyes, 1999; Docampo and García, 1999). This strategy has one important disadvantage:

the degree of soil erosion is similar to the current practice of fallowing, since the activity has no effect on soil cover;

- *Green manure crops*: they are grown when the inter-crop period is longer than 150 days. Green manure crops keep the soil covered, thus reducing soil erosion. They also reduce N leaching and weed population and they supply between 3.5 – 6.5 ton of DM, that need to be chopped and incorporated to the soil 45-75 days before the sowing of the next crop. The species used are millet (*Setaria itálica L. Beauv.*) for summer green manure, and black oat (*Avena strigosa,* Schreb) or triticale (*Triticum xx Secale*) as winter green manure. Only gramineous species were selected because priority was given to the effect of roots on soil structure and to total biomass production, and not to N fixation.
- *Forage crops*: This option is similar to the previous one but a large proportion of the organic matter produced by millet, black oat or triticale is used as feed for cattle. Consequently the input of organic C to the soil is reduced with respect to the previous option, but similar results with respect to maintenance of soil cover and reduction of weed populations are achieved.

4.2.5 Designing of production techniques

The type and amount of inputs, and the way they are applied characterize the production technique. Numerous production techniques can be used to grow a crop in a particular physical environment (Van Ittersum and Rabbinge, 1997). In our study the design criteria (Hengsdijk and Van Ittersum, 2002) used to design the crop production techniques were based on the level of mechanization, on access to irrigation, and on the use of pesticides.

Farm resource availability

- Mechanization level: according to the availability of machinery in the region we defined two levels of mechanization. The low level includes a small tractor (50 HP) and the basic tools for soil tillage. Pesticides are applied with a knapsack sprayer and mechanical weeding is done using animal traction. The high level includes a larger tractor (90 HP) with suitable tools for soil tillage, spraying, weeding and other crop specific tools. The effect of mechanization is the substitution and productivity increase of labor. We assumed that there is no significant effect of mechanization level on crop yield. In line with the current production techniques, potato, squash and wheat are assumed not to be grown at low mechanization level.

- Water for irrigation: irrigation is available in the region, but there is not sufficient water to irrigate the whole area. The area irrigated per farm varies from 0 to 50% (Klerkx, 2002). Crops may be grown rain fed or irrigated. Crops with very low economic response to irrigation are assumed to be grown only rain fed.

Use of pesticides

- Crop protection level: seeds and chemical crop protectants are the economically important external inputs in vegetable crops. Farmers with low purchasing power try to substitute use of pesticides by labor, and lower yielding but more resistant varieties. Besides, there is increasing concern about the impact of pesticides on environment and human health. We designed two levels of crop protection. At the low level, chemical crop protectants are partially substituted by the use of resistant varieties, cultural practices and labor. At the high level, inputs are geared to minimizing yield reduction due to weeds, diseases and pests.

Combination of irrigation, mechanization and crop protection levels resulted in 2-8 crop management types per crop (Table 4.1). In the same production activity, i.e. rotation, crops may be grown both under rain-fed and irrigated conditions, but all crops are cultivated at the same level of crop protection or mechanization.

4.2.6 Animal production activity

We defined one animal production activity with the purpose of exploring the potential contribution of mixed systems to the sustainability of farming systems in the region. We selected cattle fattening because it is the main type of agricultural production in Uruguay and some farmers in the region already practice it. This production activity makes the cultivation of multi-annual pastures, with the consequent beneficial effect on physical and biological soil fertility of fields under long periods of arable agriculture, economically attractive. However, when crop residues and cover crops are used to feed the cattle, input of organic matter to the soil is reduced compared to green manuring, resulting in lower positive or even negative impact on physical and biological soil fertility. Based on current farmer practices, the animal production activity was defined as the raising of cattle from 150 to 420 kg body weight using mainly on-farm-produced forage.

4.3 Quantification of inputs and outputs of production activities

We hypothesize that by judiciously combining good crop rotations with innovative inter-crop practices and animal production the sustainability of farming systems can be improved. To evaluate to what extent this is possible we used existing knowledge and expertise to quantify the amounts and costs of the resources required for each production activity, the amount and economic value of crop and animal products and the main impacts on the environment. The starting point for the quantification process is the estimation of crop yields. An important part of the inputs and outputs depends on the yield of each crop grown, viz. the balance of soil organic matter, the soil erosion, the amount of labor required for harvest and post-harvest operations, the amount of forage produced as input for animal production, the gross margin, etc. Once the yields of crops in each production activity have been estimated, the rest of the inputs and outputs can be calculated, following the target-oriented approach (Van Ittersum and Rabbinge, 1997).

4.3.1 Calculation of crop yields

The physiological characteristics of the crop, incoming solar radiation and temperature determine the potential yield of a crop. This is achieved when the crop is optimally supplied with water and nutrients and is completely free from pests, diseases and weeds (Rabbinge, 1993). In previous explorative studies the potential yield has been estimated using crop growth simulation models (e.g. van Lanen et al., 1992). In this study, due to the unavailability of validated models for the selected crops, the maximum yields were estimated based on the best yields of irrigated experiments carried out at research stations in the region. These yields were reduced by 15% to take into account reduction caused by unavoidable losses due to crop management at commercial scale. In Table 4.3 the maximum yield of each crop is compared with the current average yield and the yield of top farmers in the region.

Rabbinge (1993) classified the factors that can decrease the potential yield of a crop into growth-limiting factors: water and nutrients, and growth-reducing factors: weeds, pests and diseases. In this study we considered the physical fertility of the soil and the water availability as the growth limiting factors. The growth reducing factors were taken into account through the incidence of soil borne diseases and the effect of the crop protection level. The attainable crop yield (target yield) was calculated as the result of the product of the estimated maximum yield by the four reduction factors (0-1) mentioned:

$$\text{Crop target yield} = \text{Crop maximum yield} * (1 - \text{SQF}) * (1 - \text{WDF}) * (1 - \text{CFF}) * (1 - \text{CPLF}) \qquad \text{Eq. 1}$$

where:

SQF = Soil physical fertility factor

WDF = water deficit factor

CFF = Crop frequency factor (effect of cropping frequency on the incidence of important soil borne diseases)

CPLF = Crop protection level factor

Table 4.3. Average yield in the region, yields of top farmers, percentage of top farmers (DIEA-PREDEG, 1999), best experimental yields and maximum yields used in the study for all selected crops. The maximum yields are 85% of best experimental yields. Best experimental yields of garlic, onion, sweet potato, sweet maize and sweet pepper are from irrigated experiments, squash and wheat are from rain fed experiments.

Crop	Average yield ($Mg\ ha^{-1}$)	Yield of top farmers ($Mg\ ha^{-1}$)	% top farmers	Best yields experiments ($Mg\ ha^{-1}$)	Maximum yields ($Mg\ ha^{-1}$)
Garlic	3.3	7.0	20	12	10.8
Onion	11.1	19.1	32	51	46.3
Sweet potato early	7.2	13.6	30	28	23.8
Sweet potato	6.7	13.6	30	35	29.7
Squash	6.7	15.0	s/d	30	25.5
Sweet maize	2.3	s/d	s/d	12	10.2
Sweet pepper	11.2	24.3	33	48	40.8
Potato	14.0	20.0	s/d	-	30.0
Wheat	2.0	3.0	s/d	4.5	3.8
Sudan grass	-	-	-	-	5.7
Grass-legume pasture	-	-	-	-	26.5 (4 years)

4.3.1.1 Physical soil fertility

Heavy soils with deteriorated structure restrain normal growth and functioning of the roots. In this situation the nutrient and water uptake is hampered and plant growth is decreased. The estimated maximum yields can only be achieved with good physical soil fertility. We related yield reduction due to this factor to the inter-crop activity type and estimated reduction factors based on data from experiments in the region and elsewhere. Several experiments in Uruguay and elsewhere have shown yield increases from 20 to 80% in different crops when green or animal manure were applied in soils with deteriorated structure, compared to fallow treatments (Silenzi et al., 1983; Pelaez et al., 1984; Guadi et al., 1988; Hsieh et al., 1994; Peñalva and Calegari, 2000; Fischler et al., 1999; García and Reyes, 1999; Docampo and

García, 1999; Wadell et al., 1999). Based on experiments in the region, we estimated yield reduction to vary from 20 to 35 % for crops grown after fallow and from 10 to 15 % for crops grown after forage crops. For crops grown after fallow plus manure, green manure or after 4 years of grass-legume pasture the reduction factor due to physical soil fertility was assumed to be zero.

4.3.1.2 Water deficit

We estimated the reduction factor due to water limitation for garlic, onion, potato, sweet maize and sweet potato. The other crops are grown only under rain-fed conditions (i.e. maximum yields are rain-fed yields – Table 4.3) except sweet pepper which is grown only irrigated. We simulated the water-limited yields for each combination of crop and soil type for a series of ten years and averaged the results. The simulation model used was adapted from SUCROS2 (Van Laar et al., 1997) to estimate crop and soil water balances given leaf area index (LAI), root growth, soil physical characteristics and local daily weather data as input. The calculation of potential reference evapo-transpiration is based on the Penman –Monteith combination equation. Potential canopy transpiration and the soil evaporation are estimated for each day based on the LAI of the crop. Actual canopy transpiration depends on potential canopy transpiration, water content of each soil layer, soil exploration by the roots and crop dependent critical soil water content. The critical soil water content denotes the transition from potential to water-limited transpiration rate. It depends on the ability of the crop to extract water and on the potential transpiration rate (Denmead and Shaw, 1962; Driessen, 1986 cited by Van Laar et al., 1997). The soil water balance is calculated by dividing the soil in four layers. The thickness of each layer is an input to the model as well as the soil physical characteristics of each layer: volumetric water content at saturation, at field capacity, at wilting point and when air dry. The infiltration into the first soil layer is equal to precipitation minus interception by canopy and runoff, which is related to the water content of the top layer. Drainage is limited to the maximum drainage rate of the subsoil, that is input to the model. In SUCROS2 the crop daily gross assimilation rate is reduced with the same proportion as the ratio between daily actual crop transpiration and daily potential crop transpiration. In this way there is a feedback between water stress and crop growth rate. In the adaptation carried out for the purpose of this study the effect of water stress on crop yield is estimated as proposed by FAO (Doorenbos and Kassam, 1979):

$$1 - (WLY / PY) = Ky * (1 - (AET / PET)) \qquad \text{Eq. 2}$$

where:

WLY = water limited yield (kg ha^{-1})
PY = maximum yield (kg ha^{-1})
AET = actual total crop evapo-transpiration (mm)
PET = potential total crop evapo-transpiration (mm)
Ky = yield response factor to water supply, reflecting the sensitivity of the crop to water stress.
Derived from Doorenbos and Kassam (1979).

4.3.1.3 Crop frequency and crop protection level

The crop frequency reduction factor takes into account the effects of crop-specific soil-borne pests and diseases, following the same approach as Rossing et al. (1997). Since no information was available for the region under study, we quantified these effects using data from Molendijk and Mulder (1996) collected for clay soils in The Netherlands (Table 4.4). The frequency reduction factor is applied to a crop taking into account the time elapsed since a previous sowing of the same crop or crop of the same group. For example if onion is grown twice in a 7 years rotation and the minimum period between onion crops is 3 years, it means that onion is sown 3 and 4 years after the previous onion crop and the yields are reduced by 30 and 20% respectively.

Table 4.4 Reduction factors of yields due to crop frequency effects.

Crops	**Distance between crops in the rotation** (years)				
	2	**3**	**4**	**5**	**6**
Potato	NA	NA	0.25	0.10	0
Onion	NA	0.30	0.20	0.10	0
Garlic	NA	0.30	0.20	0.10	0
Sweet potato	NA	0.25	0.10	0	0
Squash	NA	0.25	0.10	0	0
Sweet maize	0.25	0.10	0	0	0
Sweet pepper	NA	NA	0.25	0.10	0
Wheat	0.25	0.10	0	0	0
Grass-legume pasture	NA	NA	0	0	0
Potato + sweet pepper	NA	0.25	0.10	0	0
Onion + garlic	NA	0.25	0.10	0	0
Squash + sweet pepper	NA	0.25	0.10	0	0
Potato + sweet potato	0.20	0.10	0	0	0

NA = frequency not allowed when crop rotations were designed.

The high crop protection level was defined in such a way that yield reduction due to weeds, diseases and pests is minimized. We quantified yield reduction due to low crop protection level based on expert knowledge at a fixed level of 0.2 for all crops except for sweet potato, sudan-grass and pasture (Table 4.5). For sweet potato we assumed that both crop protection levels could achieve similar yields because important air-borne pests or diseases do not affect this crop. Only the low crop protection level is considered for sudan grass and grass-legume pasture (Table 4.1).

Table 4.5. Estimated crop yield (Mg ha^{-1}) on soil type 1 when maximum values for reduction factors (RF) are applied successively, compared to average yields in the region

Crop	**Max Yield** (Mg.ha^{-1})	**Water limited yield**		**Conv. Inter-crop manag.**		**Crop freq. Limited yield**		**Crop protection level**		**Average yield farmers** (Mg.ha^{-1})
		RF	Yield	RF	Yield	RF	Yield	RF	Yield	
Garlic	10.8	0.25	8.1	0.35	5.3	0.30	3.7	0.2	2.9	3.3
Onion early	46.3	0.22	36.1	0.35	23.5	0.30	16.4	0.2	13.1	11.1
Onion late	46.3	0.38	28.7	0.35	18.7	0.30	13.1	0.2	10.5	11.1
Potato	30.0	0.18	24.6	0.35	16.0	0.25	12.0	0.2	9.6	14.0
Sweet potato early	23.8	0.35	15.5	0.35	10.0	0.25	7.5	0	7.5	7.2
Sweet potato	29.7	0.25	22.3	0.35	14.5	0.25	10.9	0	10.9	7.2
Sweet maize	10.2	0.5	5.1	0.30	3.6	0.25	2.7	0.2	2.1	2.3
Squash	25.5	0	25.5	0.30	17.8	0.25	13.4	0.2	10.7	6.7
Sweet pepper	40.8	0	40.8	0.35	26.5	0.25	19.9	0.2	15.9	11.2
Wheat	3.8	0	3.8	0.20	3.0	0.25	2.3	0.2	1.8	2.1
Grass-legume pasture	26.5	0		0		0		0		s/d

4.3.2 Soil erosion

We estimated soil loss due to erosion using the revised universal soil loss equation (RUSLE) (Renard et al., 1997). This equation enables the user to estimate the average rate of soil erosion in a period of many years for any particular combination of cropping system, management technique, erosion control practice and site. The RUSLE is an improved version of the USLE developed since the 1950's from data of more than 10,000 site x year combinations, representing a wide variation in soil type and climate (García, 1992). RUSLE estimates the average annual erosion expected on field slopes as (Renard et al., 1997):

$$A = R * K * L * S * C * P \qquad \text{Eq. 3}$$

where:

A = average soil loss per unit area per year (ton ha^{-1} yr^{-1});

R = average annual rainfall erosivity (MJ mm. ha^{-1} h^{-1} yr^{-1} 10^{-1});

K = soil erodability factor (ton h 10 MJ^{-1} mm^{-1}): the soil-loss rate per unit of R for a specified soil measured in a standard plot, which is defined as a plot of 22.1 m length and uniform slope of 9%, in continuous and clean tilled fallow (L, S, C and P equal to 1);

L = slope length factor (22.1 m = 1, longer fields > 1 and shorter fields < 1);

S = slope steepness factor (9% = 1, lower slope gradient <1, higher slope gradient > 1);

C = cover-management factor: the ratio of soil loss from an area with the specified soil cover and management, and soil loss from an identical area with tilled continuous fallow;

P = support practice factor: the ratio of soil loss with a support practice such as contouring or terracing, and soil loss with straight-row farming up and down the slope.

Since the end of the 1970’s several authors tested the validity of the USLE under the conditions in Uruguay (García and Clerici, 1996). The factor R has been calculated for 9 different locations in the country using rainstorm data of 15 to 20 years (Pannone et al., 1983). Puentes (1981) calculated the factor K for the main soil types of each of the soil units identified on the Uruguayan soil map (1:1,000,000). García and Clérici (1996) found a good match between estimated and measured values for factor K, C and soil loss ratio in experimental fields located at different sites, with natural and simulated rain and under different management practices (Figure 4.1). The main improvement of the RUSLE with respect to the previous version is the sub-model to calculate the factor C. This sub-model improves local estimations of the factor C for a wider range of crop management situations (García and Clérici, 1996). The factor C for one year is calculated in the following way:

$$C = \Sigma_i (SLR_i * EI_i) \qquad \text{Eq. 4}$$

where:

SLR_i is the soil loss ratio during a time interval of 15 days. SLR is an estimate of the ratio of soil loss under actual conditions, and losses under tilled continuous fallow;

EI_i is the fraction of the yearly rainfall erosivity (R) occurring during the same period of time.

i is each of the 24, 15 days time intervals that are part of one year.

The SLR links crop yields to soil erosion through the amount of residues incorporated, the amount of residues left on the surface, the canopy cover, and the root mass and distribution in the soil. The impact of previous crop and inter-crop activity on soil erosion becomes evident through these parameters. The rate at which residues are decomposed is a function of the type of residue, the rainfall and the average temperature during the 15 days time interval. Finally, the soil tillage practices also have an effect on the factor C through the depth at which crop residues are buried and the percentage of them left on the surface. We included the RUSLE in a computer program to automatically estimate factor C and A for each production activity.

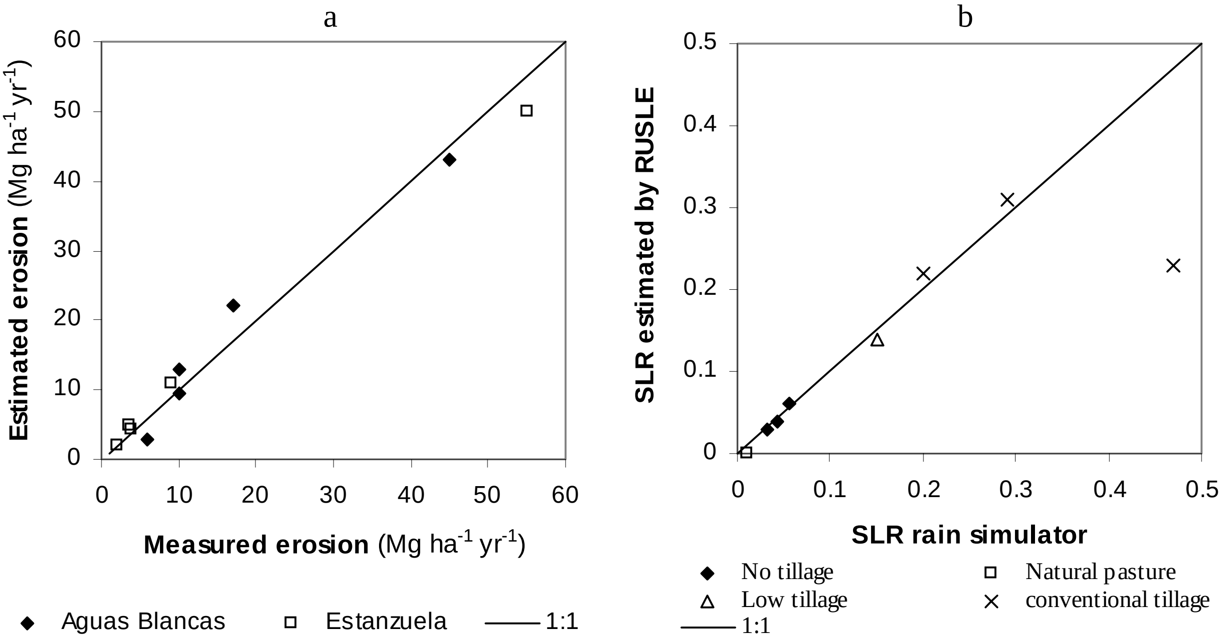

Figure 4.1. Measured and estimated erosion using RUSLE in two locations in Southern Uruguay on Typical argiudoll soil types (a), and soil loss ratio (SLR) measured with a rain simulator and estimated using RUSLE in four different situations of soil tillage and cover (b). Data in (a) is re-printed from García (1992) and data in (b) re-printed from García and Clerici (1996).

Crop canopy cover and root mass as a function of time and residue/yield ratio were input to the model. The average annual rainfall erosivity for Canelón Grande (400 MJ mm ha^{-1} h^{-1} yr^{-1} 10^{-1}) and its distribution through the year for the region were taken from Pannone et al. (1983). We calculated the soil erodability based on the physical and hydrological characteristics of each soil type, using the equation of Wischeimer et al. (1971), modified for Uruguayan soils by Puentes and Szogi (1983). We selected terracing as the standard support practice following Durán (2000). Terraces are constructed parallel to each other, i.e. 40 m apart with variable slope between 0.5 and 1.75% and maximum length of 100 to 120 m. This support practice is being used in the area and can be implemented and maintained with machinery available on the farm or rented in the region. Table 4.6 illustrates results of the procedure, and demonstrates potential erosion for each of the soil types in the region. Calculated potential erosion resulting from permanent bare tilled fallow is up to 11 times higher than the tolerance limits proposed by Puentes (1981), emphasizing the need to account for erosion in agricultural land use planning.

Table 4.6. Soil erodability (Mg h 10 MJ^{-1} mm^{-1}), slope length factor (L), slope steepness factor (S), support practice factor (P), tolerance limit to soil loss (Mg ha^{-1} yr^{-1}) and potential erosion (Mg ha^{-1} yr^{-1}) calculated as the product of R, K, L, S and P (erosion when soil is kept in permanent bare tilled fallow). Tolerance limit to soil loss defined according to Puentes (1981).

Soil type	Soil erodability K	Slope Length L	Slope steepness		Support practice P	Tolerance limit to soil loss	Potential soil erosion
			Gradient (%)	S			
1	0.26	1.22	3.5	0.408	0.5	7	55.9
2	0.36	1.22	3.5	0.408	0.5	7	77.4
3	0.44	1.15	1.25	0.165	1	5	36.4

4.3.3 Long term effects of production activities on soil organic matter

Several authors have reported on the influence of the amount of soil organic matter (SOM) on soil properties such as soil structure, water holding capacity, soil erodability and soil biological activity (e. g. Baver, 1968; Allison, 1973; Loveland, et al., 2001). Maintenance of sufficiently high levels of SOM is a prerequisite for high and sustainable crop yields. To estimate the effect of the production activities on the long term dynamics of SOM we combined the approach of Kortleven (1963) to estimate the decomposition of the initial SOM with the model of Yang and Janssen (2000) to estimate the decomposition of all organic residues added to the soil. The total amount of soil organic matter in the top 20 cm (kg.ha^{-1}) at each time step was calculated as follows:

$$SOM_t = Y_t + \Sigma_i A_{i\,t} \qquad \text{Eq. 5}$$

where:

SOM_t is the amount of soil organic matter in the top 20 cm remaining at time t (kg.ha^{-1});

Y_t is the amount of initial SOM [SOM_0] in the top 20 cm remaining at time t (kg.ha^{-1});

$A_{i\,t}$ is the amount of added organic substrate i in the top 20 cm remaining at time t (kg.ha^{-1}).

The model of Yang and Janssen (2000) is a mono-component model, which considers each organic substrate as a whole, with a characteristic relative mineralization rate, which decreases with time. The main characteristic of this type of model is that the identity of each applied residue is maintained throughout the entire simulation period. Consequently the amount of SOM at a certain moment is the sum of the amounts of organic matter remaining from each of the residues added since the beginning of the simulation and the remainder of the initial SOM (Janssen, 1984). We calculated the decomposition of each organic substrate added to the soil with a time step of one year using the Yang and Janssen (2000) approach:

$A_{i\ t} = A_{i\ 0} * \exp(-R_{9i} *(CF * t)^{1-Si})$ Eq. 6

where:

$A_{i\ t}$ is the amount of organic substrate i in the top 20 cm remaining at time t (kg ha^{-1});

Ai $_0$ is the amount of organic substrate i in the top 20 cm added to the soil on time t = 0 (kg ha^{-1});

R_{9i} is the substrate specific initial average relative mineralization rate (yr^{-1}) between t = 0 and t = 1;

S_i is the substrate specific measure of the rate at which the average mineralization rate decreases over time or speed of ‘ageing’ of the substrate ($0 \leq S \leq 1$);

CF is a correction factor to account for the effect of temperature, soil texture and tillage on organic matter decomposition

The correction factor (CF) accounts for the fact that not only the inherent resistance of substrates determines the decomposition rate of organic substrates but also by soil properties and environmental factors. Among them the most important are temperature, soil texture, soil moisture and pH (Yang, 1996). We assumed soil moisture and pH not to be limiting the decomposition rate of organic substrates (pH is between 5.5 and 6.5 for all soil types and soil moisture varies over the year, but most of the time it is over half of water holding capacity). Net mineralization of organic substrates is more rapid on sandy soils than on clay soils and under arable crops than on grassland (Verberne et al., 1990; Hassink, 1994). As CF for soil texture we used a value of 0.6 (Janssen pers. com.). During the years when soil is not tilled we further decreased the CF by 50%. The value of the CF for temperature was estimated to be 1.87 based on Equation 7 (Yang, 1996), using 10 day average temperatures calculated from 30 years data recorded at the weather station nearest in the region (Furest, 2000).

$CF_{temp} = 2^{(T-9)/9}$ Eq. 7

where

CF_{temp} is the correction factor for temperature

T is temperature in ºC

Combination of CF for soil texture and temperature resulted in a value of 1.122 (= 0.6*1.87) for years with arable crops and regular tillage, and a value of 0.561 (= 1.122*0.5) for grassland when the soil is not tilled.

The stable pool of the soil organic matter represents that part of the SOM which is strongly associated with the site specific mineral matrix (Hassink et al., 1997). The stable pool responds very slowly to changes in management and has very low turnover rates (Falloon and Smith, 2000). Kortleven (1963) proposed that SOM does not decompose completely, but the so-called inert humus stays behind. Rühlmann (1999) used data from long-term fallow soils to fit an equation estimating the amount of stable soil organic carbon as a function of soil texture. We used this equation to calculate the minimum amount of soil organic carbon for each soil type (Equation 8). We simulated the mineralization of the initial SOM with a time step (dt) of one year using Equation 9 (Kortleven, cited by Janssen, 2002):

$$\text{Cmin (\%)} = 0.017 * B - 0.001 * \exp(0.075*B) \qquad \text{Eq. 8}$$

where:

Cmin is the minimum amount of organic C in percentage;

B is clay + silt content in percentage.

$$Y_t = Y_{t-1} - ((Y_{t-1} - Y_{min}) * R) * dt \qquad \text{Eq. 9}$$

where:

Y_{min} is the minimum amount of SOM in the top 20 cm estimated by multiplying the minimum amount of soil organic carbon estimated with equation 8 by (1.723 * soil bulk density * 1000) (kg ha^{-1}). The factor 1.723 translates organic carbon to organic matter.

R is the decomposition rate (yr^{-1}) and it was set to 0.03 for this study.

The performance of the model was tested using data from a long-term rotation experiment started in 1963 on a typical argiudoll of “La Estanzuela” research station in Southern Uruguay (Días Rosello, 1992). In Table 4.7 the rotations are described that we selected to test the performance of the model. Only average crop yields per rotation were available. The straw/yield and root+stubble/yield ratios were taken from literature. The R_9 and S values for each organic substrate were taken from Yang (1996) and Janssen (1984). We found a good match between the estimated SOM and measured SOM for the four rotations selected (Figure 4.2). The model estimated most accurately the SOM change in the rotations that included only arable crops, while it showed larger differences with the measured values in the rotations that included 4 years pastures. However the estimated slope of SOM change for the 27 year period tested was similar to that measured in all rotations, being the most important aspect for the purpose of our study.

Table 4.7. Description of four of the crop rotations of the long-term rotation experiment at “La Estanzuela” research station in Southern Uruguay. The experiment started in 1963 on a typical argiudoll. The amount of SOM was estimated using a bulk density of 1.25 g cm^{-3} (1% is equivalent to 25,000 kg ha^{-1} of SOM in the top 20 cm). Elaborated with data from Dias Rosello (1992).

	Rotation	SOM% in 1963	SOM% in 1990	Cumulated grain yield (Mg ha^{-1})	Cumulated forage yield (Mg ha^{-1})	Rate of change of SOM (kg ha^{-1} yr^{-1})
1	Sorghum-Flax-Wheat-Sunflower (4 year rotation) without fertilizer	3.5	2.5	28.6	0	-929
2	Sorghum-Flax-Wheat-Sunflower (4 year rotation) with fertilizer	3.5	2.8	45.4	0	-670
3	Sorghum-Flax-Wheat-Sunflower-4 year Alfalfa (8 year rotation)	3.6	3.5	28.6	97.5	-136
4	Sorghum-Flax-Wheat-Sunflower- 4 year Grass and Legume pasture (8 year rotation)	3.8	3.6	26.8	99	-176

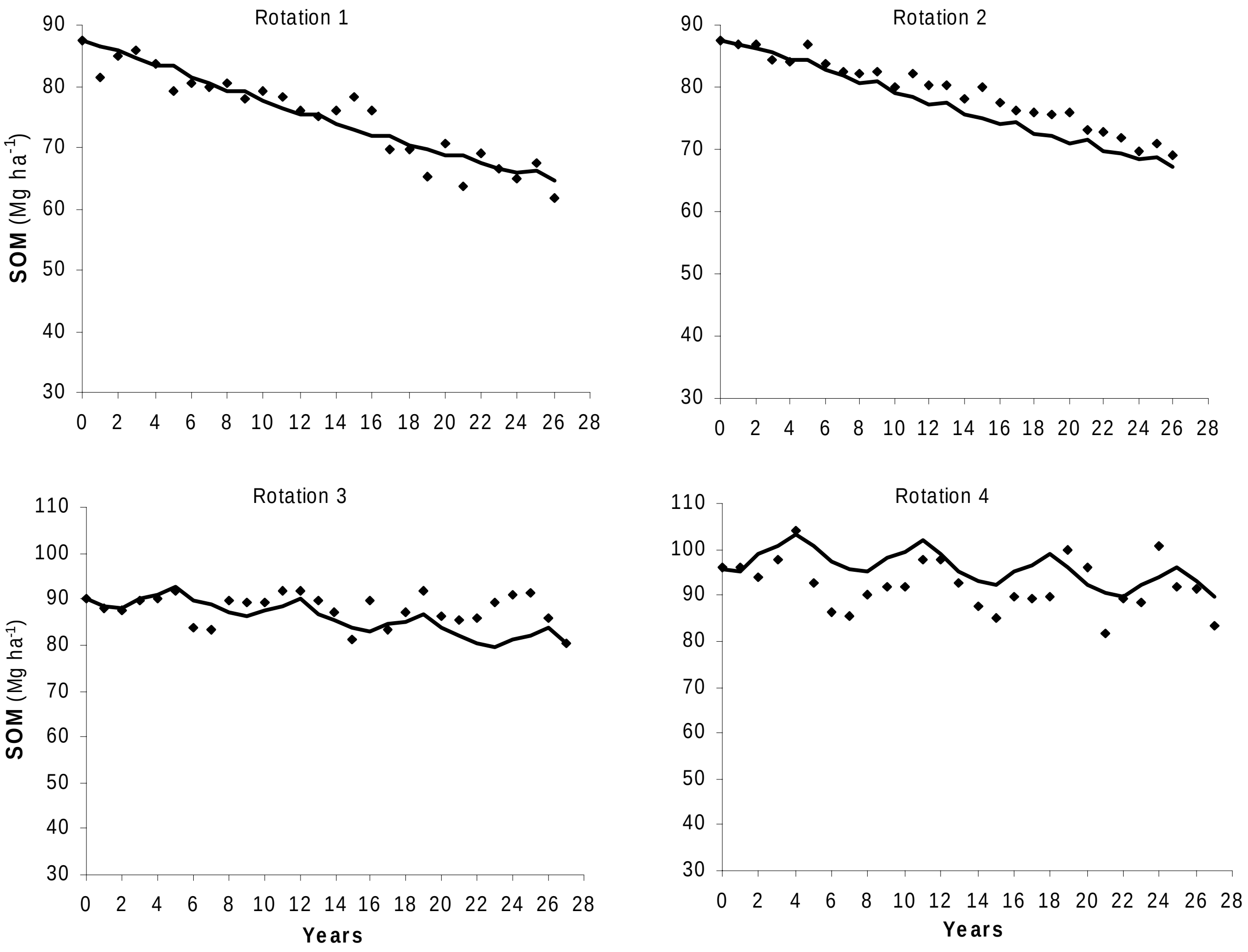

Figure 4.2. Measured (♦) and simulated (—) SOM from 1963 to 1989 for four crop rotations from the long-term rotation experiment on “La Estanzuela” research station in Southern Uruguay. For description of the rotations, see Table 4.7

Using this model we simulated SOM dynamics for 40 years for each of the production activities designed and calculated the average rate of change of SOM (kg.ha^{-1}.yr^{-1}) during that period. We set the initial percentage of organic matter in the soil to 2.5, 2.1 and 2.8 % for soil type 1, 2 and 3 respectively, based on averages from soil analysis performed in vegetable fields of farms in the region from 1993 till 2000.

4.3.4 Animal production

We calculated the daily requirements of metabolisable energy (ME) and protein (MP) of beef cattle, the metabolisability of the gross energy (q_m) and the metabolisable protein content of the diet according to AFRC (1993). We set the average daily growth rate to 0.6 kg resulting in a growth period of 15 months (from 150 to 420 kg), based on the normal growth of beef cattle in grazing systems on good quality pastures in the region (Simeone pers. com.; Risso, 1997). Variations in the quality of the diet throughout the year were not taken into account. The maximum intake rate was not limiting in any case for the target growth rate. We took the values for ME and crude protein content for each type of forage from local evaluation of nutritional values of feeds (Pigurina et al., 1991). The utilization percentage of the available forage was set to 75% based on local experiments (Risso, et al., 1991; Risso, 1997). Beside the forage produced by the grass-legume pasture and by forage crops during the inter-crop periods, we included a fraction of the residues produced by sweet maize and sweet potato as source of feed. We determined the number of animals that could be grown per year per ha based on the most limiting factor, energy or protein.

4.3.5 Nutrient inputs and balance

We used a simple method of N budgeting to estimate the N surplus from the farm system. Possible inputs of N to the system were fertilizer, chicken manure, atmospheric deposition and biological fixation by legumes. Outputs of N from the system comprised: commercialized crop products and animals. Soil organic matter could be either a source of N when SOM decreased or a sink when SOM increased. The amount of N mineralized or immobilized was calculated from the change in soil organic carbon, assuming 0.58 organic carbon per unit organic matter and a C/N ratio of 10. N surplus is the difference between N inputs and N output. Contents of N in harvested crop parts and in animals were taken from literature. We estimated the N fixation by a 4 years grass-legume pasture to be 540 kg ha^{-1} based on local measurements from Danso et al. (1991). Atmospheric N deposition was estimated to be 5 kg ha yr^{-1} since no local data were available. The amount of N in the mixture of chicken manure and rice husk was 28 kg Mg^{-1} DM (García pers. com.). We determined the input of N fertilizer to each crop following expert recommendations (derived from fertilization experiments in the region) and taking into account the inter-crop management type. N was applied in such amounts that it never became a yield-limiting factor.

The soils in Canelón Grande have high natural levels of K (0.6 – 0.8 meq. of exchangeable K per 100 g soil), with no yield response to the application of this nutrient. However we included the application of K fertilizer to crops with a high extraction rate of this nutrient such as potato and sweet pepper following expert recommendations. In most horticultural fields in the region, there is a high accumulation of P as a result of high fertilization rates for many years. We calculated the application rate of fertilizer P equal to the output of P in commercialized crop products and animals.

4.3.6 Environmental exposure to pesticides (EEP)

The potential presence of pesticides in the environment as a result of each production activity was estimated following the approach of Wijnands (1997). EEP for soil, air and groundwater were calculated based on the amount of the active ingredients (AI), their vapor pressure at 20-25 ºC (VP), 50 % degradation time (DT50) and mobility (K_{om}) (PPO, 2001). The EEP per kg of commercial product consisting of various active ingredients was calculated as follows:

$$\text{EEP soil (kg-days)} = \Sigma_i \,\%\, AI_i * DT50_i / 100 \qquad \text{Eq. 10a}$$

$$\text{EEP air (kg A.I. ha}^{-1}) = \Sigma_i \,\%\, AI_i * E_i / 100 \qquad \text{Eq. 10b}$$

$$\text{EEP groundwater } (\mu g\ l^{-1}) = 10^6 * (\Sigma_i \,\%\, AI_i * F_i\,) / PS \qquad \text{Eq. 10c}$$

where:

i represents each active ingredient in the commercial product;

E_i is the % of volatilization, as a function of Vp_i: >10 mPa = 95%, 1-10 mPa = 50%, 0.1-1 mPa = 15%, 0.01-0.1 mPa = 5% and <0.01 mPa = 1%;

F_i is the fraction of AI that leaches calculated as $F_i = \exp(-((3.9721*K_{om,i} / DT50_i) + (47.4 / DT50_i) + 1.092))$;

PS is the precipitation surplus in m^3.

4.3.7 Labor and machinery requirement

We calculated the total labor requirements as well as their distribution over the year for each crop and inter-crop activity as a function of the mechanization level, crop protection level and irrigation level. We divided the labor and machinery requirements in yield-dependent and yield-independent categories. The main sources of information were data collected for 7 years on several farms in the region by agricultural students, technical coefficients of agricultural machinery (GTZ-FUCREA, 1989) and expert knowledge. We considered the labor requirements for animal production as homogeneously distributed over the year and based on a minimum number of 15 animals.

4.3.8 Economic performance

Farm gross margin was calculated as the difference between gross product and direct costs. Gross product of each production activity is the product of the amount of crop products and animals commercialized and the market price, minus the commercialization costs. The market price of most crop products decreased during the last decade, despite intra-year and between year variations. We estimated the market prices for the year 2003 by extrapolating the linear trend in average market price per year for the period 1992-2001. We calculated the average market price per year of each product from monthly averages including only those months when the farmers in the region commercialized each product. A crop's direct costs included labor, maintenance and repairs of machinery, seeds, pesticides, fertilizers, repairs and maintenance of irrigation equipment, energy and storage. The value of labor was estimated at US$ 1.5 per hour for both own and hired labor. The animal production's direct costs included the cost of the young animals, transport to the farm and taxes, labor, health care and maintenance and repairs of electric fences.

Farm net margin was calculated as the difference between farm gross margin and indirect costs. Indirect costs included depreciation of machinery, buildings, irrigation equipment, internal roads and fences, maintenance and repairs of buildings, internal roads, terraces and fences, technical assistance, taxes and interest over farm assets. For the purpose of this chapter, we defined two variants of machinery and buildings availability. The depreciation costs were calculated for each variant. The remaining depreciation costs were calculated per ha. We estimated the family income as the gross margin plus the value of the family labor spent in production activities minus the indirect costs excluding interest over farm assets, divided by the number of households on the farm.

4.3.9 Illustration: options for sustainable development in Canelón Grande

The approach is illustrated by exploring the influence of farm size and labor availability on options for sustainable development. We used data from 25 farms, collected in a farm survey in Canelón Grande (Klerkx, 2002), which represents a wide variation in area and labor. Using the production activities designed at the cropping system level, we studied the possibilities of these farms to achieve an adequate family income while erosion was kept above tolerance levels as defined by Puentes (1981) and the rate of change of SOM was non-negative. We estimated the farm available area for cultivation by reducing the total area of the farm by 20% to take into account the area occupied by buildings, internal roads, terraces, borders, and non-productive land. We assumed that 10% of the available labor is spent on general activities such as maintenance of farm infrastructure and purchasing of inputs.

After quantification of all inputs and outputs of each production activity the results were introduced into a database. We did not combine two or more rotations per farm. By means of data base queries we selected from the subset of production activities with an erosion rate lower than the tolerable limit and with an average rate of change of SOM larger than zero, the production activity providing the highest farm net margin for each farm.

4.4 Results

4.4.1 Evaluation at production activity scale

ROTAT generated 7,447, 4,644 and 1,080 crop rotations for soil type 1, 2 and 3, respectively, within the set of rules used in this study. After combining the crop rotations with the inter-crop management types and with the crop management types we obtained 189,832, 121,528 and 24,768 production activities for soil type 1, 2 and 3, respectively. From these, 26,089, 2,473 and 5,050 production activities had lower erosion than the tolerance limit and a rate of change of SOM larger than zero for soil type 1, 2 and 3, respectively.

The estimated soil erosion varied from 17.9 to 0.3, from 25.6 to 4.0 and from 13.1 to 1.8 Mg ha^{-1} yr^{-1} for soil type 1, 2 and 3, respectively (Table 4.8). Inter-crop management type significantly affected estimated soil erosion (Table 4.9). We estimated an average reduction in soil erosion, compared to actual fallowing practices, of 46, 45 and 50 % for soil type 1, 2 and 3, respectively, by sowing green manure crops during the inter-crop periods. Crop rotation caused considerable variation in soil erosion reduction by green manure crops (Figure 4.3). For example, for soil type 1 green manuring resulted in a maximum reduction in soil erosion compared to fallow of 10.6 and a minimum of 0.1 Mg ha^{-1} yr^{-1}.

The estimated average rate of change of SOM varied from 506 to –357, from 517 to –244 and from 266 to –313 kg.ha^{-1}.yr^{-1} for soil type 1, 2 and 3, respectively (Table 4.8). The best values represent an increase of 0.78, 0.8 and 0.4 % in SOM percentage of the top soil (20 cm) over 40 years, while the worst values represent a decrease of 0.55, 0.37 and 0.50 % in the same period for soil type 1, 2 and 3, respectively. Similar to soil erosion, inter-crop management type significantly affected estimated rate of change of SOM (Table 4.9). We estimated an average increase in SOM of 281, 360 and 49 kg ha^{-1} yr^{-1} for soil type 1, 2 and 3, respectively, by applying chicken bed during the inter-crop periods, while the estimated average decrease in SOM was 233, 153 and 230 kg ha^{-1} yr^{-1} with fallow inter-crop management.

Table 4.8. Estimated maximum and minimum values of soil erosion (Mg ha^{-1} yr^{-1}), rate of change of SOM (kg ha^{-1} yr^{-1}), N surplus (kg ha^{-1} yr^{-1}), EEP soil (kg-days), labor requirements (hr ha^{-1} yr^{-1}), direct costs (US$ ha^{-1} yr^{-1}), gross margin (US$ ha^{-1} yr^{-1}), and meat production (kg ha^{-1} yr^{-1}), for all generated crop rotations for each of the soil types.

Soil type		Erosion	SOM rate	N surplus	EEP soil	Labor	Direct costs	Gross margin	Meat production
1	Max	17.9	506	213	475	1726	4998	3714	522
	Min	0.27	-357	23	15	75	403	-330	0
2	Max	25.6	517	173	411	1260	3986	3214	522
	Min	4.0	-245	19	15	82	400	-231	0
3	Max	13.3	266	97	218	637	2763	1820	684
	Min	1.8	-313	16	19	40	323	-309	0

Table 4.9. Average estimated erosion (Mg ha^{-1} yr^{-1}) and rate of change of SOM (kg ha^{-1} yr^{-1}) for each soil type as affected by inter-crop management type.

	Fallow		Fallow plus manure		Green manure		Forage crops	
	Erosion	SOM	Erosion	SOM	Erosion	SOM	Erosion	SOM
Soil type 1	13.6	-233	12.8	281	7.4	88	8.9	-69
Soil type 2	18.6	-153	17.7	360	10.3	165	12.2	10
Soil type 3	9.2	-230	8.8	49	4.6	83	6.0	-172

We also obtained a wide range of variation for all soil types in the other parameters estimated, such as N surplus, EEP-soil, labor requirements, direct costs, gross margin and meat production (Table 4.8). The values of EEP-air and EEP-groundwater were strongly correlated with those of EEP-soil, so only the latter are shown.

4.4.2 Evaluation at farm scale

From the 189,832 production activities designed for soil type 1, we chose the option with highest net margin for each of the 25 farms selected while maintaining the soil erosion below the tolerance level of 7 Mg ha^{-1} yr^{-1} (Puentes, 1981; Table 4.6) and excluding negative rates of change of SOM. The results obtained and the availability of labor and land per farm are shown in Table 4.10. Since no limitations were imposed on the irrigated area, capital for purchasing inputs or environmental impacts other than erosion and SOM level, for all farms the best production activity was irrigated and with high crop protection level. For all farms with less than 8 ha of available area and/or more than 740 hr of labor per ha, low mechanization (LM) was the best option. For farms with more than 8 ha and/or less than 710 hr of labor per ha high mechanization (HM) was the best option, except for farms No. 12 and 14. Despite the strong labor limitation of these two farms LM was better than HM, because the ratio between fixed costs (machinery and buildings) and available labor was too high for these farms with the HM option (5.4 and 4.5 US$ hr^{-1} for farm 12 and 14, respectively) compared to the LM option (2.8 and 2.5 US$ hr^{-1}).

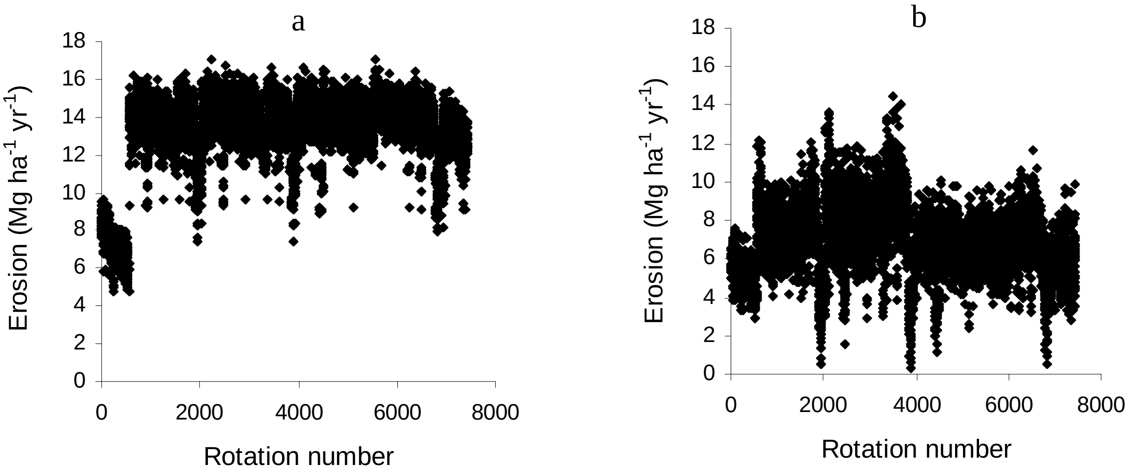

Figure 4.3. Estimated soil erosion under crop rotations in soil type 1 managed with high mechanization level, high crop protection level, irrigated and with conventional (A) or green manure inter-crop management (B)

Present average family income per year in Uruguay is US$ 9,638 (INE, 2002). Assuming that all farms had soil type 1 as the only soil type and without restrictions on irrigated area or capital to purchase inputs, we estimated that all farms could reach a family income higher than the average, except for farms No.1 and 13. If irrigation was not possible, the family income was reduced by 17-69 %, with the larger impact on the smaller farms. In this scenario, 5 farms with LM and 1 farm with HM as best option, did not reach the average family income. When the available land was assumed to be of soil type 2 quality, family income decreased by 4-25 % compared to soil type 1.

Table 4.10. Results from maximization of farm net margin for 26 farms of different size and availability of labor in Canelón Grande assuming that all available area is occupied by soil type 1 and can be irrigated. Erosion was maintained below the tolerance level of 7 Mg.ha^{-1}.yr^{-1} and negative rates of change of SOM were excluded.

Inputs from survey					Outputs from model								
Farm No.	Available area for crop growth (ha)	Available labor (hr ha^{-1})	Ratio contract : family labor	No. of house-holds	Mech level	Inter-Crop Management type (1)	Net margin (10^{3} US\$ farm^{-1})	Family income (10^{3} US\$ fam^{-1})	Income per unit family labor (US\$ hr^{-1})	Erosion (Mg ha^{-1} yr^{-1})	SOMrate (Mg ha^{-1} yr^{-1})	Excess area (ha)	Excess labor (hr ha^{-1})
1	2.4	1,076	0	1	Low	gmc	1.7	6.3	2.68	5.1	0.19	0	100
2	4.0	1,967	0	1	Low	gmc	6.6	16.4	2.88	5.7	0.07	0	542
3	5.9	1,309	0	1	Low	gmc	10.7	22.7	3.19	5.9	0.14	0	107
4	6.0	969	0	1	Low	gmc	10.2	20.3	3.50	5.1	0.19	0	0
5	7.6	743	0.093	1	Low	gmc	10.2	19.4	3.76	5.2	0.19	0.6	0
6	7.6	690	0.015	1	High	gmc	9.6	20.7	4.01	5.1	0.19	0.1	0
7	8.0	1,292	0	1	Low	gmc	15.8	31.8	3.31	5.9	0.14	0	89
8	8.0	817	0	1	Low	gmc	12.3	23.5	3.65	5.2	0.19	0	11
9	8.8	710	0.063	1	High	gmc	13.2	25.3	4.36	5.1	0.19	0	8
10	9.6	544	0.011	1	High	gmc	11.3	22.6	4.37	6.8	0.17	0.5	0
11	12.0	383	0.186	1	High	f+m	11.2	20.7	5.36	6.9	0.28	0	0
12	14.4	183	0.019	1	Low	f+m	3.4	9.5	3.66	6.1	0.31	7.9	0
13	16.0	797	0.087	2	High	gmc	32.3	26.0	5.03	5.1	0.19	0	95
14	16.8	196	0.022	1	Low	f+m	5.5	12.7	3.94	6.1	0.31	8.6	0
15	18.4	281	0	2	High	f+m	14.7	13.4	5.19	6.1	0.29	1.8	0
16	19.2	725	0.491	2	High	gmc	40.9	29.4	6.51	5.1	0.19	0	23
17	21.6	424	0	2	High	f+m	31.0	24.5	5.46	6.8	0.26	0	7
18	27.2	454	0.462	1	High	f+m	41.6	58.4	7.54	6.8	0.26	0	37
19	30.4	367	1.881	1	High	f+m	41.7	52.9	13.66	6.9	0.28	1.7	0
20	32.0	307	1.175	1	High	f+m	37.7	50.1	11.08	6.1	0.29	0.5	0
21	36.0	327	0	2	High	f+m	44.5	33.7	6.00	6.1	0.29	0	15
22	41.6	160	0.031	1	High	f+m	18.9	35.1	5.44	6.1	0.29	20.2	0
23	49.6	92	0.005	1	High	f+m	6.9	20.9	4.63	6.1	0.29	35.0	0
24	59.2	163	0.357	1	High	f+m	32.7	51.5	7.26	6.1	0.29	28.3	0
25	75.2	140	0.358	2	High	f+m	35.1	28.2	7.28	6.1	0.29	41.4	0

(1) gmc : green manure crop; f + m : fallow plus manure

Maximum gross margin per ha was 3588, 3050, 1675 and 1086 US$ ha^{-1} for crop management HM irrigated, LM irrigated, HM rain-fed and LM rain-fed, respectively (Figure 4.4). Gross margin was limited by labor availability up to 984, 1425, 760 and 690 hr ha^{-1} for crop management HM irrigated, LM irrigated, HM rain-fed and LM rain-fed, respectively. At higher labor availability the only way to increase the gross margin per farm was by increasing the area of the farm. Above these limits the excess labor could not be used on the farm in a profitable way. In our example, no farm with HM as the best option achieved the maximum gross margin per ha due to labor limitations, while only farm No. 2, with LM as best option, reached the potential gross margin per ha. This farm had an excess labor of 542 hr ha^{-1}. When the amount of labor is lower than 312 and 402 hr ha^{-1} for HM irrigated and LM irrigated, respectively, the only way to increase the gross margin per farm is by increasing the amount of labor. Below these limits part of the available area was not farmed. Within these limits we always found a production alternative that maximized the net margin of the farm by using most of both the available land and labor. The maneuvering space between area-limited and labor-limited conditions, measured in terms of labor per ha, is smaller for non-irrigated conditions.

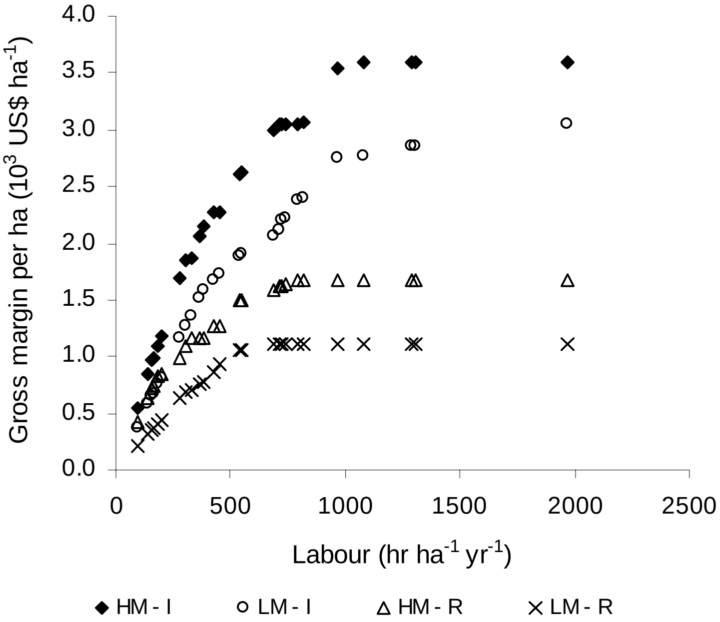

Figure 4.4. Estimated gross margin per ha as a function of the labor availability per ha and crop management type for each of the 25 farms selected in the Canelón Grande region. High mechanization and irrigated (◆), low mechanization and irrigated (o), high mechanization and rain-fed (△) and low mechanization and rain-fed (✕).

The income per unit of family labor was positively correlated to the ratio between contract and family labor, because for all farms the labor productivity (calculated as the ratio between gross margin and used labor) was higher than the price of contract labor. The inter-crop management selected was green manure or fallow plus animal manure for all farms. Few options of fallow management met the limits set to soil erosion and SOM rate. Forage and animal production was not selected for any farm when irrigation was available for the whole area. However, it became the best option for farms with low mechanization and no irrigation, increasing both gross margin per ha and labor productivity compared to other inter-crop activities.

4.5 Discussion

By applying the methodology presented in this chapter we were able to design and evaluate 336,128 production activities suitable for the different soil types in the region and for farms with very different availability of resources, i.e. land, labor, soil quality, capital and water for irrigation. We did this by combining existing knowledge and expertise in a systematic and transparent manner. After theoretical evaluation, a large set of those production activities showed promise for reducing soil erosion and maintaining soil organic matter content of the soil, two of the most important problems for sustainable production in Canelón Grande. For most objectives the worst values were unacceptable compared to the performance of current systems (e. g. negative gross margin) or to a sustainable situation (e.g. negative SOM rate and erosion over 3 times the tolerance limit). However many alternatives proved good enough to allow improvement of current farming systems in the region. Both crop rotation and inter-crop management appeared effective in reducing soil erosion and increasing SOM content. We designed 27,689, 2,473 and 5,749 production activities with lower erosion than the tolerance limit for soil type 1, 2 and 3, respectively. From these, 26,089, 2,473 and 5,050 had also positive SOM rate. Although these numbers represent only 10% of the total number of agronomically feasible rotations, the numbers are still large enough to provide a widely diverse set of strategic options for farmers in the region to choose from.

In this chapter we developed and illustrated a systematic method to design and quantitatively evaluate a large number of land use systems. In the illustration, we used simple data base queries to select promising alternatives to current systems. These promising alternatives can be discussed with all interested parties before testing a selection on pilot or commercial farms, reducing the risk of ignoring promising options. During testing, observations can be used to improve the estimation of parameters and new problems encountered contribute to changing assumptions made, thus initiating a new phase of designing and evaluation of alternatives.

Other authors have developed tools to design and quantitatively evaluate land use systems (e.g. De Koning et al., 1995; Barbier and Bergeron, 1999; Hengsdijk et al., 1999; Lu et al., 2003). These tools are generally called ‘technical coefficient generators’ (TCGs). Differently to Barbier and Bergeron (1999) and Hengsdijk et al. (1999), in our approach we calculated technical coefficients at crop rotation scale, explicitly considering interactions among crops. Compared to De Koning et al. (1995) and Lu et al. (2003), we identified and quantified all possible rotations and not just an arbitrary selection. Other unique aspects of our approach are the quantification of soil erosion, rate of change of soil organic matter, nutrients balance and the environmental impact of pesticides, and it potential use as stand alone tool, even for the evaluation of options at farm scale.

In the example presented in this chapter we considered only one rotation per farm. Furthermore, we assumed that the whole area of the farms could be irrigated and the capital for purchasing inputs was not limiting. In the next step of our methodology, the generated production activities will be input to a linear programming (LP) model. The LP model optimally allocates different production activities to different parts of the farm according to the soil type, availability of production resources such as labor, water for irrigation, capital to purchase inputs, and farmer objectives. In this way we will explore options for sustainable development of the farms in the region.

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Chapter 5

Exploring options for sustainable development at farm scale: A case study for vegetable farms in south Uruguay

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ABSTRACT

The study presented in this chapter aims at analyzing whether there is room for improvement of vegetable farmers' income in Canelón Grande (Uruguay), while soil erosion is reduced and physical and biological soil fertility is improved, and to gain insight in the influence of farmers' resource availability on the opportunities for sustainable development. We developed a mixed integer linear programming model (MILP) named SmartFarmer able to allocate production activities to land units of a farm differing in soil quality, while maximizing or minimizing socio-economic and environmental objectives, subject to constraints at the farm level. We used SmartFarmer to design farm systems for 7 existing farms in Canelón Grande with different resource availability. The farm systems designed by the model had higher family income than current systems for 6 of the 7 farms studied. The estimated average soil erosion per ha decreased by a factor of 2 to 4 in the farm systems proposed compared to the current systems, while the rate of change of soil organic matter increased from negative in the current systems to +130 to +280 kg ha^{-1} yr^{-1} in the proposed farm systems. The results suggest opportunities for increased farmers' income while soil erosion is reduced and physical and biological soil fertility is improved. The degree to which these objectives could be achieved were strongly affected by farm resource endowment, i.e., mainly the fraction of the area irrigated, soil quality and labor availability per ha. The study suggests that lowering the area of vegetable crops by introducing long crop rotations with pastures and green manure during the inter-crop periods and integrating beef cattle production into the farm systems would be a better strategy in most cases than the actual farmers' practice.

5.1 Introduction

Increased competition from imported goods and reduction of market prices challenged the subsistence of vegetable growers in South Uruguay during the last decade. Increased use of external inputs, shortening of fallow periods and specialization of the farming systems were the main strategies followed by most of the farmers to maintain their income. In the Canelón Grande micro-shed, a region in which 54% of the farms have vegetable production as main source of income, the area with vegetable crops increased by 23% from 1990 to 2000 while the number of vegetable growers and the size of the farms remained the same (DIEA, 2000, unpublished data). These changes resulted in increased pressure on the environment.

Canelón Grande is located in one of the most eroded areas of the country. More than 80% of the area has some soil erosion and at least 45% of the area has lost between 25 to 75% of the top horizon (Carmona et al, 1993). Major soil types in the region are Typic Hapluderts, Typic Argiudolls and Abruptic Argiaquolls which in natural conditions have between 4.5 to 6.5% of organic matter in the top horizon (Durán, 1998). Presently, under vegetable cropping, they contain between 2 and 2.5% of organic matter. The conditions for crop growth have degraded due to crust formation, lowered water-holding capacity and reduced gaseous exchange (Therzaghi and Sganga, 1997). Farms in this region usually own land with more than one soil type with different topographic position, risk of erosion and suitability for crop growth.

The sustainability of vegetable farming in Canelón Grande depends on the development of production systems able to reduce soil erosion, improve physical and biological soil fertility and increase farmers' income. We proposed a model-based explorative land use study to support the re-orientation of farming systems to start solving the main problems menacing sustainability of vegetable production systems in Canelón Grande. The study is divided in two main steps. In the first step we design a broad set of land use systems or production activities (Van Ittersum and Rabbinge, 1997) at the field scale, taking into account the main objectives and the farm resource availability present in the region (Dogliotti et al., 2003b). In the second step, we select and combine the best production activities at the field scale to produce optimal farm systems at the farm scale, subject to the limitations imposed by the actual resource endowment of the farmers in the region. This paper focuses on the second step of the study.

Model-based land use studies have been proposed to gain insight in future opportunities for agricultural development (de Wit et al., 1988), to support formulation of strategic policy objectives (Van Ittersum et al., 1998), to reveal trade-off between economic and environmental objectives enabling a transparent discussion on development pathways (Rossing et al., 1997), and to support decision making and strategic planning by farmers (Zander and Kächele, 1999; Castelan-Ortega et al., 2003). Explorative farm modeling is a method that integrates component knowledge at crop and animal scale, stakeholder objectives and external variables to outline the consequences of strategic choices at the farm scale (Ten Berge et al., 2000). We used Multiple goal linear programming (MGLP) as integrative modeling approach (Rossing et al., 1997; Makowski et al., 2000; Ten Berge et al., 2000). The approach we developed to support re-design of farming systems in Canelón Grande is unique in dealing with complex temporal interactions and spatial heterogeneity in one integrated method. All feasible crop rotations were generated and combined with a range of production techniques according to pre-defined design criteria to create a wide variety of production activities at the field scale by means of a technical coefficient generator. By means of an MGLP model production activities were allocated to the various land units within a farm to create alternative farm systems according to the farm resource endowment and targets in a set of sustainability objectives.

The aim of this study is to show whether there is room for improvement of Canelón Grande vegetable farmers' income, while soil erosion is reduced and physical and biological soil fertility is improved, and to gain insight in the influence of farmers' resource availability on the opportunities for sustainable development.

5.2. Methods

5.2.1 Field scale design

In the first step of the design process, for the field scale, we created a list of crops suitable to be grown on each soil type, based on the main crops currently grown in Canelón Grande. We combined those crops into crop rotations following precise agronomic rules using a computer model (ROTAT) designed for that purpose (Dogliotti et al., 2003a; Chapter 3). Finally, we combined the crop rotations with various production techniques (inter-crop management, irrigation, crop protection and mechanization) and quantified their inputs and outputs (Dogliotti et al., 2003b; Chapter 4). The list of crops and production techniques used to grow each rotation is summarized in Table 5.1.

The maximum rotation length was set to 8 years on soil types 1 and 2, and to 9 years on soil type 3, to ensure that low frequencies of the same crop or crop group could be achieved. A number of successions of crops was not allowed to avoid negative effects on biological soil quality (soil-borne pests and diseases) or long inter-crop periods. Four types of inter-crop activities were defined and combined with the crop rotations: fallow, fallow plus manure, green manure crops and forage crops. We defined two levels of mechanization according to the availability of machinery in the region. The low level uses a small tractor (50 HP) and the basic tools for soil tillage. Pesticides are applied with a knapsack sprayer and mechanical weeding is done using animal traction. The high mechanization level includes a larger tractor (90 HP) with suitable tools for soil tillage, spraying, weeding and other specific tools. Following current practice in Canelón Grande, crop rotations including potato or squash were grown with high mechanization level only. We defined three levels of irrigation. In the low irrigation level all crops are grown rain-fed. In the intermediate level irrigation is only applied to the crops with higher economic response to irrigation. In the high irrigation level all vegetable crops are irrigated, except squash. Pastures and forage crops are always rain-fed. We designed two variants of crop protection. In the first variant, chemical crop protectants are partially substituted by the use of resistant varieties, cultural practices and labor. The second variant is geared to minimizing yields reduction due to weeds, diseases and pests. We selected beef cattle production as the only animal production activity with the purpose of exploring the potential contribution of mixed systems to the sustainability of farming systems in the region. Based on current farmer practices, we defined the animal production activity as the raising of beef cattle from 150 to 420 kg body weight using mainly on-farm-produced forage.

Table 5.1 List of selected crops, suitable soil types for each crop and levels of irrigation, mechanization and crop protection used for each crop for the designing of crop production techniques.

Crop	Sowing date	Growth period (days)	Maximum frequency $(\#.yr^{-1})$ (1)	Soil type (2)	Irrigation level (3)	Mech. level (4)	Crop Prot. level (4)	Number of production techniques
Garlic	Jun-1	187	1/3	1	I - R	H - L	H – L	8
Onion early	Jul-10	138	1/3	1 – 2	I - R	H - L	H – L	8
Onion late	Sept-1	136	1/3	1 – 2	I - R	H - L	H – L	8
Potato	Feb-1	114	1/4	1	I - R	H	H – L	4
Sweet potato early	Oct-15	120	1/3	1 – 2	I - R	H - L	H – L	8
Sweet potato	Oct-15	151	1/3	1 – 2	I - R	H - L	H – L	8
Sweet maize	Oct-15	120	1/2	1-2-3	I - R	H - L	H – L	8
Sweet maize late	Dec-22	115	1/2	1-2-3	I - R	H - L	H – L	8
Sweet pepper	Nov-1	165	1/4	1-2-3	I	H - L	H – L	4
Squash	Nov-1	195	1/3	1-2-3	R	H	H – L	2
Wheat	May-15	204	1/2	1 – 2	R	H	H – L	2
Sudan grass	Nov-1	120	1/2	3	R	H - L	L	2
Pasture	Apr-1	1310	1/2	1-2-3	R	H - L	L	2

(1) The average frequency of crop X in a rotation is calculated by the ratio of the number of times the crop is sown in the rotation (N_X), multiplied by a correction factor (CF_X) that takes into account the growth period (L_X, days) of the crop, and the rotation length (L_{ROT}, years): Average Frequency Crop X $= N_X * CF_X / L_{ROT}$, with $CF_X = \text{Round}(L_X / 365)$ for $L_X > 365$ and $CF_X = 1$ for $L_X \leq 365$. Round is a function that rounds to the closest integer.
(2) Soil types are described in Chapter 2, Table 2.2.
(3) Irrigation level: I = irrigated; R = rain fed
(4) Mechanization and crop protection level: H = high; L = low

The first step of the designing process resulted in 57,032 and 279,096 production activities or land use options at the field scale completely characterized by their inputs and outputs with low and high mechanization level respectively. Those production activities were used as input for the second step. The designing process at field scale and the procedure followed to quantify all relevant inputs and outputs was future-oriented (5 years) and target-oriented, i.e., technically efficient sets of inputs needed to realize a yield target were identified, rather than current input-output relationships (Van Ittersum and Rabbinge, 1997). The procedures are detailed by Dogliotti et al., (2003b) (Chapter 4).

5.2.2 Farm scale design

In the second design step we selected and combined production activities at the field scale to produce optimal farm systems at the farm scale, subject to the limitations imposed by the actual resource availability of the farmers in Canelón Grande, and a set of objectives. We designed a mixed integer linear programming model (MILP) named SmartFarmer to optimally combine production activities at the farm scale by maximizing farm income and minimizing undesirable side effects. The MILP model takes into account the limitations imposed by the resource availability of the farm such as suitable soil area, labor, irrigation, capital, machinery, and the limitations imposed by the system complexity and the farmer’s management skills. We reduced the initial number of production activities to be used as input to the MILP model by 95 and 97% for low and high mechanization options, respectively, due to computing capacity limitations. We describe the procedure followed to select these production activities in the following section.

5.2.2.1 Selection of production activities

The field scale design process yielded 144 groups of production activities, as a result of the combination of three soil types, two mechanization levels, two crop protection levels, three irrigation levels and four types of inter-crop activities. In order to maintain a wide range of options regarding resource requirements we selected 5% and 3% of the production activities (**PAs**) from each of the 72 groups with low and high mechanization level, respectively[1]. The selection procedure comprised classifying **PAs** within each group in classes of 25 h ha^{-1} yr^{-1} width according to labor requirement, and selecting the top 5 and 3% within each class according to labor productivity (US\$ h^{-1}). We define labor productivity as the ratio between gross margin (US\$ ha^{-1} yr^{-1}) and labor requirement (h ha^{-1} yr^{-1}). The performance of these new sets of 5759 and 2931 **PAs** with low and high mechanization level, respectively, maintained

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[1] The reason we selected a higher percentage of low mechanization is that the initial amount of production activities was only 57,032 compared to 279,096 for the high mechanization level.

similar variability as the original set (Figure 5.1) with respect to important characteristics such as gross margin, soil erosion, rate of change of soil organic matter (SOM), N surplus and an indicator for the environmental impact of pesticides (environmental exposure to pesticides (EEP)). The reduced set still gave many degrees of freedom to search for optimal combinations for each farm that satisfy the farmer's needs and minimize undesirable side effects of agricultural production.

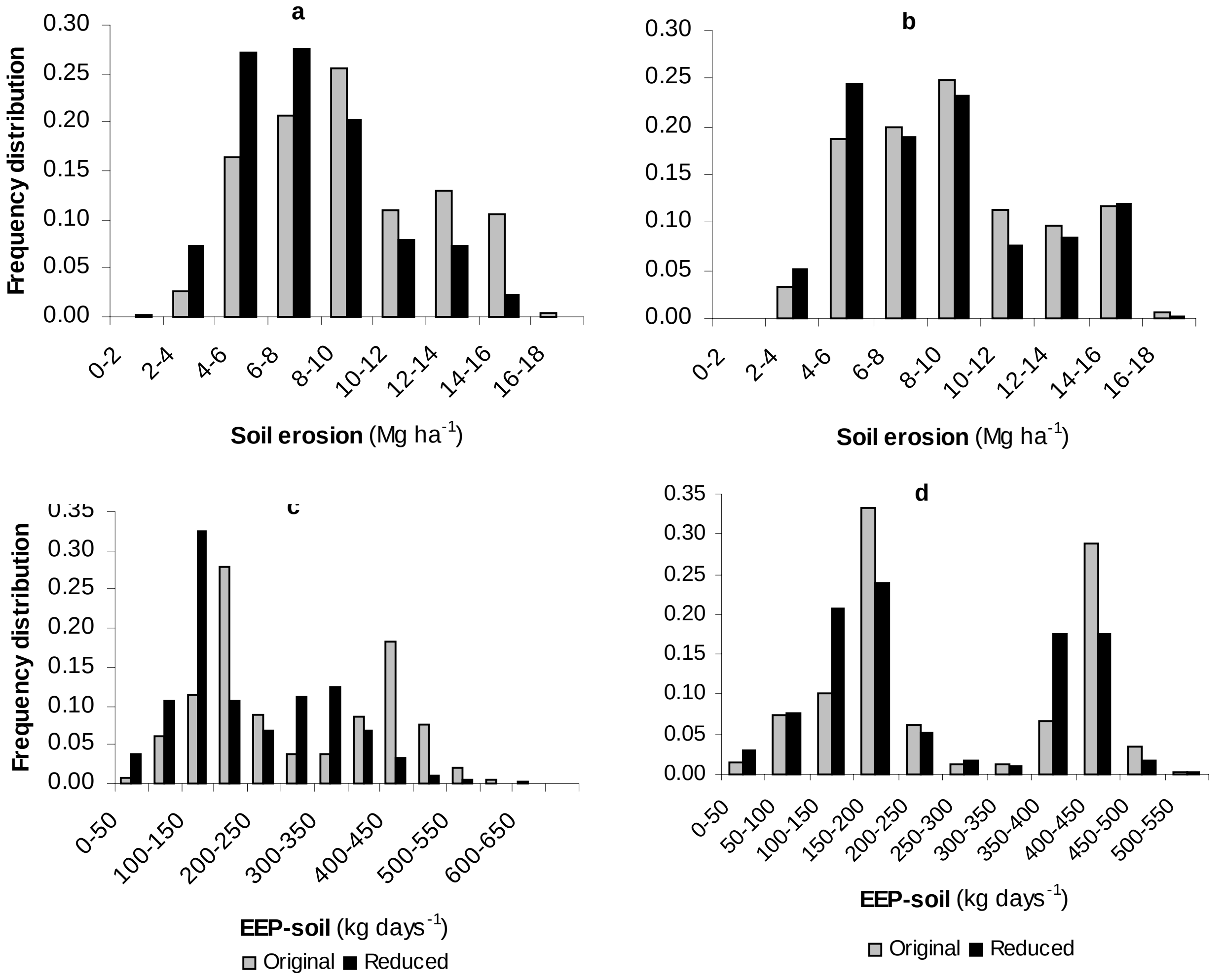

Figure 5.1. Comparison between the performance of the original set and the reduced set of production activities. Frequency distribution of classes of production activities with high mechanization according to soil erosion (a) and EEP-soil (c); frequency distribution of classes of production activities with low mechanization according to soil erosion (b) and EEP-soil (d).

5.2.2.2 The MILP model

SmartFarmer is a MILP model able to allocate production activities to land units of a farm differing in soil quality, while maximizing or minimizing different objective functions, subject to constraints at the farm level. SmartFarmer has been programmed such that can be used as an interactive multiple goal linear program (de Wit et al., 1988). We have written, compiled and solved it using XPRESS-MP (Dash Optimization Ltd.). Smart Farmer has 7 objective functions, which can be optimized one at a time. When one of them is optimized, the rest can be used as constraints. An acceptable solution would eventually be found after iterative rounds where the upper or lower bounds of each goal are successively tightened. The objective functions implemented in SmartFarmer are described in Table 5.2. When soil erosion, rate of change of SOM, N surplus and environmental exposure to pesticides – soil (EEP-soil) are used as constraints, minimum or maximum acceptable values are set per ha for each soil type of the farm. Values for EEP soil, air and groundwater were estimated following the approach of Wijnands (1997; personal communication, 2002). We used annual change in SOM (kg ha^{-1} yr^{-1}) as an estimate of the effect of the production activities on the long-term dynamics of SOM. The procedures followed to estimate rate of change of SOM and EEP are detailed in Chapter 4 (Dogliotti et al., 2003b).

Table 5.2. Description of objective functions included in SmartFarmer model.

Objective function	Units	Description
Maximize gross margin	US$ yr^{-1}	Whole farm gross margin
Maximize family income	US$ yr^{-1}	Farm gross margin plus labor costs (1)
Minimize capital requirement	US$ yr^{-1}	Farm direct production costs minus labor costs (2)
Minimize soil erosion	Mg yr^{-1}	Whole farm soil loss calculated by adding the soil loss in each soil type
Maximize rate of change of SOM	kg yr^{-1}	Whole farm SOM rate calculated by adding the SOM rate in each soil type
Minimize N surplus	kg yr^{-1}	Whole farm N surplus calculated by adding the N surplus in each soil type
Minimize environmental exposure to pesticides - soil (EEP soil)	kg-days	Whole farm EEP soil calculated by adding the EEP soil in each soil type

(1) The family income takes into account the value of the labor provided by the family.
(2) Capital requirement is the amount of currency required to purchase inputs external to the farm system.

Besides the objective functions that may be used as constraints once targets have been defined, the model has other constraints that capture the farm resources, the desired complexity of the system and the farmer's preferences. The constraints related to farm resource availability include area of each soil type suitable for cropping, maximum amount of labor available per year, maximum amount of labor available for each of the 24 periods of half a month in a year, and maximum area that can be irrigated due to water or irrigation equipment limitations. The objective function capital requirement can also be considered as a constraint related to resource availability.

The constraints related to desired complexity of the farm system include maximum number of production activities (crop rotations) per land unit, maximum number of different crops per farm and minimum plot area. Plot is the unit into which a land unit has to be divided to lay out a rotation, i.e. the plot area of a 4 ha field with an 8 years long rotation is 0.5 ha, assuming each crop of the rotation to be grown every year. For market and management reasons the farmer may like to set maximum and minimum limits to the cultivated areas of each crop. Also, in some cases the farmer may prefer not to grow a certain crop. We have implemented this using constraints for a maximum and minimum area for each crop. If the maximum area of a certain crop is set to zero, the model will not select any production activity including that crop. For the purpose of this study, the maximum number of production activities (crop rotations) per land unit was set to 1. More than 80% of the farmers in the region grows between 3 and 6 crops (Klerkx, 2002), consequently the maximum number of different crops per farm was set at 6 crops.

5.2.2.3 Case study farms and model runs

We selected 7 farms in Canelón Grande with different resource availability (land, labor, mechanization level and irrigation) in order to explore for each farm the room for improvement of farmer income, while reducing soil erosion and enhancing physical and biological soil fertility. In Table 5.3 we described the resource availability of each farm, the fixed costs and the minimum family income used as a target. We calculated fixed costs based on farm interviews and technical coefficients. Fixed costs include amortization of machinery, buildings and fences, maintenance of buildings, internal roads, terraces and fences, and technical assistance and taxes. Family income was calculated as follows:

$$FI = GM + L*\alpha - FC \qquad \text{equation 1}$$

where,

FI is family income per farm in US$

GM is the gross margin (US$ farm^{-1}) = gross product – direct costs. Direct costs include labor, maintenance and repairs of machinery, energy, seeds, fertilizers, chemical crop protectants and other inputs.

L (h) is the labor contributed by the farmer and family directly used in production activities

α is the value of labor used for calculation of direct costs, in this case 0.75 (US\$ h^{-1}).

FC (US\$ $farm^{-1}$) are the fixed costs.

We estimated a minimum family income based on the average income per household in Uruguay (INE, 2002), corrected by the number of family members.

Table 5.3. Description of resource availability of the 7 farms from Canelón Grande selected for this study.

Farm NR.	Family size (#)	Suitable Area (ha)	Soil type 1 (ha)	Soil type 2 (ha)	Soil type 3 (ha)	Prod. Labor (10^3 h) (1)	Maint. Labor (10^3 h) (2)	Available Irrigation (ha)	Mech. Level	Labor per ha ($h.ha^{-1}$)	Fixed Costs (10^3 US\$)	Minimum family income (10^3 US\$)
1	4	5.5	3.0	2.5	0.0	7.2	1.2	3.0	Low	1,531	3.7	6.8
2	4	8.5	2.5	6.0	0.0	5.6	0.8	2.0	High	756	4.8	6.8
3	3	14	5.5	5.5	3.0	7.5	0.8	2.0	Low	590	4.1	5.1
4	3	16.6	0.0	6.2	10.4	5.0	0.8	0.0	Low	351	3.9	5.1
5	4	30.4	4.4	6.0	20.0	10.9	1.3	4.0	High	402	10.2	6.8
6	6	46.4	7.0	26.8	12.6	14.0	2.3	1.0	High	352	11.0	10.2
7	11	65.2	19.2	24.0	22.0	10.0	1.5	3.6	High	177	11.5	18.7

(1) Maximum labor to be directly allocated to production activities.

(2) Labor allocated to maintenance of the farm and general management tasks such as buying inputs, getting information, etc. We estimated it as the 15% of the permanent labor.

We performed two optimization rounds per farm. In each round we optimized all 7 objective functions. In the first round we imposed no targets on any of the objective functions, but we did include a constraint forcing the minimum area used by the farm to be equal to or exceed the area selected when gross margin was optimized. In the second round we set a minimum target value for gross margin and family income calculated based on the minimum family income for each farm (Table 5.3), a maximum value for erosion in each soil type based on the tolerance levels defined by Puentes (1981) and a minimum value for rate of change of SOM of zero. The other targets in this round were defined according to the worst values obtained in the first round. Minimum used area in this round was set to zero. Model setting for each farm for both optimization rounds is shown in Table 5.4. The maximum irrigated area per farm was set according to the actual water and irrigation equipment availability at each farm as based on the farm survey. According to Duran (2000), terracing is the standard support practice for erosion control recommended for the region. Since terraces are constructed 40 to 50 m apart, with a maximum length of 100 to 120 m they divide the land in fields of 4000 to 6000 m^2. We used this as the basis to define the minimum plot area, except for Farm 1. Due to the small size of Farm 1, we used half this size as the minimum plot area (which corresponds to what can be observed in this kind of farms). The minimum area per crop was set according to the minimum plot area. No limits were set to the maximum area per crop except for sweet pepper, which was 2 ha for Farms 1 to 6 and 4 ha for Farm 7 due to market limitations.

Table 5.4 Model setting for each farm in both optimization rounds.

Constraint	Farm number						
	1	2	3	4	5	6	7
Area ST1 (ha)	3.0	2.5	5.5	0	4.4	7.0	19.2
Area ST2 (ha)	2.5	6.0	5.5	6.2	6.0	26.8	24.0
Area ST3 (ha)	0	0	3.0	10.4	20.0	12.6	22.0
Max Labor (10^3 h yr^{-1})	7.2	5.6	7.5	5.0	10.9	14.0	10.0
Max Labor September - March (h 0.5 month^{-1})	475	820	1060	580	1067	1208	1054
Max Labor April - August (h 0.5 month^{-1})	375	768	1008	528	1028	1104	976
Max irrigated area (ha)	3.0	2.0	2.0	0	4.0	1.0	3.6
Min plot area (ha)	0.25	0.4	0.4	0.4	0.4	0.5	0.5

5.2.2.4 Comparison between actual and proposed farm systems

To estimate the outputs of present farm systems we used farm data collected in the farms from 1995 to 2000 by agronomy students. Basic data were crop species and area grown in each farm, average commercial yield estimated by the farmer, current inter-crop practices, current use of hired labor, and availability of machinery, buildings and irrigation. We did not used current prices of products, but the prices estimated for the period 2003-2005, as used in the MILP study. We estimated soil erosion of current farm systems using the RUSLE equation (Renard et al., 1997) with the same settings used by Dogliotti et al., (2003b). We also estimated rate of change of SOM of current farm systems using the same method and settings reported by Dogliotti et al., (2003b).

5.3. Results

5.3.1 Objective values

For each farm except Farm 4, we selected the farm systems resulting from the maximization of family income constrained by upper bounds for soil erosion based on the tolerance levels defined by Puentes (1981) and a rate of change of SOM of at least zero for all soil types. For

Farm 4 we selected the farm system with maximum family income, resulting from the first round. This farm was the only one for which the target family income could not be achieved and soil erosion was exceeding the target for soil type 2 (Table 5.5). For the rest of the farms the model was able to find a farm system with a family income exceeding the target, a soil erosion lower than the target for each soil type and a rate of change of SOM exceeding zero (Table 5.5). The largest N surplus was 89 kg ha^{-1} in Farm 4. The largest EEP-soil was 316 kg-days at Farm 4. The largest EEP-air was 1.4 kg a.i. ha^{-1} at Farm 2. The largest EEP-groundwater was 1.66 μg l^{-1} at Farm 1. Family labor productivity, calculated as the ratio between family income and used family labor, varied from 1.23 US\$ h^{-1} in farm 4 to 4.44 US\$ h^{-1} in Farm 7.

Table 5.5 Main outputs of the best farm systems designed by SmartFarmer for each farm. We defined best farm system as the system with highest family income, with soil erosion below the tolerance levels and rate of change of SOM exceeding zero.

Objective	Target value	Farm number						
		1	2	3	4	5	6	7
Net margin (1) (10^3 US\$ yr^{-1})		4.9	5.1	7.5	1.9	10.2	11.2	22.5
Family income (10^3 US\$ yr^{-1}) (2)	See Table 2	7.9	7.0	10.7	4.7	12.8	15.9	27.1
Capital requirement (10^3 US\$ yr^{-1}) (3)		5.9	8.4	10.0	8.1	20.3	19.4	30.0
Family labor productivity (US\$ h^{-1}) (4)		1.97	2.71	2.49	1.23	3.69	2.52	4.44
Erosion soil type 1 (Mg ha^{-1} yr^{-1})	7	6.6	6.6	6.6	-	6.6	3.3	3.9
Erosion soil type 2 (Mg ha^{-1} yr^{-1})	5	3.5	4.7	4.5	9.8	4.5	2.7	2.4
Erosion soil type 3 (Mg ha^{-1} yr^{-1})	5	-	-	3.6	3.6	3.5	3.5	0
SOM rate soil type 1 (kg ha^{-1} yr^{-1})	0	157	84	157		157	261	228
SOM rate soil type 2 (kg.ha^{-1} yr^{-1})	0	270	197	183	321	222	282	315
SOM rate soil type 3 (kg ha^{-1} yr^{-1})	0			122	72	98	98	0
N surplus per ha (kg ha^{-1} yr^{-1})		47	35	49	89	53	65	39
EEP soil (kg-days)		219	203	129	147	98	76	94
EEP air (kg A.I. ha^{-1})		1.39	1.40	0.86	0.60	0.55	0.42	0.68
EEP water (μg l^{-1})		1.66	0.96	0.44	3.00	1.20	0.73	0.15

(1) Net margin = gross margin – fixed costs
(2) Family income = gross margin – fixed costs + family labor cost
(3) Capital requirement = production costs – family labor cost
(4) Family labor productivity = family income / used family labor

5.3.2 Proposed farm systems versus present systems

In Table 5.6 we compare the estimated performance of the farm systems designed using SmartFarmer with the actual farm data. Family income of the modeled farm systems was higher than of current farm systems for all farms except Farm 2 (Table 5.6). Farm 2 was the only farm reaching a net income larger than the minimum target with the current farm system. The estimated average soil erosion per ha was 2 to 4 times larger at current farm systems than for the improved farm systems. Soil erosion estimated for current farm systems was always larger than the tolerance levels defined by Puentes (1981). The average rate of change of SOM of current farm systems was always negative. The proposed farm systems had an average rate of change of SOM varying between +130 to +280 kg ha^{-1} yr^{-1}. These results show that a further decrease in physical and biological soil fertility in the future could be expected with current farm systems.

Table 5.6 Performance of farm systems designed by SmartFarmer compared with current farm systems with respect to family income, soil erosion and rate of change of SOM.

	Family income (10^3 US$ yr^{-1})		Average soil erosion per cropped area (Mg ha^{-1} yr^{-1})		Average rate of change of SOM (Mg ha^{-1} yr^{-1})	
Farm number	Current situation	Improved system	Current situation	Improved system	Current situation	Improved system
1	2.5	7.9	11.0	5.3	-0.13	0.21
2	7.2	7.0	11.8	5.0	-0.24	0.18
3	3.8	10.7	10.4	5.4	-0.12	0.17
4	0.7	4.2	13.3	4.7	-0.28	0.17
5	5.0	12.8	15.5	4.1	-0.33	0.13
6	-0.6	15.9	9.1	3.0	-0.15	0.22
7	11.7	27.1	13.3	3.0	-0.27	0.28

5.3.3 Selected crop rotations

Both type and area of crops in the farm systems designed by SmartFarmer differed from current practice in at least one crop for all farms (Table 5.7). Grass and legume pastures were selected in all farms. The share of pastures varied between 30 to 50% of the cropped area per farm. Except for Farm 4, the share of pastures increased while that of vegetables decreased with increasing area availability per farm and decreasing labor availability per ha. The most important differences between actual and proposed farm systems regarding crop types were the increased share in area of pastures, the decrease of vegetables crops and the disappearance of garlic, potato and squash in the farm systems designed by SmartFarmer (Table 5.7). While in the model garlic had the highest maximum gross margin per ha, its labor requirement per unit gross margin was only exceeded by squash. Consequently, garlic was only selected in the farm with highest availability of labor per ha. Reduction in the amount of labor required for preparing the dried crop for commercialization (almost 60% of labor is spent in post-harvest) could make this crop more attractive.

Table 5.7 Area of crops grown in each farm with current farm systems (A) and with farm systems designed in this study (B). Vegetable crops are all except pasture, wheat and sudan-grass.

	Area (ha)													
	Farm 1		Farm 2		Farm 3		Farm 4		Farm 5		Farm 6		Farm 7	
Crops	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Pasture	0.25	1.5	-	3	1.5	5.5	-	4.85	-	13.99	3.5	20.7	-	20
Garlic	0.68	0.38	1.5	-	1.25	-	0.38	-	4	-	1.5	-	2.5	-
Onion	1	0.66	2	1.75	0.8	2.75	0.43	1.55	3	2.55	3.5	3.78	3	5
Potato	0.16	-	0.3	-	-	-	-	-	6	-	6	-	3	-
Sweet Potato	1	1.03	-	1	0.4	1.38	-	1.55	-	1.28	-	3.78	-	2
Carrots	-	-	-	-	-	-	-	-	-	-	-	-	15	-
Sweet Maize	-	0.66	-	0.5	-	1.1	-	5.53	-	4.44	-	2.8	-	-
Sweet Pepper	-	0.7	0.1	1	-	0.9	-	-	-	1.28	-	-	-	3
Tomato	-	-	0.35	-	-	-	-	-	-	-	-	-	-	-
Squash	1	-	-	-	1.4	-	1.1	-	10	-	18	-	10	-
Wheat	-	-	-	-	-	-	-	-	-	-	7	7.55	-	10
Sudan-grass	-	-	-	-	-	0.63	-	2.43	-	6.67	-	4.2	-	-
Total	4.1	4.9	4.3	7.3	5.4	12.3	1.9	15.9	23.0	30.2	39.5	42.8	33.5	40.0
Vegetable crops	3.8	3.4	4.3	4.3	3.9	6.1	1.9	8.6	23.0	9.6	29.0	10.4	33.5	10.0

Crop rotations were generally longer than 6 years (Table 5.8). Apparently, shorter rotations were less cost-effective due to lower yields caused by soil-borne pest and diseases. Longer crop rotations usually have lower crop frequencies, resulting in better soil health, which is reflected in higher crop yields. Growing a green manure crop was the inter-crop management selected most, followed by growing forage crops. Apparently, the contribution to reduction of erosion, to increase of soil organic matter and to forage production made these options preferable over the inter-crop management options manure and fallow. Green manure and forage crops reduce soil erosion by keeping the soil covered. Green manure crops add between 3.5-6.5 Mg DM of organic material to the soil. This organic material contributes to enhance physical and biological soil fertility, which is reflected in the yield of the following crop. The products of forage crops are fed to animals, but still a fraction contributes to the soil organic matter. In all the farm systems designed the high crop protection level option was selected.

Table 5.8 Selected crop rotations and production orientations. (Inter crop management: A = fallow, B = animal manure, C = green manure, D = green manure crops harvested as animal feed)

Farm No.	Soil Type	Prod orientation				Crop rotation	Rotation Length (yr)
		Mech. level	Crop Prot. level	Irrig. level	Inter-Crop Manag.		
1	ST1	Low	High	High	C	Pasture4–SwPotatoE–SwPepper–Garlic	8
	ST2	Low	High	High	C	OnionLD–SwMaizeL–SwPotatoE–OnionLD–SwPepper–SwMaizeL–SwPotatoE	7
2	ST1	High	High	High	C	OnionSD–SwMaizeL–SwPotato–SwMaizeL–SwPepper	4
	ST2	High	High	Med	C	Pasture4–OnionSD–SwPotato–SwPepper–OnionSD	8
3	ST1	Low	High	Med	C	Pasture4–OnionSD–SwPotatoE–SwPepper–OnionSD	8
	ST2	Low	Low	Low	D	Pasture4–OnionSD–SwPotatoE–SwMaize–OnionSD	8
	ST3	Low	High	High	C	SwMaize–Sudan–SwMaize–Sudan–SwPepper–Sudan	6
4	ST2	Low	High	Low	B	OnionSD–SwMaize–SwPotato–SwMaize–OnionSD–SwMaize–SwPotato–SwMaizeL	8
	ST3	Low	High	Low	D	Pasture4–SwMaize–Sudan–SwMaize–Sudan	8
5	ST1	High	High	Med	C	Pasture4–OnionSD–SwPotatoE–SwPepper–OnionSD	8
	ST2	High	High	High	C	Pasture4–OnionSD–SwPotatoE–SwPepper–OnionSD	8
	ST3	High	High	Low	D	Pasture4–Sudan–SwMaizeL–Sudan–SwMaizeL–Sudan	9
6	ST1	High	High	Med	D	Pasture4–Wheat–OnionSD–Wheat–SwPotatoE	8
	ST2	High	High	Low	D	Pasture4–Wheat–SwPotatoE–Wheat–OnionSD	8
	ST3	High	High	Low	D	Pasture4–Sudan–SwMaizeL–Sudan–SwMaizeL–Sudan	9
7	ST1	High	High	Low	D	Pasture4–Wheat–OnionLD–Wheat–SwPotatoE	8
	ST2	High	High	Med	C	Pasture4–Wheat–SwPepper–OnionSD–Wheat	8

The model proposed the introduction of beef cattle production into the farm systems of farms 3 to 7 (Table 5.9). Animal production represented as much as 37% of the gross margin in the farm systems proposed for farms 4 and 6. Farms 4 and 6 had the lower fraction of area irrigated, low availability of labor per ha and 59 and 29% of soil type 3, respectively. Beef cattle was fed with forage produced by pastures and sudan grass, forage crops grown during the inter-crop periods and with residues from vegetable crops such as sweet maize and sweet potato. In this way, animal production contributed to make the maintenance of soil cover to reduce soil erosion profitable. On the other hand, animal production has a negative effect on soil organic matter by reducing the amount of organic residues from crops and from green manure incorporated in the soil.

Table 5.9 Number of beef cattle animals in current farm systems and in the farm systems designed in this study for each farm.

Farm No.	Number of animals	
	Current	Designed
1	5	0
2	0	0
3	0	9
4	0	20
5	0	45
6	0	77
7	36	25

5.3.4 Trade-off analysis

Gross margin per ha increased with the amount of labor used per ha, except for Farm 4 (Figure 5.2a) and with increasing fraction of farm area irrigated, except for Farm 5 (Figure 5.2b). The low ratio between gross margin and labor used in Farm 4 was explained by the lack of irrigation and the lower quality of used soil (59% soil type 3). The low gross margin to irrigated fraction ratio of Farm 5 was explained by the lower quality of used soil (66% soil type 3). Soil erosion per ha increased with the amount of labor used per ha till 550 h ha^{-1} (Figure 5.2c).

We selected farms 1, 3, 6 and 7 to analyze the trade-off between gross margin and soil erosion, and gross margin and EEP-soil (Figures 5.3a and 5.3b). We did this by minimizing soil erosion or EEP-soil while decreasing the target value for gross margin and keeping the cropped area in each soil type constant, starting from the value of gross margin and cropped

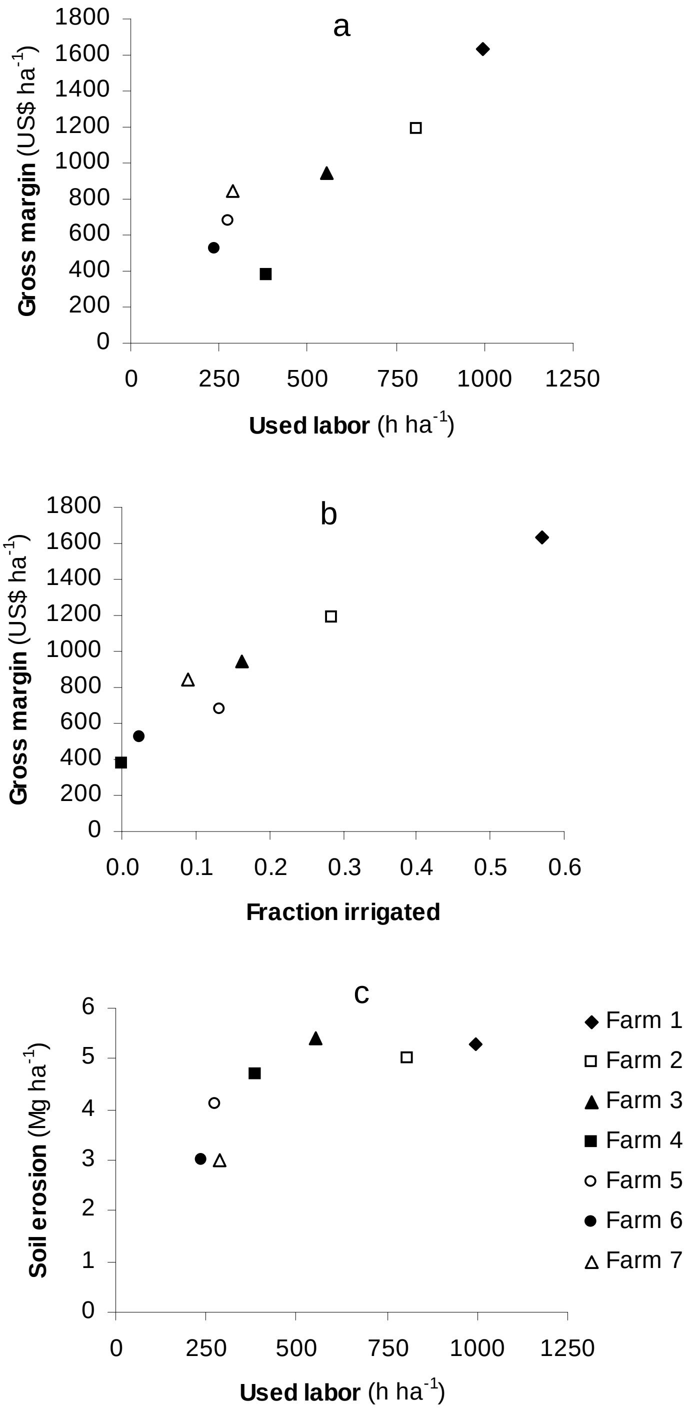

Figure 5.2 Gross margin per ha as a function of the amount of labor used per ha (a), gross margin per ha as a function of the ratio between irrigated area and total used area (b), and average soil erosion per ha as a function of the amount of labor used per ha in best farm systems designed with SmartFarmer. We defined best farm system as the system with highest family income, with soil erosion below the tolerance levels and rate of change of SOM exceeding zero.

area obtained for each farm in the first round. We set a minimum value for rate of change of SOM of zero. When EEP-soil was minimized, we set a maximum value to erosion on each soil type based on the tolerance levels defined by Puentes (1981). Trade-off analysis between gross margin and soil erosion showed that for farms 1 and 3 soil erosion could be reduced till 4.5-5 mg ha^{-1} at a cost of 27 and 78 US$ Mg^{-1}, respectively (Figure 5.3a). The room for reduction of soil erosion on farms 6 and 7 was smaller, since the erosion at maximum farm gross margin was already low. Labor availability per ha on these farms was lower than on farms 1 and 3. Consequently, the model selected less labor intensive production activities for these farms including a larger share in area of pasture, and crops such as wheat and sudan grass with better soil cover than vegetable crops. Analysis of trade-off between gross margin and EEP soil showed that reduction of EEP soil from 250 to 150 kg-days could only be achieved with reductions in gross margin of 140-160 US$ ha^{-1} for farm 1 and 3 (Figure 5.3b). This reduction represents 12 and 18% of family income of farms 1 and 3 respectively, which could be difficult to accept. Maximum EEP soil value for farm 6 and 7 (Figure 5.3b) was lower than the targets used in prototyping of farm systems in Europe. Calculations showed that further reductions from 140 to 50 kg-days costs 260-270 US$ ha^{-1}.

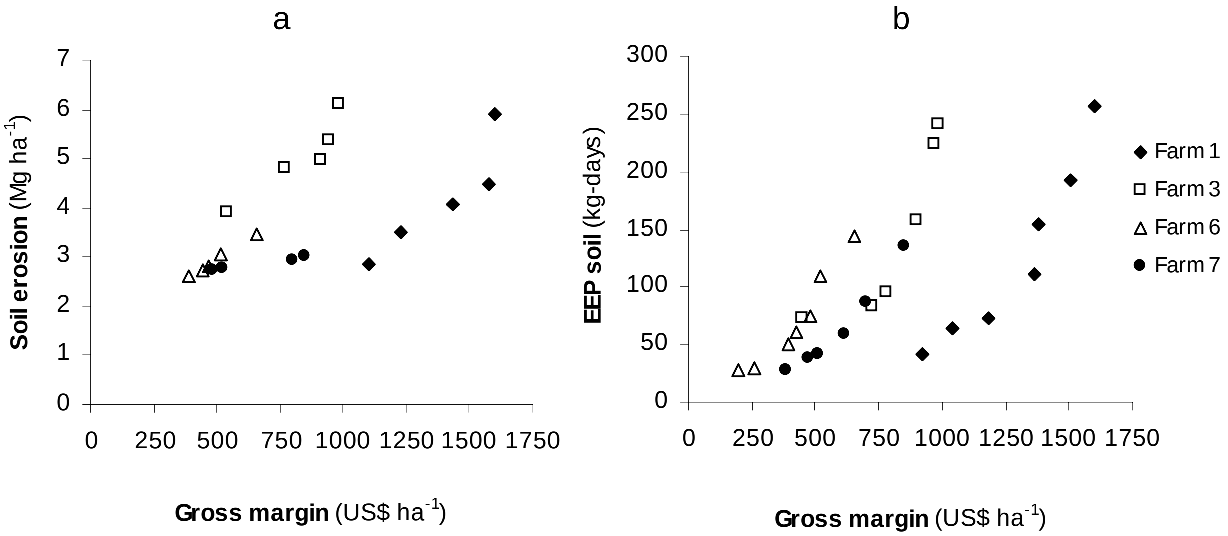

Figure 5.3 Trade-off between soil erosion and gross margin (a), and trade-off between soil exposure to pesticides (EEP-soil) and gross margin (b), for farms 1, 3, 6 and 7. EEP-soil is an indicator of the impact of pesticides in the soil estimated following the approach of Wijnands (1997; personal communication, 2002).

5.4. Discussion

The results of this model-based explorative study suggests opportunities for increased farmers' income while soil erosion is reduced and physical and biological soil fertility is improved. We showed that the degree to which these objectives could be achieved are strongly affected by farm resource endowment, mainly fraction of the area irrigated, soil quality and labor availability per ha. Increasing availability of land on farms with high labor availability per ha would help to decrease soil erosion and EEP while maintaining or increasing farmers' income.

5.4.1 Objective values and farm strategy

In this study we focussed on the re-design of farm systems to explore the scope for improvement of the sustainability of vegetable farms in Canelón Grande. The main means proposed to achieve this objective were the design of agronomically sound crop rotations, substitution of fallow by animal manure, green manure and forage crops, introduction of mixed plant-animal production systems and the optimal allocation of farm resources. After optimally allocating production activities to different fields of the farms using an MILP model, we were able to design farm systems with a family income greater than the target, soil erosion less than the tolerance levels and a rate of change of SOM greater than zero for 6 of the 7 selected farms. We could not reach a family income greater than the target for farm 4. This farm had the poorest resource endowment with respect to labor, irrigation and soil quality (Table 5.3). Moreover, for 6 of the 7 selected farms the proposed farm systems had higher family income than current systems. At the same time soil erosion was reduced by 48 to 77% and the soil organic matter content changed from a situation of slow decrease to a situation of slow increase (Table 5.6).

To achieve these results, the model suggested to increase the cropped area for all farms (Table 5.7). However, contrary to the tendency in the region during the last decade of intensifying farm systems with an increased share of vegetables and reduced fallow periods, the model suggested a lower share of vegetable crops for all farms. The model also suggested that the introduction of beef cattle into the farm system might increase family income and make the maintenance of soil cover to reduce soil erosion profitable. The results of this exploration showed that reducing cropping frequencies, substituting fallow periods by pastures, green manure and forage crops and sometimes introducing animal production may be a better strategy to increase crop yields, resource use efficiency and consequently farmer's income.

5.4.2 N surplus and environmental exposure to pesticides

We did not use N surplus and EEP as objectives in the optimization. We could not find evidence of concern by the government, farmers or NGOs about the N surplus from agriculture in Uruguay. With respect to the use of chemical crop protectants, except for the case of rice production, concerns of government agencies, organic farmers organizations and NGOs are related to their effect on human health through the residues in food rather than to their impact on the environment (Evia and Gudynas, 2000). This may of course change in future. The method allows investigation of consequences of such potential, future environmental concern. The largest N surplus estimated in our study was 89 kg N ha^{-1} in the farm system proposed for farm 4 (Table 5.5), which is, for instance, lower than the present threshold of 100 kg N ha^{-1} for N surplus used in ‘prototyping’ in The Netherlands (e.g. Wijnands and Van Asperen, 2002). Highest values for EEP estimated for the proposed farm systems were 219 kg-days, 1.4 kg A.I. ha^{-1} and 3.0 μg l^{-1} for soil, air and ground-water respectively. These values are higher than the thresholds used in prototyping of farm systems in The Netherlands: 200 kg-days for EEP soil, 0.7 kg A.I. ha^{-1} for EEP-air and 0.5 μg l^{-1} for EEP-groundwater (Van der Zee and Boesten, 1991; de Buck et al., 2000). The EEP decreased with increasing farm area and with decreasing labor availability per ha, except for farm 4. Lower labor availability per ha resulted in less intensive farm systems with higher share of pastures and crops such as wheat and sudan-grass with lower EEP values compared with vegetable crops.

5.4.3 Soil erosion

When a sample of farmers in Canelón Grande was asked about the main problem they perceive in the environment 39% mentioned the global climate, 15% pollution by residues of agrochemical products, 11% the problems with pests and diseases, and only 9% mentioned soil erosion (Klerkx, 2002). However 88% of the interviewed farmers were aware of the occurrence of soil erosion on their own farms. The most important measures they know to reduce soil erosion are terracing, and reducing runoff velocity by leaving the soil surface rough. Only 8% mentioned the use of green manure or the importance of maintaining vegetation cover (Klerkx, 2002). Calculations made in this study showed that erosion control support practices such as terracing are not enough to decrease soil erosion below the tolerance limits (Table 5.6). The inclusion of green manure during the inter-crop periods and the selection of long crop rotations including pastures had a positive effect not only on reducing soil erosion but also on increasing vegetable crops yields. Consequently, to some extent, the measures proposed in this study to reduce soil erosion and increase soil physical and biological fertility had a positive effect on estimated farmers’ income. The average erosion per ha resulting from maximizing farm gross margin without constraints on other objectives was lower for each farm than the erosion estimated for the current farm systems. Further decrease in soil erosion was achieved by increasing the share in area of pasture and decreasing the vegetable crops.

5.4.4 Application of the approach in an innovation process

The approach developed in this study is expected to support strategic thinking of farmers and technical advisers about their farm systems rather than tactical or operational decision making. The results obtained would support the design phase of an innovation process by presenting alternative farm systems, their calculated impact on family income and on environment, and the resources required for their implementation, which constitute elements to be discussed among farmers, their advisers and other stakeholders before actually embarking on a process of change. The selected promising farm systems should be tested on experimental farms or commercial pilot farms as in the "prototyping" approach (Vereijken, 1997). The results obtained on these experimental and pilot farms could be used to correct the technical coefficients and relationships used by the model and to build confidence in model outcomes. Only few farm systems can be tested in practice due to the cost and the time required to experiment with entire farming systems. The application of our approach would contribute to a thorough and more transparent discussion of a wide number of alternatives, reducing the risk of overlooking good alternatives. Since a model is always a simplified representation of reality, the calculated optimal farm system is not necessarily the best solution for all farms with similar resources and aims. Farmers probably would prefer to be presented to a number of alternatives similar in satisfaction of different objectives but different in other issues (e.g. number and type of crops, labor films, etc.) not taken into account by the model. This is possible by generating nearly optimal solutions, which are alternative farm systems that result in good, albeit not optimal, levels of satisfaction of objectives (Makowski et al., 2000; 2001),

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Chapter 6

Influence of farm resource endowment on the possibilities for sustainable development of vegetable farms in Canelón Grande

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Influence of farm resource endowment on possibilities for sustainable development: a case study for vegetable farms in South Uruguay.

6 Influence of farm resource endowment on the possibilities for sustainable development of vegetable farms in Canelón Grande.

ABSTRACT
A variety of viable patterns of farm development exists related to farm resource endowment and farmer's strategy. In a process of farming system innovation, the methodology used to design innovative farming systems should be able to capture the existing variation in resource endowment and strategies in order to have impact on strategic farm management. In this Chapter we applied the model-based approach presented in this thesis, to gain insight in the impact of current farm resource endowment on the possibilities for sustainable development of vegetable farms in Canelón Grande, Uruguay. We maximized farm income for 128 different farm types in an environment-oriented scenario and in an income-oriented scenario. Farm types were defined by combining 4 farm sizes, 2 labor endowments, 4 irrigation endowments, 2 soil quality combinations and 2 mechanization levels. The results demonstrate a strong impact of farm resource endowment on possibilities for sustainable development. Farms with 10 ha of land or less, representing 47% of the farms in the Canelón Grande region, could only achieve a family income higher than the minimum when irrigated area was c.a. 40% of the farm area. The achievement of environmental targets was less costly in terms of income on farms with a low rather than high labor availability per unit area and on farms with irrigation facilities.

6.1 Introduction

Agricultural business around the world is under pressure by the influence of market de-regulation, free trade and globalization. Dillon (1997) mentioned as major changes in agriculture during the last decade, among others: decrease of international barriers to trade and decrease of government interference, increasing demand by the consumers of a wide, convenient and safe variety of products available all year round, increasing concern about the environment, biodiversity and health, decreasing number and increasing size of farms, and decrease of the image of agriculture. These changes urge for the adaptation of actual farm systems to the new context. New tools are required to help farmers and other stakeholders to re-design farm systems. Model based land use studies have been proposed and used to support strategic thinking during the design of new farming systems in different regions of the world (Van Rheenen, 1995; Rossing et al., 1997, Zander and Kächele, 1999; Ten Berge et al., 2000; Lu et al., 2003; Mazzeto and Bonnera, 2003; Castelán-Ortega et al., 2003).

Farmers differ in their endowment with natural resources, capital and labor for agricultural production and in the strategies they adhere to. The available resources determine which options for solving problems related to the sustainability of a farm can actually be used fruitfully in a given context. Thus, farms with different resource availability in the same socio-economic environment would have different potential to satisfy a given set of sustainability objectives. In the short term resource endowment is usually fixed. However, in the long-term changes in the amount of land, labor, capital or irrigation water per farm may not only be possible, but also desirable in order to increase resource use efficiency. Insight in the consequences of different farm resource endowment on the possibilities for sustainable development is important when planning regional or on-farm development activities. Since a variety of viable patterns of farm development exists (Van der Ploeg, 1990), a method to support the design phase of a systematic farm development process should have the capability to capture those differences among farmers in resource endowment and strategies. Otherwise, the farming systems that are being designed are likely to suit only a small sector of the farming population in a given region (Leeuwis, 1999).

In this chapter we applied the approach presented in Chapters 3-5, to gain insight in the impact of current levels of farm resource endowment on the possibilities for sustainable development of vegetable farms in Canelón Grande and on the resource use efficiency at the farm scale.

6.2 Methods

6.2.1 Farm resource endowment scenarios

To study the influence of resource availability on options for sustainable development of vegetable farms in Canelón Grande we constructed different scenarios by defining theoretical farm types with different resource endowment. We combined the following resource attributes to create 128 different farm types:

- 4 farm sizes (5, 10, 20 and 30 ha);
- 2 labor endowments (5000 and 7500 man hours per farm per year, and labor availability in half month periods non-binding);
- 4 irrigation endowments (0, 20, 40 and 60% of the farm area irrigated);
- 2 soil qualities (high soil quality with 40-40-20% of soil type 1, 2 and 3, respectively and low soil quality with 30-30-40% of soil type 1, 2 and 3, respectively); and
- 2 mechanization levels (High and Low, as defined in Chapter 4).

These farm types are representative of the variation in size, labor endowment, water availability, soil quality and mechanization level existent in the vegetable farms of Canelón Grande (Chapter 2).

6.2.2 Family income

Vegetable farmers and their families in Canelón Grande contribute 84% of the permanent labor and they hire on average 350 man-hours per farm per year (DIEA, 2000 unpublished). Usually, the amount of labor hired is related to the size of the farm and the main purpose is to assist the family in periods of high labor demand such as planting and harvests of crops. To simplify the analysis, we calculated the net income per farm assuming that family members contribute all labor (Equation 1).

$$FI = GM + L*\alpha - IC \qquad \text{Equation 1}$$

where,

FI is family income per farm in US\$ farm^{-1}

GM is the gross margin in US\$ farm^{-1} calculated as gross product minus direct costs. Direct costs include labor, maintenance and repairs of machinery, energy, seeds, fertilizers, chemical crop protectants and other inputs.

L is the labor in h directly used in production activities;

α is the value of labor used for calculation of direct costs, in this case 0.75 US\$ h^{-1};

IC is the indirect cost in US\$ farm^{-1} estimated from standard values in the region and related to farm size, mechanization level and irrigated area.

We used the current average income of Uruguayan families (INE 2002) corrected for the number of family members as indicator of economic sustainability of the farm. The number of family members was assumed to be 4 and 5 for farms with 5000 and 7500 h of available labor respectively, according to Klerkx (2002). The minimum family income (MFI) was estimated to be 6800 and 8500 US\$ per year for farms with 4 and 5 family members, respectively.

6.2.3 Optimization rounds settings

For each farm type we maximized the family income using SmartFarmer in an environment oriented scenario and in an income oriented scenario. In the environment-oriented scenario the maximum value allowed for soil erosion was 7, 5 and 5 Mg ha^{-1} for soil type 1, 2 and 3 respectively, set according to the tolerance levels defined by Puentes (1981). We imposed that the rate of SOM changes was non-negative to guarantee that physical and biological soil fertility was at least maintained. Target values for N surplus and environmental exposure to pesticides were set such as applied in on-farm projects aimed at meeting EU regulations for 2003 (e.g. De Buck et al., 2000). Maximum values were 100 kg N ha^{-1}, 200 kg-days, 0.7 kg AI ha^{-1} and 0.5 μg l^{-1} for respectively, N surplus, EEP-soil, EEP-air and EEP-groundwater. Only one rotation per soil type and a maximum of 7crops per farm were allowed, in response to farmers' reluctance to accept more complex farm systems (Chapter 2). We imposed no maximum and minimum area per crop. In the income oriented scenario, we carried out an optimization round for each farm type maximizing family income without any restrictions on environmental objectives and the same settings with respect to complexity of the farm system as in the environment oriented scenario.

6.3 Results

We omitted the results of the farm endowment scenario '5 ha and 7500 h of labor', abbreviated as 5-7500, because it had identical results in all variables as the combination 5-5000 regardless the proportion of irrigated area, the soil quality and the mechanization level. The amount of labor is non-binding in these scenarios.

6.3.1 Effect of farm size-labor-irrigation-mechanization scenarios on family income

Farms with 5 ha did not reach the MFI irrespective of irrigated area and mechanization level (Figure 6.1). At high mechanization level the family income of the combinations 10-5000 and 10-7500 was lower than the MFI when irrigated area was 0 and 20% of the farm area. The other area-labor-irrigation scenarios were all at or above the MFI. At low mechanization level the family income was below the MFI when irrigation was absent for the combination 10-5000, while for the combination 10-7500 the family income was below the MFI when irrigated area was 0 and 20% of the farm area. Farms with 20 and 30 ha always surpassed the MFI, irrespective of irrigated area, labor and mechanization level.

The family income of farms with 5 and 10 ha was higher with low than with high mechanization level. The opposite result was obtained with 20 and 30 ha farms, except for farms with no irrigation where family income was similar for both mechanization levels. On small farms the increase in gross margin obtained with the higher mechanization level was not enough to pay for the increase in indirect costs per unit area.

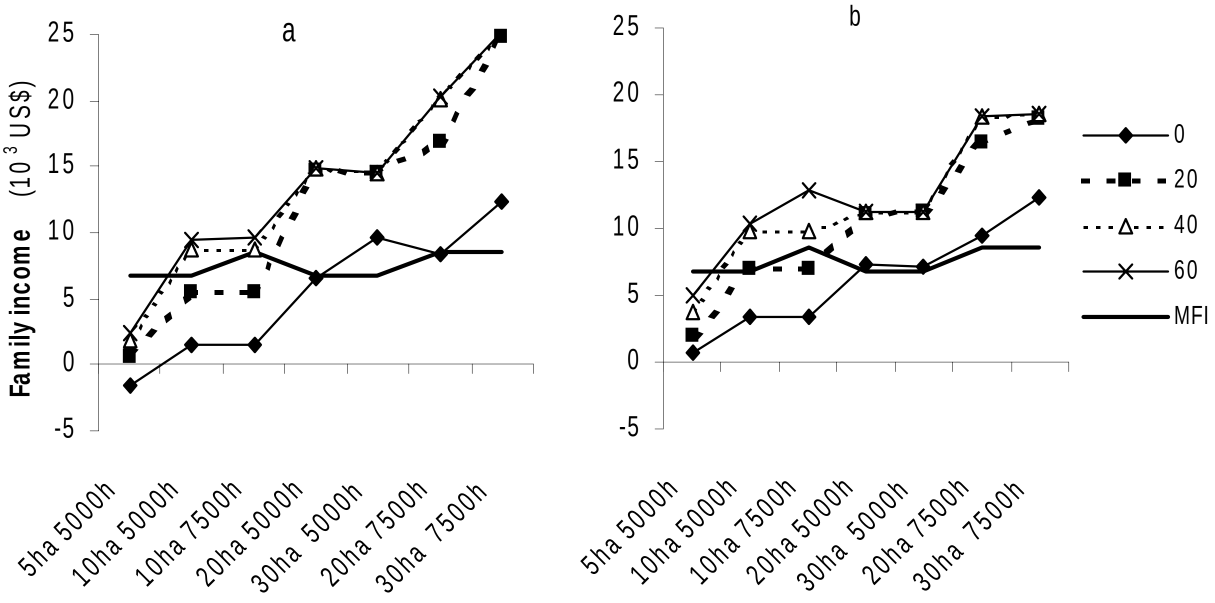

Figure 6.1. Family income as a function of the combination of area (ha) and labor (h) availability for 0, 20, 40 and 60 % of the area irrigated, and for High mechanization level (a) and Low mechanization level (b). Minimum family income (MFI) is 6800 and 8500 US$ for farms with 5000 and 7500 h of available labor respectively. Data are averages of high and low soil quality farm types.

6.3.2 Effect of irrigated area on family income

Family income of farms with 20% of the area irrigated was 63% and 110% higher than family income of farms with no irrigation for low and high mechanization level, respectively (Figure 6.2). Family income increased with increasing fraction of area irrigated but with diminishing returns. When the fraction irrigated increased to 40 and 60% other factors such as labor became limiting. Available irrigation potential was never completely exhausted on farms with a labor availability of 167 and 250 h per ha when the potential irrigated area was 40 and 60% (Table 6.1).

6.3.3 Effect of soil quality on farm gross margin

The difference in gross margin between farms with high (40-40-20) and low (30-30-40) soil quality decreased with decreasing labor availability per ha for both mechanization levels (Table 6.2). The difference was important only when area was the most limiting factor. On farms with low mechanization level and a labor availability equal to or less than 250 h ha^{-1} gross margin was slightly higher with low than with high soil quality. This can be explained by the fact that some production activities for soil type 3 have a very low labor requirement which allowed an increase in cultivated area on farms where low labor availability had limited full utilization of land, resulting in a higher gross margin on farms with larger areas of soil type 3.

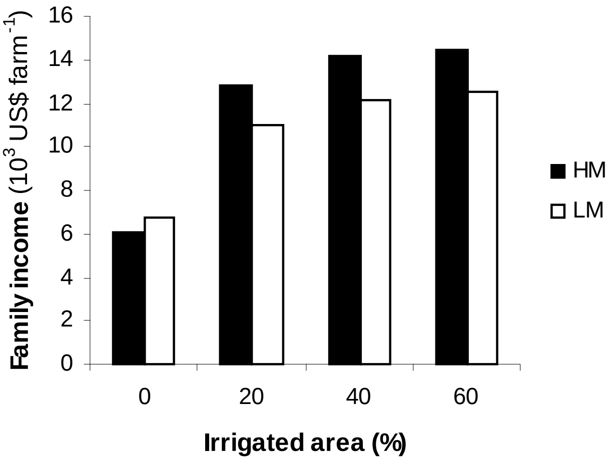

Figure 6.2 Family income as a function of the fraction irrigated (%) for high (HM) and low (LM) mechanization levels. Data is average of different combinations of area and labor availability and soil quality levels.

Table 6.1. Fraction of available labor (L), land (A) and irrigated area (I) not used in the optimal solution for each combination of resource availability (Data are average of high and low soil quality farm types).

		High mechanization level			
Irrigation available per farm (% of farm area)		0	20	40	60
Area (ha) - labor (h) per farm	Labor:area ratio	L / A / I	L / A / I	L / A / I	L / A / I
5 - 5000	1000	0.64 / 0 / 0	0.64 / 0 / 0.03	0.51 / 0 / 0	0.48 / 0 / 0.02
10 – 7500	750	0.56 / 0 / 0	0.61 / 0 / 0	0.37 / 0 / 0	0.34 / 0 / 0.03
10 – 5000	500	0.34 / 0 / 0	0.42 / 0 / 0	0.05 / 0 / 0	0.02 / 0 / 0.03
20 – 7500	375	0.16 / 0.10 / 0	0.22 / 0 / 0	0.04 / 0.10 / 0	0.04 / 0 / 0.2
20 – 5000	250	0.07 / 0.10 / 0	0 / 0.14 / 0	0 / 0.13 / 0.5	0 / 0.13 / 0.6
30 – 7500	250	0.11 / 0.10 / 0	0 / 0.14 / 0	0 / 0.12 / 0.5	0 / 0.12 / 0.6
30 - 5000	167	0.07 / 0.09 / 0	0 / 0.47 / 0.3	0 / 0.47 / 0.7	0 / 0.47 / 0.8
		Low mechanization level			
5 - 5000	1000	0.61 / 0 / 0	0.54 / 0 / 0.03	0.46 / 0 / 0.03	0.31 / 0 / 0.01
10 – 7500	750	0.60 / 0 / 0	0.49 / 0 / 0	0.40 / 0 / 0.01	0.06 / 0.03 / 0
10 – 5000	500	0.40 / 0 / 0	0.24 / 0 / 0	0.09 / 0 / 0.01	0.03 / 0 / 0.23
20 – 7500	375	0.19 / 0 / 0	0.03 / 0.07 / 0	0 / 0.06 / 0.03	0 / 0.06 / 0.35
20 – 5000	250	0 / 0.12 / 0	0 / 0.36 / 0	0 / 0.36 / 0.41	0 / 0.36 / 0.61
30 – 7500	250	0 / 0.12 / 0	0 / 0.35 / 0	0 / 0.37 / 0.42	0 / 0.37 / 0.62
30 - 5000	167	0 / 0.35 / 0	0 / 0.53 / 0.23	0 / 0.53 / 0.62	0 / 0.53 / 0.74

6.3.4 Resource use efficiency

Each production resource was used with different efficiency in each farm type. In Table 6.1 we show the fraction of available labor, land and irrigated area not used for each farm type. Only 6 and 8 farm types out of 28 used more than 85% of each of the available resources for low and high mechanization level, respectively (Table 6.1). In farms with 750-1000 h of available labor per ha and 0-40% of the area irrigated there was a large excess of labor. In farms with 167 to 250 h of available labor per ha and 40 to 60% of the area irrigated there was a large excess of irrigated area and land. There was a positive interaction among labor, land and irrigated area with respect to the gross margin per farm. For example, increasing the irrigated area from 0 to 2 ha in a farm with 5 ha, 5000 h of labor and high mechanization level increased the gross margin by US$ 3530. Increasing the available land to 10 ha on a farm with no irrigation and 5000 h of labor increased gross margin by US$ 2312. However, increasing both available land and irrigation with 5 and 2 ha, respectively, while maintaining the same labor availability increased the gross margin by US$ 7176, which is US$ 1334 more than the sum of the increments obtained by increasing irrigated area and land separately. The gross margin: labor ratio was 2.65, 1.59 and 3.47 US$ h^{-1} for 5 ha farms with 2 ha irrigated land, 10 ha farms with no irrigation and 10 ha farms with 2 ha irrigated land, respectively.

Table 6.2. Difference in gross margin per farm (%) between farms with high and low soil quality for each combination of area (ha) and labor (h) availability with high and low mechanization level. Data are averages of the four fractions irrigation land (0, 20, 40 and 60%). Difference was calculated as ((high soil quality – low soil quality)/ high soil quality)*100.

Farm Type	High mechanization level	Low mechanization level
5 ha 5000 h	24.3	20.9
10 ha 7500 h	13.3	8.5
10 ha 5000 h	13.1	8.8
20 ha 7500 h	11.0	2.6
30 ha 7500 h	5.1	-2.6
20 ha 5000 h	5.1	-3.1
30 ha 5000 h	5.0	-3.9

6.3.5 Effect of resource endowment on environmental impact

The resource endowment influenced the effect on family income of reducing the environmental impact of agricultural production. The difference in family income between the income-oriented scenario and the environment-oriented scenario increased with increasing labor availability per ha or decreasing area per farm. In Table 6.3 we show family income in both scenarios for the farm types with lowest (5 -5000 LM) and highest (30 -7500 HM) family income as a function of the irrigated area per farm. Difference in family income between both scenarios decreased with increasing irrigation per farm. Analysis of the production activities designed for each soil type showed that gross margin, soil erosion, N surplus and environmental exposure to pesticides generally increased with increasing labor requirements per ha, while no relation was apparent for SOM rate (Figures 6.3a-e). When maximizing farm income without restrictions on environmental objectives we designed farm systems with lower soil erosion, N surplus and EEP on farms with low labor per ha than on farms with high labor per ha. Lower labor availability per ha resulted in less intensive farm systems with higher share of pastures and crops such as wheat and sudan-grass with lower soil erosion, N surplus and EEP values compared with vegetable crops.

Table 6.3 Family income (US$) as a result of an environment-oriented scenario and an income-oriented scenario for each level of irrigation. Only the farm type with the lowest family income (5 ha – 5000 h and low mechanization level (LM) and the farm type with the highest family income (30 ha – 7500 h and high mechanization level (HM) are shown. Data are averages of high and low soil quality farm types.

	Irrigated area (% of total area)			
Farm type	0	20	40	60
5 ha - 5000 h - LM - Environment oriented	640	1923	3689	4963
5 ha - 5000 h - LM - Income oriented	2193	3483	6097	7420
Difference (%)	71	45	39	33
30 ha - 7500 h - HM - Environment oriented	12320	24885	25224	25224
30 ha - 7500 h - HM - Income oriented	13533	25925	26821	26821
Difference (%)	9	4	6	6

6.4 Discussion

The results presented in this chapter demonstrate that farm resource endowment has a strong impact on possibilities for sustainable development of vegetable farms in Canelón Grande. Farms with 10 ha of land or less only achieved a family income higher than the minimum when the irrigated area was close to 40% of the farm area. Farms smaller than 10 ha represent

47% of the farms of Canelón Grande where only 44% of vegetable farms had irrigation facilities in 2000, for on average 29% of the area with vegetables (DIEA, 2000 unpublished).

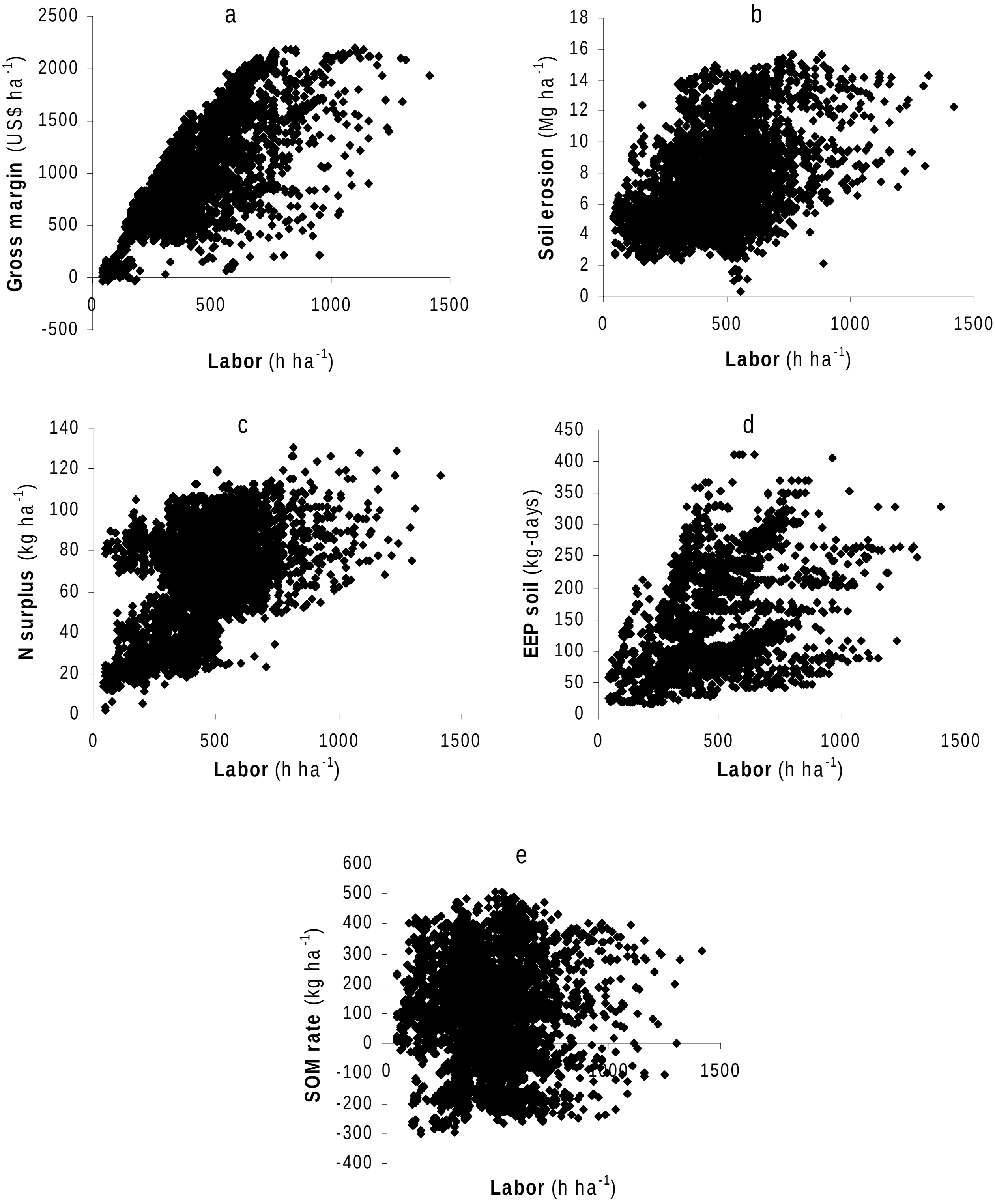

Figure 6.3. Gross margin (A), soil erosion (B), N surplus (C), EEP soil (D) and SOM rate (E) as a function of labor requirement per ha of production activities designed for high mechanization level.

Development possibilities for a large part of vegetable farms in this region depend upon changes in the resource endowment at farm level, either by access to more land, by increase in the irrigated area per farm, or by both. Introduction of more intensive vegetable production systems not considered in this study, such as greenhouse horticulture or leafy vegetables, to increase income in small farms seems difficult because these systems require high investments and special market chains. Renting land is a more feasible option, provided a reasonable distance between fields could be maintained. Irrigated area per farm increased recently and it is expected to increase further since water sources are not fully exploited and farmers perceive irrigation as one of the most important factors explaining yield increase (Klerkx, 2002). However, access to water resources and irrigation equipment is not equal to all farms and constitutes an important source of inequity on future development possibilities.

We found differences in resource use efficiency among different farm types and positive interaction between labor, land and irrigated area when we increased the availability of the most limiting of these production factors (de Wit, 1992). Differences in resource endowment resulted in different optimal farm systems; in most of these systems a significant amount of available labor or land or irrigated area was not used (Table 6.1). When given time to adjust, farmers typically re-balance their systems to remove inefficiencies resulting from imbalances (Verhoeven et al., 2003). However, socio-economic changes in the Uruguayan context operate at a faster pace than farmers can deal with empirically. Explorations for specific farms may help inform farmers on imbalances in their system, and give directions for improving resource use by investing in irrigation facilities of exchange of labor or land. Studies at the scale of two or more farms jointly can reveal to which extent cooperation will remove endowment constraints, and create rewards through positive interactions among better-adjusted production factors.

We found that achievement of environmental targets such as soil erosion and environmental exposure to pesticides is less costly in terms of income on farms with low than with high labor availability per unit area and on farms with irrigation facilities (Table 6.3). This relationship should be taken into account in environmental policy making. Other options, not taken into account in this study, need to be explored to allow a more intensive but still sustainable land use in small farms, such as use of mulching and reduced tillage to reduce soil erosion, and biological and cultural methods of crop protection to reduce the use of pesticides.

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Chapter 7

General discussion

7 General discussion

This thesis had two objectives. The first objective was the development of a method to explore future possibilities for sustainable development at the farm scale, able to handle on-farm spatio-temporal heterogeneity, and capable of generating a wide variety of technically and biophysically feasible alternatives following explicit design objectives and criteria. The second goal of this study was the application of the method to explore options for sustainable development of vegetable farms in Canelón Grande, by re-designing farm systems based on their resource endowment.

The main problems threatening sustainability of vegetable farms in Canelón Grande and an overview of the method developed in this study were presented in Chapter 2. In Chapters 3 and 4 we presented the tools and method developed to generate a wide variety of land use systems, to quantify their biophysical production possibilities and to define the optimum mix of inputs required to realize these production possibilities following a target-oriented approach (Van Ittersum and Rabbinge, 1997; Hengsdijk and Van Ittersum, 2002). In Chapter 5 these land use systems were optimally combined at the farm level to design alternative farm systems for example farms in Canelón Grande using MILP. The impact of farm resource endowment (i.e. land, labor, irrigation and machinery) on possibilities of achieving sufficient family income while physical and biological soil fertility is maintained or improved was presented in Chapter 6.

In this Chapter we evaluate the results obtained in this study from three points of view. First, we will examine the contribution made to improve the methodology of model-based future-oriented land use studies. Next we suggest in which manners this method may contribute to a systematic process of on-farm research and development. Thirdly, we will highlight the contribution made to reveal future options for vegetable farms in Canelón Grande. To finalize this Chapter and this thesis we will draw some guidelines about future research that should be considered based on the experiences gained in this study.

7.1 Contribution to model-based explorative land-use studies

Over the last 15 years, many authors have developed and applied model-based and future-oriented land use studies at farm or higher spatial scale to explore in an integrated and quantitative way the space of possible solutions for current agricultural problems in different regions of the world (e.g. De Wit et al., 1988; Rabbinge and Van Latesteijn, 1992; Van Keulen and Veeneklaas, 1993; Penning de Vries et al., 1995; Van Rheenen, 1995; Rossing et al., 1997a; Bakker et al., 1998; Bouman et al., 1998). This type of studies has been proposed as a means of supporting strategic learning and decisions about how to use land by systematically evaluating land use alternatives, selecting the alternatives that best meet specified objectives and revealing the consequences of different choices of land use. Despite the great influence that the diversity of the land use alternatives considered has on the results, many land use studies lack transparency in the criteria used to create and select the land use alternatives (Hengsdijk and Van Ittersum, 2002). Similarly, many studies do not consider temporal interactions resulting from the cropping sequence. Nevertheless, the frequency and order in which crops are grown (crop rotation) in a certain land unit determine inputs and outputs of such land use types. Hengsdijk and Van Ittersum (2002) stressed the importance of taking into account temporal interactions of agro-ecological processes by describing land use systems as entire crop rotations, and the need of developing intelligent selection procedures to reduce the enormous number of potential crop rotations. No previous model-based and future-oriented land use study at the farm level has taken into account both temporal interactions resulting from the cropping sequence and spatial heterogeneity resulting from land units with different suitability for crop growth within the farm. In this study, a methodology for model-based and future oriented land use studies at the farm scale was developed that is able to:

- Design a wide diversity of land use alternatives in a transparent manner, based on explicit design criteria.
- Describe land use alternatives as entire crop rotations and quantify the temporal interactions resulting from the cropping sequence.
- Allocate land use alternatives to different land units within a farm taking into account not only the targets defined for each socio-economic and environmental objective, but also the specific conditions in which each farmer has to operate (i.e. land, labor, capital, machinery and irrigation availability) and his preferences (i.e., number and type of crops, rotation length and number of land use types)

Another unique aspect of this study was to bring explorative land use studies to the context of real farms and the conditions in which they have to operate. When aiming to promote political debate about the future of agriculture or to set a research agenda, model-based explorative land use studies are typically applied to entire regions or to hypothetical farms. In most cases the farm size and the farm structure is not considered. In these cases, to some extent, explorative studies are detached from the real world. That is the case when farm boundaries are not taken into account as in regional studies or when very futuristic techniques are combined to produce theoretical farming systems that are far beyond the reach of current farmers. Despite their usefulness to promote political debate challenging strategic thinking or to set a research agenda, the results of these studies are of little use for farmers. In this study we aimed for developing a tool with the potential to contribute to farmers' strategic thinking about their own farms. We took most of the design criteria (i.e., crop selection, rotation length, number of crops, etc.) from the context of real farms. We also designed production techniques taking into account the existing variety in resource endowment among farms in the region. Moreover, we proposed means to overcome the lack of sustainability of current farming systems (i.e., crop rotations, inter-crop practices, mixed production systems and optimal farm resource allocation) which are empirically tested but not widespread adopted by farmers.

7.2 Revisiting the prototyping approach

The prototyping approach (Vereijken, 1997) is a widely accepted research method for systematic development of farming systems in The Netherlands and other European countries (Wijnands, 1999). Prototyping is an empirical approach in which various methods (i.e. multifunctional crop rotation, integrated/ecological nutrient management, minimum soil cultivation, ecological infrastructure management, integrated crop protection and farm structure optimization) are combined in a rather arbitrary manner to produce farming systems prototypes to be tested in pilot farms (Helander, 1997). The objectives, quantified in a set of parameters, are gradually approached by means of successive cycles of testing and improving of the prototypes, without previous assessment of trade-off among conflicting objectives. We think that model-based land use explorations and specifically the method presented in this study could contribute to strengthen strategic thinking and to promote alternative orientations for incremental engineering as often envisaged in prototyping in at least four ways.

First, if the present situation demands an integral renewal of the farming systems rather than gradual improvements to parts of the system, explorative studies can reveal what may be achieved in a given time horizon and how, based on the knowledge currently available. In this way, explorative studies provide perspective of possible futures and show possibilities not previously envisaged when focussing on incremental changes in parts of existing systems.

Implementation of these possibilities can result in a substantial shift in current trends. Moreover, trade-off among conflicting objectives is quantified, putting targets into perspective.

Secondly, in the prototyping approach the design phase relies completely on the experience of the designers (scientists) and the criteria used to create the prototype are not evident to others. Only a few production systems can be tested empirically in the field, which is the most expensive and time-consuming step of the process (Rossing et al., 1997b). Consequently, during the design phase several feasible alternative production systems are arbitrarily discarded or not even considered, introducing the risk of overlooking promising options. In fact, only one way to the future is promoted, ignoring or neglecting others. This risk could be reduced by creating and quantitatively 'ex-ante' evaluating a large number of feasible alternative production systems based on explicit design criteria and current knowledge of scientists and farmers, as it was done in this study. These alternatives could be discussed and compared by all parties involved in the innovation process before moving into the testing step. Moreover, comparing different scenarios could reveal the consequences of different priorities among the stakeholders.

Third, a great diversity exists among farmers in resource endowment and strategy, which determines a variety of viable farm development paths (Van der Ploeg, 1990). No explicit effort within the prototyping approach has been made to take into account this diversity (Leeuwis, 1999). The method developed in this study has the capability to take into account differences between farmers in resource endowment and strategy. First, by designing a wide diversity of land use types at the field scale, suitable for different resource endowment levels (i.e. machinery, irrigation) and strategies (i.e. crop protection, crop selection). Second, by allocating different land use types to different land units within the farm using an MILP model, constrained by farm resource endowment (i.e. labor, capital, land, machinery) and farmer's strategy (i.e. target levels in different objectives, number of different crops, rotation length).

Fourth, Leeuwis (1999) argues that while in the prototyping approach farmers tend to be more involved than in conventional agricultural science, prototyping is still a process dominated by researchers. Leeuwis hypothesizes that this approach would benefit from stakeholders being more involved in various steps of the process and having a leading role. Specifically the design phase is clearly the responsibility of the research team and farmers are seriously involved only when a prototype is ready (Leeuwis, 1999). In the study presented in this thesis farmers were only involved as suppliers of information through interviews (Klerkx, 2002) and on-farm surveys (Aldabe pers. com.), despite the fact that many of the design criteria reflect farmers views and conditions in which they operate. The tools developed in this study to re-design farming systems open possibilities for a more intensive involvement of farmers and other stakeholders in the design step of the prototyping process in the following manners:

- Farmers and others stakeholders could set the targets for the various objectives established during the diagnostic step of the process. Not necessarily one unique set of objectives and targets has to be agreed upon (Leeuwis, 1999) and the model-based exploration could reveal the consequences of each set of objectives and targets (Rossing et al., 1997b)
- Stakeholders could set the time horizon of the study, and in this way control how 'futuristic' or far away from the current situation the proposed production systems may be.
- Stakeholders could participate in the definition of the crops and animal production activities, the 'filters' used to combine the crops into crop rotations and the production techniques to be considered.
- Stakeholders could contribute their knowledge to elaborate technical coefficients and to quantify input-output relationships.
- As stated previously, stakeholders could be presented with a pool of alternative farm systems, some of them with similar level of achievement of the pre-defined objectives but very different in other characteristics such as crop ensemble, distribution of labor requirements along the year, etc. From the discussion of these alternatives some could be chosen to go into the testing step. When the theoretical prototypes are not satisfactory, pre-defined objectives, targets and design criteria could be modified to start a new design process. The latter is also applicable once in the testing phase, since the knowledge acquired by testing the prototype in pilot commercial farms could be used to re-set the model-based design process.

7.3 Contribution of this study to reveal future options for vegetable farms in Canelón Grande

In the last 10 years, radical changes in the economic environment in which Uruguayan vegetable farmers operate took place. Economic continuity is the greatest concern of vegetable farmers in Canelón Grande. Most of them received their farms as inheritance and they hope their children will continue with the farm after the farmer's retirement (Klerkx, 2002). Soil erosion and loss of soil physical and biological fertility are the main problems perceived by experts and farmers menacing future land productivity. Rapid and integral renewal of farming systems is required to cope with the lack of sustainability of vegetable farms in the region. Some farmers are even caught in an unsustainability spiral (Rabbinge, 1997) that has to be broken. This renewal cannot be achieved by tactical or operational decisions such as increasing the area of the most profitable crops and reducing or eliminating the less profitable crops, which are amongst the ways that most farmers used to try to maintain their income. Also the current advice of technical extensionists in tactical and operational decisions, such as selection of varieties, dosage and timing of fertilizer and chemical crop protectants applications, is not enough to solve the problems threatening the sustainability of current farming systems. The results of this study may contribute to a change in the mode of thinking of farmers and their advisers from tactical/operational to strategic, by showing them which feasible paths may be followed and their probable consequences. We showed that farmer's income could be increased even in a context of market prices still decreasing, while soil erosion is reduced and physical and biological soil fertility is improved. The strategy proposed was to increase the cropped area, but to reduce the area of vegetable crops by introducing long crop rotations with pastures, green manure and forage crops during the inter-crop periods, and to integrate beef cattle production into the farm systems (Chapter 5).

The results of this study showed that the degree to which economic and environmental objectives could be achieved will be strongly affected by farm resource endowment, mainly land and irrigation availability (Chapter 6). According to the results obtained in this study, farms with 10 ha or less were economically sustainable only when the irrigated area was 40% or more of the farm area. Farms smaller than 10 ha currently represent 47% of the farms of Canelón Grande (DIEA, 2000, unpublished). Consequently, the scope for sustainable development of a large part of the vegetable farms of Canelón Grande depends upon changes in the resource endowment at the farm level i.e. access to more land and access to irrigation water and irrigation equipment. Intensive vegetable production systems such as leafy vegetables or greenhouse horticulture were not considered in this study. This kind of systems requires high availability of labor per unit area, which is indeed available on the small farms in the region, and produces a high income per unit area. However, it also requires high investments and specific market chains, which may be difficult to implement by the small farms in the region in the near future. Renting land could be a more feasible option for some farms, since natural pastures occupy almost 45% of the land in the region (Carmona et al., 1993). However, the uncertainty about future benefits from investments makes renting not the best mode of land tenancy regarding sustainable land use. The irrigated area in Canelón Grande increased by a factor of 25 from 1990 to 2000 (DIEA, 2000 unpublished), and it will continue to increase (Klerkx, 2002). At the same time, access to water resources is not equal for all farms and on many of them the availability of irrigation equipment (or capital to purchase it) is limiting the irrigated area. Irrigation availability, thus, constitutes an important source of inequity for utilizing future development possibilities.

Only part of the problem of sustainable development of vegetable farms in Canelón Grande may be solved by farmers' strategic choices. For many farmers in the region future development would depend on actions taken at the regional level to facilitate their access to land and irrigation. Important differences in resource use efficiency among farms with different resource endowment were found in this study. When a region is regarded as one super farm and production is estimated based on regional resource availability, regional resource use efficiency and productivity is significantly better than the sum of the results obtained for each farm (Baidu-Forson et al., 1995). This is due to more favorable ratios of resource availability when farm borders are ignored. Consequently, interventions at the regional level directed to improve the resource availability at the farm level may be driven not only by the aim of increasing equity among farmers but also to let the society benefit from an increased productivity of land and other resources. The government and farmers organizations are responsible for solving this problem at the regional scale.

7.4 Implications for future research

This study may be regarded as a synthesis of decades of agronomic research done in Uruguay. At the same time, model-based explorative land use studies enable the assessment of the importance of deficiencies in knowledge relative to the problem at hand, the design of sustainable farming systems. As such, they enable agenda setting for agronomic research (e.g., Rossing et al., 1997a). In this study, during the process of design of production activities and quantification of input-output relationships, gaps in current knowledge were encountered. The most important were the effects of cropping frequency on crop yields through the incidence of soil-borne diseases and the impact of crop rotations and inter-crop management on long-term dynamics of soil organic matter. Disciplinary research is required to gain insight in the effect of cropping frequency and green manure species on several soil-borne diseases responsible for yield reductions in garlic, onion, sweet potato, sweet pepper, potato and squash in Canelón Grande. Similarly, research is needed to adapt and validate existing soil organic matter simulation models to the environmental conditions and soil characteristics in Uruguay.

It is at the farm scale where most decisions affecting the farm systems are taken (Leeuwis, 1999) and it is the farm household who provides the management (i.e. regulates component interactions within the system) among other things (Fresco and Westphal, 1988). At the farm aggregation level factors such as climate, market prices or regional infrastructure are considered exogenous and not affected by the functioning of the farm system. This assumption can not be maintained when an increasing number of farms becomes involved in a process of change. Consequently, upscaling is needed to explore the consequences that decisions made at the farm level have at the regional level for factors such as rural employment, environmental impact, food production and market prices. These factors at the regional scale will have a feedback effect at the farm scale level, which would again affect decisions made by the farm household. Some attempts to deal with this interaction between farm and regional aggregation level in explorative land use studies can be found in literature (i.e. Van Ittersum and Rabbinge, 1994; Schipper et al., 1995; Sissoko, 1998). However, methods to take into account in a dynamic manner the interaction between farm and regional aggregation level need to be further developed. This study demonstrated that there is considerable room to increase vegetable production at farm scale in Canelón Grande, mainly by increasing crop yields. This study did not deal with the consequences that such production increase would have at the regional level. In a context of a well-supplied internal market, an increase in production would aggravate competition among farmers. Farmers with less resource endowment probably would be the more affected. Such consequences can only be investigated by aggregating the results of this study at the farm scale to the regional level, while including vegetable production in other zones in Uruguay to explore consequences on market supply and prices. Such analysis should also need to consider the competitive position of the vegetable crops grown in Canelón Grande with respect to external markets within the MERCOSUR agreement, such as Buenos Aires, Porto Alegre and Sao Paulo.

Could the method presented in this thesis be used in “kitchen-table” sessions with farmers to aid their strategic thinking? In simulation-aided systems innovation processes, trained advisers use simulation models in ‘kitchen table sessions’ to respond to farmers’ specific questions, taking into account the particular conditions in which farmers have to operate (Carberry et al., 2002). Farmers are seen as capable and knowledgeable agents and the developing of innovative production systems is seen as a learning process (Leeuwis, 1999). These principles have been successfully applied in Australia's north-east dry-land cropping zone in the FARMSCAPE approach (McCown et al., 1998; Carberry et al., 2002) using APSIM to support farmers' tactical and operational decision making by answering 'what if...' questions related to complex management issues in a highly variable climate. Farmers in this zone were unwilling to engage in simulation-aided discussions about management until the credibility of the simulation model (APSIM) was demonstrated to their satisfaction (Keating and McCown, 2001). In the study presented in this thesis, changes in farm systems for Canelón Grande vegetable farms were mainly proposed at the strategic level, i.e., crop rotation, introduction of animal production, resource allocation. Implementation of long crop rotations would require a change in actual farmers’ attitude towards planning, since very few of them plan more than one year ahead (Klerkx, 2002). The impact of good crop rotations and inter-crop practices on crop yields and soil fertility need to be demonstrated to farmers by setting on-farm field experiments. The design method developed in this study may be used in a tailored designing process in which each farmer could select the crops and the rules to be used to generate crop rotations using ROTAT, the inter-crop practices and production techniques to be considered, and the targets and constraints used to allocate production activities to different land units of the farm using SmartFarmer. Three conditions could facilitate this process in Canelón Grande. First, farmers are located in a relatively small region. Secondly, many of these farmers are already involved in small groups led by technical advisers. Third, the Faculty of Agronomy has a research station close to the region, and has been involved in on-farm teaching and research activities in this region for almost a decade. Ideally, farmers, researchers and advisers would learn in this process and they would apply the knowledge gained to better understand their farming systems, to improve the method developed in this study and the ‘action research’ methodology. This study contributes in a methodological and conceptual way to tackling the problem of unsustainability at the farm scale, and it shows to vegetable farmers of Canelón Grande that possibilities for improvement exist and can be realized through their individual strategic decisions, through the work of their representative organizations and through an appropriate institutional context.

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Summary

Most important economic changes in the Uruguayan vegetable production sector during the last decade were the increase in local and regional production and imports and the decrease of product prices. The number of vegetable farms decreased by 20% in the same period, and those which stayed in business had to produce more, cheaper and better quality products to maintain their income.

The Canelón Grande micro-watershed is located 50 km North of Montevideo, in one of the most eroded areas of the country. Climate in this region allows year round cropping of vegetable crops and farms typically own land with more than one soil type with different topographic positions, risk of erosion and suitability for crop growth. In Canelón Grande, 54% of the farms have vegetable production as main source of income. Vegetable farmers in this region responded to the changes in the economic environment in which they operate by intensifying and specializing their farming systems. They increased the area with vegetable crops by shortening fallow periods and reducing the number of crops grown. These changes in the farming systems put more pressure on already deteriorated soils and on limited farm resources.

Several scientific approaches have been developed to contribute to sustainable development of farming systems, such as prototyping, participatory approaches, dynamic simulation of cropping and farming systems and model-based explorative land use studies. Prototyping is an empirical approach to design and test farming systems. Participatory approaches emphasize the involvement of stakeholders in the design process and regard the innovation of farming systems as a learning process. Dynamic simulation using computer models allows the prediction of the consequences of management actions and strategies on crop yields and long-term fate of soil resources under variable weather conditions. In that way, they are complementary to prototyping and participatory approaches. However, they are not particularly suited to evaluate a large number of crop rotations, neither do they take into account the effect of cropping frequency due to soil-borne pests and diseases. Model-based explorative land-use studies present a quantified set of alternative farming systems emphasizing different sustainability objectives, thus revealing the consequences of different development pathways. However, many explorative studies do not consider temporal interactions related to cropping sequences, and the methodology developed in previous studies for the farm scale does not allow to consider temporal interactions and spatial

heterogeneity simultaneously, which is particularly important in the context of vegetable farming in Uruguay.

The aim of this study is to explore options for improvement of vegetable farmers' income in Canelón Grande, while soil erosion is reduced and physical and biological soil fertility is improved, and to provide insight in the influence of farm resource endowment on the potential room for sustainable development. To reach this aim, this study developed an explorative farm modeling method to be applied in situations where climate allows year-round cropping and spatial heterogeneity in soil quality within the farms is an important characteristic. This method takes into account temporal interactions by designing land use activities as entire crop rotations affecting individual crop yields, input requirements and the long-term fate of soil resources.

The main measures proposed to overcome the sustainability problems described for the vegetable productions systems in Canelón Grande are *crop rotations* to improve crop yields and reduce soil erosion, *inter-crop practices* to reduce soil erosion and increase soil organic matter, *mixed plant-animal production systems* and *optimal farm resource allocation* to increase resource use efficiency and farm income.

For this study a time horizon of 1-5 years was assumed, implying that we combined crops currently grown in the region and techniques experimentally tested but not widespread adopted by farmers. Design criteria and constraints at the farm scale were based on current farm resource endowment.

We divided the design method in two main steps. The first step is conducted at the field level and the second at the farm scale.

At the field level we distinguished two phases. In the first phase, we created all feasible crop rotations for each of the three soil types distinguished in Canelón Grande, based on a list of crops suitable to be grown on each soil type and following well-defined agronomic rules. We developed a computer program named ROTAT for this purpose. Each crop rotation could be grown with four different types of inter-crop activities: fallow, fallow plus animal manure, green manure crops and forage crops. Each crop rotation was also combined with different production techniques. We defined two levels of mechanization according to the availability of machinery in the region. The low level uses a small tractor (50 HP) and the basic tools for soil tillage. Pesticides are applied with a knapsack sprayer and mechanical weeding is done using animal traction. The high mechanization level includes a larger tractor (90 HP) with suitable tools for soil tillage, spraying, weeding and other specific tools. Following current practice in Canelón Grande, crop rotations including potato or squash were grown with high mechanization level only. We defined three levels of irrigation. In the low irrigation level all crops are grown rain-fed. In the intermediate level, irrigation is only applied to the crops with a high economic response to irrigation. In the high irrigation level all vegetable crops are irrigated, except squash. Pastures and forage crops are always rain-fed. We defined two variants of crop protection. In the first variant, chemical crop protectants are partially substituted by the use of resistant varieties, cultural practices and labor. The second variant is geared to minimizing yields reduction due to weeds, diseases and pests by applying biocides as much as needed. We selected beef cattle production as the only animal production activity for exploring the potential contribution of mixed systems to the sustainability of farming systems in the region. Based on current farmer practices, we defined the animal production activity as the raising of beef cattle from 150 to 420 kg body weight using mainly on-farm-produced forage. The first phase at the field level resulted in 336,128 land use activities, i.e. combinations of crop rotations and production techniques.

In the second phase at field level, we quantified all relevant inputs and outputs for each of the 336,128 land use activities, such as crop yields, gross margin, labor requirement, capital requirement, soil erosion, rate of change of soil organic matter, N loss, indicators for the impact of pesticides on the environment and amount of energy and protein produced as feed for animals, taking into account temporal interactions between crops in the rotation. These inputs and outputs were organized in a database.

The software tool developed for creating crop rotations (ROTAT) is presented in detail in Chapter 3. In this chapter the use of ROTAT as a stand-alone tool in the process of designing crop rotations is illustrated with a published case study for an ecological pilot farm in Flevoland (The Netherlands).

The method followed to design and quantify the land use activities is explained in detail in Chapter 4. In this Chapter we introduce the software tools developed to quantify, among other parameters, water-limited yields, soil erosion and rate of change of soil organic matter for such a large amount of land use activities. Many of these land use activities proved good enough to allow improvement of current farming systems in Canelón Grande. The method presented in Chapter 4 may be used as an *ex-ante* evaluation of new cropping systems or even farming systems when farms are internally homogeneous in soil type.

The second step of the design process was conducted at farm scale. We designed a mixed integer linear programming model (MILP) named SmartFarmer to optimally allocate land use activities to land units of a farm differing in soil quality, to maximize or minimize objective functions, subject to constraints at the farm scale. SmartFarmer takes into account the limitations imposed by the resource availability at the farm, such as suitable land area, labor, irrigation, capital, machinery, and the limitations imposed by the system complexity and the farmers' management skills. To explore options for sustainable development of vegetable farms in Canelón Grande, we selected 7 existing farms with different levels of resource availability (Chapter 5). The farm systems designed by SmartFarmer had, on average, more than three times higher family income than the current systems for 6 out of the 7 farms studied. The estimated average soil erosion per ha decreased by a factor of 2 to 4 in the farm systems proposed compared to the current systems, while the rate of change of soil organic matter increased from negative in the current systems to +130 to +280 kg ha^{-1} yr^{-1} in the newly designed farm systems. The study suggests that lowering the area of vegetable crops by introducing long crop rotations with pastures and green manure during the inter-crop periods and integrating beef-cattle production into the farm systems would be a better strategy in most cases than current farmer's practice, the latter implying an increase in the area of vegetables and specialization of their farm systems.

Generally speaking, a variety of viable patterns of farm development exists related to farm resource endowment and farmer's strategy. In Chapter 6, we applied the approach developed in this study to gain insight in the impact of current farm resource endowment on the possibilities for sustainable development of vegetable farms in Canelón Grande. We defined 128 theoretical farm types by combining 4 farm sizes, 2 labor endowments, 4 irrigation endowments, 2 soil quality combinations and 2 mechanization levels. These farm types reflect the variation that currently exists among vegetable farmers in Canelón Grande. We maximized farm income in an environmental-oriented scenario and in an income-oriented scenario for each farm type using SmartFarmer. The results of this Chapter demonstrate that possibilities for development for almost half of the vegetable farms in this region depends upon changes in the resource endowment at the farm level, either by access to more land, by increase in the irrigated area or both. The results also showed important differences in resource use efficiency among different farm types and positive interaction between labor availability, land and irrigated area when the availability of the most limiting of these production factors was increased.

In this study, we developed a methodology for model-based and future-oriented land use studies at the farm scale able to:

- design a wide diversity of land use alternatives in a transparent manner, based on explicit design criteria;

- describe land use alternatives as entire crop rotations and taking into account the temporal interactions resulting from the cropping sequence;
- allocate land use alternatives to different land units within a farm taking into account not only the targets defined for each socio-economic and environmental objective, but also the specific conditions in which each farmer has to operate (i.e. land, labor, capital, machinery and irrigation availability) and his preferences (i.e., number and type of crops, rotation length and number of crop rotations)

A unique aspect of this study was to bring explorative land use studies to the context of real farms and the conditions in which they have to operate, by developing a tool with the potential to contribute to farmers' strategic thinking about their own farms.

The prototyping approach is a widely accepted empirical research method for systematic development of farming systems in The Netherlands and other European countries. We think that model-based land use explorations and specifically the method presented in this study could contribute to strengthening strategic thinking and to promoting alternative orientations for incremental engineering as often encountered in prototyping in at least four ways. First, by showing possibilities not previously envisaged when focussing on incremental changes of parts of existing systems and by quantifying trade-off among conflicting objectives, putting targets into perspective. This is particularly important when the present situation demands an integral renewal of the farming systems. Second, by creating and 'ex-ante' evaluating a large number of feasible alternative production systems based on explicit design criteria and current knowledge of scientists and farmers, the risk of overlooking promising options during the design phase is considerably reduced. In this way time and money may be saved when the prototypes are empirically tested. Third, the method developed in this study has the capability to take into account different viable farm development paths resulting from differences in farm resource endowment or farmers' strategies, or both. This considerably broadens the spectrum of farmers that could benefit from the design process. Fourth, the method developed in this study combined with the principles of participatory approaches has the potential to increase the involvement of stakeholders in the design step of the prototyping process, which till now is clearly dominated by researchers.

The results of this study have the potential to contribute to a change in the mode of thinking of farmers and technical extensionists from tactical/operational to strategic. In order to do so, the methodology developed in this study should be applied in the context of a farming systems innovation process in which farmers are actively involved. In Canelón Grande three conditions favorable to this process are met. First, farmers are located in a relatively small region. Secondly, many of these farmers are already involved in small groups led by technical advisers. Third, the Faculty of Agronomy has a research station close to the region, and has been involved in on-farm teaching and research activities in this region for almost a decade. Ideally, farmers, technical advisers and scientists can learn in this process and they can apply the knowledge gained to better understand their farming systems, to improve the methodology presented in this thesis and to improve the ‘action research’ methodology. This study contributes in a methodological and conceptual way to tackle the problem of unsustainability at the farm scale, and it shows to vegetable farmers of Canelón Grande that possibilities for improvement exist and can be realized through their individual strategic decisions, through the work of their representative organizations and an appropriate institutional context.

Samenvatting

Toename in productie en import en de afname van de prijzen zijn de belangrijkste economische veranderingen in de groenteteeltsector van Uruguay gedurende de laatste 10 jaar. Gedurende dezelfde periode nam het aantal groenteteeltbedrijven met 20% af, en de blijvers moeten meer, goedkoper en een betere kwaliteit produceren om hun inkomen te handhaven.

Het kleine stroomgebied Canelón Grande ligt ongeveer 50 km ten noorden van Montevideo, in een van de meest geërodeerde gebieden van het land. Het klimaat in deze regio maakt gewasgroei gedurende het gehele jaar mogelijk. Bedrijven bezitten doorgaans gronden met uiteenlopende eigenschappen, topografische positie, risico voor erosie en geschiktheid voor gewasgroei. In Canelón Grande heeft 54 % van de bedrijven groenteteelt als belangrijkste bron van inkomen. Groentebedrijven in deze regio reageerden op de economische ontwikkelingen met een intensivering en specialisering van hun bedrijven. Ze vergrootten het aandeel groenten in hun bouwplan door het verkorten van de braakperiodes en het reduceren van het aantal gewassen. Deze veranderingen in bedrijfssystemen oefenden veel druk uit op de reeds aanzienlijk gedegradeerde gronden en op de beperkte hulpbronnen van de bedrijven.

Diverse wetenschappelijke benaderingen zijn ontwikkeld om bij te dragen aan de duurzame ontwikkeling van bedrijven en een innovatieproces; deze omvatten: prototypering, participatieve benaderingen, dynamische simulatie van gewas- en bedrijfssystemen en model-gebaseerde verkennende land gebruiksstudies. Prototypering is een empirische methodiek voor het ontwerpen en testen van bedrijfssystemen. Participatieve benaderingen benadrukken de betrokkenheid van belanghebbenden in het ontwerpproces en beschouwen de innovatie van bedrijfssystemen als een leerproces. Dynamische simulatie met behulp van computermodellen maakt het mogelijk de gevolgen te analyseren van verschillende managementstrategieën op de gewasopbrengsten en de lange-termijn effecten op de bodem onder variabele weersomstandigheden. Echter, deze modellen zijn niet erg geschikt voor het evalueren van grote aantallen rotaties, en ze nemen ook de effecten van ziekten en plagen ten gevolge van teeltfrequenties niet in beschouwing. Modelgebaseerde verkennende studies maken het mogelijk een brede reeks van alternatieve systemen door te rekenen, rekening houdend met de verschillende prioriteiten ten aanzien van duurzaamheiddoelstellingen. Als zodanig onthullen deze studies wat de mogelijkheden zijn bij verschillende ontwikkelingstrajecten en prioriteiten. Echter, veel verkennende studies houden geen rekening met de optredende temporele interacties tussen gewassen (ten gevolge van bepaalde vruchtopvolgingen), en tot nu toe gebruikte methoden kunnen de simultane temporele interacties en ruimtelijke heterogeniteit van bedrijven niet aan. Juist deze factoren zijn belangrijk in de context van groenteteelt in Uruguay.

Het doel van deze studie was opties te verkennen voor het verbeteren van het inkomen van groenteteeltbedrijven in Canelón Grande, terwijl de bodemerosie wordt gereduceerd en de fysische en biologische bodemvruchtbaarheid worden verbeterd, en om inzicht te verschaffen in de invloed van hulpbronnen van bedrijven op de mogelijke ruimte voor duurzame ontwikkeling. Om dit doel te realiseren, is in deze studie een methode ontwikkeld voor verkennende bedrijfsmodellering, die kan worden gebruikt in situaties waar het klimaat het hele jaar gewasgroei toestaat, spatiele heterogeniteit binnen bedrijven belangrijk is, en waar temporele interacties tussen gewassen in rotaties de gewasopbrengsten, inputs en lange-termijn effecten op de bodem beïnvloeden.

De belangrijkste in deze studie voorgestelde manieren om de beschreven duurzaamheidproblemen aan te pakken zijn: gewasrotaties om de gewasopbrengsten te verbeteren en de bodemerosie te verminderen, tussen-gewasmaatregelen om erosie te beperken en het organische stofgehalte te doen toenemen, gemengde plant-dier productiesystemen en optimaal gebruik van de hulpbronnen binnen een bedrijf teneinde de gebruiksefficiëntie en het inkomen te verhogen.

Voor deze studie is een tijdshorizon van 1-5 jaar aangenomen, hetgeen inhoudt dat we gewassen die nu in de regio worden geteeld worden gecombineerd met teelttechnieken die experimenteel zijn getest, maar nog niet breed door boeren worden toegepast. Ontwerpcriteria en beperkingen op het bedrijfsniveau hielden rekening met de huidige hulpbronnen en uitrusting van bedrijven.

We onderscheiden twee hoofdstappen in de ontwerpmethode. De eerste stap werd uitgevoerd op het veldniveau en de tweede op het bedrijfsniveau.

Op het veldniveau onderscheidden we twee fasen. In de eerste fase hebben we alle mogelijke gewasrotaties voor elk van de 3 grondsoorten in de Canelón Grande gegenereerd. De gewasrotaties waren gebaseerd op een lijst van geschikte gewassen voor elk van de bodemtypes en op een reeks van goed-gedefinieerde agronomische regels. Het computerprogramma ROTAT werd voor dit doel ontwikkeld. Elke gewasrotatie kon worden geteeld met 4 verschillende typen tussen-gewasmaatregelen: braak, braak met dierlijke mest, groenbemesters en voedergewassen. Elke rotatie werd ook gecombineerd met verschillende productietechnieken. We definieerden twee niveaus van mechanisatie in afhankelijkheid van de huidige beschikbare machines in de regio. Het lage niveau gebruikt een kleine tractor (50 PK) en de basisgereedschappen voor bodembewerking. Biociden worden met een rugspuit toegediend en mechanisch onkruidwieden gebeurt met dierlijke tractie. De hoge mechanisatie variant omvat een grotere tractor (90 PK) met geschikte apparatuur voor bodembewerking, spuiten, onkruidwieden en andere specifieke hulpmiddelen. Volgens de praktijk in Canelón Grande, worden in de studie aardappel en pompoen alleen met de hoge mechanisatiegraad geteeld. We definieerden 3 niveaus van irrigatie. In de lage irrigatievariant werden alle gewassen zonder irrigatie (dus alleen regenwater) geteeld. In de tussenliggende variant werd irrigatie alleen toegepast op die gewassen die als gevolg van deze irrigatie een relatief hoge economische opbrengst hebben. In de hoge irrigatievariant werden alle groentegewassen geïrrigeerd, met uitzondering van pompoen. Grasland en voedergewassen werden altijd zonder irrigatie geteeld. We ontwierpen 2 varianten voor gewasbescherming. In de eerste variant was chemische gewasbescherming gedeeltelijk gesubstitueerd door het gebruik van resistente variëteiten, teeltmaatregelen en arbeid. De tweede variant is gericht op het minimaliseren van opbrengstreductie door onkruiden, ziekten en plagen met behulp van biociden waar nodig. Vleesveeproductie werd gekozen als de enige dierlijke productieactiviteit met als doel de mogelijke bijdrage van gemengde systemen aan duurzaamheid van bedrijfssystemen te onderzoeken. Gebaseerd op de huidige praktijken van boeren, definieerden we de dierlijke activiteit als het grootbrengen van vleesvee van 150 tot 420 kg lichaamsgewicht, waarbij alleen gebruik werd gemaakt van op het bedrijf geteeld voer. De eerste fase van het ontwerpproces op veldniveau resulteerde in 336.128 landgebruikactiviteiten (combinaties van gewasrotaties en productietechnieken).

In de tweede fase op het veldniveau kwantificeerden we voor elk van de in de eerste fase ontworpen 336.128 activiteiten alle relevante inputs en outputs, zoals gewasopbrengsten, saldo, arbeidsbehoefte, kapitaalbehoefte, bodemerosie, snelheid van verandering van organische stof in de bodem, N-verlies, indicatoren voor de impact van pesticiden op het milieu en de hoeveelheid energie en eiwit die geproduceerd werd als veevoer.

Het computerprogramma dat ontwikkeld werd voor het genereren van gewasrotaties (ROTAT) wordt in detail gepresenteerd in Hoofdstuk 3. In dit hoofdstuk wordt ook het gebruik van ROTAT als een op zichzelf staand computer programma in een ontwerpproces van gewasrotaties geïllustreerd aan de hand van een gepubliceerde case studie voor een ecologisch bedrijf in Flevoland (Nederland).

De methode die gevolgd werd om de in de verkenning gebruikte 336.128 activiteiten te ontwerpen, is gedetailleerd beschreven in Hoofdstuk 4. In dit hoofdstuk introduceren we ook de computerprogramma's die in deze studie zijn ontwikkeld om o.a. de volgende parameters te kwantificeren: water-gelimiteerde opbrengsten, bodemerosie en snelheid van verandering van het organische stofgehalte in de bodem. Veel van de landgebruikactiviteiten bleken goed genoeg om de huidige bedrijfssystemen in de Canelón Grande te verbeteren. De methode die gepresenteerd is in Hoofdstuk 4 kan worden gebruikt voor een *ex-ante* evaluatie van nieuwe gewassystemen en zelfs bedrijfssystemen, als deze bedrijven intern homogeen zijn in hun bodemtype.

De tweede stap in het ontwerpproces vond plaats op het bedrijfsniveau. We ontwikkelden een zgn. gemengd-integer lineair programmeringsmodel (MILP), genaamd SmartFarmer, dat landgebruikactiviteiten optimaal kan toewijzen aan de verschillende grondsoorten op een bedrijf, teneinde de verschillende doelen te maximaliseren of te minimaliseren, rekening houdend met de beperkingen op bedrijfsniveau. SmartFarmer houdt rekening met de beperkingen die worden gesteld door de hulpbronbeschikbaarheid op het bedrijf, zoals geschikte grond, arbeid, kapitaal, machines en de beperkingen opgelegd door de gewenste complexiteit van het bedrijfssysteem en de managementvaardigheden van de boeren. We selecteerden 7 bestaande bedrijven met verschillende uitrusting om opties voor duurzame ontwikkeling van groentebedrijven in Canelón Grande te verkennen (Hoofdstuk 5). De door SmartFarmer ontworpen bedrijfssystemen hadden gemiddeld een factor 3 hoger familie-inkomen dan de huidige systemen voor 6 van de 7 bedrijven. De geschatte bodemerosie per ha nam met een factor 2-4 af en de snelheid van verandering van organische stofgehalte verbeterde met 284-549 kg ha^{-1} jr^{-1} in de voorgestelde bedrijven. De studie suggereert dat in de meeste gevallen verlaging van het areaal groentegewassen door het introduceren van ruimere rotaties met grasland en groenbemesters gedurende de tussen-gewasperiode en het integreren van rundvleesproductie in de bedrijfsystemen een betere strategie is dan de huidige systemen, die vooral gericht zijn op specialisatie en een toename van het areaal groentegewassen.

Er bestaat een reeks van vitale ontwikkelingstrajecten voor bedrijfsontwikkeling, in afhankelijkheid van de uitrusting en hulpbronnen van een bedrijf en de strategie van de ondernemer. In Hoofdstuk 6 passen we de in deze studie ontwikkelde benadering toe, teneinde inzicht te verkrijgen in de impact van huidige bedrijfsuitrusting op de mogelijkheden voor duurzame ontwikkeling van groentebedrijven in Canelón Grande. We definieerden 128 theoretische bedrijfstypes door het combineren van 4 bedrijfsgroottes, 2 niveaus van arbeidsbeschikbaarheid, 4 irrigatie uitrustingen, 2 bodemkwaliteit combinaties en 2 mechanisatieniveaus. Deze bedrijfstypes omspannen de huidige variatie in bedrijven in de

Canelón Grande. Gebruikmakend van SmartFarmer maximaliseerden we het bedrijfsinkomen in een milieu-georienteerd scenario en in een inkomen-georienteerd scenario voor elk bedrijfstype. De resultaten van dit hoofdstuk demonstreren dat de mogelijkheden voor ontwikkeling van ongeveer de helft van de bedrijven in deze regio afhangen van veranderingen in hun uitrusting en hulpbronnen, hetzij via toename van het areaal, door toename van de irrigatiemogelijkheden of beide. De resultaten laten ook het belang van verschillen in hulpbron gebruiksefficiënte tussen verschillende bedrijfstypen zien. Tenslotte gaven de resultaten inzicht in de positieve interactie tussen arbeid, land en geïrrigeerd areaal, wanneer de meest limiterende factor van deze productiefactoren werd verhoogd.

In deze studie ontwikkelden we een methodologie voor model-gebaseerde en toekomstgeoriënteerde landgebruikstudies voor het bedrijfsniveau, met als belangrijke kwaliteiten:

- Het op een transparante wijze ontwerpen van een brede diversiteit van landgebruikalternatieven, gebruikmakend van expliciete ontwerpcriteria.
- Het beschrijven van landgebruikalternatieven als hele gewasrotaties en het kwantificeren van de temporele interacties ten gevolge van vruchtopvolgingen.
- Het toewijzen van landgebruikalternatieven aan verschillende grondsoorten binnen een bedrijf, rekening houdend met zowel de sociaal-economische en milieukundige doelen, als met de specifieke condities waarin elke ondernemer moet opereren (land, arbeid, machinepark en irrigatiemogelijkheden) en zijn voorkeuren (aantal en type gewassen, rotatieduur en aantal rotaties per bedrijf).

Een ander uniek aspect van de studie is dat de methode van verkennende landgebruikstudies geplaatst wordt in de context van echte bedrijven en de condities waaronder zij moeten opereren, door het ontwikkelen van een instrument dat de potentie heeft bij te dragen aan het strategische denken van boeren omtrent hun bedrijf.

De prototyperingsbenadering is een breed geaccepteerde empirische onderzoeksmethode voor het systematisch ontwerpen van bedrijfssystemen in Nederland en andere Europese landen. We denken dat de modelgebaseerde verkenningen en met name de methode die in dit proefschrift is gepresenteerd, op tenminste vier manieren kan bijdragen aan het bevorderen van strategisch denken en de impact van prototypering:

Ten eerste door het laten zien van mogelijkheden die niet eerder bedacht werden wanneer men zich richt op incrementele veranderingen van gedeelten van het bedrijfssysteem, en door het blootleggen van uitruil (‘trade-off’) tussen conflicterende doelen, waardoor streefniveaus in perspectief worden geplaatst. Dit is met name belangrijk wanneer de huidige situatie vraagt om een integrale vernieuwing van bedrijfssystemen. Ten tweede, door het creëren en *ex-a*nte evalueren van een groot aantal mogelijke alternatieve productiesystemen gebaseerd op expliciete ontwerpcriteria en huidige kennis van wetenschappers en boeren, wordt het risico van het over het hoofd zien van veelbelovende opties gedurende de ontwerpfase aanzienlijk verkleind. Op deze wijze kan er tijd en geld bespaard worden wanneer de prototypes empirisch getest worden. Ten derde, heeft de methode de capaciteit verschillende vitale bedrijfsontwikkelingstrajecten te beschouwen, die voortkomen uit verschillen in hulpbronnen, uitrusting en strategieën tussen bedrijven. Dit verruimt aanzienlijk het spectrum van boeren dat profijt kan hebben van het ontwerpproces. Ten vierde heeft de methode in combinatie met participatieve benaderingen de potentie om de betrokkenheid van belanghebbenden in de ontwerpfase van het prototyperingsproces te vergroten, een fase die nu nog gedomineerd wordt door onderzoekers.

De resultaten van de studie hebben de potentie bij te dragen aan het veranderen van de tijdshorizon waarover boeren en voorlichters denken, namelijk van tactisch/operationeel naar strategisch. Teneinde dit te realiseren, moet de methode toegepast worden in de context van een bedrijfsinnovatieproces, waarbij boeren actief betrokken zijn. Drie condities kunnen dit proces in de Canelón Grande bevorderen. Ten eerste zijn de boeren gelokaliseerd in een betrekkelijk klein gebied. Ten tweede, veel van deze boeren zijn al betrokken in kleine groepen geleid door technische voorlichters. Ten derde, de agronomische faculteit van de universiteit heeft een proefstation in de regio en was gedurende 10 jaar betrokken bij scholing en onderzoeksactiviteiten op de bedrijven in de regio. Idealiter, leren boeren, technische voorlichters en wetenschappers in dit proces en passen zij de verworven kennis toe, teneinde de bedrijfssystemen beter te begrijpen, en de in dit proefschrift gepresenteerde modellen en de methode van het actie-onderzoek te verbeteren. Deze studie draagt op een methodologische en conceptuele wijze bij aan het aanpakken van het probleem van onduurzaamheid op bedrijfsniveau, en het laat de groentebedrijven van Canelón Grande zien dat er mogelijkheden voor verbetering zijn en kunnen worden gerealiseerd door individuele strategische beslissingen en door het werk van de belangenorganisaties.

Curriculum Vitae

Santiago Dogliotti was born on April 10th, 1966 in Montevideo, Uruguay. He married Gabriela Perrone in 1987 and he has three children, Vera, Juan and Gina. He studied at the Faculty of Agronomy (Uruguay) from 1984 till 1991, where he graduated as agronomist engineer. From 1987 till 1989 he worked as an extensionist in a poultry company. From 1988 till 1990 he worked as a part-time research assistant for the project 'Characterization of the seed production sector in Uruguay' at the Faculty of Agronomy. In 1991 he became part-time lecturer at the Horticulture Group of the Faculty of Agronomy and in 1994 he became full-time lecturer at the same group. From 1989 till 1994 he also managed a pig farm. In August 1995 he started the M.Sc. programme Crop Science at the Wageningen University (The Netherlands), where he graduated with distinction in January 1997. In October 1997 he started a 'sandwich' Ph.D. programme within the former Theoretical Production Ecology group of Wageningen University. Currently he is working for the Plant Production Department of the Faculty of Agronomy at the South research station as assistant professor.