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Co-innovation of family farm systems: A systems approach to sustainable agriculture

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ABSTRACT

Meeting the goals of sustainable growth of food production and reducing rural poverty requires assisting family farmers to develop more productive, profitable, resource efficient and environmentally friendly farms. Faced with decreasing product prices and increasing production costs during the last two decades family farmers in south Uruguay tried to maintain their income by intensifying their farms, growing larger areas of fewer crops and increasing the use of irrigation and agrochemicals. Soil degradation was aggravated by this process, limiting crop yields, undermining the farmers' aim of maintaining their income. A model-aided explorative study had shown that decreasing the area of vegetables, introducing crop rotations, cover crops and manure applications, and including beef-cattle production would be a better strategy. To test this hypothesis, a project was started at the end of 2004 and expanded in 2007, involving farmers, technical advisers and scientists in a co-innovation process that combined systemic diagnosis and redesign of the farm systems, social learning and dynamic monitoring and evaluation. The project involved 14 farms representing a large range of variation in resource endowment. Main problems found on all farms were deteriorated soil quality and low labour productivity, which resulted in low income and high work load. At the end of 2–5 years of redesign farmers had been able to implement most innovations planned. Irrespective of endowment with land, machinery, irrigation water or labour resources, re-design increased the per capita family income (FIp) and the income per hour of family labour (IH) on 13 out of 14 farms, by 51% and 50%, respectively, averaged over all farms. Soil organic carbon content had increased on 11 out of 14 farms and estimated erosion rates in vegetable fields had halved. Farmers considered 'multi-year planning' the most important change introduced into their practice by the project. They concluded that the role of the extension service agents should change from mere consultants of operational–tactical, crop-centred decisions to supporters of the process of farm planning and evaluation. The project showed that even on commercial farms operating under highly competitive conditions, substantial improvements in economic and environmental indicators can be achieved when a whole farm strategic redesign is elaborated.

1. Introduction

The larger part of the global rural population lives on family farms, which are responsible for more than half of the world's food production (FAO, 2011; IFAD, 2012). Meeting the goals of sustainable growth of food production to provide for the increasing needs of the world's population and the alleviation of poverty requires assisting family farmers to develop farm systems that are more productive, profitable, resource efficient and environmentally friendly (IFAD, 2011). However, in many regions of the world family farmers are threatened by decreasing economic returns, deterioration of the natural resource base, and lack of access to markets and knowledge (Lipton, 2005; IFAD, 2011). Thus, 'innovation' in family agriculture, understood as a process of technical and institutional changes at farm and higher levels that impacts on productivity, sustainability, and poverty reduction, is required (Rölling, 2009).

The south of Uruguay has the highest concentration of family farms in the country, many of them with vegetables as the main source of income, and the highest degree of soil erosion, with 60–70% of the area classified as moderately to severely eroded

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(MGAP, 2004). Around 88% of the farms with vegetable production as the main source of income are family farms (Tommasino and Bruno, 2005). During the past two decades the socio-economic context was unfavourable; decreasing product prices and increasing costs of energy and agro-chemicals reduced family income both in an absolute sense and relative to the surrounding rural population. To maintain their income the strategy of most farmers was to specialize and intensify their systems growing larger areas of fewer crops and increasing the use of irrigation and agro-chemicals. Soil degradation was aggravated due to increased tillage, reduced soil cover and organic matter supply, and lack of erosion control measures. The state of the soil limits attainable crop yields and overall farm productivity and undermines farmers' strategies to maintain their income (Dogliotti et al., 2004). A major cause of this downward spiral is that the adaptation of farmers to changing conditions is mostly incremental, short-term oriented and only rarely involves strategic re-design of their rural livelihood strategies as a whole (IAASTD, 2009). As a result, livelihoods have become locked-in on unsustainable development tracks.

To identify options for sustainable development of vegetable family farms, we developed a whole-farm optimization model and carried out a model-aided explorative study in earlier work. The study showed that decreasing the area of vegetable crops by introducing long crop rotations with pastures, introducing green manures and animal manure applications during the inter-crop periods, and integrating beef-cattle production into the farm system would be a better strategy than the farmers' prevailing practice of increasing the area of vegetables and specialising in a few crops (Dogliotti et al., 2005). These results strongly suggested that there is opportunity to increase farm systems performance both in terms of productivity and impact on soil quality, even within the constraints imposed by the current socio-economic context and farm resource endowment.

To test this hypothesis we started a project at the end of 2004 with funding of INIA (national agricultural research institute) and CUDECOOP (union of production cooperatives) and participation of CNFR (a major farmers' union). The project was expanded in 2007 with support of the European Union (EULACIAS) and participation of Wageningen University. The project started from three basic assumptions. Firstly, the sustainability problems described above cannot be solved by isolated adjustments or modifications in some system components such as pest management or soil tillage. The relevance of the changes occurring in the socio-economic context and in the quality and availability of production resources at the farm level, requires the adaptation of the farm systems as a whole.

Secondly, it is possible to improve the sustainability of vegetable and mixed vegetable-beef cattle family farms by changing the organization and operation of the production systems, even in a context of low resource endowment and limited access to markets, financing, services and information. In other words, there is enough room for manoeuvre inside the family farm systems to generate significant improvements in sustainability. A per crop analysis of the 'yield gap' provides insight into the main bio-physical causes of yield variability in a region (Lobell et al., 2005; Tittonell et al., 2008). However, farmers allocate their limited resources to the different production activities to optimize performance of the whole farm, and this may conflict with maximizing yields of individual crops.

The third assumption was that solutions to problems of this level of complexity do not come as 'take it or leave it' validated packages; they need to be designed with the direct involvement of farmers in all stages of the innovation process to ensure relevance, applicability and adoption (Gibbons et al., 1994; Masera et al., 2000; Leeuwis et al., 2002). Changes in agricultural practices towards more sustainable production systems are seen as a result of a collective learning process of all actors involved in the process of change, including the researchers. We refer to this process as 'co-innovation' (Rossing et al., 2010), an approach that combines complex systems theory, social learning and dynamic project monitoring and evaluation to stimulate strategic re-orientation of family farm systems. A predecessor approach for systematic development of farming systems named 'prototyping' (Vereijken, 1997; Wijnands, 1999) has been criticized for not making an explicit effort to take into account the existing diversity among farmers in resource endowment and strategy, and for being strongly dominated by researchers (Leeuwis, 1999). The approach used in this paper involved farmers and other stakeholders from the beginning and in every phase of the process, and it was sensitive to differences in farmers' priorities and access to production resources.

The main objective of the project was to contribute to improving the sustainability of family farms in south Uruguay by engaging farmers and scientists in a joint innovation process. In this paper we present the approach developed to diagnose and re-design vegetable and mixed family farm systems and the impact on farm sustainability indicators after 2–5 years of system change.

2. Materials and methods

The study involved 20 families living on 14 farms located in Montevideo and Canelones provinces in south Uruguay, within a radius of approximately 60 km from Montevideo city. The climate in the area is temperate sub-humid with a mean annual temperature of 16.4 °C, and a mean annual precipitation of 975 mm fairly evenly distributed throughout the year but with major variation between years (Furest, 2008). Water deficits occur frequently between October and March and water surpluses between May and August. Topography ranges from very gently undulating to undulating (slopes 0–6%).

The 14 farms were selected to represent a large range of variation in resource endowment, soil quality and distance to the market. Willingness of the farmers to discuss strategic choices, and their involvement in local farmer's groups were further important selection criteria. The approach involved characterization and diagnosis of the farm system's sustainability, re-design, implementation, and monitoring and evaluation of system evolution.

2.1. Characterization and diagnosis

During characterization and diagnosis we described the structure and functioning of the farm systems based on the idea that a farm is composed of two interacting subsystems: the management subsystem and the production or bio-physical subsystem (Sorrensen and Kristensen, 1992). The management subsystem is composed of the persons who make decisions about the farm, their objectives, decision criteria and decision rules. The production subsystem includes the production resources: family and hired labour, energy and other inputs, machinery and infrastructure, soil area and quality, and water availability; the allocation of these resources to different production activities in time and space; and the desired and undesired results from the production activities in terms of performance indicators.

We studied the management system through two in-depth interviews with the farmers and their families and by studying their farm records. We assessed the management team (MT) composition, the farm succession and life cycle stage, the type of bookkeeping used, the distribution of tasks among MT members, the education level and the main sources of technical information. The production system was characterized through several interviews with the farmers and by direct observations and measurements on the farms. Farm field sizes and their slopes were measured using a theodolite and maps were created of each farm. We selected three to five fields with different topographic position and/or use history as well as one or more relatively undisturbed areas on each farm to classify the soil types and to measure soil physical and chemical properties. Soils were described following the FAO (2006) guidelines, and classified as Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (IUSS Working Group WRB, 2006). Topsoil texture ranged from silty clay loam to clayey. Soils of the selected fields and at the reference sites were sampled and analysed every autumn and spring during the project's lifetime.

Diagnosis of each farm involved assessing critical points for sustainability, and drawing a problem tree (AUSAID, 2003). Critical points were identified and assessed following the MESMIS framework (Masera et al., 2000). We identified indicators within the three dimensions of sustainability (bio-physical, economic and social) and classified them in four groups of sustainability attributes: (1) Productivity: the capacity of the system to produce the specific combination of goods and services necessary to realize the objectives and goals of the stakeholders involved; (2) Stability: the presence and effectiveness of negative feedback processes to control the internal positive loops that would lead to system self-deterioration; (3) Adaptability, Reliability, Resilience: the capability of the system to stand different types of changes in external variables or driving forces; (4) Self-reliance: capability of the system to regulate or control its interactions with the environment (Lopez-Ridaura et al., 2005).

The problem trees were used to highlight in a graphic way major critical points perceived by both farmers and researchers, and to facilitate discussion with the farmers of the main causes and consequences of these problems. The 'root causes' represented the key points to be addressed during re-design to improve the farm systems. Both, critical points tables and problem trees were discussed with the farmers and adjusted to reach agreement on the 'root causes' to be addressed during the re-design phase.

2.2. Re-design

The re-design procedure developed and applied in this study consisted of five consecutive steps.

2.2.1. Adjustment of field layout and erosion control support practices

In this step we focused on problems related to the relationship between the length and slope of the fields, the water run-off from one field to another along the slopes or from neighbouring farms, and drainage problems on parts of fields. On small farms we limited the field length to 35–50 m creating 2 m wide grassy paths between fields. These paths were constructed at a lower level than the fields and acted as conduits for run-off. On larger farms we divided fields using parallel terracing with 40 m between terraces built with an average slope of 1.5% according to the method proposed by Durán (2000). This work was done during the summer by the farmers themselves with their own or hired machinery.

2.2.2. Design of the cropping plan

In this step we modified the selection of crops and the percentage of farm area for each crop to remedy at least one of the following root causes: the existing area of a crop or of a botanical family was too large to safeguard soil health; the farm experienced a shortage of labour during some periods; the farm's cash flow was insufficient during parts of the year; some of the existing crops were not suitable for the soil types on the farm; the available resources were insufficient for some existing crops or for their surface areas; greater crop diversity was needed for biological or marketing reasons. In the re-designs discussed with the farmers we increased the area of grass-clover pastures or alfalfa whenever possible to improve soil quality and to increase forage production on farms with cattle.

2.2.3. Design of crop rotations

We used ROTAT (Dogliotti et al., 2003) to design crop rotations for each farm, based on simple agronomic rules. The number of rotations designed per farm depended on several factors. Most farms with irrigation could only irrigate part of the farm, requiring one rotation for the irrigated part and another for the rain-fed part of the farm. On mixed vegetable-cattle farms the area with vegetables usually was much smaller than the area for cattle grazing, requiring one vegetable-pastures rotation near the homestead and another rotation with pastures and forage crops on the rest of the farm. On many farms part of the fields were not suitable for some of the vegetable crops, requiring two crop rotations. We used maximum crop frequencies of 1 in 3 to 1 in 4 years, taking into account prevailing soil borne diseases and the length of the intercrop period to give room to inclusion of green manure crops.

2.2.4. Design of inter-crop activities

We selected activities between main crops to protect the soil from impaction of rain, to increase organic matter input and to reduce expansion of weeds. The inter-crop activities included summer and winter cover crops, the application of chicken manure mixed with rice husk before the most profitable vegetable crops, and soil solarisation of small areas on organic farms. The mixture of chicken manure with rice husk was widely available in the region at affordable price, since poultry breeding is concentrated in Montevideo and Canelones (DIEA-OPYPA-INIA, 2003) and rice husk is the standard bedding material used for broilers.

2.2.5. 'Ex-ante' evaluation of economic and environmental feasibility

The farm plans were evaluated 'ex-ante' before discussing them with the farmers. Gross margin, labour and input requirements were estimated based on target yields and farm gate prices of inputs and products using a spread sheet. Impact on soil erosion and soil organic matter balance was estimated using the models RUSLE (Renard et al., 1997) and ROTSOM (Dogliotti et al., 2004), respectively.

The plans were presented to the farmers in the form of maps showing the allocation of crops and inter-crop activities to fields for a planning horizon of 3–4 years, and calendars with the main management activities per field. The plans were discussed with the farmers and adjusted until an agreement was reached and implementation started.

2.3. Monitoring and evaluation

We monitored the implementation of plans on each farm and advised farmers during 2–3 weekly visits on adjustments to the plans in response to un-expected events or developments. During the visits on-going activities were discussed with the farmers, and data were gathered on economic aspects, resource use, and crop and animal management. After each year of implementation of the re-design plan and at the end of the project a report was produced for each farm, which described the main economic and environmental results and was subsequently discussed with each farmer.

The time from the selection of the farms to the beginning of implementation of re-design plans was between 6 and 12 months. The plans were implemented, monitored and evaluated during 4 years on the 5 farms that started the co-innovation process in 2005 and during 2 years on the 9 farms that started in 2007. The project finished in July 2010.

3. Results

3.1. Characterization of the farms

The farms in the project represented a wide variation in resource endowment (Table 2), soil quality and distance to the market. The distance to the main wholesale market in Montevideo varied from 15 to 70 km. Total labour availability varied between 115 and 1084 h per ha per year. Three of the farms were organic. We found between 3 and 12 different species of vegetable crops per farm. The organic farms and those closest to the main wholesale market in Montevideo had the greater crop diversity. The main economic activity of all farms was vegetable production; on ten farms animal production was an additional source of income.

There was little division of tasks among MT members, all were involved in decision making and execution of operational tasks. Only on farm 3 specific operational decision making tasks were divided over members of the rather large MT. On most farms there was a clear labour division between men and women: the tasks involving machinery, soil tillage and movement of heavy loads were done by the men, while the women participated in manual work (sowing, planting, weeding and harvest and post-harvest). Activities not related to agriculture but fundamental to the functioning of the household were mostly the responsibility of the women. As a result the women worked fewer hours on the production activities than the men. Among the MT members, three were under 30 years of age, seven from 30 to 39, twelve from 40 to 49 and eleven were 50 or more. Only four of the MT members had completed a vocational education, while six had done secondary school, and 23 had completed just primary school. The farms were in all the stages of the life cycle and at different levels of transition of the farm to the next generation (Table 2).

We distinguished four book-keeping styles. Farmers were more motivated to keep records of economic flows and activities when there was more than one household on the farm in order to support the division of income, or when they saw it as a way to improve the management of their main crops. However, no farmer calculated an annual economic balance of his farm, neither did they have advisers to do that. As a result allocation of resources to different production activities was not based on a quantitative evaluation of costs and benefits of different production activities but on a general perception of costs and returns in cash and expected market prices. Investments on the farms were strongly related to cash surpluses during financially good years or to the opportunity presented by rural development projects providing subsidies. Usually there was no quantitative evaluation of viability or impact of investments and there was very limited use of credit.

The main sources of technical information for most conventional farmers were the local agrochemical and seeds shops, while organic farmers mentioned field days and workshops organized by different institutions. Specialized radio broadcasts were mentioned by all farmers as sources of information on market prices of products and inputs, and also on technical information. The retailers or middle men were also relevant sources of information about market behaviour and prices of vegetable products.

3.2. Diagnosis of sustainability

Results of the farm diagnosis are presented in Tables 4–6 as the 'initial' situation. We found the weakest points of the farms to be associated with the productivity (Table 4) and stability attributes (Table 5) of sustainability described in Table 1. Both physical and economic productivity were low. Yields of eighteen out of twenty-eight main crops were less than half the attainable yield, resulting in RYMC values lower than 0.50 (Table 4). Per capita family income (FIp) on ten farms was lower than the average FIp in rural areas and small towns in the region. Labour productivity on nine farms was less than the opportunity cost of labour, estimated as the cost of temporary hired labour in the region. The financial input/output ratio exceeded 0.9 on eight farms, meaning that these farms were not able to make even the small investments needed to maintain their assets.

We assessed a variety of quality-of-life indicators reflecting the quality of the homestead and its surroundings, access to health services and social security, etc., but we only found important differences between farms and low values in the indicators 'amount of leisure time' and 'prevalence of work-related health problems'. Most farmers had long working days and took only half the day off on Sundays and holidays. Only a few of them were able to leave the farm for a whole week or more per year. On eight farms at least one member of the MT had had or had a health problem related to the spine or a hernia caused by their work. We identified one case of intoxication due to application of pesticides.

The main problem related to conservation of natural resources was the loss of soil fertility. We identified severe losses of soil organic carbon (SOC), erosion rates that exceeded the tolerance level of 5–7 Mg ha^{-1} yr^{-1} (Puentes and Szogi, 1983) by a factor of 2 to 6, and negative balances of soil organic matter in the vegetable fields on all farms. On only two of the fields relative active SOC content exceeded 0.5, and on 42 out of 53 fields relative active SOC was smaller than 0.33, indicating that most vegetable fields were much closer to the lower limit of SOC than to the SOC content at the undisturbed references sites (Table 5). The erosion rate was lower than the tolerance level only in fields under pastures and forage crops or with slopes less than 1%. Soil organic matter balances were positive only in fields under pasture with no tillage for more than three years and in most fields of Farm 7, which was an organic farm applying large amounts of chicken manure and rice husk and sowing cover crops as a common practice.

The problem trees brought out a number of important common problems and consequences for the performance of the farms, even though with different relative importance per farm. The farmers stressed as their main problems the low family income and the deterioration of soil fertility. Based on the farm characterization we added excessive work load as a root cause of the poor quality of life of the families. Deterioration of soil fertility was a problem in itself, but it was also one of the root causes of low productivity and consequently low family income. A 'summary problem tree' which describes cause – consequence relations found on the majority of farms is presented in Fig. 1. The main causes of low family income, excessive work load and deteriorated soil quality were:

- Mismatch between labour demand and availability in the course of the year resulting in major peaks in work load. This mismatch also led to delays in crop management activities and consequently to crop yield losses.
- Low water availability for irrigation of summer crops together with deteriorated soil quality resulting in a low capacity to supply water to vegetable crops and reduced crop yields. Farmers underestimated the water requirements of their irrigated crops and/or overestimated the capacity of their water sources, and planted more area than they could irrigate properly.
- Deterioration of soil fertility, explained by a combination of several problems. Most vegetable crops provide little soil cover during their growth period and leave little residue, which, combined with the standard practice of a clean fallow during the intercrop periods resulted in negative soil organic matter balances and high risk of soil erosion. The decisions about allocation of crops to fields were tactical; no farmer was implementing a planned crop rotation. This lack of planning led to high cropping intensity on some fields and high frequencies of the same crop or crop family, causing increasing impact

Table 1
Main critical points of 14 pilot farms in south Uruguay, classified by sustainability dimension, sustainability attributes, diagnosis criteria and the indicators used to quantify each critical point.

Sustainability attribute	Diagnosis criterion	Indicator	Calculation method	Sustainability dimensions	Critical point
Productivity	Production and economic efficiency	Relative yield of main crops (RYMC)	Actual Yld/ Attainable Yld[a]	Bio-physical	Low crop yields
		Family income per capita (FIp)	FIp/Average FIp[b]	Economic	Low family income (FI)
		Relative family income per capita (RFIp)			
		Income per hour of labour (IH)	FI/Family labour	Economic	Low labour productivity
		Input/output ratio	Total costs/gross product	Economic	Low resource use efficiency
Stability	Life quality	Amount of leisure time	[c]	Social	High work load
		Prevalence of work related health problems	[d]	Social	Incidence of work related health problems
	Natural resources conservation	Relative active SOC (RASOC)	[e]	Bio-physical	Severe loss of soil fertility
		SOM balance	ROTSOM model	Bio-physical	
		Erosion risk	RUSLE model	Bio-physical	
Resilience, adaptability and reliability	Production system fragility	Irrigated fraction	Irrigated/total veg. area	Bio-physical	Low irrigation water availability
		Family labour fraction (FLF)	FL/total labour	Social	High family labour availability
		Family labour per vegetable area (FLVA)	FL/total veg. area	Bio-physical	
	Production system diversity	Income distribution among production activities	Ginni Index[f]	Economic	Diversity of income sources
		Crop diversity in area	Ginni index[g]	Bio-physical	Diversity of crops
Self-reliance	Financial and input dependency	Solvency	Total debt/Assets	Economic	Low indebtedness
		External/total inputs	Purchased/Total inputs Cost[h]	Economic	Low dependency on external inputs
	Social and human capital accumulation	Degree of participation in training activities	[i]	Social	Low participation in training activities
		Degree of participation in groups and networks	[j]	Social	High participation in local groups and networks

[a] We selected the two main crops per farm and we defined attainable yields as the rain-fed and irrigated yields obtained by best farmers in the region based on expert knowledge.
[b] Family income per capita (FIp) is defined as the sum of net profit and the value assigned to family labour divided by the number of family members. Average income per capita in small cities and rural areas is derived from national surveys of household incomes (INE, 2010).
[c] Leisure time index, 1 = 1 day per month; 2 = 2–4 days per month; 3 = 1 day per month and one week per year; 4 = 2–4 days per month and one week per year, 5 = more than 2–4 days per month and one week per year.
[d] Work related Health index, 1 = one chronic un-treated problem, 2 = one chronic treated problem, 3 = more than one temporary problem during the past year, 4 = one temporary problem during the past year, 5 = no problems.
[e] RASOC = ((Actual SOC – Min SOC)/(Max SOC – Min SOC)) * 100, determined in representative fields of each farm. Min SOC is an indicator of 'stable' SOC estimated based on soil texture using the equation of Rühlmann (1999). Max SOC is the amount of carbon found in each soil type under the original vegetation of the region and un-disturbed conditions, based on Durán and García-Prechác (2007).
[f] Income distribution = ($\sum$gross income from activity$_i^2$)/(total gross income)^2, includes also off-farm sources of income.
[g] Crop diversity = ($\sum$area crop$_i^2$)/(total crop area)^2, includes vegetables, cereals, forage crops and pastures.
[h] Purchased inputs include hired labour, agrochemicals, fuel, electricity, etc. Total inputs include also family labour, seeds, manure, etc. produced on the farm, valued at farm gate prices.
[i] Participation in training activities, 1 = zero, 2 = one MT member in one activity during the past year, 3 = one MT member in more than one activity, 4 = >1 MT member in one activity during the past year, 5 = >1 MT member in more than one activity.
[j] Groups and networks, 1 = few links with neighbours, no membership of any organization, 2 = good links with neighbours, no membership of any organization, 3 = few links with neighbours, participates regularly in a local organization, 4 = good link with neighbours, participates regularly in a local organization, 5 = good link with neighbours and leader of local group or organization.

of weeds and diseases on crop yields. Finally, on many farms the layout of fields and the absence of erosion control support measures increased soil erosion risk.

3.3. Re-design of farm production systems

Based on the 'root problems' described above, we proposed system re-design with three aims: to better match resource demand and supply, to adopt multi-year planning, and to rehabilitate the soil.

Matching resource demand and supply

- We reduced the area of vegetable crops to match the availability of and demand for labour and irrigation water and to allow the implementation of a crop rotation with frequencies of the same species and families smaller than 1 in 3 to 4 years.
- We modified the selection of crop species and/or combined early, intermediate and late varieties of the same crop to improve the distribution along the year of sowing, planting and harvesting activities.

Multi-year planning

- We introduced crop rotation to stimulate farmers to increase their planning horizon of spatial and temporal allocation of crops to fields. We combined vegetable crops and 3–4 year pasture phases whenever possible.
- Farmers usually thought of weeds as a problem of individual crops, and control measures (mechanical or chemical) were applied during the crop growth period. We tried to make them think of weeds as a field-specific problem to be reduced in the

Table 2
Resource endowment and other relevant characteristics of the pilot farms at the start of the re-design phase.

Farm no.	Area (ha)	Family labour (FTE)[a]	Family/total labour	Mechanisation level[b]	Soil types[c]	Irrigated area[d] (ha)	Vegetable area (ha)	Animal production[e]	Production type[f]	Life cycle stage[g]	Farm succession[h]	Management team[i] #	Book keeping type[j]
1	12.0	3.0	0.97	2	3	4.4	4.4	2	C	2	1	3 F, C	3
2	38.0	2.5	0.83	2	1	0	5	2	C	2	2	3 C, S	3
3	59.0	6.0	0.90	4	1, 3	5.0	25	2	C	2	1	4 F, B	4
4	5.7	2.0	0.78	1	2, 3	1.0	3.6	1	C	3	0	2 C	3
5	19.0	2.5	1.00	2	1	0	3.2	2	O	3	0	2 C	1
6	4.4	1.7	0.85	3	1, 2	0.1	3.6	0	C	3	0	2 C	4
7	25.4	2.0	0.34	3	1, 2	4.0	7.3	2	O	2	1	2 C	3
8	26.0	4.5	0.96	2	1, 2	2.0	8.9	2	C	2	2	3 C, S	3
9	13.0	1.2	0.87	1	1	0	1.5	2	C	4	0	2 C	2
10	5.5	2.0	0.67	3	2, 3	2.5	2.5	0	C	4	0	2 C	3
11	20.0	2.0	1.00	1	1, 2, 3	0	5.0	2	C	1	1	2 M,S	1
12	10.5	2.0	1.00	2	3	0.1	2.7	0	O	1	1	2 P	3
13	48.0	2.3	0.92	2	1, 2	1.0	2.3	2	C	3	1	2 C	2
14	29.0	3.5	0.69	4	1	1.0	14.8	2	C	2	1	2 B	3

[a] Full time equivalent (FTE) = 300 days of work and 8 h per day = 2400 h per year of labour.
[b] Mechanisation level, 1 = Low: without tractor, 2 = Medium – Low: with tractor, without sprayer machine, 3 = Medium – High: with tractor, with sprayer machine, 4 = High: 2 tractors and sprayer machine.
[c] Soil types, 1 = Mollic Vertisols, 2 = Luvic/Vertic Phaeozems (Pachic), 3 = Luvic Phaeozems (Abruptic).
[d] Irrigated area estimated based on available water and irrigation equipment, maybe underutilized in some cases.
[e] Animal Production, 0 = no animals, 1 = only for self-consumption purpose, 2 = self-consumption and source of income.
[f] Production type, refers to vegetable production, C = conventional, O = organic.
[g] Life cycle stage, 1 = entry or establishment, 2 = expansion, 3 = consolidation or stabilization, 4 = exit.
[h] Farm succession, 0 = not succession expected or possible, 1 = possible but not defined yet, 2 = defined or in transition to next generation.
[i] Management team composition: number of members of the management team, C = couple, F = father, M = mother, S = son, B = brothers, P = partners non relatives.
[j] Book keeping type, 1 = only sales receipts, 2 = sales receipts plus incomes and expenses, 3 = incomes and expenses plus details of the main production activity, 4 = detailed information of most of the production activities.

long term by combining several methods including the crop rotation, cover crops and timely mechanical or chemical control.

Soil rehabilitation

- We tried to leave at least 4–6 months between crops to allow a summer or winter cover crop during the intercrop periods to keep the soil covered, supply organic matter to the soil and decrease weed reproduction.
- We modified the layout of fields when necessary and possible to aid erosion control and the implementation of the crop rotations.

3.4. Impact on farm sustainability

In this section we present the uptake of the re-design plans negotiated between the researchers and the farmers and their impact on the sustainability attributes distinguished in Table 1.

3.4.1. Uptake of re-design plans

Most farmers implemented the majority of elements of the re-design plans, with adjustments to adapt to unexpected weather events, new market opportunities and changes in resource availability. The degree of uptake of the elements of the re-design plans differed among farmers. At the end of the project six farms had implemented between 50% and 80% of re-design elements while the remaining eight farms had taken up more than 80% (Table 3). Keeping records and implementing crop rotations were the most difficult elements. The proposed records system did not meet most farmers' needs and capabilities, and keeping records was regarded as 'chores' imposed by the research team rather than something useful to improve their control over their farms. Crop rotation was the most demanding task in terms of long-term planning skills and affected most farm operations.

3.4.2. Changes in farm productivity

As a result of the re-design the performance of most farms improved in terms of most productivity indicators. Comparing yields of 25 crops of 8 species in the initial year of the project with those in the final year of the project, we found yield increases by more than 50% for 11 crops, between 15% and 50% for 5 crops and less than 15% for 2 crops. Among the 7 crops of which yields decreased, 4 were onion crops with high yields but major post-harvest losses due to excess rain during harvest time in the summer 2009–2010. The indicator 'Relative Yield of Main Crops' (RYMC) increased on 10 of the 14 farms (Table 4). On farms 3, 4 and 9 post-harvest losses of onion explained the decrease in RYMC. Ten of the farms had beef cattle production as a source of income. Meat production per ha increased on 8 farms, by almost 65% on average. On farm 3 meat production decreased slightly, while on farm 9 it decreased from 462 to 214 kg LW ha^{-1}. The per capita Family Income (FIp) and the Income per Hour of family labour (IH), estimated in constant Uruguayan pesos (reference July 2009), improved on all farms except on farm 3. The average increase in FIp was 51% and the average increase in IH almost 50%. At the beginning of the project 8 farms had an IH lower than the estimated opportunity cost of labour of $45\ \$\ h^{-1}$, while at the end this was the case for three farms (Table 4). The IH was related to the level of mechanization and the irrigated area of the farm. At the start of the project, average IH was 25.0, 35.2, 56.1 and $83.8\ \$\ h^{-1}$ for mechanization level 1 to 4, respectively. Also the area irrigated affected IH. We found that average IH was 25.9, 39.5 and $89.6\ \$\ h^{-1}$ for farms with irrigated areas of less than 0.5 ha, 0.5–2.5 ha, and more than 2.5 ha, respectively. From 2006/2007 to 2009/2010, the average income of the rural population estimated in constant Uruguayan pesos (reference July 2009), increased by almost 21% (INE, 2010). The per capita income of participating farmers relative to this average rural income, expressed by the indicator 'Relative per capita family income' improved on ten farms (Table 4), by 25% averaged over all farms (Table 4). The number of farms unable to recover the opportunity cost of family labour and the amortization of machinery and infrastructure decreased from six to three. The average financial input/output ratio decreased by almost 15%.

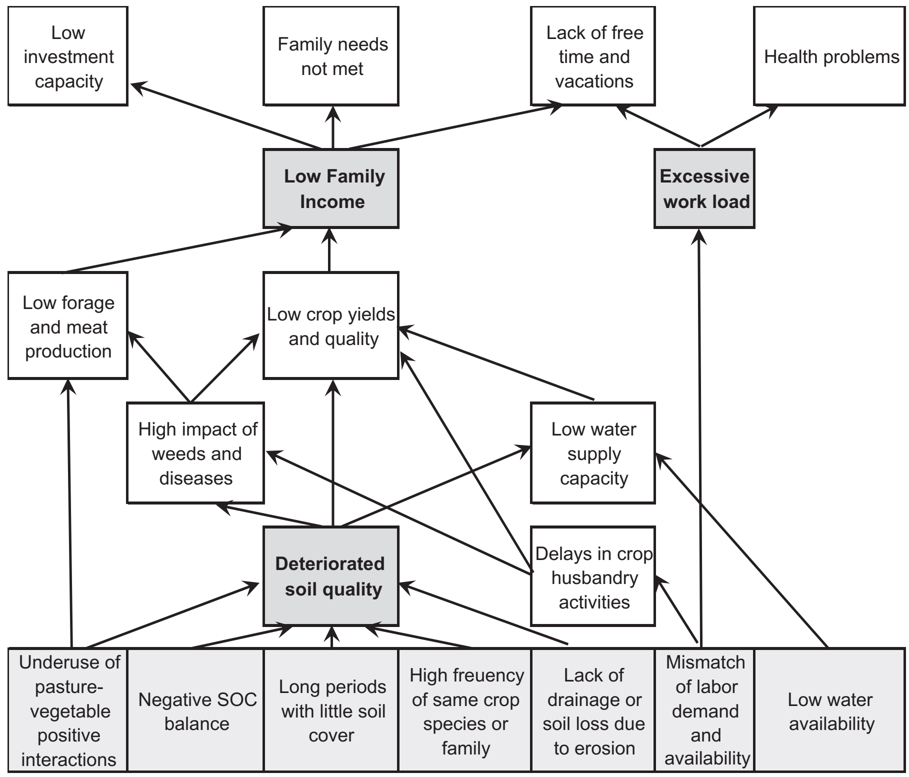

Fig. 1. Problem tree summarizing problems trees of the 14 pilot farms in South Uruguay. Dark grey boxes with bold lettering represent central or main problems of the farms; light grey boxes at the bottom are 'root' problems.

3.4.3. Changes in farm system stability

We did not find improvements in the life quality indicators. The work load continued to be high and the availability of leisure time low. The indicator of work-related health problems even deteriorated on two farms due to two small work-related accidents. The other life quality indicators, which revealed rather good values at the beginning of the project did not change or improved slightly.

The farm system redesign had a positive impact on soil quality, measured by the changes in SOC of 53 fields over the course of the project. SOC increased by 3.1 g kg^{-1} on average in 35 fields, an average increase of 26% compared to the initial SOC. SOC decreased by 2.0 g kg^{-1} on average in 15 fields and remained stable in 3 fields. The fields in which the SOC decreased had an average initial SOC of 17.9 g kg^{-1}, while the average initial SOC of the 35 fields where SOC increased was 14.0 g kg^{-1}. The Relative Active SOC (RA-SOC) increased on 11 farms (Table 5). Using RUSLE (Renard et al., 1997) we estimated that erosion rates in vegetable fields at the start of the project were between 13.1 and 31.4 Mg ha^{-1} yr^{-1}. Redesign reduced erosion rates to between 7.3 and 15.5 Mg ha^{-1} yr^{-1}, still above the tolerance level of 5–7 Mg ha^{-1} yr^{-1}.

3.4.4. Changes in farm system resilience, adaptability and reliability

An important change proposed to the farmers was to reduce the area of vegetables to make better use of the available labour and irrigation water, and to allow the implementation of a healthy crop rotation. As a result, the area of vegetables was reduced on 12 of the 14 farms, decreasing from 6.4 to 4.6 ha per farm on average. At the same time 4 farmers made investments to increase the water available for irrigation. The increment in irrigated area was small, going from 1.5 ha to 1.6 ha per farm on average. Due to the smaller area with vegetables, the fraction irrigated vegetable area increased on 9 farms, while 2 already had irrigation for the whole area at the beginning of the project (Table 6). Overall, the fraction irrigated vegetable area increased from 0.27 to 0.40.

The availability of family labour did not change, except on farms 6, 10 and 13 where it decreased because the farmers wanted to reduce their workload (farm 6) or a son left the farm (10 and 13). Hired labour increased on farms 1, 6 and 10, and decreased in five farms. Given the reduction in vegetable area, the time available for crop management improved: family labour per vegetable area increased for 11 farms. On farms 10 and 13 the vegetable area was maintained but family labour available decreased by 800 and 480 h per year, respectively. The family labour fraction remained 0.86 on average (Table 6).

The indicators of production systems diversification improved slightly. The distribution of income between productive activities increased on 8, decreased on 4 and remained approximately the same on 2 farms. The average Gini index of income distribution among production activities decreased from 0.29 to 0.27 (Table 6). The distribution of the area among crops improved on 8 farms, worsened on 4 and was unchanged on 2 farms. The average Gini index went from 0.36 to 0.28, not so much due to an increase in the number of activities or crops, but to a better balance between areas of different crops. We sought to reduce the number of crops on farms that were too diversified to improve crop management. On other farms we changed the areas allocated to crops to allow healthy rotations.

3.4.5. Changes in farm system self-reliance

There were changes in the debt situation of some farms. Farm 7 took a bank loan to buy a tractor, farms 4 and 11 received financial support from the local cooperative to improve water sources, and farms 2, 4 and 11 were supported by MEVIR (Rural Housing Agency) for repair or construction of their homes. The three farms that were in debt at the start of the project were able to pay it off.

Table 3
Degree of implementation by the farmers of the main re-design elements planned for each farm.

Main changes planned	Farm nr														%
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Drainage, erosion control support measures	1	0.5	1	1	0	1	–	1	–	1	–	1	1	1	86
Green manure and cover crops	1	1	1	1	1	1	1	1	1	1	1	1	0	1	93
Chicken bed applications	1	1	1	1	1	1	1	1	1	1	1	1	1	0	93
Crop rotations	1	0	0.5	1	1	1	1	1	0.5	1	1	1	0	1	78
Crop&pasture rotations	–	0	0	–	1	–	1	1	1	1	1	0.5	0	1	68
Crop choice and area of crops	1	1	0.5	1	1	1	1	1	0.5	1	0.5	0.5	1	1	86
Crop management	1	1	–	1	1	1	1	1	1	1	0.5	0.5	1	1	92
Weed control and solarization	1	1	1	1	1	1	1	1	0.5	1	0.5	1	0	1	86
Keeping activity and economic records	0	0	0	0.5	0	1	0.5	0	0.5	1	0	1	1	1	46
%	87	61	63	94	78	100	94	89	75	100	69	83	56	89	

1 = Innovation planned and implemented successfully to a great extent.
0.5 = Innovation planned and implemented partially or with difficulty.
0 = Innovation planned and not implemented.
– = Innovation not planned.

Table 4
Impact of redesign on the productivity indicators of the participating farms at start (initial) and end (final) of the re-design phase. Indicators are explained in Table 1.

Farm no.	Relative yield of main crops (RYMC)		Relative Family Income[a] (RFIp)		Income per hour of family labour[b] (IH)		Input/output ratio[c]	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
1	0.41	0.22	0.89	1.01	53.8	56.7	0.98	0.92
2	0.08	0.73	0.59	2.10	24.1	94.7	1.27	0.57
3	0.56	0.51	1.54	0.72	117.2	72.6	0.60	0.80
4	0.45	0.34	0.80	1.06	30.4	53.5	0.87	0.87
5	0.57	1.00	0.43	0.68	21.7	47.6	1.45	0.96
6	0.52	0.84	0.88	1.14	43.0	71.5	1.07	0.75
7	0.50	0.82	1.61	1.79	97.7	120.7	0.79	0.74
8	0.53	0.55	0.85	0.77	38.8	45.6	1.02	0.95
9	0.70	0.46	0.47	0.37	31.1	33.4	0.65	1.17
10	0.46	0.70	0.86	1.74	27.6	88.0	0.93	0.73
11	0.15	0.42	0.19	0.49	13.4	41.5	1.49	1.13
12	0.35	0.70	0.73	0.81	22.2	41.1	1.47	1.05
13	0.42	0.48	1.09	0.92	50.3	67.6	0.84	0.76
14	0.37	0.67	1.06	1.37	50.4	97.3	0.85	0.72
Avge	0.43	0.60	0.86	1.07	44.4	66.5	1.02	0.87

[a] The average income per capita per year (from 1st of July till 30th of June) in small cities and rural areas (INE, 2010) and corrected to constant Uruguayan pesos (reference month July 2009) was: 2004–2005 = $59,990; 2005–2006 = $64,827; 2006–2007 = $67,016; 2007–2008 = $73,407; 2008–2009 = $84,730; 2009–2010 = $81,056. In July 2009 one US dollar was $23.32.
[b] Constant Uruguayan pesos (reference month July 2009) per hour of family labour.
[c] Inputs include all costs in cash, the opportunity cost of family labour and amortization of machinery and infrastructure. Output is the gross income of the farm.

The ratio of purchased and total inputs did not change significantly. The overall average was identical (0.47), on 5 farms it improved, on 5 it decreased and on 4 it remained about the same (Table 6).

Participation in training activities, groups and local networks did not change significantly. Besides the activities organized by the project itself, farmers lacked opportunity and means of transportation to attend to field days or other activities organized by research stations and the extension service in the region. At the baseline, 10 of the 14 farmers were already members of local groups and networks, and participated in activities with variable frequency.

4. Discussion

Despite large variability between farms in resource endowment, production system structure, stage in the farm life cycle, and farm succession possibilities (Table 2), we found that the farms faced similar problems, which they share with many family farmers around the world (FAO, 2011): low labour productivity which results in low income and high work load, and deterioration of soil fertility. At the end of 2–5 years of redesign the farmers participating in this study had been able to implement most of the jointly designed innovations to overcome those problems. As a result, family income and labour productivity increased on 13 out of 14 farms by 51% and 50%, respectively, averaged over all farms. Soil organic carbon content had increased on 11 out of 14 farms and estimated erosion rates in vegetable fields had halved.

4.1. The relevance of labour productivity in family farming

Viability of family farming is strongly linked to labour productivity and opportunity costs of labour in the wider economy (Woodhouse, 2010; Van der Ploeg, 2008). There is no point in increasing farm productivity and family income through greater 'self-exploitation' because that course is not sustainable (van den Ban, 2011). Our diagnosis results show that there was no room to increase family workload on the participating vegetable farms. Consequently, the only option to increase family income was to increase labour productivity. Labour productivity in agriculture can be increased by improving land productivity through better management and intensification, or by investments in mechanization (Woodhouse, 2010). Investment capacity of family farms is impaired when family income is low. Furthermore, the size of the farms and production scale might limit the feasibility of mechanization. At the start of redesign, the productivity of most of the

Table 5
Impact of redesign on the soil organic carbon content of the participating farms. Data is an average of the fields monitored on each farm.

Farm no.	Nr fields where SOC increased or stable	Nr fields where SOC decreased	Average SOC initial (g kg^{-1})	Average SOC final (g kg^{-1})	Relative Active SOC initial (%)	Relative Active SOC final (%)	Difference in relative Active SOC (%)
1	2	1	12.0	12.8	9.1	13.2	+4.1
2	3	0	14.9	16.1	21.0	25.2	+4.2
3	3	1	14.5	15.7	17.5	21.9	+4.4
4	3	1	11.5	12.2	9.4	12.4	+3.0
5	3	1	13.6	14.5	15.4	18.1	+2.7
6	3	0	9.3	15.3	3.5	21.0	+17.5
7	1	3	24.1	21.8	53.6	44.6	−9.0
8	2	1	12.4	13.0	9.4	12.0	+2.6
9	3	1	16.6	21.3	26.8	43.6	+16.8
10	6	0	13.2	15.9	16.1	26.4	+10.3
11	3	1	12.8	15.5	12.9	23.5	+10.6
12	3	0	18.2	20.7	37.4	47.9	+10.5
13	2	3	17.8	17.5	30.6	30.0	−0.6
14	1	2	19.0	18.4	35.6	33.1	−2.5

farms participating in this study was not enough to make investments in mechanization and/or irrigation. Consequently, the strategy followed in this study to increase labour productivity was to improve the allocation of available labour and other resources to production activities, increasing land productivity through better management and improved soil quality.

The indicator we used to estimate labour productivity was income per hour of family labour, which increased by 50% on average, and on 13 out of 14 farms, irrespective of their initial level of mechanization and irrigation. This was not a consequence of an increase in market prices of vegetables or favourable weather. On the contrary, from 2006/2007 to 2009/2010 the vegetable price index at the main wholesale market in Montevideo corrected to constant prices (reference month July 2009) decreased by 24% (CAMM, 2010). From May 2008 till January 2009, accumulated rainfall was 50% less than the average (Furest, 2012). The drought impacted severely on those farms where income from cattle production was important (farms 9 and 13). Furthermore, during January and February 2010 the rainfall was 119% more than the average (Furest, 2012), causing high postharvest losses of onion crops planted with late cultivars (farms 1, 3, 4, 8, 9 and 13) and decreasing yields of field tomato (farms 1 and 11). The overall increase in IH and FIp can therefore be attributed to increased yields, which were achieved without significant increases in external inputs. Even on those farms where the indicator RYMC decreased, we still were able to improve FIp and IH due to yield increases of other crops and a more balanced distribution of areas across crops (farms 1 and 9).

A major concern when introducing new technologies in family farm systems should be their impact on labour demand through the year (Giller et al., 2011). In this project, adjusting the production systems to the particular quality and quantity of labour on each farm was one of the main goals of the re-design. We introduced new activities such as cover crops, applications of chicken manure, and weed control during intercrop periods, which could be adopted by most farmers (Table 3) because the re-designs freed up labour for those activities by reducing the area of vegetable crops, changing the crop or variety choice and the distribution of areas among different crops. A better distribution of labour demand in the course of the year allowed farmers to improve the timing of crop management activities, which had a positive impact on crop yields.

4.2. The impact of improved soil management

Several studies documented significant yield benefits derived from the use of cover crops in south Uruguay (García and Reyes, 1999; Docampo and García, 1999) and elsewhere (Scholberg et al., 2010), and from the use of animal manure (Rabuffetti et al., 2010; Russo and Taylor, 2010). However these practices are not widespread among vegetable farmers in south Uruguay (Berrueta et al., 2012). Only 2 of the 14 farms participating in this study were using cover crops and applying animal manure to some extent at the start of the redesign, but almost all had adopted these techniques at the end of the project. Cover crops and chicken manure applications combined with lower frequencies of the same crop or family, and improved timing of crop management activities were most likely responsible for the increase in crop yields achieved by most farmers in this study. On farms 6, 11 and 12 the increase in irrigated area of vegetables contributed additionally to the increase in crop yields.

The loss of soil fertility was identified by both farmers and scientists as a main cause of un-sustainability (Fig. 1). A decline in SOC results in crust formation, reduced water holding capacity and poor soil aeration (Terzaghi and Sganga, 1998). As a consequence of the changes introduced in soil management by the redesign of the farm systems, the farmers were able to improve the SOC and reduce the soil erosion rates for most of their vegetable fields. SOC decreases were observed in fields with high initial SOC (average 17.9 g kg^{-1}). At a given soil texture, the SOC mineralization rate is proportional to the initial amount of SOC and consequently more organic matter input is required to maintain high SOC levels (Hassink et al., 1997; Stewart et al., 2007). In a parallel study, García et al. (2011) estimated that with the average amount of organic matter applied to the vegetable fields in the course of the project (3950 kg DM ha^{-1} yr^{-1} of green manure and 3200 kg DM ha^{-1} yr^{-1} of chicken manure) the vegetable fields with the largest SOC contents would lose 2.5 Mg ha^{-1} yr^{-1} of SOC, while in the vegetable fields with the lowest SOC contents, SOC would increase by 3.06 Mg ha^{-1} yr^{-1}. Farmers were able to reduce significantly soil erosion rates, but in the vegetable fields rates remained above the tolerance level of 5–7 Mg ha^{-1} yr^{-1}. More innovations in soil management, such as reduced tillage and permanent organic soil cover as mulch (Scopel et al., 2004; Johnson and Hoyt, 1999) have to be evaluated in order to achieve higher SOC levels and reduce soil erosion to acceptable levels.

4.3. The challenge of long term planning

Although crop rotation is a very old agronomic practice with well documented benefits for productivity and stability of production systems (Struik and Bonciarelli, 1997), it is rare among vegetable farmers in south Uruguay (Dogliotti, 2003; Berrueta et al., 2012). Most farmers plan the use of their fields six months to

Table 6
Impact of re-design on indicators of resilience, adaptability, reliability and self-reliance for 14 pilot farms in South Uruguay. Fraction irrigated vegetable area, family labour as fraction of total labour, family labour input per unit vegetable area, income distribution among production activities (Ginni index), crop diversity in area (Ginni index) and ratio between external and total input costs per farm. Indicators are explained in Table 1.

Farm no.	Irrigated fraction		Family labour fraction		Family labour/vegetable area (h ha^{-1})		Income distribution among production activities		Crop diversity in area		External/total input costs	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
1	1.00	1.00	0.97	0.75	1636	1946	0.37	0.29	0.32	0.28	0.74	0.70
2	0.00	0.00	0.83	0.93	1200	1565	0.35	0.31	0.22	0.15	0.29	0.34
3	0.20	0.29	0.90	0.97	576	754	0.40	0.60	0.37	0.23	0.49	0.41
4	0.28	0.50	0.78	0.95	1333	2000	0.25	0.31	0.19	0.22	0.44	0.29
5	0.00	0.00	1.00	1.00	1875	2133	0.17	0.19	0.46	0.21	0.34	0.50
6	0.03	0.18	0.82	0.77	1100	1114	0.46	0.37	0.31	0.24	0.48	0.54
7	0.55	1.00	0.34	0.44	658	1200	0.15	0.17	0.20	0.32	0.70	0.71
8	0.22	0.44	0.96	0.98	1213	2133	0.17	0.10	0.26	0.16	0.47	0.45
9	0.00	0.00	0.87	1.00	1920	2769	0.43	0.29	0.86	0.59	0.45	0.27
10	1.00	1.00	0.67	0.58	1714	1286	0.31	0.21	0.18	0.20	0.49	0.58
11	0.00	0.25	1.00	0.95	960	2400	0.49	0.31	0.53	0.22	0.34	0.32
12	0.04	0.35	1.00	0.99	1778	2823	0.16	0.12	0.14	0.15	0.34	0.29
13	0.43	0.53	0.92	0.97	2609	2208	0.20	0.32	0.85	0.84	0.45	0.54
14	0.07	0.10	0.69	0.71	568	760	0.13	0.17	0.13	0.11	0.57	0.59
Avge	0.27	0.40	0.84	0.86	1367	1792	0.29	0.27	0.36	0.28	0.47	0.47

one year ahead of time. Farmers justify this behaviour by the variability in market and weather that they have to deal with (Klerkx, 2002). However, from the experience gained in this project, we conclude that they lack long-term planning skills and the basic tools to do it. During the discussions on the redesign of the farm systems, most farmers were astonished to see a plan for their farms that looked 3–4 years ahead. However, in the evaluation interviews at the end of the project 10 farmers mentioned 'multi-year planning' as the most important change that the project had introduced into their practice. They found that having a farm plan made it actually easier to adapt to weather and market events. A main conclusion by the farmers during the final project evaluation meeting, and taken up in the policy brief produced for the extension service office, was the need to change the role of the extension service agents and technical advisers from mere consultants on operational and tactical decisions to supporters of the process of planning and evaluation of the farm systems.

4.4. The influence of farm resource endowment on possibilities for improving sustainability

We found a relationship between income per hour worked (IH) and mechanization level and irrigated area at the start of the re-design. The improvements in IH and FIp, and SOC content, however, were not related to resource endowment. The approach in this project to diagnose and re-design the farm systems supported farmers to improve their income, labour productivity and soil quality irrespective of the availability of land, machinery, irrigation water or labour. Nevertheless, at the end of the project there was still a considerable gap between actual and desirable values for most sustainability indicators on most farms. It might be that longer time periods are required for the re-designed systems to show their impact or that novel production techniques are called for, as was discussed for SOC management. However, the problem of farm size and scale should not be ignored when evaluating the potential room for improving sustainability of family farming (Tavernier and Tolomeo, 2004; Woodhouse, 2010). Dogliotti et al. (2006) showed that farm resource endowment has a strong impact on possibilities for sustainable development of vegetable farms in south Uruguay. We confirmed the hypothesis that by re-designing the farm systems within their current context and resource endowment farm system performance could be significantly improved. However, for many farms with low availability of land, machinery and water for irrigation, further progress to desirable higher levels of income, labour productivity and soil quality will not be possible without actions taken at the regional level by farmers' unions and rural development offices to improve access of family farmers to production resources, markets, information and knowledge.

5. Conclusion

In this paper we presented the diagnosis and re-design of farm systems as part of an innovation process involving farmers and scientists to improve the sustainability of family farms in south Uruguay. Although we selected farms with a large variation in resource endowment, they shared the main critical points of sustainability: low productivity and deteriorated soil quality. The participatory approach followed to diagnose and re-design the farm systems was successful in improving significantly family income and labour productivity and at the same time reducing soil erosion and improving SOC on most farms. These results demonstrate that it is possible to improve the sustainability of family farms within the limitations imposed by their current resource endowment and socio-economic context. Key system changes included decreasing the area of vegetable crops, introducing long crop rotations with pastures, cover crops and animal manure applications, and integrating beef-cattle production to add value to pastures. To be successful any change strategy should be adapted to the particular situation of a farm. Such adaptation can be achieved by a systemic process of characterization, diagnosis, redesign, implementation and evaluation planned as a learning process with the farmers and technical advisers as main participants.

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References

AUSAID, 2003. Ausguidelines: the logical framework approach. Australian Agency for International Development, Australia, p. 41.

Berrueta, C., Dogliotti, S., Franco, J., 2012. Análisis y jerarquización de factores determinantes del rendimiento de tomate para industria en Uruguay. Agrociencia Uruguay 16 (2), 39–48.

CAMM, 2010. Indice de precios de hortalizas elaborado por la Comisión Administradora del Mercado Modelo de Montevideo. <http://www.mercadomodelo.net/indices/indepe.htm> (accessed 04.04.12).

DIEA-OPYPA-INIA, 2003. Encuesta avícola 2002. Serie Trabajos Especiales No. 30, May 2003. <http://www.mgap.gub.uy/portal/hgxpp001.aspx?7,5,110,O,S,0,MNU;E;31;1;MNU> (accesed February 2013).

Docampo, R., García, C., 1999. Sistemas de cultivos para la producción hortícola sostenible en la Región Sur. PRENADER Proyecto No. 35, Montevideo, Uruguay.

Dogliotti, S., 2003. Exploring options for sustainable development of vegetable farms in South Uruguay. PhD Thesis, Wageningen University, The Netherlands.

Dogliotti, S., Rossing, W.A.H., Van Ittersum, M.K., 2003. ROTAT, a tool for systematically generating crop rotations. Eur. J. Agron. 19, 239–250.

Dogliotti, S., Rossing, W.A.H., Van Ittersum, M.K., 2004. Systematic design and evaluation of crop rotations enhancing soil conservation, soil fertility and farm income: a case study for vegetable farms in South Uruguay. Agric. Syst. 80, 277–302.

Dogliotti, S., Van Ittersum, M.K., Rossing, W.A.H., 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in south Uruguay. Agric. Syst. 86, 29–51.

Dogliotti, S., Rossing, W.A.H., Van Ittersum, M.K., 2006. Influence of farm resource endowment on possibilities for sustainable development: a case study for vegetable farms in South Uruguay. J. Environ. Manage. 78, 305–315.

Durán, J., 2000. An alternative model for soil systematisation. Agrociencia Uruguay 4, 111–123.

Durán, A., García-Prechác, F., 2007. Suelos del Uruguay: Origen, Clasificación. Manejo y Conservación, Montevideo, Hemisferio Sur, p. 358.

FAO, 2006. Guidelines for Soil Description. 4th ed. Rome.

FAO, 2011. Save and Grow: A Policymaker's Guide to Sustainable Intensification of Smallholder Crop Production. FAO, Rome, Italy, p. 102.

Furest, J., 2008. Estadisticas Agroclimtológicas Mensuales 1971–2000. INIA Las Brujas. <http://www.inia.org.uy/online/site/base_clima_esta_mens_vizu.php?bus=Las+Brujas&base=72> (accessed 04.04.12).

Furest, J., 2012. Base de datos climátológica, Estación Experimental INIA Las Brujas. <http://www.inia.org.uy/gras/> (accessed 04.04.12).

García, M., Reyes, C., 1999. Estudio de sistemas productivos hortícolas en el largo plazo, teniendo como base el manejo de suelos. PRENADER Proyect No. 35, Montevideo, Uruguay.

García, M., Alliaume, F., Mancassola, V., Dogliotti, S., 2011. Soil organic carbon and physical properties in vegetable farms in South Uruguay. Agrociencia Uruguay 15 (1), 70–81.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies. Sage Publications, London, Great Britain, p. 179.

Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crops. Res. 124, 468–472.

Hassink, J., Whitmore, A.P., Kubát, J., 1997. Size and density fractionation of soil organic matter and the physical capacity of soils to protect organic matter. Eur. J. Agron. 7 (1–3), 189–199.

IAASTD, 2009. Agriculture at a Crossroads: Synthesis Report. Island Press, Washington, DC, 95 p.

IFAD, 2011. Rural Poverty Report 2011. IFAD, Rome, Italy, p. 317.

IFAD, 2012. Sustainable smallholder agriculture: Feeding the world, protecting the planet. IFAD, Rome, Italy, p. 45.

INE, 2010. Instituto Nacional de Estadísticas: estimación de algunas medidas descriptivas del ingreso del hogar y las personas – localidades pequeñas y zonas rurales. <http://www.ine.gub.uy/socio-demograficos/socioeconomicos2008.asp#localidades>.

IUSS Working Group WRB, 2006. World Reference Base for Soil Resources 2006. World Soil Resources Reports No. 103. FAO, Rome.

Johnson, A.M., Hoyt, G.D., 1999. Changes to the soil environment under conservation tillage. Hortechnology 9, 380–393.

Klerkx, L.W.A., 2002. Using information on farming and farmers in a model-based exploration of horticultural production systems in the south of Uruguay. MSc Thesis, Wageningen University, The Netherlands.

Leeuwis, C., 1999. Integral design: innovation in agriculture and resource management. Mansholt Studies Series, nr. 15, Mansholt Institute, Backhuys Publishers, p. 277.

Leeuwis, C., Pyburn, R., Rölling, N., 2002. Wheelbarrows Full of Frogs: Social Learning in Rural Resource Management, International Research and Reflections. Koninklijke Van Gorcum, The Netherlands, p. 479.

Lipton, M., 2005. The Family Farm in a Globalizing World: The Role of Crop Science in Alleviating Poverty. 2020 Discussion Paper No. 40. Washington, DC: International Food Policy Research Institute, p. 29.

Lobell, D.B., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R.L., Falcon, W.P., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Res. 94, 250–256.

Lopez-Ridaura, S., Van Keulen, H., Van Ittersum, M.K., Leffelaar, P.A., 2005. Multiscale methodological framework to derive criteria and indicators for sustainability evaluation of peasant natural resource management systems. Environ. Dev. Sust. 7, 51–69.

Masera, O., Astier, M., López-Ridaura, S., 2000. Sustentabilidad y manejo de recursos naturales: el marco de evaluación MESMIS. Mundi-Prensa, México, p. 109.

MGAP – PRENADER, Programa Recursos Naturales y Desarrollo del Riego, 2004. Interpretación de la carta de erosión antrópica. División Suelos y Aguas, MGAP, Montevideo. <http://www.mgap.gub.uy/renare/SIG/ErosionAntropica/mapaindices.jpg> (accessed 04.04.12).

Puentes, R., Szogi, A., 1983. Manual para la utilización de la ecuacion universal de perdida de suelo en Uruguay. Serie: Normas de Conservación de Suelos, No 1. DSA, MAP, Montevideo, Uruguay, p. 80.

Rabuffetti, A., García, C., Docampo, R., Casanova, S., Moura, M., Smolark, C., Cabral, H., 2010. Evaluación agronómica y ambiental del estiércol de ave como fuente de nitrógeno en sistemas de producción intensiva. In: Seminario de actualización técnica: manejo de suelos para producción hortícola sustentable. Serie Actividades de Difusión 624, Montevideo, Uruguay, pp. 33–50.

Renard, K.G., Foster, G.R., Weesies, G.A., Mc Cool, D.K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook No. 703, United States Department of Agriculture.

Rölling, N., 2009. Pathways for impact: scientists' different perspectives on agricultural innovation. Int. J. Agr. Sust. 7 (2), 83–94.

Rossing, W.A.H., Dogliotti, S., Bacigalupe, G.F., Cittadini, E., Mundet, C., Mariscal Aguayo, V., Douthwaite, B., Alvarez, S., 2010. Project design and management based on a co-innovation framework. In: Building Sustainable Rural Futures: The Added Value of Systems Approaches in Times of Change and Uncertainty – IFSA 2010, Viena, Austria, pp. 402–412.

Rühlmann, J., 1999. A new approach to estimating the pool of stable organic matter in soil using data from long-term field experiments. Plant Soil 213, 149–160.

Russo, V.M., Taylor, M., 2010. Frequency of manure application in organic versus annual application of synthetic fertilizer in conventional vegetable production. HortScience 45 (11), 1673–1680.

Scholberg, J.M.S., Dogliotti, S., Zotarelli, L., Cherr, C.M., Leoni, C., Rossing, W.A.H., 2010. Cover crops in agrosystems, innovations and applications. In: Lichtfouse, E. (Ed.), Sustainable Agriculture Reviews 4: Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming, pp. 59–98.

Scopel, E., Da Silva, F.A.M., Corbeels, M., Affholder, F., Maraux, F., 2004. Modeling crop residue mulching effects on water use and production of maize under semiarid and humid tropical conditions. Agronomie 24, 383–395.

Sorrensen, J.T., Kristensen, E.S., 1992. Systemic Modelling: A research methodology in livestock farming. In: Gibon, A., Mathron, G., Vissac, B. (Eds.), Global Appraisal of Livestock Farming and Study on their Organizational Level: Concepts, Methodology and Results. CEC Proceedings, pp. 45–57.

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86 (1–2), 19–31.

Struik, P.C., Bonciarelli, F., 1997. Resource use at the cropping system level. Eur. J. Agron. 7, 133–143.

Tavernier, E.M., Tolomeo, V., 2004. Farm typology and sustainable agriculture: does size matter? J. Sust. Agric. 24 (2), 33–46.

Terzaghi, A., Sganga, J.C., 1998. Physical Characteristics of Main Agricultural Soils of Canelones and Montevideo: Agronomic Interpretation. Technic Bulletin No. 8. M.G.A.P., Montevideo, Uruguay.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya – an application of classification and regression tree analysis. Agric. Ecosyst. Environ. 123, 137–150.

Tommasino, H., Bruno, Y., 2005. Algunos elementos para la definición de productores familiares, medios y grandes. In: Anuario 2005, OPYPA-MGAP, Montevideo, Uruguay, pp. 267–278.

Van den Ban, A., 2011. Increasing labour productivity in agriculture and its implications. J. Agric. Educ. Ext. 17 (5), 401–409.

Van der Ploeg, J.D., 2008. The New Peasantries. Struggles for Autonomy and Sustainability in an Era of Empire and Globalization. London, Earthscan, p. 356.

Vereijken, P., 1997. A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. Eur. J. Agron. 7, 235–250.

Wijnands, F.G., 1999. A methodical way of prototyping more sustainable farming systems in interaction with pilot farms. In: Härdtlein et al. (Eds), Nachhaltigheit in der Landwirtschaft. Imitiatieven zum Umweltschutz. Band 15, Schmidt Verlag, Berlin, pp. 365–391.

Woodhouse, P., 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. J. Agrar. Change 10 (3), 437–453.