Plant production

AGROCIENCIA URUGUAY

How to foster changes towards farm sustainability?: learning outcomes from a co-innovation project on vegetable-beef cattle family farms in Uruguay

¿Cómo fomentar cambios hacia la sostenibilidad?: aprendizajes desde un proyecto de coinnovación en predios familiares hortícola-ganaderos de Uruguay

¿Como promover mudanças para a sustentabilidade?: aprendizados de um projeto de co-inovação em sitios familiares hortícolas-pecuárias no Uruguai

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Abstract: Current global challenges for family farmers, such as the deterioration of arable land and low family income, cannot be addressed only by working on single farm components. Improving the sustainability of family farms requires a multi-objective systems approach and may be seen as an evolutionary process composed of iterative learning cycles. We developed a co-innovation project from 2014 to 2017 that involved characterisation, diagnosis, redesign, and implementation and evaluation of the redesigns on farms. Low family income, low labour productivity and the deterioration of soil quality were the main problems impacting farm sustainability. We identified crop management factors and soil fertility deficiencies as the main causes of low yields. After three cycles of diagnosis, redesign, implementation and monitoring, the average family income increased by 32%, labour productivity increased by 22%, and all the farms implemented soil erosion control measurements. Greater implementation of the farm redesign plans resulted in greater improvements in family income, labour productivity, and crop yields. We identified four types of activities that supported learning throughout the co-innovation process: regular farm visits; meetings to discuss diagnosis, planning and evaluation; field days, and reflection workshops. The strategic use of system analysis tools to promote learning eased communication among different actors, allowing shared learning.

Keywords: participatory research, advisory system, system analysis tools.

Resumen: Los desafíos que enfrentan los productores familiares, como el deterioro de la calidad del suelo y los bajos ingresos familiares, no se pueden abordar trabajando por componentes individuales. Mejorar la sostenibilidad de estos

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predios requiere un enfoque de sistemas multiobjetivo y puede verse como un proceso evolutivo compuesto por ciclos de aprendizaje. Desarrollamos un proyecto de coinnovación con trece productores familiares desde 2014 a 2017, que involucró la caracterización, el diagnóstico, el rediseño y la implementación y la evaluación de los predios. Los bajos ingresos familiares, la baja productividad de la mano de obra y el deterioro de la calidad del suelo fueron los principales problemas que afectaron la sostenibilidad. Identificamos factores de manejo de los cultivos y deficiencias de fertilidad del suelo como las principales causas de los bajos rendimientos. Luego de tres ciclos de diagnóstico, rediseño, implementación y seguimiento, el ingreso familiar promedio aumentó 32%, la productividad del trabajo aumentó 22% y todos los predios implementaron medidas de control de la erosión. Una mayor implementación de los planes mejoró el ingreso familiar, la productividad del trabajo y el rendimiento de los cultivos. Identificamos cuatro tipos de actividades que contribuyeron al aprendizaje a lo largo del proceso de coinnovación: visitas prediales regulares; reuniones para discutir diagnóstico, planificación y evaluación; días de campo, y talleres de reflexión. El uso estratégico de herramientas de análisis de sistemas para promover el aprendizaje facilitó la comunicación entre diferentes actores, y permitió el aprendizaje compartido.

Palabras clave: investigación participativa, sistema de asesoramiento, herramientas de análisis de sistemas.

Resumo: Os desafios enfrentados pelos agricultores familiares, como a deterioração da qualidade do solo e a baixa renda familiar, não podem ser enfrentados trabalhando em componentes individuais. A melhoria da sustentabilidade desses sitios requer uma abordagem sistêmica multiobjetiva e pode ser vista como um processo evolutivo composto por ciclos de aprendizagem. Desenvolvemos um projeto de coinovação com treze agricultores familiares de 2014 a 2017 que envolveu a caracterização, diagnóstico, redesenho e implementação e avaliação nos sitios. Baixa renda familiar, baixa produtividade do trabalho e deterioração da qualidade do solo foram os principais problemas que afetaram a sustentabilidade. Identificamos fatores de manejo de culturas e deficiências de fertilidade do solo como as principais causas de baixos rendimentos. Após três ciclos de diagnóstico, redesenho, implantação e monitoramento, a renda média familiar aumentou 32%, a produtividade do trabalho aumentou 22% e todas os sitios implementaram medidas de controle da erosão. A maior implementação dos planos melhorou a renda familiar, a produtividade do trabalho e o rendimento das colheitas. Identificamos quatro tipos de atividades que contribuíram para o aprendizado ao longo do processo de coinovação: visitas regulares os sitios, reuniões para discussão de diagnóstico, planejamento e avaliação, dias de campo e oficinas de reflexão. O uso estratégico de ferramentas de análise de sistemas para promover o aprendizado facilitou a comunicação entre diferentes atores, permitindo o aprendizado compartilhado.

Palavras-chave: investigação participativa, sistema de avaliação, ferramentas de análise de sistemas.

1. Introduction

Family farmers are threatened by decreasing economic returns, deterioration of the natural resources base, and lack of access to markets and knowledge[1][2][3]. The most common consequences are high workloads to secure family income, lack of or low re-investment capacity, and lack of incentives to continue farming, compromising farm succession and aggravating soil deterioration[3][4].

Globally, farmers need to produce more food by matching objectives to preserve local natural resources, produce healthy food and improve their livelihoods[4][5][6][7][8]. In order to head towards more sustainable food production systems, farms need to improve the productive, social and environmental dimensions of sustainability.

Advisory services, educational training and research are components of the agricultural knowledge and innovation system[9]. The complex challenges that farmers face require innovative solutions and imply understanding farms as complex systems[10][11][12][13]. A well-functioning advisory service provides farmers with relevant knowledge and networks for innovation and adjustments to policies and agricultural markets[9].

Most Uruguayan vegetable farms (88%) are family farms concentrated in the southern region[14]. During the last decades, the socio-economic context was unfavourable, resulting in a reduction of farm family income due to decreasing product prices and increasing energy and agrochemical costs. Between 2000 and 2011, the number of total family farms decreased by 22%; in the vegetable sector, the number of farms decreased by 51%[15]. However, the volume produced and the gross vegetable product maintained stable, showing an intensification process. The decreasing income obtained pushed most farmers to specialise and intensify their systems growing larger areas of fewer crops[16]. Soil degradation was aggravated due to intensive tillage, limited soil cover and organic matter supply, and lack of erosion control measures[17][18].

Several co-innovation projects implemented in Uruguay over the past 15 years proved that farmers could enhance their productivity by improving resource management and whole-farm organisation[16][19]. For vegetable family farmers, Dogliotti and others[16] reported increases in family income and labour productivity by 51% and 50%, respectively, on average, while estimated soil erosion rates were halved. Working with beef-cattle family farmers, Albicette and others[19] and Ruggia and others[42] reported 24% increase in meat production, 58% increase in forage production, and 69% increase in family income. They showed that successful change strategies were specific for each farm and required characterisation and diagnosis of the farm, followed by redesign, implementation, and evaluation of the redesigns.

Co-innovation is a method of participatory systems research and development in which it is assumed that, to ensure relevance, applicability and adoption of innovations, they must be developed in their context of application and with the active participation of those who make decisions[19][20][21]. Conceptually, co-innovation combines complex adaptive systems thinking with social learning and reflexivity based on monitoring and evaluation, involving different actors[10][11][21].

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In this paper, we report on a co-innovation project with thirteen farm families in vegetable beef-cattle farms conducted from 2014 to 2017 to improve farming sustainability. We present the co-innovation methodology, describe the implemented changes, and analyse the key enabling factors. Finally, based on the project experience and previous co-innovation project reports, we discuss which could be essential ingredients for a systemic way of working with farmers.

2. Materials and methods

2.1 Selection of case study farms

The research strategy was based on case studies[22] selected to represent the variation in resource availability in the south of Uruguay (Lat -34,346/-34,546 / Long -55,579/-55,873 range). Farm selection followed a participatory process involving two local farmers' organisations located northeast of Canelones, SFR Arenales and SFR Migues, and the research team. Fourteen family farms (seven in each region) were selected, considering the diversity of resource endowment levels. Farms differed in total and cultivated area, number and type of vegetable and forage crops, grazing area, number of cattle units, share of beef cattle in farm gross product, soil types, availability of family labour and hired labour, amount of water for irrigation, and level of mechanisation.

One of the farms left the project due to family issues at the beginning of the second year; therefore, we report on the thirteen farms' processes and results.

2.2 Co-innovation cycle

The co-innovation cycle[16] involved initial farm characterisation and diagnosis (May 2014 to February 2015), followed by three winter seasons and two summer seasons of iterative agreement on the redesign proposals, implementation and evaluation until the end of the project in October 2017. For the initial diagnosis, we asked farmers about the previous agricultural year results based on their records and estimations.

During characterisation, we described each farm system considering two interacting subsystems: management and production. The management subsystem comprises the people who make decisions on the farm, their objectives, perspectives and decision criteria, and the amount of labour they contribute[16]. The production subsystem consists of the biophysical farm components and their interactions. We performed physical and chemical soil analyses to classify the soils and to analyse their current status. We characterised water resources, water availability, and the area under irrigation. We recorded animal stock, grazing area and its composition. We also assessed the infrastructure and machinery resources. The characterisation required 6-8 visits to each farm and was based on semi-structured interviews, direct observation, sampling and laboratory analysis, satellite images, field measurements, and secondary sources of information. We analysed the yields of the main crops of each farm in relation to the attainable yield, i.e. the best yields achieved by farmers in the region under similar conditions (soils, cycle length, and irrigation)[16][23][24].

For the sustainability assessment, we used the MESMIS framework[25] with a set of indicators previously adapted to vegetable and vegetable-livestock systems in southern Uruguay by Dogliotti and others[16][19]. Critical points were identified and a problem tree was drawn for each farm. The diagnosis results were presented and discussed with each family.

Based on the diagnosis, we developed redesign plans for each farm to improve sustainability. The redesign method comprised six steps[16]: adjustment of field layout and erosion control support practices; design of the cropping plan; design of crop rotations; design of a weed and soil management plan for the inter-crop periods; design of the crop and animal management plan; and 'ex-ante' evaluation of the environmental and economic impact of the plan as a whole. The plans were discussed with the farmers and adjusted until an agreement was reached and implementation began. We compared average values for the first two years (2013-2015) with data averaged over the two years of implementation (2015-2017), instead of comparing single years to reduce the "year effect" due to climate or market-induced variations. To measure the degree of implementation of the proposals, we listed all the changes included in each one and organised them into categories: soil management, crop management, crop protection, and so on. We scored from 0 to 1 depending on the degree of implementation. This evaluation was done by the project team, the same members who had been involved in the design of the proposals.

2.3 Learning-support activities

Four types of activities were implemented to support learning: regular farm visits; meetings to discuss diagnosis, planning, and evaluation; field days, and reflection workshops.

The research team visited the farms bi-weekly throughout the project. The routine during the visits was to go around the entire farm with the farmers, and then discuss the observations. Each visit was planned according to the stage of the co-innovation process.

A joint discussion of the diagnosis developed a common vision of the farm system, and agreed on the main problems and the general strategy to alleviate them. When discussing the farm redesign plan, the research team presented the main changes and the actions needed. The plans were modified as a result of the ensuing discussions. Every summer, the results of the implementation were presented and discussed among the research team, the technical advisor and the farm family.

Three field days were organised: in 2015, 2016, and 2017, where farmers and other stakeholders visited a couple of the case study farms. The purpose of the field days was to foster the exchange of experiences among farmers based on concrete examples of changes implemented and results obtained in the host farms, sensitising organisations' leaders on the need for an alternative approach to extension. Upon request of local farmer organisations, two workshops were organised on options to reduce soil erosion (March 2015), and building and managing greenhouses (April 2016).

We held two reflection workshops (February 2016 and February 2017) with the participation of farmers, local farmers' organisations' representatives, technical advisors, and the research team. The objectives were to reflect on the changes that occurred, to encourage the exchange of experiences and learning among farmers, and to plan the next steps. Besides evaluating the effects on sustainability, during the reflection workshops we asked ourselves how the changes were facilitated. Farmers reflected on the questions: What were the main contributions of the project? What things ran well and which did not?

3. Results

3.1 Characterisation of vegetable-livestock farm systems

On all farms, even the ones with part-time farmers (Table 1, farms 1, 11 and 12), agricultural production was the main source of income. In addition to vegetables and livestock, two farms had poultry, one made cheese, and five sold surplus hay bales. Most vegetable products were sold through intermediaries in Montevideo. Beef cattle were sold to other farmers, local cattle markets, and slaughterhouses. All farmers had cow-calf systems, and one farm had a complete cycle system.

TABLE 1
Characterisation of the case study farms

Farm	Area (ha)	Veg. area (ha)	GH (1) area (m2)	Irrig. area (ha)	Crops (#)	Forage crops (ha)	Cattle (CU) (2)	Predominant soil type (3)	Family la-bour (hr yr-1)	Hired labour (hr yr-1)	Mech. Level (4)	Other
1	12	0.3	750	0.28	5	1.5	21.8	Typic Arg./ Argisols	5000	80	1	-
2	14.1	1.2	2900	0.8	11	4.9	24	Typic Arg. / Inceptisols	6666	2130	1	hay bales sale
3	16	5.8	0	0.5	5	1.0	4.5	Typic hap.	4836	639.9	3	hay bales sale
4	86	14.0	0	0.5	18	9.4	89.8	Typic hap. and Arg.	9180	1240	3	Poultry/ bales
5	97	0.2	1466	0.15	1	11.3	81.8	Typic Arg.and hap.	5000	40	3	Poultry farming
6	31	0.8	5400	0.54	6	17.7	62.9	Typic Arg.	5090	2560	4	-
7	7	0.6	2786	0.28	7	1.0	8.5	Typic hap.	3744	0	2	-
8	9	0.7	5200	0.52	2	3.5	...	Typic hap.	3960	1820	2	-
9	27	6.0	0	0.5	5	3.9	23.2	Typic Arg.	4114	330	1	-
10	115	9.0	0	1.5	8	75	113	Typic hap. and Arg.	5460	1760	5	hay bales sale
11	27	0.8	0	0	1	6.9	26	Typic hap.	3328	54	1	cheese
12	22.2	2.9	1236	0.9	10	4.9	16.8	Typic hap. and Arg.	3473	261	2	hay bales sale
13	46	1.2	0	0	3	6.0	40.3	Typic Arg./ Argisols	3718	0	2	-

1 GH: greenhouse
2 1 CU is equivalent to a cow of 380 kg of live weight
3 Typic Arg. = Typic Argiudoll; Typic hap. = Typic hapluderts
4 Mechanization level = mechanization level, 1 = Low: without tractor; 2 = Medium - Low: with tractor, without sprayer; 3 = Medium - High: with tractor, with sprayer; 4 = High: 2 tractors, sprayer, and 5 = Very High: 3 or more tractors and sprayer.

Team management, farm leadership and bookkeeping varied strongly across farms. In seven farms, the management team consisted of the farmer couple; the leadership was shared on four farms; the man had the final say on three farms. The management team included another family member in five other farms, and a mother and son ran two farms. Farm succession was already defined in five farms, while it was still unclear in the other seven farms with children. Two farms had no successor. The availability of family labour ranged from 3328 to 9180 h/year^{-1}. The labour hiring was linked to work peaks and never exceeded half of the family's contribution (Table 1). All farmers worked part-time on Saturdays and rested on Sundays. Family members took turns on Sunday routine work in farms with poultry production.

The predominant soils in the region were Typic Argiudoll and Typic hapluderts. Slopes ranged from 1 to 5%. Most farmers did not apply erosion control practices, and there was a lack of knowledge of soil conservation practices. We observed symptoms of severe erosion on several farms. None of the farms planned crop rotations, although they tried not to grow the same crop in the same plot more than twice in a row as a general criterion.

Water availability for irrigation was a limited production resource. The main water sources were small excavated ponds used for greenhouse crops.

Beef cattle grazed on uncultivated plots, mixed grass-legume multi-year pastures or forage crops. Alfalfa was mainly grown to make bales. On average, selling pastures and forage crops represented 40% of the grazing area. The cultivated vegetable area was hardly rotated with pastures or alfalfa areas.

All farmers saw beef cattle as a complementary activity, even in those farms where the beef cattle gross product was similar to or even larger than that of vegetables. The predominant system was cow-calf with continuous mating. The bull remained with the herd throughout the year, leading to early pregnancy of heifers, low pregnancy rates of primiparous cows, and calving occurring during long periods of the year. Control over weaning varied; in most farms, calves stayed with the cow for up to a year. Using vegetable crop residues and discarded vegetable products for cattle feeding was common. We identified various informal agreements between farmers that gave them access to off-farm paddocks for grazing when needed. All these practices resulted in low production efficiency. Still, they were effective regarding the predominant farmers' strategy to use beef-cattle herds as a savings account and for self-consumption.

3.3 Diagnosis of farm sustainability

Vegetable production accounted for more than 50% of the total gross product in ten farms, and more than 75% in seven. The livestock gross product was equal to or greater than the vegetable gross product in farms 11 and 13. Poultry farming was an important source of income, explaining 37% and 50% of the total gross product for farms 4 and 5, respectively (Table 2). The monetary I/O ratio, on average, was low (0.53). In vegetable production, the value of purchased inputs is usually higher than in beef cattle production (Table 2, farms 6, 7, 8 and 9). The low I/O ratio was a strength and indicated a moderate use of external inputs (Table 3).

TABLE 2

Fraction of Gross Product (GP) explained by vegetable, beef or other production, family income (FI) and family income per hour (FI hour), input/output ratio (I/O), labour productivity (LP), ratio between actual and attainable yield, Gini index, meat production and percentage ranges of mineralisable organic carbon lost compared to similar soils used for vegetable or pasture-forage production

Farm	GP_veg/ total[1]	GP_beef/ total	GP_ other/ total	FI[2] (10*3)	FI/ FI INE[3]	I/O ratio[4]	FI hour ($/h)[5]	LP veg[6]	LP beef	Actual Yield/ Attain.[7]	GI[8]	Meat (kg ha -1)	SOC loss (range%)[9]	
													Veg. Area	Livestock paddocks
1	0.74	0.26	0.00	349	0.4	0.36	83	82.5	44.4	0.65	0.46	134	31-65	2-34
2	0.82	0.14	0.04	732	0.5	0.55	108	118.4	102.3	0.48	0.19	sd	43-68	49-100
3	0.94	0.01	0.05	1051	1.1	0.38	213	197.4	25.8	0.45	0.31	42	18-36	40
4*	0.51	0.13	0.37	1560	1.1	0.48	168	150.7	50.3	0.51		113	27-39	0-100
5	0.33	0.17	0.50	1100	1.1	0.46	174	318.1	82.7	0.51	1.00	85	7.9-66	19-53
6	0.88	0.12	0.00	492	0.3	0.58	89	64.5	38.5	0.30	0.28	70	21-29	1-55
7*	0.97	0.03	0.00	435	0.3	0.61	131	127.1	28.3	0.49		239	34-96	48
8	1.00	0.00	0.00	1018	1.0	0.57	261	269.4	0.0	0.68	0.50	-	33-35	19-30
9	0.81	0.19	0.00	377	0.8	0.42	80	129.0	53.8	0.46	0.32	119	3.1	17-37
10	0.57	0.16	0.27	96	0.1	0.88	30	103.6	-85.9	0.55	0.69	165	26-76	50-87
11	0.41	0.42	0.17	253	0.3	0.56	74	80.5	45.9	0.63	0.76	187	40-44	18-58
12	0.78	0.13	0.09	489	0.3	0.66	120	88.8	31.7	0.43	0.40	103	18-32	39-49
13	0.40	0.40	0.21	347	0.3	0.65	50	45.9	12.4		0.45	69	6-56	24-32
14	0.44	0.53	0.04	311	0.3	0.38	71	75.8	92.6	0.50	0.47	134	15-37	29-47

1 GP: gross product per activity was calculated as: (sales (kg) – purchases (kg) ± change in stock (kg))* farm gate price.
2 FI ($): Total farm gross product – total cost (without taking family labour as a cost)
3 FI INE ($) = FI per capita according to Statistics National Institute (INE) = 176.2 $U*103
4 I/O ratio: ratio between monetary value of purchased inputs and gross product
5 FI hour ($ h-1) = FI/total hours contributed by the family
6 LP veg. /beef ($/h): (GP per activity ($) – Total Cost per activity excluding labour costs ($))/total hours allocated to each activity (vegetable or meat production)
7 Actual Yield / Attain yield. We established the attainable yield for each crop from the yield obtained by the best farmers in the region. This information was provided by technical advisors working with farmers or from research results for the region(16)(23)(24).
8 GI: Gini index based on the allocation of area per crop. Ginni Index = ∑((area of each crop)2)/total cultivated area
9 SOC: soil organic carbon. ((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(42). Max SOC is the amount of carbon found in each soil type under undisturbed conditions, based on Durán and García-Prechác(43)
* without accurate information of the area of each crop to build the index for the baseline.

TABLE 3
Critical points of 13 mixed farms classified by sustainability attributes diagnosis criteria and the indicators used to quantify each critical point

Sustainability Attributes	Diagnosis criteria	Critical Points	Indicators	Value
Productivity	Production efficiency	(-) Low crop yields	Average yield gap	50%
		(-) Low labour efficiency in livestock	Average efficiency	3.1 Kg LW hour-1
		(-) Low production scale	Average vegetable area Greenhouse area (median) Cattle units (median)	3.5 ha 0.28 ha 26
	Economic efficiency	(-) Low family income	FI per capita FI / Average income INE (1)	99700 $ year-1 0.59
		(-) Low income per hour of labour	FI per hour of labour FI per hour/labour opportunity cost	89 $ hour-1 0.89
		(-) Low labour productivity (LP)	LP_veg LP_beef	136 $/hora 38 $/hora
		(-) High production cost in livestock	Average total cost	24 $/Kg
		(+) Low Input/output ratio	Low Input/output	0.54
Stability	Life quality and farm succession	(-)High work load	Leisure time index2	1 farm = 1; 8 farms = 2; 5 farms=3
		(+) Most farms in transition	Farm succession stage3	2farms = 0; 7farms=1; 5 farms =2
		(+)High availability of social and recreational activities	Participation in local social activities	13/13 involved in recreational activities
	Natural resources conservation	(-)Presence of moderate and severe soil erosion	Presence of gullies	7 farms
		(-)Negative soil organic balance (SOM)	Actual C /mineralisable C SOM balance	30-40%, OM inputs lower tan mineralisation rate
		(-)Deterioration of biological soil quality	Presence of nematodes, soil diseases and weeds in vegetable and pastures area	13/13 farms
Resilience, adaptability, and reliability	Production system fragility	(-)Irrigated area	Area irrigated/total vegetable area	Average = 40%; 6 farms less than 10% and 3 farms less than 50%
		(-)Low family labour availability	Amount of hours contributed by the family	13/13 farms 4800hours year -1 From 2 to 4 workers per farm
		(+) Subsidies availability and development programs	Number of farms with one or more program support	13/13 farms
		(-) Cultivated area insurance	Percentage of the cultivated area with insurance	100% in greenhouse and without insurance in open field crops
	Diversification	(-) Low diversification of sales channels	Number of salesman per farm for vegetable production	Most of the farms with only 1 salesman
		(+) High crop diversity	Gini index (GI) according to the allocation of area per crop	GI = 0.46
Self-reliance	Financial and input dependency	(+) Low level of debt	Number of farms with medium and long term debts	0/13
	Social and human capital accumulation	(-) Low availability and analysis of production records	Number of farms with production records and number of farms that use it to make decisions	6/13 save bills and only 1 used it for decision making
		(-) Low educational level	Education level reached and participation in training activities	None farmers finish the secondary school and few attended farmers training activities
		(+) Participation in local farmer organisation	Number of farms involved in local farmer organisation (SFR)	13/13 farms are part of SFR

1 INE = National Institute of Statistics
2 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 (Dogliotti et al., 2014).
3 Farm succession, 0 = not succession, 1 = possible but not defined yet, 2 = defined or in transition to next generation

The average income per family member was above the per capita average income for rural areas on only five farms (Tables 2 and 3). Low family income was explained by low labour productivity in vegetable and livestock production, low production volumes, and high production costs in beef cattle (Table 2, Figure 1). Labour productivity was compared with the opportunity cost of labour, calculated as the cost of hiring labour; only four farms surpassed that threshold.

Low production of vegetable crops was due to low yields and, in some farms, small cultivated areas. Farmers achieved, on average, 47% of the attainable yield in main crops; only three farms exceeded 50% (Table 2). We identified crop management factors and deterioration of soil fertility as main causes of low yields (Figure 1).

Common problems with crop management were delays in planting dates and weed management, and failure to control diseases and pests. Delays were explained by mismatches between demand and supply labour. The proportion of the cultivated area under irrigation in farms without greenhouses was lower than 20%, representing a weakness since it affected productivity, compromised the stability of yields, and the farms' adaptability, reliability, and resilience.

Soil fertility loss was the main environmental problem affecting crop productivity and farm stability (Table 3). The lack of soil conservation support practices, continuous tillage of vegetable fields, long periods of bare soil, and negative soil organic matter balances explained the loss in soil structure and low soil carbon contents (Table 3).

The lack of adequate machinery and the lack of maintenance of tractors resulted in high labour demand for operation and repairs. In farms with no tractor and low capital availability, the possibility of increasing the cultivated area was limited (Farms 1, 2 and 11, Table 1).

Meat production ranged between 69 and 239 kg ha^{-1}. These values are low for production systems based on sown, fertilised pastures and forage crops with high feed costs compared to natural grassland-based production systems predominant in other regions of the country.

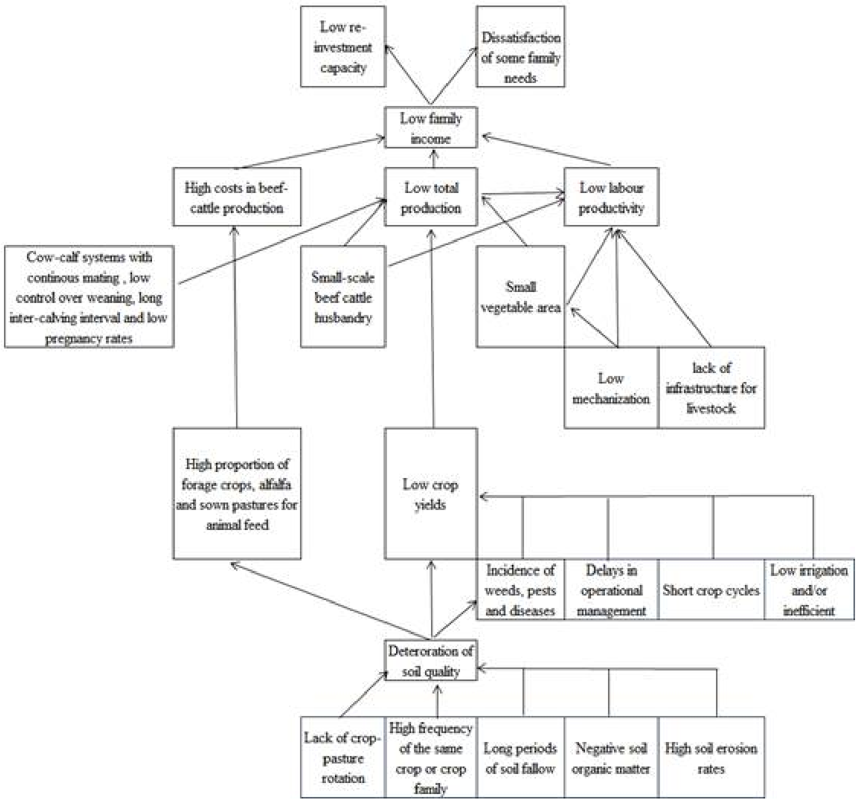

FIGURE 1
Problem tree for 13 case study farms in northeast Canelones Uruguay

Farmers generally worked more than 8 hours per day, and those who took annual rest did so for no more than a week. During the peaks of work, farmers exceeded 10 hours of work per day. The workload differed among farms. Nine farmers rested 2 to 4 days a month and did not take any annual break; 2 farmers rested only 2 days a month and 1 week a year, and 1 farm rested 4 days a month and went on vacations at least a week per year. All farms were members of the local farmers' organisation (Table 3). On average, the 13 farms worked 19% more than a "full-time equivalent" (FTE), estimated as 300 days of work and 8 hours a day per worker.

We identified the level of diversification in productive activities as a strength for most farms (Table 2). Only 3 farms presented a Ginni index value higher than 0.69, showing a specialisation strategy (Table 3). Farmers had a low level of formal education and low non-formal training, and kept very few production records (Table 3).

No farm had long-term financial liabilities. Several farms were beneficiaries of subsidies and/or payment facilities for acquiring machinery and expanding irrigation and the greenhouse area.

The strengths and weaknesses identified were discussed with farmers through a critical point table and a problem tree built for each farm (Figure 1).

3.4 Redesign of farm systems

Redesign plans included adjusting field layout and erosion control support practices, changes in crop choice, cultivated area, and crop and soil management practices. We proposed to increase the area of open field crops (8 farms) or greenhouse crops (5 farms) to increase the production volume (Table 4). In others, the cultivated area was too large for current labour availability, which led to bad timing of management operations and yield losses. We proposed reducing areas and removing some crops in these farms (8 farms). We also suggested improvements in greenhouse infrastructure.

TABLE 4
Degree of implementation 0 to 11 of the activities proposed in the plans for each farmer evaluated at the end of the project Data only appear if the activity was included in the plan presented to each family

	Farm n°													
Changes included in the proposals	1	2	3	4	5	6	7	8	9	10	11	12	13	Average
Crop areas and growing cycles:														
- increase vegetable area	0.75	1	1		0.75		1	1	0.75		0.5			0.84
- increase greenhouse area	1				0.75		1	1	1					0.95
- decrease crops areas or remove crops	1		1	0.25		0.75			0.5	0.75		0.75	0	0.63
- changes in sowing data	0.75	0.75	0.75	0.5	1	0.75	0.75		0.75	0.75	1	0.75	1	0.79
- changes in crop choice	0.75	1	1		1			0.25	1		0.5	1	0.75	0.81
Soil management:														
- crop rotations adding pastures or alfalfa	1	0.5	0.75	0.25	0		0.5	0.25	0.25	0.25	0.25	0.5	0.25	0.40
- sowing green manure in intercrops periods	0.25	0.5	1	0.25	0.25	0.75	0.75	1	0.25	0.25	0.5	0.5	0.75	0.54
- reduce tillage and organic mulch			1				0.5	1				0		0.63
- soil systematisation	0.25	1	1	0.75	0.25	0.75	1		0.75	0.75	0.75	0.5		0.70
- use of manure and compost	0.5	1	1	0.5	1	1	0.75	1	0.75	0.5	1	0.5	1	0.81
- solarisation	0.5	1	1	0		0.25	0.5	0.5	1	1	1	0.5	0.5	0.65
Crop management:														
- weed control in intercrop periods; herbicides, products, dose and timing	0.5		1	0.5	0.25		0.25		0.5	0.5	0.5	0.75	0.75	0.55
- pest and disease control; products, dose and timing	0.5	0.75	1	0.75	0.75	1	0.75	1	0.75	0.5	1	0.75	0.5	0.77
- introducing biological control	0.5	0.75	0.75		1	1	0.5	1	1			0.5		0.78
- crop density	0.5		1	0.5		0.75	0.75	0.75	1		0.5	0.75	0.5	0.70
- plant management; pruning, removing leaves	1					1	0.75	0.75	1			0.75		0.88
- irrigation	1	0.5	0.75	0.75		1	1		1			0.5		0.81
- fertilisation; timing, dose and products	1	0.5	1	0.75	1	0.75	0.75	1	1	0.5	0.75	0.75	0.75	0.81
- varieties	1	1	1	0.75			0.5		1			0.75	0.5	0.81
Book keeping system:														
- improve farmers' book keeping	0.5	0.5	1	1		1	0.5		0.25	0	1	0.25	1	0.64
Average per farm	0.70	0.77	0.94	0.54	0.67	0.83	0.69	0.81	0.76	0.52	0.71	0.60	0.63	

1 0 = no implemented; 1: full implemented. An intermediate value indicates the change was partially implemented. Example: if it was proposed in a farm to change the area of 4 crops and the farmers changed the area of 3 crops, we scored 0.75.

We designed crop rotations introducing pastures whenever possible to improve carbon balance and reduce average erosion rates. We proposed green manures, cover crops and applications of animal manure and compost for intercrop periods to improve soil chemical and physical quality (Figure 2). Farm 3 introduced reduced tillage combined with a cover crop kept as organic mulch for melon and squash crops. We included the solarisation of nursery beds and greenhouses to reduce the weed seed bank and soil-borne diseases. We also proposed adjustments to crop nutrition, water supply, and crop protection against pests, diseases, and weeds.

For beef production, redesign plans included increasing forage production through better grazing management, adjusting stocking rates, and increasing the area of forage crops and grass and legume pastures in rotation with vegetable crops. We also proposed changes in supplementary feeding, weaning, and health management. Design and discussion of changes in beef cattle management took longer than in vegetable crops. Consequently, implementation of changes began in 2016-2017, reducing the period for impacts to become apparent.

None of the redesign plans required significant increases in inputs or investments, and all plans considered existing farm resource endowment, particularly related to labour.

3.5 Implementation of redesign plans and impact on farm sustainability

All farms implemented more than 50% of the main changes in the redesign plans. Six farms implemented 70% or less, and only 3 farms implemented more than 80%. Changes related to crop management had the highest levels of implementation. Crop rotation was the most difficult change to be implemented for farmers. All farmers introduced green manure crops in the intercrop periods (Figure 2). The degree of implementation was positively correlated with FI, FI hour, and crop yields (Figure 2).

3.6 Impact of co-innovation on sustainability indicators

On average, the volume of vegetables produced increased by 47% in 10 farms (Figure 2). This increase was explained by both yield and cultivated area. Yields increased in 11 farms by 35% on average and fell in 2 farms by 9 and 19%, respectively. Seven farms accessed facilities to increase water availability (farms 1, 2, 3, 5, 7, 8, and 12) and the area under irrigation increased by 49%, impacting yields. Although a 9.5% lower average yield, improvements in crop management and changes in the crop areas in farm 4 increased the production volume (Figure 2).

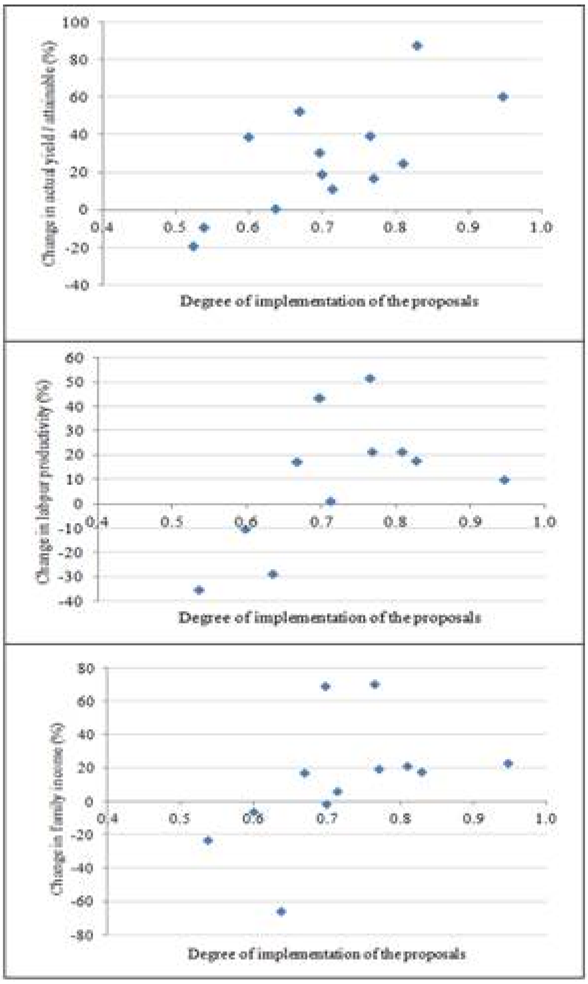

FIGURE 2
Relationship between changes in actual yield attainable yield labour productivity and family income according to the degree of adoption of the proposals

The vegetable area increased in 10 farms (Table 1) and reduced in 3 farms. Greenhouse area increased by 26.5% (farms 1, 5, 6, 7 and 8). In farms 10 and 13, the production decreased due to the decrease in the area (both) and yields (farm 10). Farm 10 had the lowest level of implementation of the redesign plan (Figure 2), while the farmers on farm 13 reduced labour allocation to the farm and increased off-farm work.

The area of forage crops and grasslands increased in 8 farms and decreased in 2. Meat production increased in 4 farms and fell in 7 (Figure 2).

Vegetable gross product (GP) increased by 38% (Figure 2), and the livestock gross product increased in 7 cases, remained almost the same in 1, and decreased in 3. On average, meat production increased by 8% and livestock gross product by 40%. The contribution of livestock in total gross product remained unchanged in 8 farms, increased by 20% or more in 2, and decreased by 15% in 1 farm.

Family income increased by 57% on average in 9 farms and decreased by 23% in 4 farms. The family income per hour of work (IF/h) increased in 10 farms and fell in 3 (Figure 2). The I/O ratio increased by an average of 13% in 10 farms and decreased by 7% in 3 farms. Between 2015 and 2017, the use of purchased inputs decreased, but a significant increase in the I/O ratio was observed, explained by the reduction in product prices. Except for 2016, between 2014 and 2017, there was a 23% reduction in the price of the main vegetables grown. Prices of greenhouse products decreased more than those for open field crops; 29% and 18%, respectively[26].

3.7 Changes identified and experienced by farmers

When farmers met to evaluate the co-innovation process, they identified the relationship built with technical advisors, the importance of the advisor's visits and going around the farm together, and the changes implemented as the key contributions of the project. After the first reflection workshop, we identified an inflexion point; farmers enhanced their interest on the project and aimed to have more organised farms with better economic outcomes and a lower workload. Farmers recognised difficulties in following the redesign plans; "we did not know how to do it". At the end of the project, they had gained a method of work and demanded the type of technical advice the project had contributed with.

Farmers also said: "At the beginning, we did not know each other. The advisor asked many questions about crops and animals and took samples and measures. We did not know well what they were doing. We were not used to this type of advice, working with all crops together". "It is better to build the plan together instead of the advisors coming with a pre-defined plan"; "I think more farmers would like to engage in this type of technical assistance". They discussed how to continue after the project ended since they would not be able to afford the technical assistance individually.

Besides these improvements, they identified the introduction of bookkeeping as a significant change. Farmers evaluated positively having more information about their financial results: "The records help us to know which crops are more profitable, how much we gain and our production cost".

Field days helped to strengthen the learning process, where all actors observed and discussed some practices and their results in situ. Advisors gained trust in their work. It was an opportunity to spread the results and the co-innovation approach to the community, creating legitimacy for the approach by enabling the case study farmers to tell their stories.

4. Discussion

Despite selecting farms that differed in resource endowment, we found similar problems among them. Issues encountered resembled those in previous co-innovation projects in different farming systems in Uruguay[(16)(19)(27)], and on family farms worldwide: low family income and labour productivity and soil degradation[(1)(2)(3)(4)].

Regarding farm sustainability (Figure 1), we could differentiate structural factors (related to resource constraints) and functional factors (organisation and resource allocation). Structural problems are difficult to solve in farms with low re-investment capacity. Lack of machinery, water scarcity, and low labour availability restrict the cultivated area and the volume produced (Farms 1, 2, 9 and 11). During the project, farmers accessed public programs that allowed them to increase their resource endowment, directly impacting their production capacity (Farms 1, 2, 3, 5, 6, 7, 8 and 12).

Functional problems lead to poor interaction between beef cattle and vegetable production, underutilising the potential benefit from long crop and pasture rotations. It was partially explained by infrastructure limitations like the availability of fences (interacting with structural factors —Farms 2, 4, 5, 11 and 13).

4.1 Improvements at the farm level: a co-innovation approach to foster changes

The results of our study on vegetable beef-cattle farms are consistent with previous co-innovation projects. On average, substantial increases could be achieved in family income and in family income per hour of labour. Although the overall workload remained high —19% higher than a full-time equivalent per worker—, it was lower than 25% reported by Dogliotti and others[(16)]. Like in previous projects, improved farm sustainability resulted from changes in several farm components and their interactions based on better management and control over internal biological processes and improved management skills, without the need for important financial investments.

We identified a lack of knowledge on available technologies and some common management practices during characterisation and diagnosis. While still engaged in characterisation and diagnosis, the research team allocated considerable time to improving management skills by introducing changes in crop practices, resulting in trust-building between farmers and researchers.

Comparing the degree of plan implementation, we noticed differences in the type of changes implemented. Changes that impacted the system structure, like removing or adding a new crop, had a high degree of implementation. In contrast, changes that affected organisational issues requiring many resources and a systemic view of the farm had a lower degree of implementation (Table 4). Implementation of crop rotation entails adjusting many crops growing cycles, where the farmers' management and organisational skills and a long-term perspective matter.

The farm redesign plans were strongly legitimised through the agreements reached during the diagnosis discussion and the proposed changes (Table 4). The plans were founded on scientific data, farmers' knowledge, and technical information already available and known by farmers. Therefore, it is not only the set of technologies applied to each farm that explains the improvements observed, but also the process that led to innovation understood as creative problem solving[(10)(21)].

The technologies proposed for soil and crop management were not new[(16)(17)(18)(23)]. Despite being well known, these technologies are not widely used by farmers as they have been reported in previous projects[(16)(19)(27)] and confirmed in our baseline characterisation. The hypothesis is that they are complex process technologies that require changes in the system's organisation and, mainly, medium-long-term planning, which is not a common practice in farmers[(16)]. The evaluation and reflection done by farmers during the reflection workshops support this hypothesis.

Complex problems are difficult to identify and require technical support for farmers[(28)(29)]. The technical assistance, methods deployed, and interaction among peers facilitated and promoted the on-farm innovation process. The methodology provided a framework to innovate, nourished by technological knowledge, scientific knowledge, and the farmer's experience[(10)(29)]. The results also show that changes need time to impact overall farm sustainability and this requires sustaining long-term commitment between farmers and advisors. The terms of the project were not enough to evaluate the possible impacts of the changes made to livestock.

Co-innovation has been described as the interaction between the systemic approach of the farm, the activities to support learning (monitoring and evaluation), and the social learning promoted by the reflections made on that experience[(9)(10)(30)]. A common element of co-innovation projects is the systemic approach used. Considering all the components, their interactions and the socio-economic environment surrounding each farm enabled the design of tailor-made solutions[(10)(16)(19)(20)(21)].

The co-innovation approach requires time and diverse technical skills in the team to design proposals and reflect on the process. The project team was composed of several scientists with different specialisations: soil science, crop physiology and management, systems dynamics, and sociology. The project field team was composed of two agronomists who worked directly with farmers; one of them specialised in vegetable production, and the other in beef cattle production. Both have sound experience working with family farmers. Besides the time allocated to work directly with farmers, it was essential to build the farm proposals among the team members.

The dialogue between social and agricultural fields is vital for real comprehension of the family farming system, and this has to be reflected in the team composition and included in advisors' training.

The application of systems analysis tools to promote learning —diagnosis reports, problem trees, critical points tables, redesign plans, field days, and reflective workshops— promoted effective communication between actors (farmers, advisors, research team, and local government actors), enabling innovation to take place[(29)(30)(31)(32)].

4.2 How to scale out the co-innovation approach to foster changes towards sustainability?

Participatory research approaches are essential when working in dynamic environments with complex systems to face current challenges[(10)(11)(33)]. The institutional context —as defined by Klerkx and others[(10)]: "the environment in which the sets of norms, rules, routines or shared expectations are present and govern actors' behaviour"— plays a key role in participatory projects, influencing their effectiveness.

The extension service has the challenge of handling complex systems, developing effective communication strategies, and fostering learning among actors[(9)(10)(34)(35)]. This means promoting a whole farm system vision that implies not only institutional changes, but also changes in the mindset of advisors, researchers and farmers themselves[(29)(30)(36)]. During the co-innovation project, the technologies introduced in redesign proposals were similar among farmers. Still, strategies widely differed, reinforcing the idea of a farm systems innovation perspective and the need for a tailor-made farm management strategy. Each family farm should be involved in selecting the required technologies that bring about improvements in farm performance[(11)(13)(37)]. This necessarily requires interactive learning and mutual trust among the partners involved.

Further, we want to point out the key aspects of scaling out this approach and contributing to enhancing farm sustainability.

- Local actors such as farmers' organisations, local government and advisors should be empowered to plan and implement their improvements. The success depends on the engagement and participation of farmers and advisors. For this to happen, farmers must value advisors' contributions to improving farm performance. The degree of implementation of farm plans could be a useful indicator to identify farmers' engagement and commitment[(29)].

- Farmers do not demand a whole-farm-centred and systemic advisory service since they are unaware of the approach and its potential contribution to improving their farms. Therefore, dissemination is a key issue. The field days during project development were a good example of dissemination activities where farmers and stakeholders could observe, question, meet with peers, exercise their voices and formulate demands[(34)].

- Sustainability improvement is an evolutionary process composed of continuous learning cycles[(38)]. Any change strategy should be adapted to local agro-ecological and socio-economic conditions of the farm to be successful[(9)(29)(34)]. Such adaptation can be achieved by a systemic process of characterisation, diagnosis, redesign, implementation and evaluation, planned as a learning process with farmers and technical advisors as main participants[(16)(19)].

- Technical advisors' knowledge and training are vital for co-innovation processes. Training should include solid scientific knowledge to understand, interpret and transform production systems, and proficient soft communication and interpersonal skills[(9)(29)(34)(39)(40)(41)].

- Trust-building between farmers and technical advisors takes time. Therefore, the advisory system should promote long-term relationships, opposite to the current “one season only” type of technical advice encouraged by subsidised technical assistance plans[(39)(29)(41)].

- Finally, clear standards are required to monitor and evaluate any advisor service regularly. It is important to set short, medium and long-term objectives. Also, indicators and procedures should monitor and assess the progress of economic, social and environmental goals pursued by farmers and other stakeholders.

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