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Brechas de productividad e impacto ambiental en sistemas de producción familiar hortícola-ganaderos del sur de Uruguay

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A Vicente.

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RESUMEN

Los sistemas de producción familiar son diversos en tamaño y tecnologías utilizadas, así como en características ecológicas y socioeconómicas. La sostenibilidad de estos sistemas se ve amenazada por la degradación del suelo, los bajos rendimientos y la carga de trabajo excesiva, lo que resulta en una baja productividad del trabajo (PT), bajos ingresos familiares (IF) y altas tasas de erosión. Se ejecutó un proyecto de co-innovación (2014- 2017) con 14 predios del noreste de Canelones seleccionados para abarcar diversas situaciones de disponibilidad de recursos. Este estudio tuvo por objetivos; 1) analizar el impacto de la co-innovación en la sostenibilidad de predios hortícola-ganaderos, 2) desarrollar un método para analizar la PT, 3) cuantificar brechas de sostenibilidad en diferentes situaciones de disponibilidad de recursos, utilizando modelos de simulación y 4) explorar opciones para reducirlas. La PT fue baja en la horticultura (114$U h^{-1}) y en la ganadería (47$U h^{-1}), explicada por la brecha de rendimiento de los cultivos, la asignación de tiempo de trabajo entre actividades productivas y su eficiencia, y los precios. Luego de dos ciclos de re-diseño e implementación de propuestas, el IF aumentó 32% y la PT aumentó 22% debido a mejoras en la gestión y control sobre los procesos biológicos y sin inversiones importantes. El uso de herramientas de análisis de sistemas facilitó la comunicación entre actores promoviendo los cambios. Las brechas estimadas (distancia entre resultados al finalizar el proyecto y los estimados con el modelo) mostraron que el IF y la PT podrían aumentar entre 1,8 a 9,9 veces y entre 2,2 a 9,5 respectivamente, manteniendo la erosión debajo del nivel de tolerancia. Los recursos que limitaron las opciones de desarrollo fueron el agua para riego y la mano de obra. Las estrategias identificadas difirieron según la dotación de recursos y las tecnologías disponibles, lo que confirma la necesidad de una perspectiva sistémica multiobjetivo donde la mejora de la sostenibilidad puede verse como un proceso evolutivo compuesto por ciclos de aprendizaje iterativos.

Palabras clave: Co-innovación, Sistema de asesoramiento, Análisis de sistemas, Modelo de simulación FarmIMAGES, Productividad del trabajo

SUMMARY

Farm productivity gaps and environmental impact on vegetable-beef cattle family farming systems in the south of Uruguay

Family farming systems are diverse in size and technologies used, as well as in ecological and socioeconomic characteristics. The sustainability of family farms is threatened by soil degradation, low yields and excessive workload resulting in low labor productivity (LP), low family income (FI) and high erosion rates. A co-innovation project was carried out (2014-2017) with 14 farms in the northeast of Canelones, selected to cover different situations of resource availability. The objectives of this study were; 1) to analyze the impact of co-innovation on the sustainability of vegetable-beef cattle farms, 2) to develop a method to analyze LP, 3) to quantify farm productivity gaps in land and labor, and environmental impact with different resource endowment using simulation models, and 4) to explore options to reduce those gaps. The LP was low in vegetable and in beef-cattle productions (114 \$ U h^{-1} and 47 \$ U h^{-1} respectively), explained by the crop yield gaps, the allocation of labour between production activities and their efficiency, and prices. After two cycles of re-design and implementation of proposals, the FI increased 32% on average and LP increased 22%. The improvements achieved resulted from better management and control over biological processes and without significant investments. The use of systems analysis tools facilitated communication between stakeholders promoting changes. The estimated gaps (distance between the results obtained at the end of the co-innovation project (ImpFP) and the attainable estimated with the FarmImages model (AttFP)) showed that FI and LP could increase between 1.8 to 9.9 times and between 2.2 to 9.5 respectively in relation to ImpFP value, while maintaining the erosion below the tolerance level. The resources that limited development options were water for irrigation and labor. The strategies identified differed depending on their resource endowment and the technologies available, confirming the need for a multi-objective systemic perspective where the improvement of sustainability can be seen as an evolutionary process composed of iterative learning cycles.

Key words: Co-innovation, Advisory systems, System analysis, FarmIMAGES model, Labour productivity

1
INTRODUCCIÓN GENERAL

1.1. CONTEXTO GLOBAL

Hay estimaciones que muestran que en 30 años la demanda de alimentos aumentará aproximadamente en un 70%. Esto se basa en el crecimiento de la población y en los cambios en la dieta (de alimentos básicos a alimentos más procesados, carne y aceite vegetal), y sin tener en cuenta la demanda de biocombustibles (Lobell et al. 2009, Tilman et al. 2012). Por lo tanto, es necesario aumentar la producción mundial de alimentos y para lograr este objetivo, los sistemas de producción deben cambiar. El modelo de expansión e intensificación agrícola, basado en el uso de fertilizantes externos, agua para riego y agroquímicos para el control de malezas, enfermedades y plagas, ha tenido gran impacto en el medio ambiente (Keating et al. 2010, Foley et al. 2005, Foley 2011).

La expansión de tierras para la agricultura es limitada y pone en riesgo ecosistemas más frágiles. Por lo que cobra importancia incrementar la productividad de la tierra basado en las regulaciones biológicas, haciendo un uso más eficiente de la energía y reduciendo el impacto ambiental (Doré et al. 2011, Tittonell y Giller 2013). Varios autores han planteado la hipótesis de que la intensificación ecológica requiere sistemas de producción diversificados, apoyados en procesos biológicos internos que requieren un grado de control y manejo difícil o imposible de estandarizar y aplicar a grandes escalas de producción (D'Souza y Ikerd 1996, Woodhouse 2010).

1.2. DESAFÍOS DE LA PRODUCCIÓN FAMILIAR

Los sistemas de producción familiar representan más del 90% a nivel global, utilizan el 53% de las tierras agrícolas y son responsables de más del 50% de la producción agrícola mundial (Graeub et al. 2016, Lowder et al. 2016). Los predios familiares constituyen un grupo diverso en términos de tamaño, tecnologías utilizadas e integración en los mercados, así como en términos de características ecológicas y socioeconómicas. Además de su papel en la producción de alimentos, los productores familiares pueden contribuir a mantener la cohesión social, ofrecer servicios recreativos y conservar el paisaje cultural (Renting et al. 2009, Darnhofer y Strauss, 2010, Darnhofer et al. 2016).

Algunas tendencias que amenazan los sistemas de producción familiar son la degradación de los recursos naturales, fundamentalmente el suelo (Lipton 2005, IFAD 2011, World Food Programme 2013), la falta de acceso a los mercados y al conocimiento, y el hecho de que la mano de obra es un recurso cada vez más escaso debido a la migración de miembros de la familia en busca de oportunidades fuera de la agricultura (Lipton 2005, IFAD 2011, Nye 2018, Tittonell 2014, Paresys et al. 2018). La degradación del suelo y la escasez de mano de obra afectan la productividad de la tierra (García de Souza et al. 2011, Alliaume et al. 2013, Tittonell y Giller 2013), limitan las opciones de producción y dificultan el manejo oportuno de cultivos y animales; en conjunto, contribuyen a una baja productividad a nivel de explotación (Dogliotti et al. 2014, Colnago y Dogliotti 2020).

1.2.1. El contexto uruguayo y los desafíos para la intensificación sostenible

El sur de Uruguay concentra la mayoría de las explotaciones hortícolas del país, y el 88% son explotaciones familiares (Ackerman, 2016). Durante las dos últimas décadas los productores familiares tuvieron que hacer frente a una reducción de los ingresos debido a la disminución de los precios de los productos y al aumento de los costos de la energía y agroquímicos. Esta situación empujó a la mayoría de los agricultores a especializarse e intensificar sus sistemas, cultivando áreas más grandes con menos cultivos y aumentando el uso de riego y agroquímicos (Dogliotti et al., 2014). La degradación del suelo se agravó debido al aumento del laboreo, la reducción de la cobertura del suelo y de suministro de materia orgánica y la falta de medidas de control de la erosión. El estado del suelo limita los rendimientos alcanzables de los cultivos (Ernst et al., 2018) y la productividad general y socava las estrategias de los productores para mantener sus ingresos (Dogliotti et al., 2014).

El bajo rendimiento actual de muchos predios familiares, tanto desde el punto de vista económico como ambiental, resulta en ingresos insuficientes para el sustento familiar y genera impactos ambientales negativos. Dogliotti et al. (2014) reportaron ingresos familiares 10% más bajos que el ingreso promedio de áreas rurales en predios hortícolas. En el mismo estudio, se encontró que las tasas de erosión eran de 2 a 6 veces mayores que el nivel de tolerancia de 5-7 Mg ha^{-1} $año^{-1}$, y que el carbono mineralizable del suelo representaba el 20% del valor original (basado en 59 muestreos en 14 predios hortícolas). La carga de trabajo excesiva y los bajos ingresos afectan negativamente la calidad de vida y pueden comprometer la salud (Colnago y Dogliotti 2020, Dogliotti et al. 2014). Se señala como aspecto central en la sostenibilidad de los predios familiares la productividad del trabajo. La carga de trabajo es en general alta por lo que la mejora de los ingresos prediales no puede estar basada en aumentar el trabajo sino en mejorar su productividad (Dogliotti et al., 2014).

El enfoque actual de los servicios de extensión está orientado a la resolución de problemas específicos en componentes del sistema. Este tipo de asistencia técnica no ha ayudado a los productores a resolver los principales problemas que enfrentan con respecto a la sostenibilidad de sus sistemas de producción. Problemas como los bajos ingresos familiares, el deterioro de la calidad del suelo y la alta carga de trabajo, que son frecuentes en las explotaciones agrícolas familiares del sur de Uruguay, requieren ser abordadas con un enfoque holístico y sistémico (Rossi 2011, Dogliotti et al. 2012).

1.2.2. Sistemas de producción más sostenibles: predios hortícola-ganaderos

El aumento de la producción ganadera en Canelones ha sido identificado como una estrategia de respuesta al contexto desfavorable para la horticultura. Entre el 2000 y el 2011 la cantidad de predios que declararon la horticultura como principal fuente de ingresos se redujo de 5300 a 2600 (51%) (MGAP-DIEA, 2020). De 2002 a 2010, el ganado vacuno aumentó en un 43% y casi la mitad del crecimiento se produjo en pequeñas explotaciones (menos de 50 hectáreas). En estos predios, el ganado aumentó un 60% durante este período. Los sistemas agrícolas combinados tienen muchas ventajas. La rotación de hortalizas con cultivos forrajeros y pasturas ayuda a mantener y mejorar los niveles de nitrógeno y carbono orgánico del suelo y reducir la tasa de erosión por debajo del umbral de tolerancia (García de Souza et al. 2011, Alliaume et al. 2013).

Un estudio exploratorio utilizando modelos de simulación (Dogliotti et al. 2005, 2006) demostró que es posible reducir la erosión e incrementar o mantener el contenido de materia orgánica del suelo (MOS) en suelos con hasta un 3% de MOS inicial disminuyendo el área de cultivos de hortalizas mediante la introducción de rotaciones prolongadas de cultivos con pasturas e introduciendo abonos verdes y aplicaciones de abono animal durante el período entre cultivos. Estos estudios concluyeron que la inclusión de ganado vacuno en predios hortícolas mejora los ingresos familiares y ayuda a mantener la erosión por debajo del nivel de tolerancia y a lograr un balance positivo de MOS, en la medida que valoriza la inclusión de pasturas y verdeos en la rotación.

A partir de estos resultados se implementaron desde 2005 una serie de proyectos de co-innovación para mejorar la sostenibilidad de los sistemas de producción familiar. La co-innovación se definió como "un enfoque que combina la teoría de sistemas complejos, el aprendizaje social y el seguimiento y la evaluación de proyectos para estimular la reorientación estratégica de los sistemas de producción familiar" (Rossing et al. 2010, Dogliotti et al. 2014, Albicette et al. 2017). Después de dos o tres años de ciclos sucesivos de análisis y rediseño en los que colaboraron investigadores, extensionistas y agricultores, los productores participantes pudieron aumentar el ingreso familiar y el ingreso familiar por hora de trabajo en un 51% y 50%, respectivamente, en promedio. El aumento de la productividad del trabajo, fue producto de mejoras obtenidas en los rendimientos de los cultivos y en la producción de carne. Las tasas estimadas de erosión del suelo en cuadros hortícolas se redujeron a la mitad (Dogliotti et al., 2014). Estas mejoras fueron posibles al abordar el predio como un todo y no enfocarse solo en componentes individuales. Los cambios específicos dependieron en gran medida de la situación particular en cada predio (Dogliotti et al., 2014). Se implementaron cambios que resultaron en un mejor desempeño económico y ambiental en la mayoría de los predios piloto (Dogliotti et al. 2014, Albicette et al. 2017).

1.3. ¿PODEMOS HABLAR DE BRECHAS DE PRODUCTIVIDAD A NIVEL PREDIAL?

Los antecedentes citados en la sección anterior, muestran que el desempeño socioeconómico, productivo y ambiental de los sistemas de producción familiar uruguayos es menor del que podrían lograr con la disponibilidad actual de recursos. Incluso en el contexto socioeconómico adverso en el que se encuentran inmersos, es posible mejorar su performance económica, social y ambiental mejorando la gestión de los recursos y la organización del sistema en su conjunto (Dogliotti et al. 2014, Albicette et al. 2017).

En la última década, muchos estudios analizaron las brechas de rendimiento para los principales cultivos y desarrollaron metodologías para comprender mejor y establecer una jerarquía para las causas de las brechas (Lobell et al. 2009, Tittonell et al. 2008, Doré et al. 2011, Scarlato et al. 2017, Berrueta et al. 2020). El desafío que enfrentan los productores es asignar sus recursos limitados entre diferentes actividades de producción para mejorar los resultados de todo el predio, lo que puede entrar en conflicto con la maximización de los rendimientos de cultivos individuales. Aumentar el rendimiento de los cultivos es una de las principales vía de mejora de los ingresos prediales pero no la única. Decisiones como ajustar el ciclo de un cultivo, acortándolo para permitir un abono verde en una rotación, puede tener un impacto inmediato de reducción de rendimientos en ese cultivo, pero contribuye a mejorar el balance de carbono en el suelo, a la regeneración de propiedades físicas y a disminuir el riesgo de erosión por generar una cobertura permanente del suelo. Estas decisiones estratégicas pueden tener impactos en un horizonte temporal mayor que un ejercicio agrícola y afectan atributos como la productividad y estabilidad contribuyendo a la sostenibilidad del predio en el tiempo.

Mejorar la organización del trabajo, balancear mejor la demanda y oferta de la mano de obra para la atención de los cultivos y animales resulta en un impacto en el sistema de producción como un todo. Detectar dónde están los cuellos de botella que explican una baja performance del predio es vital para diseñar estrategias de mejora. Aún para mejorar los rendimientos en un determinado cultivo, se requiere considerar un nivel jerárquico mayor que la escala cultivo, ya que hay factores estructurales o de organización predial que explican los resultados obtenidos en los cultivos (Berrueta, 2021). Decisiones estratégicas que involucran todo el predio como la asignación de recursos (agua, tierra, capital, trabajo) deben ser consideradas para diseñar mejoras en los distintos componentes.

La mano de obra es cada vez más, un recurso escaso, por lo que las estrategias para aumentar la producción, los ingresos familiares y reducir el impacto ambiental, deben tener en cuenta la disponibilidad de mano de obra y su productividad a nivel predial para garantizar su viabilidad (Bendahan et al. 2018, Komarek et al. 2018, Nye 2018, Moraru y Munteanu 2015, Prasad 2014). Los sistemas de producción familiar suelen se diversificados, complejidad que desafía la organización del trabajo (Darnhofer 2010, Darnhofer y Strauss 2010, Madelrieux y Dedieu 2008). Diseñar innovaciones con impacto positivo en la productividad del trabajo requiere comprender la organización del trabajo y la distribución de la mano de obra entre la diversidad de actividades y tareas desarrolladas. Esto podría facilitar la adopción de nuevas técnicas y prácticas que incrementaran la productividad de la tierra y del trabajo (Naresh et al. 2012, Houstiou et al. 2006, Petit et al. 2006).

1.4. PREGUNTAS DE INVESTIGACIÓN, HIPÓTESIS, OBJETIVOS Y ESTRUCTURA GENERAL DE LA TESIS

1.4.1. Preguntas de investigación

En los antecedentes de trabajo en predios hortícola familiares, la productividad del trabajo se identificó como un aspecto clave para mejorar la sostenibilidad de estos sistemas de producción.

1) ¿Cuánto puede mejorar la productividad de la tierra y de la mano de obra y cuánto disminuir el impacto ambiental, explotando el potencial de combinación de la ganadería con la horticultura? En otras palabras, ¿cuáles son las brechas entre los resultados prediales actuales y los alcanzables, medidos en términos de productividad, eficiencia del uso de los recursos e impacto ambiental?

2) ¿Cuáles son los factores que subyacen a la baja productividad del trabajo en predios hortícola-ganaderos?

Para responder estas preguntas, necesitamos conocer los resultados actuales de sistemas de producción hortícola-ganaderos con diferente disponibilidad de recursos y estimar cuáles son los resultados alcanzables dada una determinada disponibilidad de recursos.

3) ¿Cómo podemos reducir esas brechas?, ¿cuáles son las estrategias para diferentes tipos de predios?

1.4.2. Hipótesis

- Existe una brecha importante entre los resultados que actualmente se obtienen en los sistemas de producción y los que se podrían obtener en términos de productividad, eficiencia del uso de los recursos e impacto ambiental con los recursos actuales disponibles en los predios.
- La productividad de la tierra y del trabajo son factores clave para aumentar la sostenibilidad de los predios familiares. Es posible aumentar significativamente las dos a través de una mejor asignación de los recursos mejorando la eficiencia de su uso, sin incrementar el uso de insumos externos y reduciendo el impacto ambiental.
- Las estrategias y opciones tecnológicas para reducir estas brechas dependen fuertemente de la disponibilidad de recursos de cada sistema de producción.

1.4.3. Objetivos

Objetivo general:

Contribuir al desarrollo sostenible de los sistemas de producción familiar mediante la comprensión de las brechas entre la productividad actual y alcanzable de la tierra y la mano de obra, y el impacto ambiental de los predios hortícola-ganaderos familiares en el sur de Uruguay, y explorando y diseñando opciones para reducirlas.

Objetivos específicos:

1_Analizar el impacto de la co-innovación en la sostenibilidad de predios hortícola-ganaderos y los factores que promueven los cambios (capítulo 2).

2_Desarrollar y aplicar un método para analizar la productividad del trabajo en sistemas de producción diversificados, identificando las principales causas de la baja productividad y utilizando sus resultados para mejorar los planes de rediseño predial (capítulo 3).

3_Cuantificar las brechas prediales en términos de productividad de la tierra y la mano de obra y de impacto ambiental (balance de materia orgánica, excedente de nitrógeno y erosión estimada) en diferentes situaciones de disponibilidad de recursos, mediante el uso de modelos de simulación (capítulo 4).

4_Explorar opciones de desarrollo sostenible para la reducción de las brechas prediales en diferentes situaciones de disponibilidad de recursos (capítulo 4).

1.4.4. Estructura general de la tesis

El capítulo 1 presenta la justificación general del trabajo realizado, situando los principales problemas que enfrentan los sistemas de producción hortícola del sur de Uruguay. Se presentan los objetivos e hipótesis del trabajo.

El capítulo 2 presenta la caracterización, el diagnóstico, el re-diseño y los resultados obtenidos luego de 3 años de co-innovación en 14 sistemas de producción hortícola-ganaderos del noreste de Canelones. Se presentan los cambios constatados en la sostenibilidad de estos predios y los factores que facilitan y promueven los cambios. Se discute el aporte de la metodología implementada como herramienta para el análisis y diseño de sistemas de producción.

El capítulo 3 profundiza en el análisis de la productividad del trabajo como elemento central en la sostenibilidad de la producción familiar. En este capítulo se propone e implementa una metodología que permite identificar los principales factores que explican la baja productividad del trabajo en los predios familiares y se estima cuánto podría aumentar frente a dos escenarios; el primer escenario cuantifica el impacto de reorganizar recursos entre actividades productivas (planes de re-diseño predial propuestos) y el segundo escenario estima cuánto más podría aumentarse incorporando la mecanización en tareas específicas.

El capítulo 4 analiza las brechas de sostenibilidad en términos de productividad de la tierra y el trabajo así como el impacto ambiental de cuatro predios contrastantes en disponibilidad de recursos. Para analizar las brechas de sostenibilidad se definen distintos niveles de performance prediales: el inicial –IniFP- que surge del diagnóstico, la performance resultante luego de 3,5 años de co-innovación –ImpFP- y un tercer nivel definido como el alcanzable –AttFP-, estimado con un modelo de simulación bioeconómico, FarmIMAGES. La distancia entre la performance al final del proyecto de co-innovación y la resultante de la exploración con el modelo, se define como la brecha predial. A partir de estos cuatro predios, se discuten distintas estrategias para el desarrollo sostenible y en qué medida la disponibilidad de recursos restringe las opciones de desarrollo.

Finalmente en **el capítulo 5** se discuten los principales resultados y aprendizajes obtenidos en la investigación y su alcance. Se plantean nuevas interrogantes emergentes del proceso.

2.
HOW TO FOSTER CHANGES TOWARDS FARMS' SUSTAINABILITY? LEARNINGS FROM A CO-INNOVATION PROJECT ON VEGETABLE-BEEF CATTLE FAMILY FARMS IN URUGUAY[1]

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2.1. RESUMEN

Los desafíos actuales 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 prediales. Mejorar la sostenibilidad de los predios familiares requiere un enfoque de sistemas multiobjetivo y puede verse como un proceso evolutivo compuesto por ciclos de aprendizaje iterativos. Con estos principios en mente, participamos con trece productores familiares en un proyecto de co-innovación de 2014 a 2017. El proyecto involucró la caracterización, diagnóstico, rediseño e implementación y evaluación en los estudio de caso. Los bajos ingresos familiares, junto con la baja productividad de la mano de obra y el deterioro de la calidad del suelo, fueron los principales problemas que afectaron la sostenibilidad. Los agricultores lograron, en promedio, solo el 47% del rendimiento alcanzable en

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sus cultivos principales. Identificamos los factores de manejo de cultivos y las deficiencias de fertilidad del suelo como las principales causas de los bajos rendimientos. La producción de carne por hectárea osciló entre 69 y 239 kg ha^{-1}. Luego de tres ciclos de diagnóstico, rediseño, implementación y seguimiento, el ingreso familiar promedio aumentó 32% y la productividad del trabajo aumentó 22%. Una mayor implementación de los planes de rediseño resultó en mayor impacto en 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 co-innovación: 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 – informes de diagnóstico, árboles de problemas, tablas de puntos críticos, planes de rediseño, jornadas de campo y talleres de reflexión– facilitó la comunicación entre diferentes actores permitiendo el aprendizaje compartido. Los resultados y enfoques desafían las formas tradicionales de operar de los servicios de extensión. En Uruguay, esto significa pasar del asesoramiento predominante centrado en los cultivos a una visión de sistema predial integral que puede requerir no solo cambios en la forma en que se organiza el servicio de extensión, sino también en la mentalidad de los asesores e investigadores.

Palabras clave: Investigación participativa; Sistema de asesoramiento, Herramientas de análisis del sistema

2.2. ABSTRACT

Current global challenges for family farmers, such as deterioration of arable land and low family income, cannot be addressed by working on single farm components only. 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. With these principles in mind, we engaged with thirteen family farms in a co-innovation project from 2014 to 2017. The project involved characterisation, diagnosis, redesign, and implementation and evaluation of the redesigns in the case study farms. Low family income, together with low labour productivity and the deterioration of soils quality were the main problems impacting on-farm sustainability. Farmers achieved, on average, only 47% of the regionally attainable yield in their main crops. We identified crop management factors and soil fertility deficiencies as the main causes of low yields. Meat production per hectare ranged between 69 and 239 kg ha^{-1}. After three cycles of diagnosis, redesign, and implementation and monitoring, the average family income increased by 32% and labour productivity increased by 22%. 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 –diagnosis reports, problem trees, critical points tables, redesign plans, field days, and reflective workshops- eased communication among different actors allowing shared learning. The results and approaches challenge incumbent ways of operating of the extension services. In Uruguay, this means to shift from prevailing crop-centred advice to a whole farm system vision that may require not only changes in the way the extension service is organised but also in the mindset of advisors and researchers.

Key words: Participatory research; Advisory system, System analysis tools

2.3. INTRODUCTION

In many regions of the world family farmers are threatened by decreasing economic returns, deterioration of the natural resources base, and lack of access to markets and knowledge (IFAD 2011, Lipton 2005, World Food Programme 2013). The most common consequences impacting farm systems are: high workloads to secure family income, no or low re-investment capacity that leads to loss of capital, and lack of incentives to continue farming, which compromise farm succession and enhance deterioration of natural soil resources (Keating et al. 2010, Lobell et al. 2009).

Globally farmers need to produce more food by considering how to match objectives on natural resources conservation locally, production of healthy food and contributing to good livelihoods of family farmers (Lobell et al. 2009, Paresys et al. 2018, Tittonell and Giller 2013, Tittonell 2014, Van Ittersum 2011). To move towards more sustainable food production systems farms need to have better performance in the productive, social and environmental dimensions, which requires understanding at the farm system level.

Agricultural advisory services aim at transforming the skills, knowledge and attitudes of the people involved in farming activities. Advisory services, together with educational training and research, are components of the agricultural knowledge and innovation system (Prager et al., 2017). The complex challenges that farmers face as soil degradation, diversity loss, and high workload require innovative solutions and imply understanding the farms as complex systems (Klerkx et al. 2017, Neef and Neubert 2011, Srinivasan and Turner 2014, Sylvestre et al. 2013). The conception of a functional advisory service is to provide farmers with relevant knowledge and networks for innovation, adjustments to policies and agricultural markets (Prager et al., 2017). The predominant advisory system in Uruguay has promoted the diffusion of capital and inputs dependent technologies driven by industry-dominated technical advice. It is assumed that farmers are homogeneous, and neither structural aspects of their farms (scale) nor their objectives are considered. Public and private advisory services typically address problems at the level of farm components rather than at the level of the farm system and have failed to help farmers solve their main problems (Rossi et al. 2002, Chía et al. 2003).

Most of the Uruguayan vegetable farms (88%) are family farms, concentrated in the south of the country (Ackermann, 2016). During the last decades, the socio-economic context was unfavourable, resulting in a reduction of farm family income due to decreasing prices of products and increasing costs of energy and agrochemicals. This situation pushed most farmers to specialise and intensify their systems growing larger areas of fewer crops and increasing the use of irrigation and agrochemicals (Dogliotti et al., 2014). Soil degradation was aggravated due to intensive tillage, limited soil cover and organic matter supply, and lack of erosion control measures (Alliaume et al. 2013, García De Souza et al. 2011).

The co-innovation projects implemented in Uruguay over the past 15 years proved that even under adverse socio-economic conditions farmers were able to enhance their productivity by improving resource management and whole-farm organisation (Albicette et al. 2017, Dogliotti et al. 2014). In projects with vegetable family farmers, Dogliotti et al. (2014) reported increases in family income and labour productivity of 51% and 50%, respectively on average, while estimated soil erosion rates were halved. Working with beef-cattle family farmers, Albicette et al. (2017) reported a 24% increase in meat production, a 58% increase in the biomass production of natural grasslands 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, and 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 the 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 (Albicette et al. 2017, Colnago and Dogliotti 2020, Dogliotti et al. 2014, Rossing et al. 2021). Conceptually co-innovation combines complex adaptive systems thinking with social learning and reflexivity based on monitoring and evaluation, involving different actors (Klerkx et al. 2017, Neef and Neubert 2011, Rossing et al. 2021).

Here we report on a co-innovation project with thirteen farm families that ran from 2014 until 2017 to improve farming sustainability. We describe the main changes implemented and analyse the key enabling factors. Finally, we discuss which could be essential ingredients for a systemic way of working with farmers, to improve actual predominant advisory services approach to agricultural extension.

2.4. MATERIALS AND METHODS

2.4.1. Selection of case study farms

The research strategy was based on case studies (Johansson, 2003) selected to represent the variation in resource availability in the northeast of Canelones (Lat -34,346/-34,546 – Long -55,579/-55,873 range), in the south of Uruguay. The case study methodology allows studying complex systems in the context in which they work, and for which experimental control is not desirable or possible.

Farm selection followed a participatory process involving two local farmers' organisations located in the northeast of Canelones, SFR Arenales and SFR Migues, and the project research team. Forty farmers proposed by the farmers' organisations were visited, and fourteen family farms (7 in Arenales and 7 in the Migues region) were selected, taking into account 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, the share of beef cattle in farm gross product, soil types, availability of family labour and hired labour, amount of irrigation 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 the process done with thirteen farms.

2.4.2 Co-innovation cycle

The co-innovation cycle (Dogliotti et al., 2014) 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 in terms of two interacting subsystems: management and production. The management subsystem is composed of the people who make decisions on the farm, their objectives, perspectives and decision criteria, and roles, including the amount of labour they contribute (Dogliotti et al., 2014). We collected data by direct observations during the bi-weekly monitoring visits and through a semi-structured interview performed at the end of each visit (Colnago and Dogliotti 2020).

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). This information was provided by technical advisors working with farmers or taken from research results for the region (Berrueta et al. 2020, Dogliotti et al. 2014, Scarlato et al. 2017).

For the sustainability assessment, we used the MESMIS framework (Masera et al., 2000) adapted to vegetable and vegetable-livestock systems in Southern Uruguay by Dogliotti et al. (2014). Critical points were identified, and a problem tree was drawn for each farm. The diagnosis results were presented and discussed with each farm family.

Based on the diagnosis, we developed redesign plans for each farm to improve sustainability. The redesign method comprised six steps (Dogliotti et al., 2014): the adjustment of field layout and erosion control support practice; 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. The same frequency of visits was maintained during the implementation stage. Three cycles of diagnosis-redesign-implementation and monitoring were completed.

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.

2.4.3. Learning support activities

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.

Bi-weekly visits by the research team to each farm were maintained throughout the project. The common routine during the visits was for the technical advisor and the farmers to go around the entire farm together, and then to sit down to discuss the observations. The advisor previously planned the content of each visit according to the stage of the co-innovation process and the redesign plan.

For the discussions of the diagnosis and the farm redesign plan, and the annual evaluation of the farm results, the entire research team accompanied the technical advisor to the farm. The discussion of the diagnosis had the goal of building a common vision of the farm system and reaching agreement on the main problems and the general strategy to alleviate them. During the visit to discuss the farm redesign plan, the research team presented the main changes and the actions needed to implement them. The redesign plans were modified as a result of the ensuing discussions. Every summer, results of the implementation of redesign plans were presented and discussed in a meeting between the research team, the technical advisor and the farm family. During these meetings, adjustments to the redesign plans were discussed.

Three field days were organised: in November 2015, in December 2016, and in April 2017, during which farmers and other stakeholders were invited to visit one (or two) of the case study farms. Purposes of the field days were to foster the exchange of experiences and learnings among farmers based on the discussion of concrete examples of changes implemented and results obtained in the host farms, and sensitising to different organisation leaders invited about 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 (in February 2016 and February 2017) with the participation of farmers, local farmers' organisations' representatives, the technical advisors, and the research team. The objectives were to reflect on the changes that occurred and to plan the next steps, and also to encourage the interchange of experiences and learning among farmers. A facilitator from the research team recorded all the comments and the evaluation done by the farmers. Besides to evaluate the impact on sustainability, during the reflection workshops, we asked ourselves how the changes were facilitated. Farmers reflect around the questions: *What were the main contributions of the project? What things did run well and which not?*

2.5. RESULTS

2.5.1. Characterisation of vegetable-livestock farm systems in northeast Canelones

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 farm made cheese, and five farms sold surplus hay bales. Most vegetable products were sold through intermediaries in the main wholesale market in Montevideo. Beef cattle were sold to other farmers, local cattle markets, and slaughterhouses. All farmers had cow-calf systems and one farm complete cycle system. Most farmers sold calves between 180 to 250 kg live weight, and few of them also sold steers between 300 and 500 kg live weight.

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

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 as a general criterion they tried not to grow the same crop in the same plot more than twice in a row.

Water availability for irrigation was a limited production resource. Main water sources were polders or small excavated ponds for animal consumption. Water was reserved for greenhouse crops.

The main field crops were onion and sweet potato, and tomato and sweet pepper in greenhouses. Beef-cattle grazed on uncultivated plots, mixed grass-legume multi-year pastures or forage crops: oats in winter and moha and sorghum in summer. Alfalfa was mainly grown to make bales. Sowing pastures and forage crops represent 40% of the grazing area, on average. The cultivated vegetable area was hardly rotated with pastures or alfalfa areas.

Table 1. Characterisation of the case study farms

Farm	Area (ha)	Veg area (ha)	GH[1] area (m^2)	Irrig. area (ha)	Crops (#)	Forage crops (ha)	Cattle (CU) [2]	Predominant soil type ([3])	Family labour ($hr\ yr^{-1}$)	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.

All farmers defined themselves as vegetable growers, seeing beef-cattle as a complementary activity, even in those farms where the beef-cattle gross product was similar or even larger than that of vegetables (farms 11 and 13). The predominant system was cow-calf with continuous mating. The bull remained with the herd during the whole year, which led to early pregnancy of heifers, very low pregnancy rates of primiparous cows, and calving occurring during long periods of the year. Control over weaning varied and in most farms, male and female calves stayed with the cow up to a year. The use of 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 in terms of the predominant farmers' strategy to use beef-cattle herds as a saving account and for self-consumption.

2.5.2 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 I/O ratio on average was low (0.53), even on farms where vegetable production accounted for most of the gross product. In vegetable production, usually purchased inputs are higher than in beef cattle production (Table 2, farms 6, 7, 8, and 9). Low I/O ratio was strength and indicated a moderate use of external inputs (Table 3).

Family income was low. The average income per family member was above the per capita average income for rural areas on only five farms (Table 2 and 3). Low family income was explained by low labour productivity, both in vegetable and livestock production, low amount of production, and high production cost in beef-cattle (Table 2, Figure 1). Labour productivity was compared with the opportunity cost of labour, calculated as the cost of hiring labour. At the beginning of the project, only four farms obtained labour productivity higher than the opportunity cost.

Low production of vegetable crops was due to low yields and in some farms due to small cultivated areas. Farmers achieved, on average, 47% of the attainable yield in their main crops; only three farms exceeded 50% (Table 2). We identified crop management factors and deterioration of soil fertility as chief causes of low yields (Figure 1). The most frequent problems with crop management were delays in planting dates affecting the growth duration of the crops and in weed management, and failures to control diseases and pests. Delays were explained by mismatches between the demand and supply of labour. The proportion of the cultivated area under irrigation in farms without greenhouse was lower than 20%, representing a weakness since it affected productivity, compromised the stability of yields as well as the adaptability, reliability, and resilience of farms.

Loss of soil fertility was the main environmental problem affecting not only crop productivity but also farm stability (Table 3). The lack of soil conservation support practices, continuous tillage of vegetable fields, long periods of bare soil, as well as negative soil organic matter balances explained loss in soil structure and low soil carbon contents (Tables 3).

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

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

In general, farmers 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 associated with harvesting, sorting, and packing during the summer, 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; two farmers rested only 2 days a month and one week a year, and one 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, and they were used to attending recreational activities frequently organised by these organisations (Table 3). In average the thirteen farms worked 19% more than estimated supposing a base of a "full-time equivalent" (FTE) estimated as 300 days of work and 8 hours a day.

We identified as strength the level of diversification in productive activities for most farms (Table 2). Only three farms presented a Ginni index value higher than 0.50 (Table 3).

No farm had long-term liabilities, and only two farms had short-term debts; farm 3 due to the purchase of a new field, and farm 8 for enlarging the greenhouse area. Both farms settled the debts within the first year of the project.

Farmers had a low level of formal education and low non-formal training and kept very few records on production (Table 3).

A common strength was their social integration into groups that facilitated access to state plans and programs. All farmers were linked to farmer organisations, and several were beneficiaries of subsidies and/or payment facilities for the acquisition of machinery, for the expansion of irrigation capacity and the expansion of the greenhouse area. Social integration into groups and low use of credit were strong points regarding farms' self-reliance.

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

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, Ginni index, meat production and percentage ranges of mineralisable organic carbon lost compared to similar soils not 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*10^3

[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 (Dogliotti et al. 2014; Scarlatto M. 2017; Berrueta et al., 2019).

[8] GI: Gini index based on the allocation of area per crop. Ginni Index = $\sum$((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 (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-Precház (2007).

*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	3.5 ha
			Greenhouse area (median)	0.28 ha
			Cattle units (median)	26
	Economic efficiency	(-) Low family income	FI per capita	99700 \$ $year^{-1}$
			FI / Average income INE ([1])	0.59
		(-) Low income per hour of labour	FI per hour of labour	89 \$ $hour^{-1}$
			FI per hour/labour opportunity cost	0.89
		(-) Low labour productivity (LP)	LP_veg	136 $/hora
			LP_beef	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 index[2]	1 farm = 1; 8 farms = 2; 5 farms=3
		(+) Most fams in transition	Farm succession stage[3]	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 expected or possible, 1 = possible but not defined yet, 2 = defined or in transition to next generation

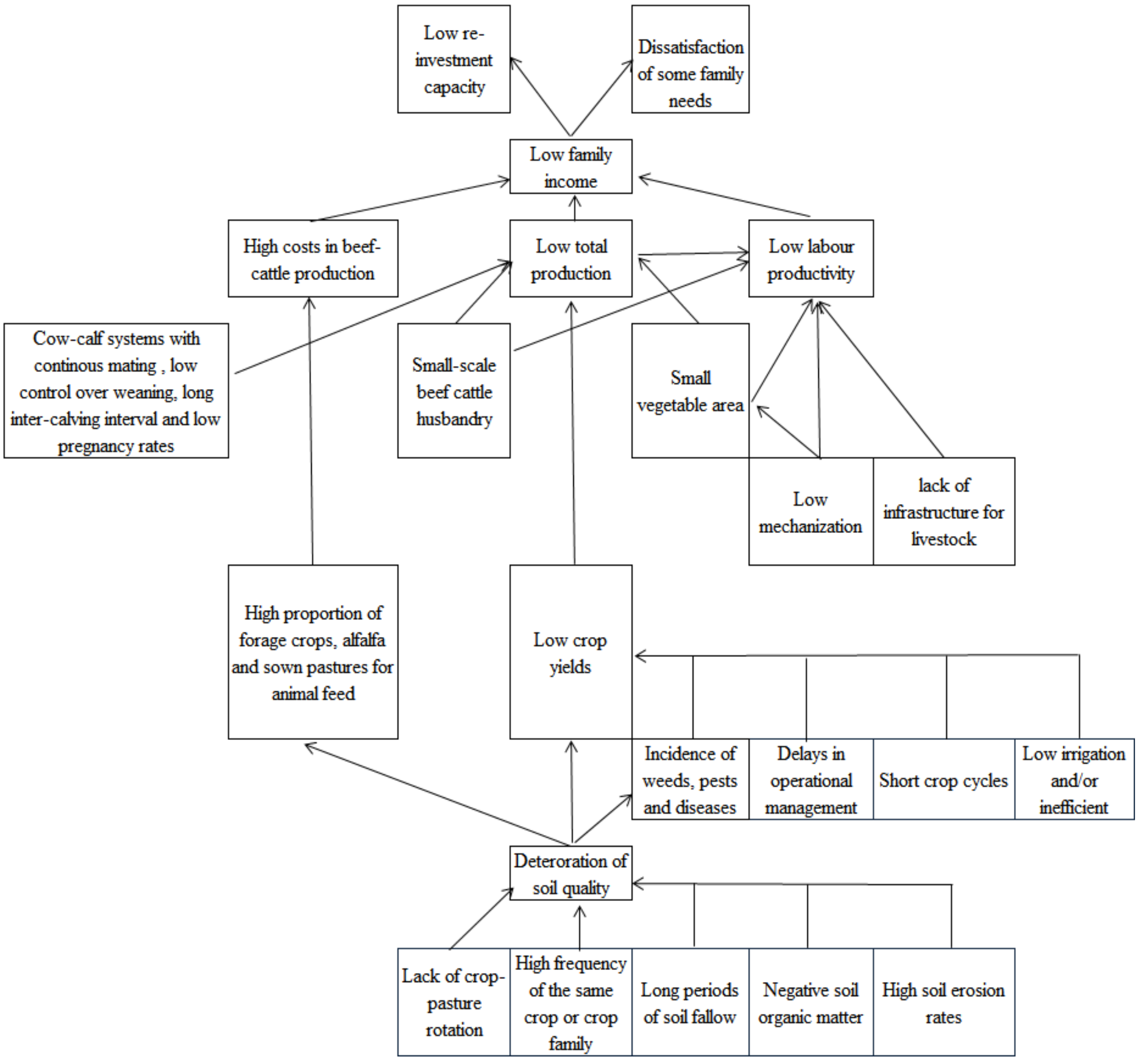

Figure 1. Problem tree for the thirteen case study farms in northeast Canelones

2.5.3. Redesign of farm systems

Redesign plans included the adjustment of field layout and erosion control support practices, changes in crop choice, cultivated area, and crop and soil management practices. In some farms, 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. In these farms, we proposed to reduce areas and remove some crops (8 farms). We also suggested improvements in greenhouse infrastructure.

We designed crop rotations taking into account soil quality in each field. We introduced pastures in the vegetable rotation whenever possible to improve carbon balance and reduce average erosion rates. We proposed activities for intercrop periods to improve soil chemical and physical quality, such as green manures and cover crops and applications of animal manure, and compost (Tab. 5). In farm 3, reduced tillage combined with a cover crop kept as organic mulch for melon and squash crops was introduced. 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 cattle production, redesign plans included increasing forage production through better grazing management, adjusting stocking rates, and by increasing the area of forage crops and grass&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 took into account existing farm resource endowment, particularly related to labour.

2.5.4. Implementation of redesign plans and impact on farm sustainability

All farms implemented more than 50% of the main changes included in the redesign plans. Six farms implemented 70% or less, and only three farms implemented more than 80%. Changes related to crop management had the highest levels of implementation. Crop rotations were the most difficult change to implement by farmers. However, all farmers introduced and implemented green manure crops in the intercrop periods (Table 5). Implementation of elements from the redesign plans was positively related to FI, FI hour, and crop yields (Figure 2).

2.5.5. Impact of co-innovation on sustainability indicators

The volume of vegetables produced increased in ten out of thirteen farms, by on average 47% (Table 5). This increase was explained by yield increase and by the increase in the cultivated area. Yields increased in eleven farms, by 35% on average, and fell in two 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 on 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 (Table 5).

The vegetable area increased in ten farms where the initial area was small (Table 1), and it reduced in three farms. Greenhouse area increased 26.5% (farms 1, 5, 6, 7, and 8). Farm 2 did not increase the area but improved the pre-existing infrastructure. In farms 10 and 13, the production decreased as a consequence of the decrease in the area (both) and yields (farm 10). Farm 10 had the lowest level of implementation of the redesign plan (Table 5), 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 eight farms, and a decreased in two. Meat production increased in four farms and fell in 7 (Table 5).

Vegetable gross product (GP) increased 38% (Table 5) and the livestock gross product increased in 7 cases, remained almost the same in 1 and decreased in 3. The average balance was an 8% increase in meat production and a 40% increase in livestock gross product. The contribution of livestock in total gross product remained unchanged in eight farms, increased 20% or more in two, and decreased 15% on one farm.

Family income increased by 57% on average in nine farms and decreased by 23% in four farms. The family income per hour of work (IF/h) increased in ten farms and fell in three (Table 5). 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 reduced further than open field crops -29 % and 18% respectively- (CAMM, 2020).

Table 4. Degree of implementation (0 to 1) of activities proposed in the plans for each farmer, evaluated at the end of the project. Data only appears if the activity was included in the plan presented to each farm

	Farm nº													
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 in vegetable cultivated 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 choise	0.75	1	1		1			0.25	1		0.5	1	0.75	0.81
Soil management:														
- design crop rotations adding pastures or alfalfa when possible	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 sistematization	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
- fertilization; 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	

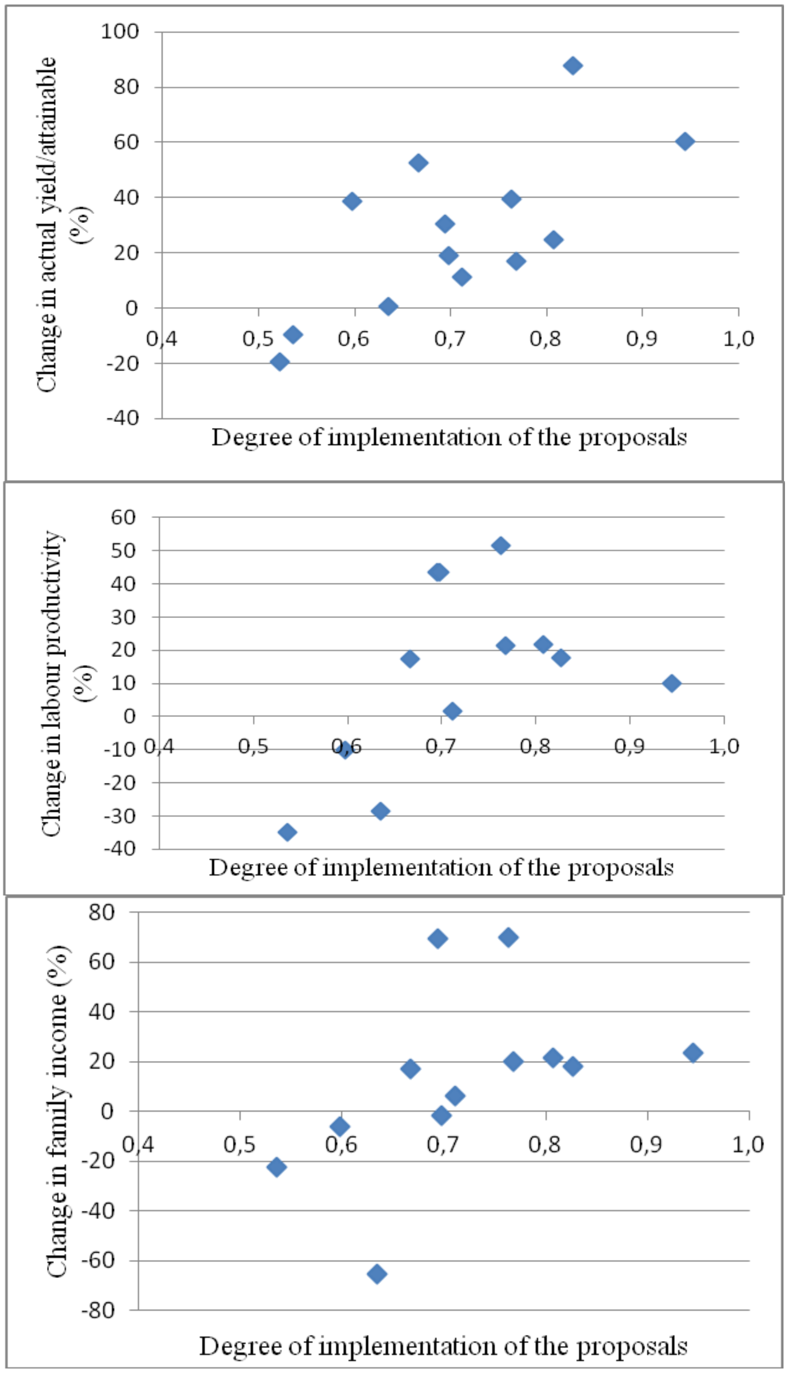

Figure 2. Relationship between changes in actual yield/ attainable yield, labour productivity and family income according to the degree of adoption of the proposals

Table 5. Changes in the main indicators at the end of the co-innovation project. The value obtained for the average of the last two years, 2015-17, is compared to the average of the first two years, 2013-15, according to: (Average final value – average initial value)/ Average initial value * 100

Farm	Veg production	Yields	Veg area	Forage area	Meat production	GPveg	GPmeat	Family Income	FI hour	GI	I/O
1	46.4	18.9	98.3	50.0	-30.5	23.9	-70.3	-0.2	45.3	-0.52	6.1
2	12.4	16.8	30.9	66.7	22.3	22.9	-3.8	21.1	22.6	-0.26	1.8
3	69.2	60.4	14.6	334.3	176.4	23.8	625.9	25.0	11.5	-0.04	8.4
4	42.5	-9.5	0.82	22.3	-6.8	-16.8	131.1	-21.8	-34.3	-0.01	15.6
5	263.0	52.7	126.2	36.2	29.1	86.5	148.6	18.7	18.9	-0.09	14.9
6	20.7	87.6	80.0	-7.5	-99.9	21.0	92.6	19.4	19.2	-0.10	4.8
7*	147.9	30.4	16.0	---	---	58.0	---	71.2	45.3	0.09	-9.0
8*	22.0	24.7	45.0	---	---	24.0	---	22.8	22.8	0.66	8.9
9	-2.8	39.4	-33.1	188.6	-18.5	43.9	23.9	72.6	53.9	0.01	-4.2
10	-31.2	-19.4	-5.5	-1.5	-47.9	-48.0	-10.4	253.2	113.9	-0.33	-8.7
11	20.6	11.2	16.7	69.6	-13.1	-0.6	25.5	7.6	2.6	-0.19	9.4
12	43.7	38.6	30.2	8.1	87.9	-2.8	57.4	-5.2	-9.0	0.07	6.9
13	-25.6	0.7	-11.5	1.2	-11.0	-40.8	0.6	-65.1	-27.6	0.04	53.9

*For Farms 7 and 8, livestock is for self-consumption.

2.5.6. Changes identified and experienced by farmers

When farmers met to evaluate the co-innovation process, they identified the way to be related to technical advisors and the way they worked -the importance of the advisor visits and their frequency and going around the farm together-, as key aspects the project contributed. The second aspect mentioned was the changes implemented in their farms. Among them, they highlighted improvements in erosion control measures and layout of fields, increased yield of crops, improvements in soil management, soil tillage, crop nutrition, and the introduction of green manure crops.

We identified an inflexion point after the first reflection workshop in 2016. Farmers' aimed to have more organised farms with better economic outcomes and with a lower workload. Farmers recognised difficulties to follow the redesign plans; *"we did not know how to do it"*. At the end of the project, they had gained a method to work and demand the type of technical advice the project contributed.

They also said: "*at the beginning, we did not know each other. The advisor asked a lot of questions about crops and animals, 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 together the plan when the advisors come with a complete pre-defined plan is not the same"; "I think more farmers would like to engage in this type of technical assistance*". They asked themselves how to continue after the project ends since they would not be able to afford the technical assistance individually.

Besides these improvements, they identified the introduction of bookkeeping as a big 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 involved took advantage to observe and discuss in-situ some practices and its result. Advisors gained trust in their work, and it was an opportunity to spread out not only the results but also the way of working of a co-innovation project to the community, creating legitimacy for the approach by enabling the case study farmers to tell their story.

2.6. 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 (Dogliotti et al. 2014, Albicette et al. 2017), and on family farms worldwide: low family income and labour productivity, and soil degradation (Lipton 2005, Lobell et al. 2009, Keating et al. 2010, IFAD 2011, World Food Programme 2013)

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

As management problems - a functional farm trait - we found a poor interaction between beef-cattle and vegetable production, partially explained by infrastructure limitation like availability of fences (interacting with structural factors –Farms 2, 4, 5, 11 and 13-). Farmers underutilised the potential benefit from long crop&pasture rotations since they did not rotate between vegetable and pasture fields. A high share of pastures in the rotation decreases soil erosion and increase soil organic matter balance (Díaz-Zorita et al. 2002, García-Préchac et al. 2004, Ernst and Siri-Prieto, 2009).

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

The results of our study are consistent with previous co-innovation projects. On average substantial increases could be achieved in family income (here: 32% compared to 51% reported by Dogliotti et al. (2014) and 69% reported by Albicette et al., (2017)) and in family income per hour of labour (here: 22% compared to 50% reported by Dogliotti et al. (2014)). Although the overall workload remained high

(19% higher than a full-time equivalent per worker, it was lower than 25% reported by Dogliotti et al. (2014). Albicette et al. (2017) reported a 25% decrease in workload. 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 investments.

During the characterisation and diagnosis stages of the project, we identified a lack of knowledge of available technologies and some common management practices (crop nutrition, density, planting dates). While still engaged in characterisation and diagnosis, the research team allocated considerable time to improving basic management skills by introducing changes in crop practices and technologies. This helped to build trust between farmers and researchers.

Comparing contrasting farms according to the degree of plan implementation (farms 3 and 6 against farms 4 and 10) they differed in the type of changes implemented. Changes that impact in the system structure like removing or adding a new crop had a degree of implementation ranged from 0.75 to 1 in farms 3 and 6 against 0.25 to 0.75 in farms 4 and 10 (Table 4). Changes planned and implemented that affected organisational issues also differed between these groups, mainly those that involve many resources and that require a systemic view of the farm. Implementation of crop rotation entails adjusting many crops growing cycles where the management and organisational' farmers skills and a long-term perspective matter.

The redesign plans were based on the agreements obtained during diagnosis discussion and with the general strategy of change. Hence, changes included in the plans respond not only to the problems identified by the research team but also to what a priori the farmers were willing to carry out that was reflected in each proposal profile (table 4). The farm redesign plans were founded on scientific and 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 (Klerkx et al. 2017, Rossing et al. 2021).

Complex problems are difficult to identify and require complex solutions which support the need to provide technical support to farmers (Pacín and Oesterheld 2015, Farrell et al. 2008). The technical assistance, the methods deployed, and the share among peers fostered through the project facilitated and promoted the on-farm innovation process. The methodology carried out provides a framework that is nourished by different contributions of knowledge, the technical, the scientific, and the farmer's experience to innovate (Farrell et al. 2008, Klerkx et al. 2017).

Co-innovation has been described as the interaction among 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 (Fielke et al. 2017, Klerkx et al. 2017). A common thought among co-innovation projects is the need for a systemic approach that considers all the components, interactions among them, and the socio-economic environment surrounding each farm, to tailor-made solutions instead to adjust single parts of the system (Klerks et al. 2017, Rossing et al. 2021, Dogliotti et al. 2014, Albicette et al. 2017, Colnago and Dogliotti, 2020).

Innovation is based on the integration of ideas from different sources of knowledge and actors involved (Prager et al., 2017). The strategy followed in this study, applying various system analysis tools to promote learning –diagnosis reports, problem trees, critical points tables, redesign plans, field days, and reflective workshops- eased effective communication among different actors (farmers, advisors, research team, local government actors) allowing that innovation to take place (Clark et al. 2016, Ditzler et al. 2018, Farrell et al. 2008, Reed et al. 2010).

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

Participatory research approaches and methods are essential when working with complex systems, in dynamic environments and facing up current challenges (Klerkx et al. 2017; Rossi 2011; Neef and Neubert 2011). The institutional context - understood as was defined by Klerkx et. al. (2017); "*the environment in which the sets of norms, rules, routines or shared expectations are present and govern actors'* *behaviour"* - plays a key role in enabling or not participatory projects and affecting their effectiveness.

The advisory or extension service has the challenge to apply approaches to handle complex systems and to develop strategies to ease the dialogue between different actors and foster their learning (Farrell et al. 2008, Birner et al. 2009, Leeuwis and Aarts 2010, Prager et al. 2017, Klerks et al. 2017). In Uruguay, this means to shift from prevailing crop-centred advice to whole farm system vision that implies not only institutional changes but also changes in the mindset of advisors, researchers and farmers themselves (Dogliotti et al. 2012, Rossi 2011, Farrell et al. 2008). During the co-innovation project, the technologies introduced in redesign proposals were similar among farmers. Still, strategies widely differed, reinforcing the idea of farm systems innovation perspective and the need for a tailor-made farm management strategy. Each agent (farm family) should be involved in selecting the required technologies or artefacts that bring about improvements in farms performance (Darnhofer et al. 2016, Dogliotti et al. 2014, Neef and Neubert 2011). As we learned from different co-innovation experiences, the key aspects to scale out this approach and contribute to enhancing farm sustainability are:

- Local actors should be empowered to plan and implement their improvements. The success depends on high levels of engagement and participation of farmers and advisors. For this to happen, farmers have to recognise the contribution that advisors can make in improving farm performance by supporting strategic thinking. The degree of implementation of farm plans could be a useful indicator to identify their engagement and commitment (Farrell et al., 2008).
- Farmers do not demand a whole-farm centred and systemic advisory service since as they explained during the reflection workshop, it is not known to them either its existence or its potential contribution to improving their farms. Therefore dissemination is key. The field days during project development are a good example of dissemination activities where farmers and other stakeholders can observe, ask and meet between peers. Likewise, to exercise voice and formulate demand is important to improve the quality of advisory services (Birner et al., 2009).

- Sustainability improvement is an evolutionary process composed of continuous learning cycles (Groot and Rossing, 2011). To be successful, any change strategy should be adapted to the local agro-ecological and socio-economic conditions of the farm (Farrell et al. 2008, Birner et al. 2009, Prager et al. 2017). 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 advisors as main participants (Dogliotti et al. 2014, Albicette et al. 2017).
- Technical advisors' knowledge and training is 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 (Rossi et al. 2002, Farrell et al. 2008, Birner et al. 2009, Prager et al. 2017).
- Trust-building between farmers and technical advisors takes time to build. 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 (Rossi et al. 2002, Farrell et al. 2008).
- Clear standards are required to monitor and regularly evaluate any advisor service. It is important to set objectives for short, medium, and long-term and to define indicators and procedures to monitor and assess their progress, including the economic, social and environmental goals pursued by the farmers and other stakeholders.

2.7. REFERENCES

Ackermann N. 2016. Horticultura: situación y perspectivas. Anuario OPYPA (Oficina de Programación y Política Agropecuaria). (En línea). Consultado 10 de noviembre de 2020. Disponible en: https://descargas.mgap.gub.uy/OPYPA/Anuarios/Anuario%202016/anuario_opypa_2016_en_baja.pdf

Albicette MM, Leoni C, Ruggia A, Scarlato S, Blumetto O, Albín A, Aguerre V. 2017. Co-innovation in family-farming livestock systems in rocha, Uruguay: A 3-year learning process. Outlook on Agriculture. 46: 92–98. doi:10.1177/0030727017707407

Alliaume F, Rossing WAH, García M, Giller KE, Dogliotti S. 2013. Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms. European Journal of Agronomy. 46: 10–19. doi:10.1016/j.eja.2012.11.005

Berrueta C, Heuvelink E, Giménez G, Dogliotti S. 2020. Estimation of tomato yield gaps for greenhouse in Uruguay. Scientia Horticulturae. 265, 109250. doi:10.1016/j.scienta.2020.109250

Birner R, Davis K, Pender J, Nkonya E, Anandajayasekeram P, Ekboir J, Mbabu A, Spielman DJ, Horna D, Benin S, Cohen M, 2009. From best practice to best fit: A framework for designing and analyzing pluralistic agricultural advisory services worldwide. The Journal of Agricultural Education and Extension. 15(4): 341–355. doi:10.1080/13892240903309595

CAMM (Comisión Administradora del Mercado Modelo). 2020. Información estadística de volúmenes, precios e índices del comercio de frutas y hortalizas frescas en el Mercado Modelo (En línea). Consultado 10 de octubre de 2020. Disponible en: http://www.mercadomodelo.net/planillas;jsessionid=C70945471B1C8D0837F121A0BC662D7E

Caniglia G, Schäpke N, Lang DJ, Abson DJ, Luederitz C, Wiek A, Laubichler MD, Gralla F, von Wehrden H. 2017. Experiments and evidence in sustainability science: A typology. Journal of Cleaner Production. 169: 39–47.

doi:10.1016/j.jclepro.2017.05.164

Chía E, Testut M, Figari M, Rossi V. 2003. Comprender, dialogar, coproducir: reflexiones sobre el asesoramiento en el sector agropecuario. Agrociencia Uruguay 7(1): 77–91.

Clark WC, Van Kerkhoff L, Lebel L, Gallopin GC. 2016. Crafting usable knowledge for sustainable development. Proceedings of the National Academy of Sciences 113: 4570–4578. doi:10.1073/pnas.1601266113

Colnago P, Dogliotti S. 2020. Introducing labour productivity analysis in a co-innovation process to improve sustainability in mixed family farming. Agricultural Systems. 177: 102732. doi:10.1016/j.agsy.2019.102732

Darnhofer, Ika Lamine, Claire Strauss AN, Mireille N. 2016. The resilience of family farms: Towards a relational approach. J. Rural Stud. 44: 111–122. doi:10.1016/j.jrurstud.2016.01.013

Díaz-Zorita M, Duarte GA, Grove JH, 2002. A review of no-till systems and soilmanagement for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil and Tillage Research. 65: 1–18.

Ditzler L, Klerkx L, Chan-Dentoni J, Posthumus H, Krupnik TJ, Ridaura SL, Andersson JA, Baudron F, Groot JCJ. 2018. Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation. Agricultural Systems. 164: 20–30. doi:10.1016/j.agsy.2018.03.006

Dogliotti S, García MC, Peluffo S, Dieste JP, Pedemonte AJ, Bacigalupe GF, Scarlato M, Alliaume F, Alvarez J, Chiappe M, Rossing WAH. 2014. Co-innovation of family farm systems: A systems approach to sustainable agriculture. Agricultural Systems. 126: 76–86. doi:10.1016/j.agsy.2013.02.009

Dogliotti S, Colnago P, Favretto G, Fernández JL, Morales G, Riet L, Sierra F, Vieta A. 2012. Co-innovando para una agricultura más sostenible: apoyando el desarrollo de un sistema de extensión para la agricultura familiar. En: 1er congreso de ciencias sociales agrarias. "Desafíos y contribuciones para el desarrollo rural"’(1º, 2012, Montevideo-Uruguay). 16p

Durán A, García Préchac F. 2007. Suelos del Uruguay, Origen, Clasificación,

Manejo y Conservación. Vol. II. Montevideo: Hemisferio Sur. 358 p.
Ernst O, Siri-Prieto G. 2009. Impact of perennial pasture and tillage systems on carbon input and soil quality indicators. Soil and Tillage Research. 105 (2): 260–268,http://dx.doi.org/10.1016/j.still.2009.08.001.
Farrell M, Mcdonagh J, Mahon M. 2008. The Options for Farm Families Programme: Rhetoric and Reality of Change Maura. The Journal of Agricultural Education and Extension. 15: 39–58.
Fielke S, Nelson T, Blackett P, Bewsell D, Bayne K, Park N, Rijswijk K, Small B. 2017. Hitting the bullseye: Learning to become a reflexive monitor in New Zealand. Outlook Agriculture. 46: 117–124. doi:10.1177/0030727017708490
García De Souza M, Alliaume F, Mancassola V, Dogliotti S, 2011. Carbono orgánico y propiedades físicas del suelo en predios hortícolas del sur de Uruguay. 15 (1): 70–81.
García-Préchac F, Ernst O, Siri-Prieto G, Terra JA. 2004. Integrating no-till intocrop and pasture rotations in Uruguay. Soil and Tillage Research. 77: 1–13. doi.org/10.1016/j.still.2003.12.002
Groot JCJ, Rossing WAH. 2011. Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. Methods in Ecology and Evolution. 2: 643–650. doi.org/10.1111/j.2041-210X.2011.00114.x
IFAD (International Fund for Agricultural Devolopment), 2011. Rural Poverty Report.New realities, new challenges: new opportunities for tomorrow's generation (En línea). Consultado 10 de noviembre de 2019. Disponible en: 2020https://reliefweb.int/sites/reliefweb.int/files/resources/0761B50B87EC879BC12577F10051867C-IFAD_Dec2010.pdf
Johansson R. 2003. Case study methodology. En: International Conference "Methodologies in Housing Research" (2003, Stockholm). The Royal Institute of Technology and the International Association of People–Environment Studies.14p
Keating BA, Carberry PS, Bindraban PS, Asseng S, Meinke H, Dixon J. 2010. Eco-efficient agriculture: Concepts, challenges, and opportunities. Crop Science. 50:109-119. doi:10.2135/cropsci2009.10.0594

Klerkx L, Seuneke P, de Wolf P, Rossing WAH. 2017. Replication and translation of co-innovation: The influence of institutional context in large international participatory research projects. Land use policy 61: 276–292. doi:10.1016/j.landusepol.2016.11.027

Leeuwis C. Aarts N. 2011. Rethinking communication in innovation processes: creating space for change in complex systems. The Journal of Agricultural Education and Extension 17(1):21-36. Doi: 10.1080/1389224X.2011.536344

Lipton M. 2005. The family farm in a globalizing world: The role of crop science in alleviating poverty. 2020 Discussion Paper No. 40. International Food Policy Research Institute (En línea). Consultado 10 de noviembre de 2019.Disponible en: http://cdm15738.contentdm.oclc.org/utils/getfile/collection/p15738coll2/id/59428/filename/59429.pdf

Lobell DB, Cassman KG, Field CB. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annual Review of Environment and Resources. 34: 179–204. doi:10.1146/annurev.environ.041008.093740

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

Neef A, Neubert D. 2011. Stakeholder participation in agricultural research projects: A conceptual framework for reflection and decision-making. Agriculture and Human Values 28: 179–194. doi:10.1007/s10460-010-9272-z

Nye C. 2018. The ‘blind spot’ of agricultural research: Labour flexibility, composition and worker availability in the South West of England. Cahiers Agricultures. 27: 35002. doi:10.1051/cagri/2018018

Pacín F, Oesterheld M. 2015. Closing the technological gap of animal and crop production through technical assistance. Agricultural Systems 137: 101–107. doi:10.1016/j.agsy.2015.04.007

Paresys L, Saito K, Dogliotti S, Malézieux E, Huat J, Kropff MJ, Rossing WAH. 2018. Feeding the world while reducing farmer poverty? Analysis of rice relative yield and labour productivity gaps in two Beninese villages. European

Journal of Agronomy. 93: 95–112. doi:10.1016/j.eja.2017.10.009

Prager K, Creaney R, Lorenzo-Arribas A, 2017. Criteria for a system level evaluation of farm advisory services. Land use policy 61: 86–98. doi:10.1016/j.landusepol.2016.11.003

Reed MS, Evely A.C, Cundill G, Fazey I, Glass J, Laing A, Newig J, Parrish B, Prell C, Raymond C, Stringer LC. 2010. What is social learning? Ecology and Society. 15(4), 1-10 doi:10.5751/ES-03564-1504r01

Rossi V, Nougué M. 2002. Impacto de una metodología de asesoramiento técnico alternativo en sistemas de producción lechera familiar. Agrociencia Uruguay 6: 61–74.

Rossi V. 2011. Aportes metodológicos para el asesoramiento técnico y la extensión rural. Cangüé. 31: 51–60.

Rossing WAH, Albicette MM, Aguerre V, Leoni C, Ruggia A, Dogliotti S. 2021. Crafting actionable knowledge on ecological intensification: Lessons from co-innovation approaches in Uruguay and Europe. Agricultural Systems 190: 103103. doi:10.1016/j.agsy.2021.103103

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

Scarlato M, Gimenez G, Lenzi A, Borges A, Bentancur O, Dogliotti S. 2017. Análisis y jerarquización de factores determinantes de las brechas de rendimiento del cultivo de frutilla en el sur del Uruguay. Agrociencia Uruguay. 21(1):43-57.

Srinivasan, M.S., Turner, J.A., 2014. Addressing complex challenges using a co-innovation approach : lessons from five case studies in the New Zealand primary sector. Outlook on Agriculture. 46(2): 108-116. doi:10.1177/0030727017712321

Sylvestre D, Lopez-Ridaura S, Barbier JM, Wery J. 2013. Prospective and participatory integrated assessment of agricultural systems from farm to regional scales: Comparison of three modeling approaches. Journal of Environmental Management. 129, 493–502. doi:10.1016/j.jenvman.2013.08.001

Tittonell P. 2014. Ecological intensification of agriculture-sustainable by nature.

Current Opinion in Environmental Sustainability. 8:53–61.

Tittonell P, Giller KE. 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research. 143: 76–90. doi:10.1016/J.FCR.2012.10.007

van Ittersum, M.K., 2011. Future harvest, the fine line between myopia and utopia. Wageningen University. https://edepot.wur.nl/169680

World Food Programme, 2013. The World Food Programme' s Achievements in 2013 (En línea). Consultado en agosto 2019. Disponible en: https://publications.wfp.org/en/apr/2013/

3
INTRODUCING LABOUR PRODUCTIVITY ANALYSIS IN A CO-INNOVATION PROCESS TO IMPROVE SUSTAINABILITY IN MIXED FAMILY FARMING[2]

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3.1. RESUMEN

Los sistemas de producción familiar que combinan la producción animal y vegetal producen casi la mitad de los alimentos del mundo. El aumento de la producción de alimentos en los países en desarrollo requiere aumentar la productividad tanto de la tierra como del trabajo como clave para aumentar los ingresos familiares, la seguridad alimentaria y reducir la pobreza. Un proyecto de investigación desarrollado en predios familiares hortícolas en Uruguay (2006-2010) reveló que los principales problemas de calidad de vida eran los bajos ingresos familiares, la alta sobrecarga de trabajo, la falta de tiempo libre y los problemas de salud asociados al trabajo. En muchos de estos predios, la productividad del trabajo (LP) era menor que el costo de oportunidad del trabajo. Comprender los factores determinantes de LP ayudaría a orientar los procesos de co-innovación de los sistemas de producción familiar. El objetivo de este estudio fue desarrollar y aplicar un método para analizar la LP a nivel de predio, identificando las principales causas de baja la LP, para utilizar sus resultados en un proceso de co-innovación. Seleccionamos 14 predios hortícola-ganaderos con diferente dotación de recursos. El método desarrollado

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involucró la caracterización y cuantificación de la asignación de mano de obra a las actividades productivas, cálculo de coeficientes técnicos que explican la LP y cuantificación de escenarios de mejora. El primer escenario estimó el impacto de los planes de rediseño en los predios y el segundo agregó el efecto de mecanizar algunas tareas. La LP fue menor que el costo de oportunidad de la mano de obra (4 USD h^{-1}) en 10 de 14 predios. La LP en la producción de hortalizas (LPv) se explicó tanto por el rendimiento neto (NR, \$ kg^{-1}) como por la eficiencia del trabajo (LE, kg h^{-1}). LE se correlacionó con la cantidad de producto vendido (APS, kg de hortalizas o carne por año). La LP en la producción de ganado de carne (LPb) fue menor que la LPv. La LPb fue mayor en predios con más de 80 unidades ganaderas (UC) y 60 ha debido a una menor mano de obra por hectárea y por UC que muestra un efecto de escala. Los escenarios proyectados mostraron que la LP podría triplicarse mejorando la asignación de recursos y el manejo de cultivos y animales. La mecanización de algunas tareas que requieren mucha mano de obra podría aumentar aún más el LP en un 12%. Este estudio contribuye al desarrollo de la metodología de co-innovación al agregar el análisis de productividad del trabajo en la etapa de diagnóstico y utilizar los resultados para guiar el desarrollo participativo de estrategias aplicables y apropiadas para mejorar la sostenibilidad de los sistemas de producción familiar.

Pablaras Clave: organización del trabajo; asignación de trabajo; co-innovación; costo de oportunidad del trabajo; mecanización

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Introducing labour productivity analysis in a co-innovation process to improve sustainability in mixed family farming

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ABSTRACT

Mixed family farms produce almost half of the world food. Increasing food supply in developing countries requires increasing productivity of both land and farmers' labour as key to increase household income, food security and reduce poverty. A research project developed into Uruguayan vegetable family farms (2006–2010) revealed that the main life quality problems were low family income, high work overload, lack of leisure time, and health problems associated with work. In many of these farms, labour productivity was lower than the opportunity cost of labour. Understanding labour productivity determinants would help to guide co-innovation processes of family farm systems. The objective of this study was to develop and apply a method to analyze labour productivity (LP) at farm level, identifying the main causes of low LP, to use its results in a co-innovation process. We selected 14 vegetable-beef cattle farms with different resource endowment. The method developed involved characterization and quantification of labour allocation to farm activities, calculation of technical coefficients that explained LP and quantification of improvement scenarios. The first scenario estimated the impact of farm redesign plans and the second one added the effect of mechanizing some tasks. LP was lower than the opportunity cost of labour (4 USD h^{-1}) in 10 out of 14 farms. LP in vegetable production (LPv) was explained by both, net return (NR, \$ kg^{-1}) and labour efficiency (LE, kg h^{-1}). LE correlated with the amount of product sold (APS, kg of vegetables or meet per year). LP in beef cattle production (LPb) was lower than LPv. LPb was higher on farms with more than 80 cattle units (CU) and 60 ha due to lower labour per ha and per CU showing a scale effect. Projected scenarios showed that LP could be tripled by improving resource allocation, and crop and animals management. Mechanizing some labour consuming tasks could further increase LP by 12 %. This study contributes to co-innovation methodology development by adding labour productivity analysis at diagnosis stage and using the results to aid participatory development of applicable and appropriate strategies to increase family farm systems sustainability.

1. Introduction

Most of the world's rural population live in mixed family farms and produce almost half of the world food (Herrero et al., 2010). Consequently, meeting the increasing food demand (Lobell et al., 2009; Keating et al., 2014), requires supporting family farmers to develop more sustainable and productive farm systems (Ifad, 2011). Increasing yield by reducing yield gaps might be one of the strategies to increase food supply in developing countries (Koning et al., 2008; Nonhebel and Kastner, 2011; van Ittersum et al., 2013). However, in family farms increase in land productivity should go along with increase in farmers' labour productivity as key to increase household income, food security and reduce poverty (De Schutter, 2011; Schneider and Gugerty, 2011; Alston et al., 2009; Cornia, 1985). Increasing family income without increasing labour productivity will only be possible as a result of greater self- exploitation (Tittonell, 2014; Weis, 2010).

There is a growing concern about the reduction of labour availability in rural areas, the changes in the composition of the work force, as well as the loss of knowledge, skills and experience. In many regions of the world, family workforce has decreased and off-farm work has increased (Nye, 2018). The restriction of labour availability at farm level requires focusing on how different practices affect the use and productivity of labour (Bendahan et al., 2018; Komarek et al., 2018; Paresys et al., 2018; Parodi, 2018). Strategies to increase food production and family income, while reducing environmental impact, should take into account labour availability and productivity at farm level to ensure feasibility (Bendahan et al., 2018; Komarek et al., 2018; Nye, 2018; Moraru and Munteanu, 2015; Prasad, 2014;). Family farms

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systems are often diversified. They usually produce a variety of different agricultural products and sometimes obtain income from off-farm activities. Although these features might increase farms resilience and adaptability, they also challenge on-farm work organization (Darnhofer, 2010; Darnhofer and Strauss, 2010; Madelrieux and Dedieu, 2008). Designing production system innovations with positive impact on labour productivity in mixed family farms, requires understanding of work organization at farm level, and labour allocation among the diversity of activities and tasks developed at farms. Improving work organization would facilitate adoption of new techniques and practices that could increase land and labour productivity (Naresh et al., 2012; Houstiou et al., 2006; Petit et al., 2006).

In the last decades Uruguayan family farmers have faced decreasing product prices and increasing costs of energy and agro-chemicals resulting in reduced family income. The strategy followed by vegetable and mixed vegetable and beef-cattle family farmers to maintain their income was to intensify their farm systems, using more external inputs and growing larger areas of vegetable crops (Dogliotti et al., 2014). Intensification had a negative impact on soil quality. Negative soil organic carbon balance and high erosion rates resulted from low use of manure and cover crops, lack of crop rotation and lack of erosion control measures (Alliaume et al., 2013; García et al., 2011). Intensification also impacted in overall farm organization. The increasing workload caused periods of mismatch in operations and tasks timing, which combined with deteriorating soil quality brought about vegetable yields and gross income increasing less than production costs (Aguerre, 2014; Dogliotti et al., 2014).

Low labour productivity is a major cause of un-sustainability of family farm systems in South Uruguay and elsewhere. A research project developed between 2006 and 2010 into Uruguayan vegetables family farms reveled that main farmers' life quality problems were low family income, high work overload, lack of leisure time, and health problems associated with work (Dogliotti et al., 2014). The timing of activities throughout the year and the difficulty to delegate tasks on hired labour are some of the most important causes that explained the problems mentioned (Dogliotti et al., 2014). In these farms, labour productivity is low. Frequently is even lower than the opportunity cost of labour, estimated as the cost of temporary hired labour in the region. Dogliotti et al. (2014) reported labour productivity increase in 13 out of 14 farms after three years of co-innovation process explained by improvements in crop yields and family income, but workload in most farms remained high.

Mechanization is an alternative to reduce labour demand and improve labour productivity and work conditions (Naresh et al., 2012). The feasibility of this strategy is limited because smallholders are usually not able to generate and save surpluses to invest and they have limited access to credit. Moreover, lack of scale makes maintenance and depreciation costs excessive for smallholders. In this context, co- operative farming and sharing of machinery among farmers' groups might facilitate mechanization (Nye, 2018; Paresys et al., 2018; Prasad, 2014). Mechanization could relieve workload and improve efficiency, but to make decisions about which processes to mechanize and their convenience it is necessary to evaluate the impact that mechanization could have over productive results and on the current working conditions.

With the purpose of studying labour organization at farm level, a set of methodologies have been developed by French researchers considering both, social and technical dimensions (Hostiou and Dedieu, 2012; Madelrieux et al., 2010, 2009; Hostiou et al., 2006; Dedieu et al., 1999). "Work assessment" ('Bilan Travail') (Dedieu et al., 1999), "Atelage"(Madelrieux et al., 2009), and "QuaeWork" (Hostiou and Dedieu, 2012), were developed in a context of diversification of farming activities and farmers multiple job-holding, decreasing number of rural workers and increasing average farm size (Madelrieux and Dedieu, 2008). The "Work assessment" approach was developed for livestock systems aiming to understand work organization by building a conceptual model of work at farm level. Labour devoted to different activities and work dynamics throughout the year is characterized in a non-exhaustive way. This methodology has been widely applied in livestock and dairy farm systems (Cournut et al., 2018; Hostiou et al., 2006; Petit et al., 2006) to provide individual or collective support and guidance on work organization to livestock farmers. "Atelage" methodology emphasizes the daily work organization and allows an analysis of a diversity of farm management systems and improved understanding of organizational patterns. This approach contributes to the debate on how to take into account work organization as a dimension in the design of new systems (Madelrieux et al., 2009). The "QuaeWork" method was developed to analyze work organization in a livestock farm over the year. This method proposes criteria to assess work duration, work efficiency and work flexibility in terms of room for maneuver or capacity to adapt to internal and external events (Hostiou and Dedieu, 2012).

In diversified and complex systems such as mixed systems, achieving an accurate understanding of what are the causes of their current labour productivity, requires addressing different production activities individually to identify constraints as well as to understand their contribution to whole farm results. Understanding labor productivity determinants would help to guide co-innovation of family farm systems.

This study was carried out in the context of a co-innovation project aiming to improve sustainability of mixed vegetable-beef cattle family farms in south Uruguay. The objective of this study was to develop and apply a method to analyze labour productivity at farm level of diversified farm systems, identifying the main causes of low labor productivity, and using its results to improve farm re-design plans.

2. Materials and methods

2.1. Region under study and selection of pilot farms

The Northeast of Canelones is located 50–90 km from Montevideo, in the south of Uruguay (Lat -34,346/-34,546 – Long -55,579/-55,873 range). Climate is temperate sub-humid with a mean annual temperature of 16 °C, and a mean annual precipitation of 1000 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 1–6 %).

We selected 14 case studies farms belonging to two local farmer's organizations. Case study farms were selected to represent the variability in resource endowment and soil types found in the region with the aid of farmers' organizations boards and their technical advisors. These fourteen farms differed in family composition; number of family members and life cycle stage, but all families had their farm as main source of income. All farms combined vegetables and beef production.

2.2. The co-innovation process

In 2014 a co-innovation process started that involved characterization, diagnosis, re-design, implementation and evaluation of pilot farms' systems, following the approach developed by Dogliotti et al. (2014).

During characterization we assessed the management team composition, farm succession and life cycle stage, type of bookkeeping used, distribution of tasks among family members, education level and main sources of technical information. Within the production subsystem we quantified 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 production activities in terms of performance indicators (Dogliotti et al., 2014).

Diagnosis was based on the analysis of economical and productive results for the period July 2013 to June 2014. Sustainability indicators were adapted in a participatory way according to farm systems characteristics in the region and to farmers' interests and aims. During characterization and diagnosis phase we visited farms every two weeks and we obtained information through interviews, farmers' records, direct observation and measurements.

The re-design phase followed the steps proposed by Dogliotti et al. (2014): adjustment of field layout and erosion control support practices, design of a cropping plan and crop rotations, design of inter-crop activities and crop management activities, ex-ante evaluation of farm plans performance. Plans were discussed with the farmers and adjusted until an agreement was reached and implementation started.

2.3. Understanding labour productivity

In order to study labour productivity in the pilot farms and to get a deeper understanding of its main causes we improved the approach proposed by Dogliotti et al. (2014). We studied labour productivity at whole farm, production activities and operational tasks levels. We summarized the method developed in three steps. Steps one and two were carried out during characterization and diagnosis, while step three was part of the '*ex-ante*' evaluation during the re-design phase.

2.3.1. Step 1. Quantifying labour allocation

To obtain data on labour allocation and to understand work organization on each farm, we conducted semi –structured interviews to farmers and their families. We also made direct observations and we measured the time consumed during the performance of specific operations and tasks, for example; transplanting onions, lay down of plastic mulch and grading and packaging onions. During the interviews key questions asked to understand work organization were when?, how much time?, who does the work?, and in which way the task or activity is done? (Dedieu, 2016).

We distinguished routine and seasonal work (Dedieu et al., 1999). We classified as routine work activities performed every day during a relatively long period of the year. As seasonal work we listed all activities performed once or several times but concentrated in relatively short periods during the year. Seasonal work included crop management tasks such as tillage, sowing, and harvest, and cattle management tasks like vaccination, weaning and castration, among others. There were many activities that did not report to any particular production activity, like time dedicated to buy inputs, maintenance and repairs of farm facilities and participation in famers' group meetings. We computed labour allocated to these 'general activities' as the difference between total family labour and total labour allocated to production activities. Total family labour was estimated as the sum of labour that each member of the family contributed to the farm. We estimated labour contribution of each family member by describing with the family a single day work routine and identifying variations through the year. Labour allocated to domestic chores and children care, was not taken into account for the analysis.

2.3.2. Step 2. Labour productivity analysis and diagnosis

Based on labour allocation and other farm data collected during characterization phase, we calculated technical coefficients for each crop and animal production activity in each farm and indicators at different hierarchical levels and drew a 'labour productivity tree' for each farm (Fig. 1). For economical indicators we used the calculation method proposed by McConnell and Dillon (1997). They distinguished between Net Actual Return and Net Sustainable Returns, and Family Available Income and Family Sustainable Income. They use the term 'sustainable' when depreciation is included as a cost. For all calculation we included depreciation. In this paper we used 'Net Return' and 'Family Income' to express Net Sustainable Return and Family Sustainable Income. All prices were converted to U.S. dollars.

We distinguished between 'farm labour productivity' **(FLP)** and 'family income per hour' **(FIh)**:

$$\text{FLP } (\$ \text{ hour}^{-1}) = \text{Net Return (NR) } (\$ \text{ yr}^{-1}) / \text{ Total Labour (hour yr}^{-1}) \quad (1)$$

$$\text{NR} = \text{Total Gross Return (TGR) } (\$ \text{ yr}^{-1}) - \text{Total Enterprise Cost (TC) } (\$ \text{ yr}^{-1}) \quad (2)$$

Where,

TGR ($\$$ yr^{-1}) is total gross return of the farm calculated as the sum of all outputs multiplied by their prices;

TC ($\$$ yr^{-1}) is total enterprise cost, including total variable and fixed costs with the exception of labour costs.

Total Labour (hour yr^{-1}) is the sum of family labour and hired labour.

'FIh' ($\$$ hour^{-1}) is the ratio between Family Income (FI) ($\$$ yr^{-1}) and total hours worked by the family (hour yr^{-1}). Family Income was calculated as Net Return ($\$$ yr^{-1}) minus the cost of hired labour ($\$$ yr^{-1}).

When there is no hired labour in a farm, the value of FIh is equal to FLP. We disaggregated labour productivity at farm level. Labour productivity (LP) for each production activity (beef cattle, vegetable crops and other activities like poultry or cheese making) was calculated as the product between net return per activity ($NR_{activity}$) and labour efficiency per activity ($LE_{activity}$).

$$LP_{activity} (\$ \text{ hour}^{-1}) = NR_{activity} (\$ \text{ kg}^{-1}) * LE_{activity} (\text{kg hour}^{-1}) \quad (3)$$

$$NR_{activity} (\$ \text{ kg}^{-1}) = (\text{Farm gate price} - TC_{activity} - GFEa_{ctivity}) \quad (4)$$

$$LE_{activity} (\text{kg hour}^{-1}) = APS_{activity} (\text{kg yr}^{-1}) / \text{ Labour allocated}_{activity} (\text{hour yr}^{-1}) \quad (5)$$

Where,

$NR_{activity}$ ($\$$ kg^{-1}) is the net return of each production activity in US dollars per kg of product sold;

$LE_{activity}$ (kg hour^{-1}) is the labour efficiency of each production activity estimated as product sold per hour of labour.

Labour allocated$_{activity}$ (hour yr^{-1}) is the number of working hours allocated to each activity, regardless of who does the work, family or hired workers.

$APS_{activity}$ (kg yr^{-1}) is the amount of product sold per year for each production activity

$TC_{activity}$ ($\$$ kg^{-1}) is the cost per unit of product calculated as the sum of all costs, excluding labour costs, involved in each activity per year (variable and fixed cost), divided by $APS_{activity;}$

$GFE_{activity}$ is the amount of general farm expenses per year allocated to each production activity proportional to its $GR_{activity,}$ divided by $APS_{activity;}$

Farmers sell various types of vegetable and animal products and farm gate prices vary throughout the year, so we estimated an average farm gate price for each production activity as the ratio between $GR_{activity}$ and total amount of product sold per year.

$$\text{Farm gate price } (\$ \text{ kg}) = GR_{activity} (\$ \text{ yr}^{-1}) / APS_{activity} (\text{kg yr}^{-1}) \quad (6)$$

Where,

$GR_{activity}$ ($\$$ yr^{-1}) is the gross return per production activity calculated as the sum of product sold on each sale multiplied by its farm gate price in US dollars at the moment each sale was done;

Beef-cattle production includes forage production. Pastures are installed for feeding cattle and bales are produced to store forage for winter. In farms where bales were sold it was considered as another production activity.

During interviews we listed all management tasks performed on crops and animals. This allowed us to compare working time spent in similar tasks on each farm. In order to explain differences among farms

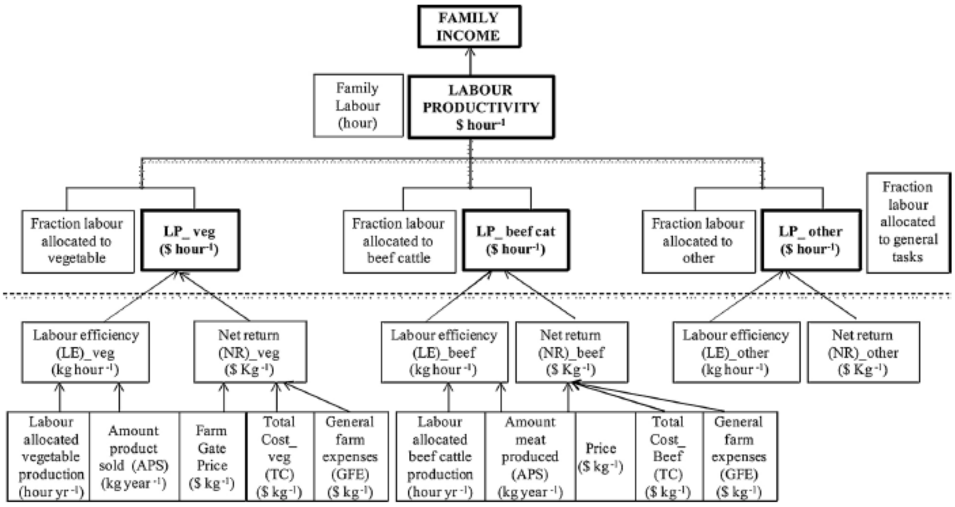

Fig. 1. Labour productivity tree at farm level.

we calculated a 'Relative time indicator' per area and per unit of product sold. Relative time $_{area}$ was calculated as the ratio between labour allocated per area of vegetable production on each farm (hours ha^{-1}) and the average labour allocation from all farmers per area of vegetable crops (hours ha^{-1}). Relative time$_{kg}$ was calculated as the ratio between labour allocated to vegetable production and APS.

Relative time$_{area}$(*farm n*) = Labour allocated per ha (h ha^{-1})$_n$ /Average labour allocated per ha (h ha^{-1}) (7)

Average labour allocated per ha = Σ (Total labour vegetable /cultivated area) (8)

Labour requirements in greenhouse crops are higher than open field crops. We calculated average labour allocated per hectare separately, for farms growing open field crops to those growing greenhouse crops.

Relative time $_{kg}$ (*farm n*) = (Labour allocated to vegetable production/ APS)/Average labour per kg. (9)

Average labour allocated per kg (h kg^{-1}) = Σ (Total labour vegetable /APS) (10)

A Relative Yield (RY) indicator per farm was calculated to show differences in production efficiency among farmers. We calculated RY as the sum of the ratios between actual and attainable yield of each vegetable crop in the farm, weighed by fraction of gross return that each crop explained (Eq. 11). Actual yield for each crop was calculated from sales records available in all farms. We defined attainable yields as rain-fed and irrigated yields obtained in local experimental stations when it was available. For crops lacking this information, we used as attainable yield 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 (Dogliotti et al., 2014; Scarlato et al., 2017; Berrueta et al., 2019).

Relative Yield = Σ (actual/attainable yield$_{crop}$ * Fraction GR$_{crop}$) (11)

We performed a correlation analysis to identify relations among indicators. Spearman coefficient measures the magnitude of the relation between two variables, independently of the units of the original variable (Balzarini et al., 2008). For $\alpha = 0.05$ we considered significant the r_{ij} values when, $|r_{ij}|\sqrt{n} > 1.96$, being n the number of cases (Johnson and Wichern, 1992).

2.3.3. Step 3.Quantifying the impact of farm plans on labour productivity

At re-design phase we produced a plan for each farm designed based on diagnosis results and a problem tree per farm, previously discussed and agreed with farmers (Dogliotti et al., 2014). Draft plans were discussed with farmers and changed as result of those discussions till an agreement was reached. The farm plans aimed at improving allocation of available labour and other resources to production activities, increasing land productivity through better and timely management, and improved soil quality. Redesign plans included adjustment of fields layout and erosion control support practices, changes in crops choice, cultivated area and crop and soil management practices such as green manures and cover crops during intercrop periods, applications of animal manure, improved weed control measures, improvements in crops nutrition, water supply and crop protection (Dogliotti et al., 2014). In beef cattle production, redesign plans included increasing forage production through better grass management and larger area of forage crops and grass&legume pastures in rotations with vegetable crops. We also proposed changes in cattle management practices such as grazing control, weaning and health management. All plans were laid down taking into account current farm resource endowment, particularly labour availability, and did not require significant increase in inputs or investments.

Based on technical coefficients taken from results of previous studies in the region (Dogliotti et al., 2014; Aguerre et al., 2014; Alliaume et al., 2016), we estimated the impact of farm plans on vegetable and forage crops yield, production costs, and labour demand. We estimated impact on FLP and FIh using current farm labour availability and current farm gate product prices.

Although it was not included on farm plans, to estimate potential improvements of LP in beef cattle production, we explored the effect of replacing current cow-calf and complete cycle systems by backgrounding-fattening systems (Modernel et al., 2016), which have been proven more efficient for mixed vegetable-beef farm systems in previous studies in the region (Aguerre et al., 2014). To estimate beef production we used the whole-farm model "FarmImages" (Dogliotti et al., 2005; Aguerre et al., 2014). Based on estimated forage production and availability throughout the year and restricting external sources of feed to less than 10 % of metabolizable energy requirements,

Table 1
Resource endowment and other relevant characteristics of the case study farms.

Farm N°	Area (ha)	Veg area (ha)	Irrig. area (ha)	Type of Production[a]	Main Crops[b]	Crops (#)	Grazing área (ha)	Forage crops (ha)	Cattle Units (CU)[c]	Mech. Level[d]	Family labour ($h\ yr^{-1}$)	Hired labour ($h\ yr^{-1}$)	Off-farm labour ($h\ r^{-1}$)
1	12	0.28	0.28	FC/GC	tom/sw pep	5	10	1.5	22	1	5000	80	216
2	7	0.53	0.28	FC/GC	tom/gr beans	7	4.3	1.6	9	2	3744	0	
3	27	0.70	0.00	FC	Onion	1	24.2	6.9	26	1	3328	54	1080
4	100	2.95	1.80	FC	Onion/tom	3	52.8	11.6	41	3	4002	188	
5	31	0.75	0.54	GC	tom/cher tom	6	28.0	17.7	63	4	6075	2560	
6	46	1.20	0.00	FC	onion/pea	3	40.0	6.0	40	2	3718	0	
7	14	1.14	0.80	FC/GC	tom/cher tom	11	9.9	4.9	24	1	6666	2130	
8	22	2.88	0.90	FC/GC	onion/sw pep	10	14.0	4.9	17	2	3473	261	315
9	27	4.63	0.50	FC	sw pep/sw pot	5	19.9	3.9	23	1	4114	330	
10	9	0.68	0.52	GC	sw pep/tom	2	…	3.5	2	2	3960	1820	
11	10	5.90	0.00	FC	onion/sw maize	5	6.0	1.0	4	3	4836	640	
12	115	8.60	1.50	FC	onion/carrot	8	69.0	75.0	113	5	5300	1760	
13	97	0.15	0.15	GC	sw pep	1	99.0	11.3	82	3	5000	40	
14	86	15.50	0.00	FC	onion/sw pep	18	66.0	9.4	90	5	9180	1240	

[a] **FC:** Field Crops; **GC:** Greenhouse Crops.
[b] Tom = tomate; cher tom = cherry tomato; sw pep = sweet pepper; pot = potato; gr beans = green beans.
[c] **Cattle Units (CU):** 1 CU equivalent to 1 cow of 400 kg live-weight.
[d] **Mechanization level:** 1 = Low: without tractor. 2 = Medium – Low: with tractor, without sprayer machine. 3 = Medium – High: with tractor and sprayer machine. 4 = High: 2 tractors and sprayer machine. 5 = Very High: 3 or more tractors and sprayer machine.

the model estimated number of animals that the farm can grow and meat production per year.

In order to explore the impact that investments in mechanization could have on FLP and FIh, we built a second scenario. We added to farm plans the labour saving effect, and increasing maintenance and depreciation costs of mechanization. For each farm we selected mechanization options available in the region for the most labour demanding tasks: cleaning, classifying and packing of vegetable products, machinery to improve soil tillage and to spray crops, taking into account current mechanization level and production scale.

3. Results and discussion

3.1. Farm systems characterization

All families had their farms as main source of income. However, three farmers were part time workers outside the farm (Table 1). Two farms had poultry in addition to beef-cattle and vegetable crops, five farms sold surplus bales and one farm made cheese. All greenhouses were gable roof single structures made from wood and covered with plastic film. Area per greenhouse was between 400 and 800 m^2. Most vegetable products were sold through middlemen in the main wholesale market in Montevideo. Middlemen charged farmers the product transport costs and a fee of 10–15% of the gross value of products sold. Beef cattle were sold through a wide diversity of channels. Most important ones were sales to other farmers, local cattle markets and slaughterhouses. Most farmers had low or very low level of mechanization. Family labour availability ranged between 3328 and 9180 $h\ yr^{-1}$ depending on number of family members contributing labour and practice of part time off-farm work. Hired labour per farm was at most half of the available family labour and it was contributed mostly by temporary workers during periods of high labour demand (Table 1). Farms 5, 7 and 10 hired a permanent worker and they highlighted the importance of their reliance on hired help and the prospect of delegating some tasks. The opposite was pointed out by other farmers who identified the lack of experience and specific skills of temporary workers as a constraint. Management team was in many farms integrated by the couple. However, we observed diversity in composition of the management team, in leadership of the farm and in book keeping systems (Table 2).

We observed a division of tasks between men and women. Women worked fewer hours than men directly on the farm because they were in charge of children care and all domestic chores. Men carried out tasks involving machinery, soil tillage and crop fumigation. Women were involved in manual work like sowing, weeding, and harvest and post-harvest tasks. There was also a gender division of labour related to animal production work. Only in farms 2 and 9 were women in charge of some cattle chores. Women played an important role at local farmers' organizations. They were members of the organizations' boards and leaders of several of the organizations' activities.

Farmers usually started their work-day around 7:00 during spring and summer and 8:30 in winter. They stopped at midday to have lunch and rest and then continued working till near sunset. During high workload periods in summer they may resume work earlier or continue after sunset, busy with classifying and packing vegetables before 'delivery days'. All farmers rested on Sundays and worked half-day on Saturdays. Farms with poultry production had some routine work to do on Sundays, so they took turns between family members. For most of the farms we found people worked more than 8 h a day and despite taking days off, none of them took off of more than one week per year. To assess general workload we used as a quality-of-life indicator the leisure time index (Table 2). Particularly during peak periods, farmers work more than 10 h even when they hire temporary workers.

3.2. Labour productivity

Ten out of fourteen farms had in 2013-14 a FIh lower than the

Table 2
Characterization of farm management subsystem: composition of management team, life cycle stage, farm succession, leadership and book keeping types per farm.

Farm	Family workers	Life cycle stage[a]	Farm sucession[b]	Management team	Leadership	Leisure time index[c]	Book keeping type[d]
1	1 full, 2 part-time	1	1	Couple	Farmer (man)	2	2
2	1 full, 1 part-time	2	2	Mother and son	Mother and son	2	2
3	1 full, 1 part-time	4	0	Couple	Couple	2	2
4	2 full	2	1	Couple	Couple	2	1
5	1 full, 2 part-time	3	2	Couple and a son	Farmer (woman)	4	2
6	1 full, 1 part-time	3	1	Couple	Couple	2	3
7	2 full, 2 part-time	2	1	Couple and father	Couple	4	2
8	1 full, 1 part-time	3	1	Couple	Couple	2	3
9	2 full	2	1	Mother and son	Son	2	3
10	1 full, 1 part-time	2	1	Couple	Couple	4	3
11	2 full	2	0	Couple	Couple	2	2
12	1 full, 3 part-time	3	2	Couple and a son	Farmer (man)	2	2
13	1 full, 3 part-time	3	2	Couple and a son	Couple	3	3
14	4 full, 2 part-time	3	2	Couple and a daughter	Farmer (man)	4	2

[a] Life cycle stage, 1 = entry or establishment, 2 = expansion, 3 = consolidation or stabilization, 4 = exit.
[b] Farm succession, 0 = not succession expected or possible, 1 = possible but not defined yet, 2 = defined or in transition to next generation.
[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 (Dogliotti et al., 2014).
[d] Book keeping type, 1 = only sales receipts, 2 = sales receipts plus income and expenses, 3 = income and expenses plus details of the main production activity, 4 = detailed information of most of the production activities (Dogliotti et al., 2014).

Table 3
Family income per hour of labour, Farm labour productivity, Labour Productivity (LP) in vegetable, cattle and forage production and in other production activities, and proportion of total available labour allocated to each activity. Currency is US dollars.

						Labour Allocation			
Farm (#)	FIh ($ $hour^{-1}$)	FLP ($ $hour^{-1}$)	LPv ($ $hour^{-1}$)	LP cattle ($ $hour^{-1}$)	LP other ($ $hour^{-1}$)	Veg	Cattle	Other prod.	General activities
4	0.84	0.92	1.91	0.52	…	0.34	0.52	…	0.18
3	1.50	1.52	3.36	1.91	1.28	0.15	0.28	0.38[a]	0.19
5	1.84	1.98	2.69	1.60	…	0.67	0.11	…	0.22
1	2.14	2.15	3.44	1.85	…	0.47	0.29	…	0.24
8	2.22	2.27	3.70	1.32	5.47	0.52	0.24	0.01[b]	0.24
6	2.53	2.53	3.16	3.86	…	0.33	0.39	…	0.28
12	2.80	2.83	4.31	−3.58	11.74	0.53	0.24	0.12[b]	0.11
9	3.18	3.28	5.38	2.24	…	0.53	0.20	…	0.27
7	3.91	3.57	4.93	4.26	12.04	0.60	0.13	0.005[b]	0.25
2	3.85	3.85	5.30	1.18	…	0.69	0.16	…	0.15
14	5.54	5.23	6.28	2.09	10.67	0.55	0.09	0.14[2y3]	0.19
13	6.23	6.21	13.26	3.45	12.29	0.12	0.32	0.29[c]	0.27
11	6.87	6.45	8.23	1.08	14.40	0.75	0.06	0.017[b]	0.18
10	8.25	7.11	11.22	0.00	…	0.63	0.06	…	0.30

[a] Made cheese.
[b] Sold bales.
[c] Poultry.

opportunity cost of labour (4 $ $hour^{-1}$), defined as the cost of hiring temporary workers (Table 3). This value was calculated taking into account average wage paid in the region including social loads and taxes. For most of these farms FIh was lower than FLP. Except Farm 6, LP in vegetable production was higher than LP in cattle production.

In 10 out of 14 farms, most of available labour was allocated to vegetable production. LPv higher than the threshold of 4 dollars per hour was the result of high LE and/or high NR. Farm 4 had high LE but the lowest NR, resulting in the worst LPv. Contrary, farms 10 and 13 obtained the highest LPv due to above average LE and the highest NR and farm gate prices (Table 4). Except farms 2 and 13, all farms reaching an LPv higher than 4 dollars per hour had higher APS than farms with LPv lower than threshold. Five out of six farms with LPv under 4 dollars had Relative Time per unit of product over 1. Four out of six farms with LPv lower than threshold showed RY lower than average, while seven out of eight farms with LPv > 4 dollars per hour had RY higher than average (Table 4). Low LPv with a RY of 0.65 in Farm 1 was explained by low LEv caused by high Relative Time per area and product. Opposite was observed in farm 14, which had a relatively high LPv with a RY of 0.45, explained by low relative time per area and per unit of product, saving 33 % of labour compared to average (Table 4). These two farms, 1 and 14, had two contrasting mechanization levels (Table 1) that could explain differences in relative time.

LE was positively correlated with APS, labour allocated to vegetables and crop area, and negatively correlated with relative time per unit of area (Table 5). NR correlated only with average farm gate price. Farms with greenhouse crops obtained better farm gate prices than farms with open field crops only.

Labour productivity in beef-cattle production was lower than in vegetables. Only one farm obtained more than 4 dollars per hour (Table 6). Farm 10 was not considered in this analysis since beef cattle were for self-consumption only. LEb and NR were negatively correlated (Table 7). LPb above 3 dollars per hour were obtained by two farms with high NR and near average LEb and one farm with high LEb and near average NR. LEb was positively correlated with APS, grazing area, CU and negatively with labour per ha and per CU, showing a positive production scale effect. LEb was high on big farms (12, 13 and 14) with more than 80 CU and more than 60 ha of grazing area, explained by low labour allocation per ha and per CU. NR was correlated with TC and farm gate price. TC was positively correlated with the amount of cattle

Table 4
Components of LPv: LE (kg hour^{-1}), NR per amount of marketable product (\$ kg^{-1}), APS (kg) and labour allocation to vegetable production.

Farm	LPv	LE (kg hour^{-1})	APS[b] (kg)	Labour allocation Veg (hours)	NR[a] (\$ kg^{-1})	Farm gate price (\$ kg^{-1})	TC (\$ kg^{-1})[c]	GFE (\$ kg^{-1})[d]	Crop area (ha)	Relative Yield [e] weighted (all crops)	Relative time [f] (hs ha-1)	Relative time (kg hs)
4	1.91	19.1	27,000	1410	0.10	0.32	0.17	0.05	2.95	0.17	0.86	0.88
5	2.69	4.9	28,372	5819	0.55	1.24	0.63	0.05	0.75	0.40	1.32	1.59
6	3.16	7.8	9550	1224	0.41	0.69	0.15	0.14	1.20	0.57	0.98	1.20
3	3.36	13.3	6680	503	0.25	0.73	0.41	0.08	0.70	0.34	1.30	1.27
1	3.43	5.5	12,900	2366	0.63	1.08	0.31	0.14	0.28	0.65	1.47	1.43
8	3.70	11.1	21,674	1947	0.33	0.79	0.37	0.10	2.88	0.31	1.22	1.52
12	4.31	27.7	103,975	3756	0.16	0.49	0.30	0.03	8.60	0.51	0.79	0.61
7	4.93	7.4	38,988	5282	0.67	1.17	0.45	0.06	1.14	0.54	0.79	1.05
2	5.30	10.8	27,860	2588	0.49	1.04	0.49	0.06	0.53	0.78	0.83	0.72
9	5.38	18.5	43,297	2338	0.29	0.58	0.20	0.09	4.63	0.51	0.91	0.91
14	6.28	25.2	145,822	5778	0.25	0.49	0.22	0.02	15.50	0.45	0.67	0.67
11	8.23	18.3	75,457	4129	0.45	0.64	0.16	0.03	5.90	0.58	1.26	0.93
10	11.22	15.2	55,655	3664	0.74	1.46	0.60	0.12	0.68	0.64	0.92	0.51
13	13.26	17.8	10,450	586	0.74	1.84	1.01	0.09	0.15	0.53	0.68	0.71

[a] $NR_{activity}$(\$ kg^{-1}) = Farm gate price – $TC_{activity}$ – $GFE_{activity}$.
[b] $APS_{activity}$ is the amount of product from each production activity sold per year.
[c] TC (\$ kg^{-1}) = sum of all the cost involved in each activity per year (variable and fixed cost), excluding labour costs, divided by $APS_{activity}$.
[d] GFE (\$ kg^{-1}) = is the amount of general farm expenses per year allocated to each production activity proportional to its $GR_{activity}$, divided by $APS_{activity}$.
[e] Relative Yield: Actual/attainable yield of all crops weighted for their participation in vegetable gross return.
[f] Relative time is the ratio between labour used in each farm (hours) per area and per unit of product and the estimated average time (M&M).

in the farm, showing that production scale increased total costs per unit of product (Table 6 and 7).

3.3. *Estimating the impact of re-design on labour productivity*

Farms' plans showed potential to improve LP and FIh in all farms, having more potential impact in farms with FIh lower than the opportunity cost of labour (Table 8). On average FIh could be tripled on these farms, with huge variations among them (1.68 to almost 7 fold). In scenario 1 increase in LP was due to increase in both, LPv and LPb. Increase in LPv was mainly explained by increase in vegetable crops yield and by changes in crop choice and allocation of area and other resources to different crops. Increase in LPb was due mostly to increase in meat production, but in some cases also to reduction in the amount of labour per cattle unit.

LP and FIh increase in Farm 12 was explained by high reduction in beef cattle production costs and re-distribution of labour between vegetable crops and beef cattle production. High cost in beef cattle production in this farm (Table 6) was explained by a high proportion of annual forage crops as base of animal feed. The plan included rotation of four-year grass& legumes pastures with vegetable crops, reducing the area of forage crops, and the cost of feed.

Mechanization of some tasks (scenario 2), might improve labour productivity further. We estimated an average impact in FIh of 12 % (Table 8). Estimated improvement in labour productivity due to mechanization was larger in farms with very low mechanization level (Table 1). Farm 9 used to hired machinery for tillage, so the impact of acquiring a tractor and soil tillage tools was lower. The introduction of grading and packing equipment, showed an increase of 10 % or more in FIh in farms 2, 4, 8, 10, 11 and 12. In farms 8 and 11 the introduction of equipment to clean and grade onions would reduce total farm labour demand by 19 y 13 %, respectively. In farms 5 and 6 potential impact of mechanization was very low since crops and tasks possible to mechanize occupied a small area out of the total cultivated it in these farms. For farm 13 where only sweet pepper was grown, no mechanization was proposed (Table 8).

To illustrate the effects of redesign plans in LP indicators, we presented LP trees for farms 5 and 11 as examples (Fig. 2). For these farms FI increased as a result of LP increase. In farm 5 the increase of LPv was due to LEv and NRv increase. LE improved 59 % because of the APS increase and the reduction of labour required. In this farm we aimed at increasing greenhouse crops yields by improved matching of labour demand and availability. We proposed to decrease the cultivated area from 7500 to 5700m2 and adjust the area allocated to each crop with the purpose of improving crop management and timing of management tasks. These allowed to decrease labour demand, increase yield and consequently APS. We did not increase the amount of inputs used so TC per kg decreased 59 % due to higher yields. GFE per kilo also decreased

Table 5
Spearman correlation analysis of LP-veg components.

Probability/ Coefficients	LPv	LE	APS	Labour allocation Veg	NR	Farm gate price	TC	GFE	Crop area	Relative Yield [1]	Relative time per area	Relative time per kilo
LPv	1.00	0.29	0.14	0.16	0.26	0.73	0.08	0.89	0.87	0.22	0.29	0.53
LEv	0.32	1.00	0.01	0.03	0.13	0.43	0.17	0.15	0.04	0.09	0.08	0.10
APS	0.45	**0.77**	1.00	0.02	0.93	0.89	0.10	0.06	0.09	0.09	0.46	0.68
Labour_veg	0.42	**0.64**	**0.69**	1.00	0.83	0.96	0.23	0.22	0.15	0.33	0.42	0.98
NR	0.34	−0.45	−0.03	−0.06	1.00	0.06	0.27	0.69	0.33	0.44	0.26	0.19
Farm gate price	0.10	−0.24	−0.04	−0.01	**0.57**	1.00	0.11	0.22	0.82	0.11	0.58	0.85
TC	**0.53**	0.41	0.49	0.36	0.34	0.48	1.00	0.68	0.43	0.02	0.58	0.69
GFE	0.04	−0.43	**−0.57**	−0.37	0.12	0.37	0.13	1.00	0.46	0.64	0.49	0.80
Crop area	0.05	**0.63**	0.51	0.43	−0.29	−0.07	0.24	−0.22	1.00	0.83	0.02	0.76
Relative Yield 1	0.37	0.50	0.52	0.29	0.23	0.48	**0.70**	−0.14	0.06	1.00	0.96	0.55
Rel. time (area)	−0.32	**−0.53**	−0.22	−0.24	0.34	0.17	−0.17	0.21	**−0.69**	−0.01	1.00	0.27
Rel. time (kg)	−0.20	−0.49	−0.13	0.01	0.41	0.06	−0.13	−0.08	−0.10	−0.19	0.35	1.00

Bold numbers indicates statistical significance for $\alpha = 0.05$.

Table 6
Components of Labour productivity in beef-cattle production (LPb): Labour Efficiency (LE), NR per kilo of meat and forage ($\$ kg^{-1}$), APS (kg), labour allocation to beef-cattle production (hours), Net Return grazing area, Meat production per hectare, total Cattle Units (CU) and labour efficiency indicators per farm.

Farm	LPb ($ hour)	LE (kg $hour^{-1}$)	APS Beef Cattle (Kg)	Labour allocation Beef (hours)	NR ($ kg^{-1})	Price ($ kg meat)	TC ($ kg^{-1})	GFE ($ kg^{-1})	Grazing area (ha)	Meat production (kg/ha)	CU Total	Time (hours/ha)	Hour/CU
12	−3.58	6.78	11,372	1678	−0.53	1.29	1.73	0.083	69	165	113	24.3	14.9
4	0.52	1.68	3643	2165	0.31	1.60	0.96	0.34	53	69	41	41.0	52.5
11	1.08	0.83	252	303	1.29	1.56	0.19	0.07	6	42	4.48	50.5	67.6
2	1.18	1.90	1160	609	0.62	1.25	0.57	0.07	5	239	9	125.3	71.7
8	1.32	1.63	1442	885	0.81	1.49	0.5	0.18	14	103	17	63.2	52.7
5	1.60	2.11	1960	930	0.76	2.08	1.22	0.09	28	70	63	33.2	14.8
1	1.86	1.30	1946	1492	1.42	1.71	0.05	0.23	15	134	22	102.9	68.6
3	1.91	4.76	4527	952	0.40	1.04	0.50	0.14	24	187	26	39.3	37.0
14	2.09	7.57	7470	987	0.23	1.25	0.96	0.06	66	113	90	15.0	11.0
9	2.24	2.60	2360	902	0.86	1.84	0.69	0.29	20	119	23	45.3	38.9
13	3.45	5.21	8415	1613	0.66	1.18	0.46	0.06	99	85	82	16.3	19.7
6	3.86	3.53	5080	1438	1.09	1.55	0.16	0.30	40	127	40	36.0	35.7
7	4.26	3.71	4138	1116	1.15	1.91	0.67	0.1	sd*	sd	24	sd	46.5

([1]) $NR_{activity}(\$ kg^{-1}) = Price - TC_{activity} - GFEa_{ctivity}$.
([2]) $APS_{activity}$ is the amount of product from each production activity sold per year.
([3]) TC ($\$ kg^{-1}$) = sum of all the cost involved in each activity per year (variable and fixed cost), excluding labour costs, divided by $APS_{activity}$.
([4]) GFE ($\$ kg^{-1}$) = is the amount of general farm expenses per year allocated to each production activity proportional to its $GR_{activity}$, divided by $APS_{activity}$.
*This farm used surrounding borrowed areas for grazing. So total grazing area and indicators related to this data were not possible to estimate with accuracy.

as a consequence of higher APS. We used the prices already obtained by each farmer for all the estimations. In beef cattle production the improvement in LPb was obtained through higher LE. Using the same amount of labour we estimated a 453 % improvement. This improvement is not only due to increased forage production and better animal management but also to changes in beef cattle business. As was explained in M&M section, we estimated meat production using Farm-IMAGES simulation model and assuming fattening systems based on the actual labour availability and grazing area. Price per kilo is lower due to different final product, but NR remained almost the same due to cost reduction.

In scenario 2, FLP further improved 1.5 % and FI by 1 %. We included in this scenario the labour saving and amortization cost of using a machine to install plastic mulch in the greenhouses. A tomato grading machine was not included because tomato area was too small to justify amortization costs.

In farm 11 the re-design plan included a 11 % reduction of cultivated area of onions which was the highest labour demanding crop in this farm. LE increased by 32 % as a result of 16 % labour demand reduction and 14 % APS increase. In farm 11 we also aimed at improving matching of labour demand and availability to improve task timing. We introduced two new varieties of onion to extend the optimal time for transplanting and harvesting. Higher APS with lower area of onions would result from increased crop yield by 44 % due to improved management: better timing of transplanting, weed control and improved crop nutrition. Adjustments in crop nutrition and weed control increased TC by 5 %.

LP increased in beef cattle in farm 11 was explained by higher LE. We proposed to increase the area of alfalfa in rotation with vegetable crops and save the alfalfa bales for animal feed instead of selling it. The number of animals increased from 4 to 8. Despite the important increase, beef-cattle production only explained 6 % of labour allocation in farm 11 having a lower impact in FLP and FI.

In scenario 2 we estimated the impact of investing in a machine to clean, grade and pack onion machine which could save 18 % of labour used in vegetable production. LPv increased by 20.5 % due to LE increase 22 %. Due to maintenance and amortization costs, NR would be reduced almost 1 % but the overall effect on FLP would be an increase of 31 %. However, mechanizing onion post-harvest operations would not have an effect on FI, but mainly on alleviating work overload.

4. Discussion

Results of this study confirm that low labour productivity is a major cause of un-sustainability of family farm systems in South Uruguay, as found in previous studies in the region (Dogliotti et al., 2014). We found that 10 out of 14 farms had a FIh lower than the opportunity cost of labour, which made almost impossible for farmers to generate cash

Table 7
Spearman correlation analysis of LP-Beef components.

Probability/ Coefficients	LPb	LEb	APS Beef	Labour allocation	NR	Price	TC	GFE	Grazing area	Meat production	CU Total	Hours/ha	Hours/CU
LPb	1.00	0.17	0.25	0.83	0.20	0.83	0.30	0.86	0.44	0.71	0.75	0.30	0.34
LEb	0.40	1.00	0.002	0.16	0.04	0.11	0.11	0.17	0.01	0.28	0.01	0.01	0.01
APS Beef	0.34	**0.90**	1.00	0.01	0.06	0.17	0.26	0.63	0.002	0.58	0.002	0.004	0.01
Lab alloc	0.06	0.40	**0.71**	1.00	0.28	0.86	0.62	0.40	0.01	0.94	0.02	0.09	0.23
NR	0.37	−0.60	−0.54	−0.31	1.00	0.05	0.02	0.29	0.06	0.52	0.02	0.08	0.08
Price	0.06	−0.47	−0.40	−0.05	**0.57**	1.00	0.68	0.11	0.38	0.19	0.46	0.30	0.57
TC	−0.30	0.46	0.32	0.14	**−0.70**	0.12	1.00	0.49	0.20	0.98	0.05	0.14	0.06
GFE	0.05	−0.40	−0.14	0.24	0.31	0.47	−0.20	1.00	0.69	0.91	0.51	0.26	0.34
Graz. area	0.23	**0.76**	**0.94**	**0.81**	−0.56	−0.27	0.38	−0.12	1.00	0.64	0.002	0.003	0.01
Meat prod	0.11	0.33	0.17	0.02	−0.20	−0.40	−0.01	−0.03	−0.14	1.00	0.91	0.53	0.64
CU Total	0.09	**0.79**	**0.88**	**0.70**	**−0.66**	−0.21	**0.58**	−0.19	**0.95**	−0.03	1.00	0.003	0.002
Hours/ha	−0.31	**−0.83**	**−0.85**	−0.51	0.53	0.31	−0.45	0.34	**−0.90**	0.19	−0.91	1.00	0.00
Hours/CU	−0.27	**−0.80**	**−0.77**	−0.35	0.50	0.16	−0.54	0.27	**−0.81**	0.14	−0.88	0.96	1.00

Bold numbers indicates statistical significance for $\alpha = 0.05$.

Table 8
Family Income per hour (FIh), Farm Labour productivity (FLP) and incremental change of FIh and Family Income under scenarios 1 and 2.

Farm (#)	Scenario 1 Family Income per hour (FIh)	Farm labour productivity	Incremental change: FIh Scn1/actual FIh	**LPv Scn1/ actual**	**LPb Scn1/ actual**	Scenario 2 Family Income per hour (FIh)	Farm labour productivity	Incremental change: FIh Scn2/ FIh Scn1
4	5.84	5.47	6.84	4.29	7.63	6.58	6.18	1.13
5	7.80	5.98	4.25	2.88	5.57	7.99	6.07	1.02
12	9.89	6.54	3.53	2.06	7.38	11.34	7.75	1.15
8	7.35	6.01	3.30	2.19	3.08	9.04	6.88	1.23
3	4.67	4.60	3.10	2.02	3.95	5.15	4.76	1.10
9	8.39	7.50	2.64	2.27	1.69	8.89	7.88	1.06
14	10.49	9.46	1.89	1.96	3.76	11.56	10.28	1.10
1	2.98	2.92	1.88	1.19	1.37	3.38	3.02	1.14
6	4.67	4.67	1.84	2.43	1.37	4.83	4.89	1.03
2	6.47	6.47	1.68	1.75	1.05	7.19	7.19	1.11
11	10.31	8.22	1.50	1.48	7.13	12.04	10.77	1.17
10	16.62	10.55	2.01	1.25		18.95	12.45	1.14
7	5.77	4.98	1.48	1.50	0.69	7.46	6.70	1.29
13	9.74	8.91	1.56	1.22	2.21	9.74	8.91	1.00

surpluses to invest in their farms and/or hire temporary workers to help them during periods of high workload. Since their access to credit was very limited, investments on the farms were related to opportunities presented by rural development projects. Low labour productivity also affected farmers' life quality through reduced family income and pressure on workload. The method we used to study and disaggregate labour productivity showed that there was huge variability among farms not only in their labour productivity but also on which were the most relevant factors that explained it.

Most farmers allocated most of their available labour to vegetable production, which had higher LP than beef-cattle production. However, we found several farms allocating more labour to less rewarding activities. Farm 3 labour allocation followed an inverse relationship with LP (Table 3). Even though it had a very low LP, cheese making was important for this farm because it provided a daily source of cash to cover daily household expenses. We found that most farmers did not realize the amount of labour used for beef-cattle production, since a significant part of it was due to routine work done during time slots of daily activities. During interviews farmers had to describe how their workday was. This helped them to realize how time consuming each activity was and to reflect about that. Which purpose it has? What for? Is it worth to maintain it? Some of these questions were addressed when discussing with farmers the redesign proposals for each farm. Farmers and researchers gained insights about the reasons behind time allocation to different activities. In the example of Farm 3, cheese making gave the family assurance about income to cover household daily expenses. In case of beef-cattle the study of labour productivity helped farmers and researchers to think about alternatives to reduce labour allocated to this activity. Collective learning was promoted by the co-innovation framework applied in this project (Dogliotti et al., 2014, Rossing et al., 2010).

Beef-cattle production showed lower LP than vegetable production in most farms. LPb was explained more by NR than by LE. We observed a positive production scale effect on LEb probably because routine work is to a great extent independent of the number of animals in the herd. This is supported by several authors which analyzed work organization in livestock farms (Sraïri et al., 2018; Hostiou and Dedieu, 2012; Madelrieux et al., 2010). In the other hand, TC was higher at larger farms, reducing NR. High TC was due to higher feeding costs explained by large areas of forage crops, sown pastures and forages reserves such as bales which are cost effective within backgrounding and finishing systems (Aguerre et al., 2014), but not within the traditional cow-calf systems predominant in these farms.

LPv was explained by both LE and NR. LE was higher in farms with larger areas of field vegetable crops and high mechanization level and was positively correlated with APS, evidencing a positive relation between LE and farming scale (Woodhouse, 2010). However, we also found high LE in farms with only greenhouse vegetables (Farms 10 and 13), and consequently low cultivated area. Through LP trees analysis we showed different ways to improve LE and NR that depended on each farm diagnosis results. For example, Farm 13 achieved the highest LPv and LE (Table 4) due to the highest farm gate prices and low labour allocation to vegetables production (12 % of available labour). Farm LP and income could be increased by both a significant increase in crop yields (Relative yield was 0.53) by adjusting soil and crop management, and a slight increase in cropped area. These changes would result in increased labour allocation to vegetable production, which has to be taken into account for the planning of beef-cattle production and other activities in the farm.

The average relative yield of all vegetable crops was 0.5, similar to the value found in this region by Dogliotti et al. (2014). This means that there is ample room for improving LEv by reducing the yield gap. Vegetable yield gap was explained by deteriorated soil quality, and timing and performance of management operations, which were taken into account to build the re-design plans. Dogliotti et al. (2014) observed a yield gap reduction of 30 % in two-three years of implementation of re-design plans in 14 pilot farms.

The analysis of work organization at farm level gave us a first insight on criteria and rules behind decisions and also provided information about general work load and their distribution over the year. The way we chose to study and desegregate labour productivity in terms of income per hour of labour ($/h) allowed us to identify crops yield gap, labour allocation to different production activities and their efficiency, and net return (prices and costs) as main drivers of low labour productivity, with different degree of relevance between farms. All these drivers were mediated by farm resource endowment that influenced choice of crops and animals products to be produced in the farm. How resources were allocated among activities as well as current production technology and techniques explained the productive and economic results of each farm. In our research we approached labour productivity at farm level as a general sustainability indicator but we deepened in the way this indicator was built.

Farms were selected from two nearby locations, less than 20 km apart. Despite of that, we found diversity in terms of resource endowment and productivity performance as well as causes that explained it. In farms 1, 3, 5, 6 and 8 low LPv was due to low LE (Table 3). LE correlated with APS, but the amount of labour used was also important. Farms 3, 5 and 8 had also a RY lower than the average of 0.5. Farm 1 and 6 had a RY above average, but low LE explained by high relative time. Farm 4 had the lowest LPv with a LE well above average, but the lowest observed RY and Farm gate price. These results support the idea that yield gaps and time allocated to each activity are important drivers of labour productivity but there are not enough to explain the performance of every farm. Differences in prices were sometimes relevant and

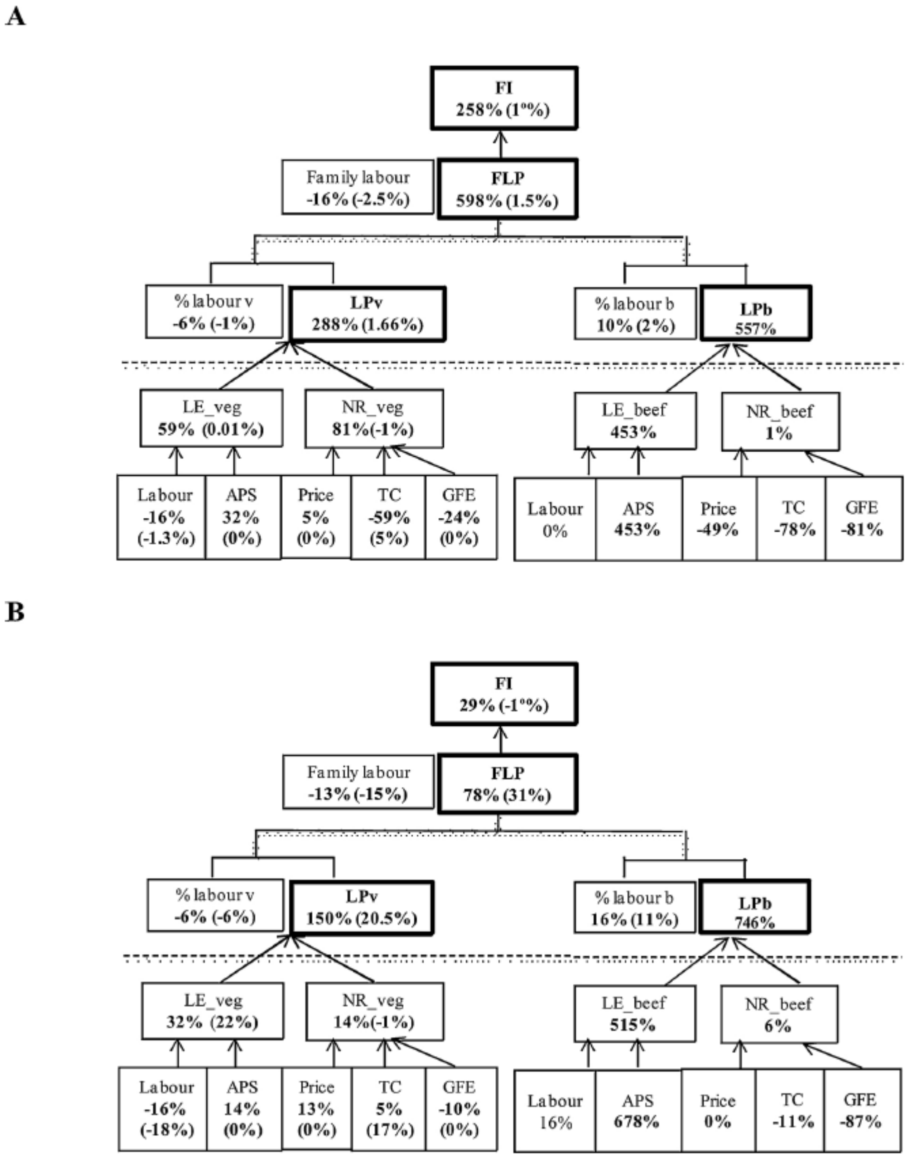

Fig. 2. Labour productivity trees for Farms 5 (A) and 11 (B). Values with no brackets indicate changes in percentage between current situation and scenario 1, and values between brackets indicate changes in percentage between scenario 1 and scenario 2.

were explained by selection of crops and type of production. Open field crops achieved lower prices than greenhouse crops.

The foregoing shows there were several ways to improve LP and the path chosen depends on understanding the main components that affect it. The indicators proposed to disaggregate and analyze labour productivity in family farming were useful to capture main causes and explained differences between farms. Improving labour productivity in vegetable production requires increasing the amount of production and/or improving efficiency. Adjusting the selection of crops and vegetable area to match labour availability and capital requirements allows to use resources and inputs more efficiently (Sraïri et al., 2018; Komarek et al., 2018; Bardhan, 2016; Okoye et al., 2008). To improve labour productivity in cow-calf beef-cattle production systems, total cost has to remain low. Farms with higher total cost based their production in forage crops and bales instead of multiannual pastures and natural grasslands.

The estimation of farm performance after implementation of re-design plans (Table 7, Scenario 1) showed that it would be possible to increase farm labor productivity and family income, exceeding the threshold in 9 out of 10 farms with LP lower than the opportunity cost of labour. This would be possible by addressing the main causes of low productivity identified for each farm, without significant increase in production costs or large investments.

Paresys et al. (2018) analyzing labour productivity in rice fields in Benim identified some local best viable practices to improve crops yield without increasing labour demand. They emphasize the need to combine yield, labour use and labour productivity analysis and to focus on labour-saving technologies. They also identified some time consuming tasks which could be mechanized to save labour and improve productivity. In our 'scenario 1' improvements were based on agreements reached with farmers and target yields were feasible to be obtained without significantly increasing labour demand. It is essential that famers' knowledge, abilities and skills are taken into account while building re-design plans (Chia et al., 2003; Figari et al., 2002).

In 'scenario 2' we explored the direct effect of mechanization in improving labour productivity. The impact of mechanization varied depending on farm current mechanization level, the amount of labour saved by mechanization and increased maintenance and depreciation costs. We found mechanization could improve farm labour productivity and family income per hour in average 12 % over 'scenario 1'. Besides the quantitative effect on LP, mechanization of some tasks could alleviate workload in work-peak moments, having a strong effect in diminish workload during specific moments of the year and the burden of heavy tasks. This reduction implies releasing time for other activities or for leisure time, increasing life quality.

Our research integrated different levels of analysis by providing a method to consider the complexity of mixed farms. Starting from general farm socioeconomic and productive results we desegregated and deepened in LP components to identify main drivers for different real farms situations. We developed a quantitative analysis method that relates LP variables through a logical tree that makes explicit how LP is built and helps to design case specific plans to increase LP and farm income. This study contributes to co-innovation processes by adding labour productivity analysis at diagnosis stage and using the results to aid participatory development of applicable and appropriate strategies to increase family farm systems sustainability.

5. Conclusions

We confirmed labour productivity is a key factor to improve sustainability of family farm systems in South Uruguay, to improve family income and life quality. The main drivers that explained labour productivity were crops yield gap, labour allocation to different production activities and their efficiency as well as net return (prices and costs). But the magnitude in which each driver affected changed widely among farms, showing there are several ways to improve LP, requiring understanding of the main components that affect it. We also found that there is ample room to improve labour productivity with current resource endowment, by increasing vegetable crops yield, adjusting the selection of crops and vegetable area to use resources more efficiently, and by reducing beef production cost and labour allocation.

Declaration of Competing Interest

The authors declare not to have conflict of interest

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References

Aguerre, V., Dogliotti, S., Chilibroste, P., Casagrande, M., 2014. Exploración de alternativas para el desarrollo sostenible de sistemas de producción hortícola-ganaderos familiares en el Sur de Uruguay. Agrociencia Urug. 18 (1), 24–40.

Alliaume, F., Rossing, W., Tittonell, P., Dogliotti, S., 2016. Modelling soil tillage and mulching effects on soil water dynamics in raised-bed vegetable rotations. Eur. J. Agron. 82, 268–281. https://doi.org/10.1016/j.eja.2016.08.011.

Alliaume, F., Rossing, Wa.H., García, M., Giller, K.E., Dogliotti, S., 2013. Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms. Eur. J. Agron. 46, 10–19. https://doi.org/10.1016/j.eja.2012.11.005.

Alston, J.M., Beddow, J.M., Pardey, P.G., Balzarini, M.G., Gonzalez, L., Tablada, M., Casanoves, F., Di Rienzo, J.A., Robledo, C.W., 2009. Manual del Usuario. Editorial Brujas, Córdoba, Argentina and Food Prices in the Long Run.

Bardhan, P.K., 2016. Size, productivity, and returns to scale: an analysis of farm-level data in Indian agriculture. J. Polit. Econ. 81 (6), 1370–1386.

Bendahan, A.B., Poccard-Chapuis, R., De Medeiros, R.D., De Lucena Costa, N., Tourrand, J.F., 2018. Management and labour in an integrated crop-livestock-forestry system in Roraima, Brazilian Amazonia. Cah. Agric. 27. https://doi.org/10.1051/cagri/2018014.

Berrueta, C., Borges, A., Giménez, G., Dogliotti, S., 2019. On-farm diagnosis for greenhouse tomato in south Uruguay: explaining yield variability and ranking of determining factors. Eur. J. Agron. 110. https://doi.org/10.1016/j.eja.2019.125932.

Chia, E., Téstut, M., Figari, M., Rossi, V., 2003. Comprender, dialogar, coproducir: reflexiones sobre el asesoramiento en el sector agropecuario. Agrociencia Urug. 7 (1), 77–91.

Cornia, G., 1985. Farm size, land yields and the agricultural production function: an analysis for fifteen developing countries. World Dev. 13, 513–534. https://doi.org/10.1016/0305-750X(85)90054-3.

Cournut, S., Chauvat, S., Correa, P., Dos Santos, J., Dieguez, F., Hostiou, N., Pham, D., Seviere, G., Sariri, M., Turlot, A., Dedieu, B., 2018. Analyzing work organization on livestock farm by the work assessment method. Agron. Sustain. Dev. 38 (58). https://doi.org/10.1007/s13593-018-0534-2.

Darnhofer, I., 2010. Strategies of family farms to strengthen their resilience. Environ. Policy Gov. 20, 212–222.

Darnhofer, I., Strauss, A., 2010. Diversification diversity as key to resilience 1777–1787. In: 11th European IFSA Symposium, on "Farming Systems Facing Global Challenges: Capacities and Strategies". Berlin. . www.ifsa-europe.org.

de Schutter, O., 2011. How not to think of land-grabbing: three critiques of large-scale investments in farmland. J. Peasant Stud. 38 (2), 249–279.

Dedieu, B., Servière, G., Jordan, A., 1999. Work organization and livestock management: lessons from 'bilan travail' studies. In: Proceedings of the Fifth EAAP Symposium on Livestock Farming Systems. Posieux, Switzerland. pp. 374–377.

Dedieu, B., 2016. Changes in Work and Its Organization: The Example of Livestock Farming Structural Evolutions, in International Syposium on Work in Agriculture. http://sites.uem.br/symposiumwa2016/workshop/workshop-4-transformations-in-work-organizations-in-farms.

Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., Rossing, W.A.H., 2014. Co-innovation of family farm systems: a systems approach to sustainable agriculture. Agric. Syst. 126, 76–86. https://doi.org/10.1016/j.agsy.2013.02.009.

Dogliotti, S., van Ittersum, M.K., Rossing, Wa.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. https://doi.org/10.1016/j.agsy.2004.08.002.

Figari, M., Rossi, V., Nougué, M., 2002. Impacto de una metodología de asesoramiento técnico alternativo en sistemas de producción lechera familiar. Agrociencia Urug. 6 (2), 61–74 Uruguay.

García, M., Florencia, A., Victoria, M., Santiago, D., 2011. Carbono orgánico y propiedades físicas del suelo en predios hortícolas del sur de Uruguay Soil organic carbon and physical properties in vegetable farms in South Uruguay. Agrociencia Urug. 15 (1), 70–81.

Herrero, M., Thornton, P.K., Notenbaert, A., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop–livestock systems. Science 327, 822–825. https://doi.org/10.1126/science.1183725.

Hostiou, N., Tourrand, J.F., Bastos da Veiga, J., Negreiros, A., Barbosa, T., 2006. The labour organization of small-scale breeders in the Brazilian amazon is a key point for sustainable development. In: Langeveld, H., Röling, N. (Eds.), Changing European Farming Systems for a Better Future. Wageningen Academic Publishers, pp. 247–251.

Hostiou, N., Dedieu, B., 2012. A method for assessing work productivity and flexibility in livestock farms. Animal 6, 852–862. https://doi.org/10.1017/S1751731111002084.

Ifad, 2011. Rural Poverty Report.NEw Realities, New Challenges: New Opportunities for Tomorrow's Generation. Ifad.

Johnson, R.A.Y., Wichern, D.W., 1992. Applied Multivariate Statistical Analysis. Prentice Hall, Englewood Cliffs, NJ.

Keating, B., Herrero, M., Carberry, P., Gardner, J., Cole, M., 2014. Food wedges: framing the global food demand and supply challenge towards 2050. Glob. Food Sec. 3 (3-4), 125–132.

Komarek, A.M., Koo, J., Haile, B., Msangi, S., Azzarri, C., 2018. Trade-offs and synergies between yield, labor, profit, and risk in Malawian maize-based cropping systems. Agron. Sustain. Dev. 38, 32. https://doi.org/10.1007/s13593-018-0506-6.

Koning, N.B.J., Van Ittersum, M.K., Becx, G.A., Van Boekel, M.A.J.S., Brandenburg, W.A., Van Den Broek, J.A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R.A., Schiere, J.B.,

Smies, M., 2008. Long-term global availability of food: continued abundance or new scarcity? NJAS - Wageningen J. Life Sci. 55, 229–292. https://doi.org/10.1016/S1573-5214(08)80001-2.
Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34, 179–204.
McConnell, D.J., Dillon, J.L., 1997. Farm management for Asia: a systems approach. FAO Farm Systems Management Series, 13. Food and Agriculture Organization of the United Nations.
Madelrieux, S., Dedieu, B., 2008. Qualification and assessment of work organisation in livestock farms. Animal 2, 435–446. https://doi.org/10.1017/S175173110700122X.
Madelrieux, S., Dedieu, B., Dobremez, L., Girard, N., 2009. Patterns of work organisation in livestock farms: the ATELAGE approach. Livest. Sci. 121, 28–37. https://doi.org/10.1016/j.livsci.2008.05.014.
Madelrieux, S., Nettier, B., Dobremez, L., 2010. Farm, family and work: new forms, new adjustments? Liveability in the dynamics of livestock farming systems. Manager 1055–1065. In: 9th European IFSA Symposium, 2010. Vienna (Austria).
Modernel, P., Rossing, W., Corbeels, M., Dogliotti, S., Picasso, V., Tittonell, P., 2016. Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. Environ. Res. Lett. 11 (113002).
Moraru, A., Munteanu, R.F., 2015. " Workforce deruralization" -a consequence of migration with implication over agriculture. Lucrări Ştiinţifice – Seria Agron. 58 (2), 277–281.
Naresh, R.K., Prakash, S., Singh, M., 2012. Role of conservation agriculture and agricultural mechanization on productivity sustainability and income generation in north west India. Int. J. Agric. Eng. 5 (1), 103–113.
Nonhebel, S., Kastner, T., 2011. Changing demand for food, livestock feed and biofuels in the past and in the near future. Livest. Sci. 139, 3–10. https://doi.org/10.1016/J.LIVSCI.2011.03.021.
Nye, C., 2018. The 'blind spot' of agricultural research: labour flexibility, composition and worker availability in the South West of England. Cah. Agric. 27, 35002. https://doi.org/10.1051/cagri/2018018.
Okoye, B.C., Onyenweaku, C.E., Ukoha, O.O., Asumugha, G.N., Aniedu, O.C., 2008. Determinants of labour productivity on small-holder cocoyam farms in Anambra State, Nigeria. Sci. Res. Essays 3, 559–561.
Paresys, L., Saito, K., Dogliotti, S., Malézieux, E., Huat, J., Kropff, M.J., Rossing, W.A.H., 2018. Feeding the world while reducing farmer poverty? Analysis of rice relative yield and labour productivity gaps in two Beninese villages. Eur. J. Agron. 93, 95–112. https://doi.org/10.1016/j.eja.2017.10.009.
Parodi, G., 2018. Agroecological transition and reconfiguration of horticultural work among family farmers in Buenos Aires, Argentina. Cah. Agric. 27, 35003.
Petit, S., Dobremez, L., Fleury, P., 2006. Working conditions: a challenge for sustainability of mountain family farming systems diagnosis at farm level and responses designed by farmers in the Alps. In: Langeveld, H., Röling, N. (Eds.), Changing European Farming Systems for a Better Future. Wageningen Academic Publishers, pp. 272–277.
Prasad, S., 2014. Int. J. Agric. Extens. 02, 57–64.
Scarlato, M., Giménez, G., Lenzi, A., Borges, A., Bentancur, O., Dogliotti, S., 2017. Análisis y jerarquización de factores determinantes de las brechas de rendimiento del cultivo de frutilla en el sur del Uruguay. Agrociencia Urug. 21 (1), 42–57.
Schneider, B.K., Gugerty, M.K., 2011. Agricultural productivity and poverty reduction: linkages and pathways. Evans School Rev. 1, 56–74.
Sraïri, M.T., Bahri, S., Ghabiyel, Y., 2018. Work management as a means to adapt to constraints in farming systems: a case study from two regions in Morocco. Cah. Agric. 27. https://doi.org/10.1051/cagri/2017066.
Tittonell, P., 2014. Ecological intensification of agriculture—sustainable by nature. Curr. Opin. Environ. Sust. 8, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006.
van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance – a review. Field Crop Res. 143, 4–17.
Weis, T., 2010. The accelerating biophysical bontradictions of industrial capitalist agriculture. J. Agrar. Change 10 (3), 315–341. https://doi.org/10.1111/j.1471-0366.2010.00273.x.
Woodhouse, P., 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. J. Agrar. Change 10 (3), 437–453.

4.
CLOSING SUSTAINABILITY GAPS ON FAMILY FARMS: COMBINING ON-FARM CO-INNOVATION AND MODEL-BASED EXPLORATIONS[3]

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4.1. RESUMEN

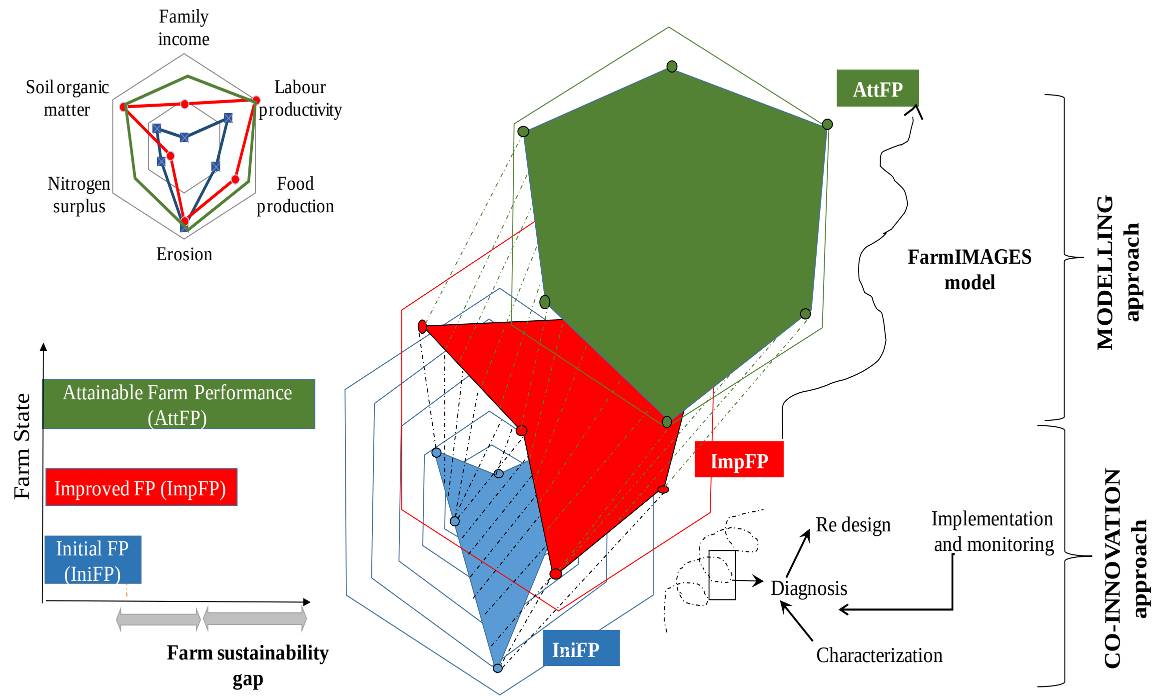
En Uruguay, la sostenibilidad de los sistemas de producción familiar se ve amenazada por la degradación del suelo, los bajos rendimientos y la carga de trabajo excesiva, lo que resulta en una baja productividad del trabajo, bajos ingresos familiares y altas tasas de erosión. Los resultados productivos y ambientales de la mayoría de los predios familiares uruguayos están muy por debajo de los niveles alcanzables con la disponibilidad actual de recursos. Este artículo tiene como objetivo mostrar las mejoras productivas y ambientales simultáneamente posibles al abordar la gestión de recursos y la organización del sistema predial en su conjunto. Reportamos los resultados de dos ciclos de aprendizaje en cuatro estudios de caso y abordamos su interdependencia. El primer ciclo involucró el rediseño del predio en un proceso de co-innovación que condujo a mejoras significativas en la performance de los predios. Los conocimientos adquiridos durante el trabajo de co-innovación se utilizaron para parametrizar un modelo bioeconómico predial para explorar el espacio de mejora del rendimiento y contribuir a la discusión de futuros procesos de co-innovación. Los dos ciclos de aprendizaje caracterizaron tres niveles de

[3] Colnago P.; Rossing W.A.H.; Dogliotti S. Closing sustainability gaps on family farms: Combining on-farm co-innovation and model-based explorations. Agricultural Systems 188. https://doi.org/10.1016/j.agsy.2020.103017

performance predial: performance inicial (IniFP), que representa el estado predial al inicio de la co-innovación, performance mejorada (ImpFP) al final de la co-innovación, y el performance alcanzable (AttFP) estimado con el modelo FarmImages. La diferencia entre el desempeño de ImpFP y AttFP representa la brecha de sostenibilidad. Después de tres años de co-innovación, los ingresos familiares en los cuatro predios mejoraron entre un 16% y un 350%, mientras que la productividad del trabajo aumentó entre un 11% y un 214%. Las exploraciones del modelo mostraron que era posible una mejora significativa adicional en los resultados socioeconómicos mientras se mantenía la erosión del suelo por debajo del nivel de tolerancia. Las estrategias identificadas diferían entre los cuatro predios según su dotación de recursos y las tecnologías disponibles, lo que confirma la necesidad de una perspectiva sistémica y soluciones a medida. Mostramos cómo un enfoque sistémico del predio que comprende la co-innovación y las exploraciones basadas en modelos contribuye a conectar los conocimientos científicos con la contextualización práctica para cerrar las brechas de sostenibilidad en predios familiares.

Palabras clave: Modelo FarmImages; Sistemas de producción hortícola-ganaderos; Ingreso familiar; erosión; productividad del trabajo

4.2. GRAPHICAL ABSTRACT



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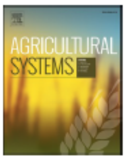

Closing sustainability gaps on family farms: Combining on-farm co-innovation and model-based explorations

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ABSTRACT

In Uruguay sustainability of family farm systems is threatened by soil degradation, low yields and excessive workloads resulting in low labour productivity, low family income and high erosion rates. The productive and environmental performances of most Uruguayan family farms are well below levels achievable with current resource availability. This paper aims to show the productive and environmental improvements simultaneously possible by addressing resource management and organization of the farm system as a whole. We report results from two learning cycles on 4 case study farms and address their interdependence. The first cycle involved on-farm re-design in a co-innovation process that led to significant improvements in the performance of the case study farms. The insights gained during co-innovation work were used to parameterize a bio-economic whole-farm model to explore the space for further performance improvement and to inform future co-innovation processes. The two learning cycles characterized three farm performance levels: the initial farm performance (IniFP), representing the state of the farm at the start of co-innovation, the improved farm performance (ImpFP) at the end of co-innovation, and the attainable farm performance (AttFP) estimated with the FarmImages model. Difference between ImpFP and AttFP represent the sustainability gap. After three years of co-innovation, family income on the four farms improved by 16 to 350%, while labour productivity increased by 11% to 214%. Model explorations showed that significant further improvement in socio-economic results was possible while maintaining soil erosion under the tolerance level. The strategies identified differed among the four farms depending on their resource endowment and the technologies available, confirming the need for a systemic perspective and tailor-made solutions. We show how an inclusive whole-farm approach comprising co-innovation and model-based explorations contributes to connecting scientific insights with practical contextualization to close sustainability gaps on family farms.

1. Introduction

Family farms represent more than 90% of landholdings, use 53% of agricultural land, and are responsible for more than 50% of global agricultural production (Graeub et al., 2016; Lowder et al., 2016). Globally, family farms constitute a diverse group in terms of size, technologies used, and integration into markets, as well as in terms of ecological and socio-economic characteristics. Only a few countries have adopted a formal definition of family farms. These definitions have in common that the family provides most of farm labour and that farming constitutes the main source of income (Graeub et al., 2016).

Next to their role in producing food, family farmers contribute to maintaining social cohesion, offer recreational and health care services, and harness cultural landscape features (Darnhofer and Strauss, 2010; Darnhofer et al., 2016; Renting et al., 2009). Some critical trends that threaten family farm systems are soil degradation (García de Souza et al., 2011; Alliaume et al., 2013 and 2019; Tittonell and Giller, 2013), the lack of access to markets and knowledge, and the fact that labour is an increasingly scarce resource due to the migration of family members in search of opportunities outside agriculture (IFAD, 2011; Lipton, 2005; Nye, 2018; Tittonell, 2014; Paresys et al., 2018; Woodhouse, 2010). Soil degradation and labour shortage affect land productivity, constrain production options, and make timely management of crops and animals difficult; together, these contribute to low farm-level productivity (Dogliotti et al., 2014). Current underperformance of many family farms from both economic and environmental points of view, result in

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insufficient income for family sustenance and investments in the farm, and negative environmental impacts. Dogliotti et al. (2014) reported family income 10% lower than the average income for rural areas in vegetable farms. In the same study, they found that erosion rates were 2 to 6 times larger than the tolerance level of 5–7 Mg ha^{-1} yr^{-1}, and the mineralizable soil carbon was 20% of the original value (based on 59 vegetable fields on 14 farms). Excessive workload and low income negatively affect life quality and may compromise farmer health (Colnago and Dogliotti, 2020; Dogliotti et al., 2014; Paresys et al., 2018).

Several studies analyzed yield gaps for main crops and developed methodologies to understand better causes of yield gaps (Doré et al., 2011; Lobell et al., 2009; Tittonell et al., 2007). Despite the importance of closing yield gaps at crop level, the challenge that farmers face at farm level is how to allocate their limited resources among different production activities to improve the performance of the farm as a whole. This multi-objective perspective of a farm sustainability gap may lead to different results compared to a perspective of maximizing individual crop yields (Mandryk et al., 2014; Dogliotti et al., 2014).

Uruguay has an Internal Gross Product (PIB) per capita of 21,983 USD. The agricultural sector accounts for 8% of total PIB, and the agricultural chain means 74% of total exports (IDB, 2015). Vegetable production in Uruguay occupies third place after beef-cattle and dairy production in terms of the number of farmers and labourers, playing an important social role as a source of work and food security. It is essential for food security since 90% of the production is allocated to the domestic market, and less than 10% of total Uruguayan fresh vegetable consumption is imported (Ackermann, 2016). Most of the vegetable production area is located in the south of the country. Of the total vegetable production volume 72% comes from field production and 28% from greenhouses. The large majority (88%) of vegetable farms are family farms Greenhouses in Uruguay are mostly wood structures covered with plastic film and cultivation is on the soil. Almost 30% of vegetable farms also produce beef-cattle. Despite being market-oriented, family income in rural areas is 20% lower than the average for the country (INE, 2020).

The development trajectory followed by vegetable farmers over the past 20 years was to grow larger areas of fewer crops and increase the use of irrigation and agrochemicals. However, this intensification increased pressure on already deteriorated soils, causing further losses in soil quality. Achieving good yields on deteriorated soils became difficult and expensive, causing family income to decrease even further. An explorative study using FarmIMAGES, a whole-farm simulation model, suggested strategies out of the un-sustainability cycle that were radically different from the prevailing farmer strategy of increasing the area of vegetables and specializing in a few crops (Dogliotti et al., 2005). Solutions featured reducing the area of vegetable crops, introducing long rotations with 3 to 4 years grass and legume pastures or alfalfa, forage and cereal crops, introducing cover crops and animal manure applications during the inter-crop periods, and for some farm types, introducing beef-cattle production to diversify income sources and make the inclusion of pastures and forage crops in rotation more profitable. The explorative study showed that there was considerable room for improvement of farm economic and environmental performance, even within the prevailing socio-economic context and farm resource availability.

Based on the results of the explorative study, farmers, local farmers organizations, farmers' technical advisors and a group of scientists from Universidad de la República (Uruguay) and Wageningen University (The Netherlands) engaged since 2005 in a series of co-innovation projects searching for pathways out of the un-sustainability cycle (FPTA 160, 2005–2007, 6 pilot farms; EULACIAS and FPTA 209, 2007–2010, 16 pilot farms; CAF-IMM 2011–2012, 38 pilot farms; INIA Rocha, 2012–2015, 7 pilot farms, FPTA 290, 2014–2017, 14 pilot farms). Co-innovation was defined as "an approach that combines complex systems theory, social learning and dynamic project monitoring and evaluation to stimulate strategic re-orientation of family farm systems" (Dogliotti et al., 2014; Rossing et al., 2010). These projects showed that after two to three years of iterative analysis-and-redesign cycles in which researchers, extension agents and farmers collaborated, most of the participating farmers were able to increase farm sustainability performance significantly. These improvements were possible by addressing the farm as a whole and not focusing on single components only. Specific changes were highly dependent on the particular situation at each farm (Dogliotti et al., 2014; Albicette et al., 2017).

Despite the potential benefits of whole-farm modelling to enhance innovation processes, very few studies have been reported that have successfully used simulation models to support an innovation process with farmers (Woodward et al., 2008; Le Gal et al., 2010). In design support methods, it is essential to involve farmers and technical advisors because the primary goal of these methods is to accompany farmers in the process of changing their production systems by exploring new management processes and technologies. Modelling is used to share a common understanding of a system and the dynamics between stakeholders involved in its operation, and to assess the impact of alternative management processes. It uses field data or local knowledge to describe real farms or typical farms. These kinds of models serve to support discussion between different actors, for example, farmers, advisors, and researchers (Le Gal et al. 2010; Martin, 2015).

Tittonell et al. (2009) developed a whole-farm model to assess the potential impact of options for sustainable intensification of mixed farming systems in Kenya. They found that there was ample scope to improve the biophysical performance for most farms in the region and the way for achieving this would imply the interaction and adjustment of several resource endowment and management variables. Another successful example of the use of models in fostering farm innovation and promoting knowledge exchange among actors is the Forage Rummy serious game (Martin, 2015). Forage Rummy workshops include collectively and iteratively designing and evaluating livestock systems able to be adapted to new contextual challenges and new farmers' objectives. The workshops aim at promoting farmers' adaptive capacity through learning about the management of livestock systems by stimulating farmers' discussion and knowledge exchange (Martin, 2015).

During discussions among farmers, extension agents, advisors and scientists on the results of the last co-innovation project that ran from 2014 to 2017, two questions arose that we address in this paper:

- How much room exists to continue improving family income and labour productivity beyond the performance at the end of the co-innovation project, while maintaining soil quality and reducing negative environmental impacts within current farm resource endowment and socio-economic context?
- Which could be promising strategies to continue improving the performance of vegetable and mixed vegetable-beef-cattle farms with contrasting resource availability?

To answer these questions, this paper first analyses the impact of three years of co-innovation on farm performances and, secondly, explores the room to continue improving farm sustainability. In the next sections, we report the work developed during co-innovation with farmers and describe the use of a farm simulation model to explore the farm gap. The results obtained by the model explorations reveal possible pathways to improve farm sustainability performance. We show how an inclusive whole-farm approach based on model-based explorations and co-innovation contributes to connecting scientific insights with practical contextualization to enhance sustainable development of family farm systems.

2. Materials and methods

2.1. General framework

The research approach combined a three-year co-innovation process and model-based explorations to identify strategies towards more sustainable farms. The performance of each farm at the beginning of co-innovation is denoted as the **initial** farm performance (IniFP). It was evaluated in terms of family income (FI), labour productivity, food production (vegetable and meat), soil erosion, N surplus and soil organic carbon (SOC) balance. After three years of co-innovation, we calculated the same sustainability indicators to estimate the **improved** farm performance (ImpFP). We defined **attainable** farm performance (AttFP) based on the results of explorations with the FarmIMAGES model starting from resource endowment at the end of the co-innovation project. We determined the farm sustainability gap as the distance between ImpFP and AttFP for all parameters assessed (Fig. 1).

In the subsequent sections, we describe the methodologies in co-innovation and model-based exploration of farm sustainability gaps.

2.2. Closing farm sustainability gaps through co-innovation

From 2014 to 2017 a co-innovation project was carried out with family farmers and their local organizations located in the northeast of Canelones, south of Uruguay, between 50 and 90 km from Montevideo, the capital (Fig. 2. Lat −34.346/−34.546 – Long −55.579/−55.873). The climate is temperate with 16 °C mean annual temperature and four seasons differentiated by temperature. The mean annual precipitation is 1000 mm fairly evenly distributed throughout the year but with significant variation between years (Furest, 2008). Between October and March, water deficits occur, and water surpluses are frequent between May and August. Slopes of 1 to 6% characterize topography. Canelones is the region of the country with a higher incidence of soil erosion (MGAP, 2004).

Vegetable-beef cattle is a farming system present exclusively in Canelones. To select participant farms, we involved the National Committee of Rural Development (CNFR), the most important farmer organization, which represents tens of local farmer organizations all over the country.

We did not select a representative sample of mixed farming systems in the South of Uruguay. Instead, we aimed for diversity that reflected the variability in resource endowment found in the region. We selected fourteen pilot farms with the aid of the boards of the local farmer organizations and their technical advisors. 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 total production, soils type, labour availability –family and hired labour-, water availability for irrigation, and level of mechanization. Farms also differed in family composition, the number of family members, and the farm life cycle stage, but all families used the farm as their main source of income.

The co-innovation process entailed characterization, diagnosis, re-design, implementation and evaluation of pilot farm systems following the approach developed by Dogliotti et al. (2014). During characterization, we assessed the management and production subsystems. The management system assessment addressed the composition of the management team, the distribution of tasks among family members, the stage in the farm life cycle and farm succession, and the main sources of technical information. Within the production subsystem, we quantified the production resources: family labour and hired labour, machinery and infrastructure, land area and quality, water availability, use of energy and other inputs. We described the allocation of the resources to the different production activities, i.e. the vegetable crops and beef cattle production, in time and space, and we quantified the results obtained in terms of social, economic and environmental performance indicators (Dogliotti et al., 2014).

The diagnosis was based on the analysis of economic and productive results, averaged over the two first years (2013–2014 and 2014–2015) (IniFP). During characterization and diagnosis, we visited the farms every two weeks and obtained information through interviews, farmer records, direct observation and measurements (see supplementary material 1).

The re-design phase entailed several steps: adjustment of field layout and erosion control support practices, design of a cropping plan and crop rotations, design of inter-crop activities and crop management activities, and ex-ante evaluation of the farm plan (Dogliotti et al., 2014). Farm plans were created and adjusted by the research team and discussed with the farmers. Design of a cropping plan and crop rotations was a critical phase in the interaction with farmers. It took time to reach an agreement since it implied changes in the allocation of resources -land, labour, water, capital- among the crop and animal activities. When possible, we introduced pastures on degraded lands to start restoring soils and provide animal feed (Dogliotti et al., 2014). Implementation began in 2015, and progress was assessed annually. The co-innovation project ended at the end of 2017, resulting in two years of monitoring data.

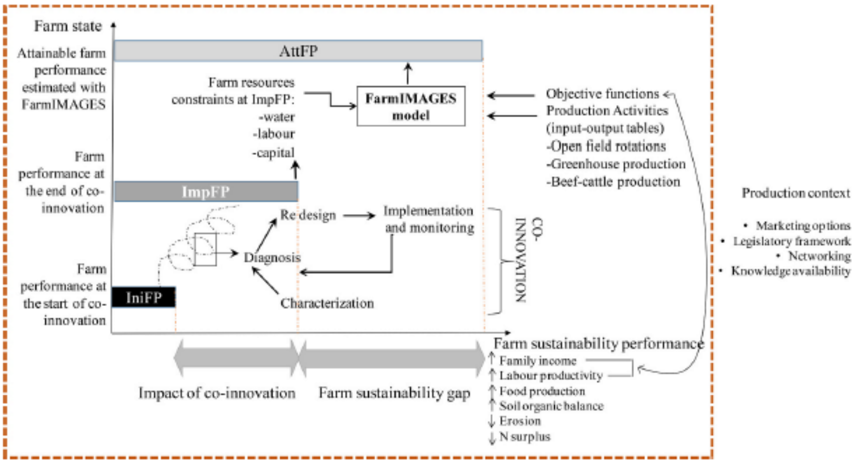

Fig. 1. Relation between farm performance levels IniFP (farm performance at the start of co-innovation), ImpFP (improved farm performance at the end of co-innovation) and AttFP (model-based attainable farm performance), and farm sustainability gaps. Farm sustainability in this study is measured in terms of the indicators described, where ↑ indicates maximization and ↓ minimization as desired optimization directions. The gap between IniFP and ImpFP is closed by co-innovation, comprising farm characterization, followed by iterative cycles of diagnosis, systems re-design, and implementation and evaluation. The gap between ImpFP and AttFP is estimated using the FarmIMAGES model.

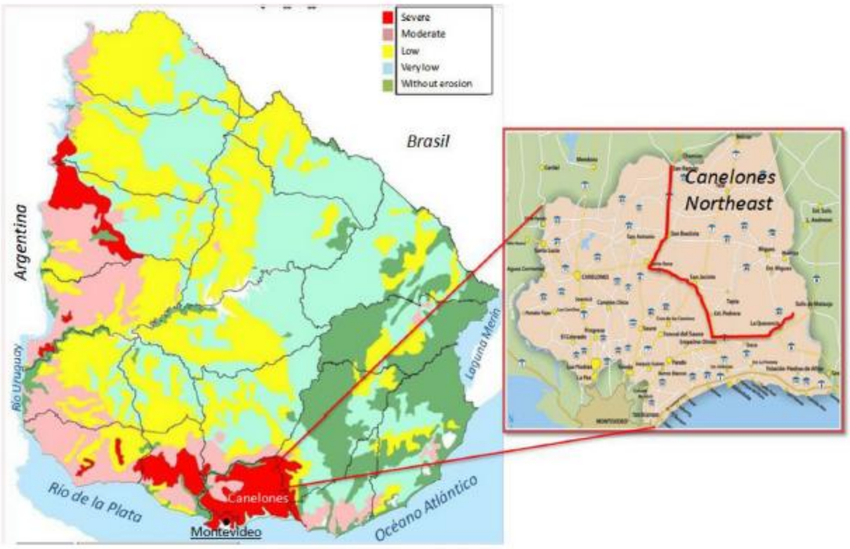

Fig. 2. Uruguay soil erosion map. Source: MGAP PN41 Prenader. 2004.

To investigate the impact of co-innovation, we compared average values for the first two years (IniFP) with data averaged over the two years of implementation (ImpFP). We compared averages of two years instead of single years to reduce the "year effect" in the results caused by weather or market induced variations.

2.3. Exploration of farm sustainability gaps after co-innovation

We explored the farm sustainability gaps after co-innovation for 4 of the 14 farms. The 4 farms were selected for their diversity in resources in terms of arable land and greenhouse areas, soil quality (% soil organic matter or SOM), labour availability, level of mechanization and share of animal production in overall farm income (Table 1). From Farm 1 to Farm 4, resource endowment increased. For each family, the main source of income was the farm. Vegetable products were sold through intermediaries in the main wholesale market in Montevideo. Beef cattle were sold through diverse channels: to other farmers (Farms 1, 2 and 3), local cattle markets (Farm 3) and slaughterhouses (Farm 4). The farms differed in life cycle stage and the possibilities of farm succession. Farms 1 and 2 were in the expansion stage; Farm 1 had small children, and farm 2 was a young recently started farmer. These farms did not have a successor yet. Farm 3 had no successor as the daughters were studying in the city, and were not interested in running the farm. Farm 4 was in transition to the next generation.

To estimate attainable and sustainable farm performance, we explored alternative farm system configurations following the approach proposed by Dogliotti et al. (2004, 2005). The time horizon of the study was 1 to 5 years, implying that all options explored were available for implementation in the short term. The method is composed of two main steps: field scale design (sections 2.3.1 to 2.3.3) and farm scale design (section 2.3.4). During the field scale design step, all feasible crop rotations are generated and combined with a range of production techniques according to pre-defined design criteria to create a variety of production activities utilizing a technical coefficient generator (Dogliotti et al., 2005). Biophysical models evaluated with local data were used to quantify inputs and outputs of the production activities. During farm scale design, a whole-farm multi-objective mixed-integer linear programming model (MGLP), named Farm Images allocates production activities to the various land units within a farm to create alternative farm systems according to the farm's resource endowment and set of sustainability objectives (Dogliotti et al., 2005) (see supplementary materials 2).

Table 1
Resource availability of each case study farm used during model-based exploration of farm sustainability gaps.

Farm n°	1	2	3	4
Area (ha)	12	18	16	115
Vegetable area (ha)	0.5	2.4	6.4	8
Greenhouse area (m^2)	2268	2250	0	0
Main crops[e]	tom/sw pep	sw pep/sw pot	onion/sw maize	onion/carrot
Crops (#)	5	5	5	8
Beef-cattle GP (%)[a]	11	12	3	18
Main soil type[b]	Typic Argiudoll	Typic Argiudoll	Typic hapluderts	Typic hapluderts
SOM (%)[c]	2.9	1.8	3.6	5.7
Slope (%)	4	2	2	3.5
Mech. Level[d]	2	2	3	5
Family members (#)	4	2	4	5
Family labour (h yr^{-1})	4000	4400	5600	5300

[a] Percentage of the total gross product (GP) from beef-cattle production.
[b] Predominant soil type.
[c] Percentage of soil organic matter (SOM).
[d] Mechanization level: 1 = Low: without tractor; 2 = Medium – Low: with tractor, without sprayer; 3 = Medium – High: with tractor and sprayer; 4 = High: 2 tractors and machine; 5 = Very High: 3 or more tractors and sprayer.
[e] Main crops were defined together with farmers based on profitability and amount of labour allocated: tom = tomato, sw pep = sweet pepper, sw pot = sweet potato, sw maize = sweet maize.

2.3.1. Crop production activities

The in silico design of new land use alternatives at field level was oriented to improving crop yields, reducing input requirements and reducing soil erosion and N surplus, while enhancing the contribution to soil organic matter. Each land use option (also called production activity) was defined as a particular set of crop and intercrop activities (which take place between two successive crops) combined in a crop rotation, and the set of techniques used to grow each crop. We quantified production techniques already applied by innovative farmers in the region and new promising ones that at the time were tested in farmers fields (Alliaume et al., 2014).

We used the ROTAT model to generate agronomically feasible crop rotations (Dogliotti et al., 2004). In line with the time horizon of the study, the selection of candidate crops for rotation design included the crops already grown in the region, which guaranteed that farmers would have the experience and skills to grow them in the short term (Table 2). We selected winter and summer crops, and different cycles of the same crop with different labour requirements to enable an even distribution of labour throughout the year. For open field rotations, we set the maximum rotation length to 11 years to allow enough variation in the frequency of crops and four years pastures. For greenhouse rotations maximum rotation length was set to 3 years, contrasting with the predominant practice of mono-cropping. We set the maximum number of different crops to 8 and 7 for field and greenhouse rotations, respectively. We generated open field rotations that combined vegetables with pastures or alfalfa to improve the soil organic matter balance and reduce soil erosion risk (Dogliotti et al., 2006), and additionally generated rotations including only forage crops and pastures for animal feeding (Albicette et al., 2014; Dogliotti et al., 2006). We distinguished crops that could be only grown under irrigation, rain-fed crops and crops that could be grown under irrigated or rainfed conditions (Table 2).

2.3.2. Animal production activities

Based on the characteristics of the region and case study farms, we selected four beef-cattle production activities from the six designed by Aguerre et al. (2014) for mixed vegetable – beef cattle family farms in south Uruguay (Table 3). We did not include short cycle options due to their high capital requirements and commercial risk (Aguerre et al., 2014). The selected activities were based on strip grazing of sown pastures, supplementation with hay and grains if required, and a health plan for the herd.

Table 3
Beef-cattle production activities options.

	Activity 1	Activity 2	Activity 3	Activity 4
Replacement category	Calf	Yearling	Steer >300 kg	Calf
Start body weight (kg)	160	190	335	150
Slaughter body weight (kg)	492	525	506	422
Average gain (kg/day)	0.650	0.656	0.950	0.646
Meat production (kg/animal)	332	335	171	272
Start date (month)	June	June	June	July
Fattening cycle (months)	17	17	6	14

2.3.3. Quantification of inputs and outputs of production activities

For each crop production activity, we estimated crop yields, irrigation water requirements, soil organic matter balance, amount and distribution of labour over the year, costs of inputs and machinery, gross margin, estimated erosion and nitrogen surplus (Dogliotti et al., 2004).

We established the attainable yield for each crop from the yield obtained by the best farmers in the region. The information was provided by technical advisors working with farmers or from research results for the region (Dogliotti et al., 2014; Scarlatto, 2017; Berrueta et al., 2019). We took into account water deficit and crop frequency (affecting the incidence of important soil-borne diseases) as yield

Table 4
Yield reduction factors due to crop frequency.

Crop/Frequency	1	0.5	0.33	0.25	0.20
Pasture/alfalfa	1	0	0	0	0
Onion	1	1	0.3	0.25	0.1
Potato Autumn	1	1	0.25	0.1	0
Potato Spring	1	1	0.25	0.1	0
Sweet potato	1	0.33	0.25	0.1	0
Squash	1	0.33	0.25	0.1	0
Small pumpkin	1	0.33	0.25	0.1	0
Water melon	1	0.33	0.25	0.1	0
Strawberry	1	1	0.25	0.1	0

Table 2
Candidate crops, sowing date and growth period (days), minimum intercrop period after harvest (days), maximum frequency in the rotation (1/number of times a crop is sown over the total duration of the rotation), water regime and attainable yield (Mg ha^{-1}).

Crop	Sowing date	Growth period (days)	Min Intercrop (days)	Max frequency	Water regime[a]	Attainable yield (Mg ha^{-1})
Pasture	1 Apr	1309	90	0.50	R	26.5
Alfalfa	1 Apr	1309	90	0.50	R	26.5
Onion	1 Aug	141	20	0.33	R or I	44
Potato Autumn	1 Feb	121	30	0.33	R or I	40
Potato Spring	1 Sep	106	30	0.33	R or I	40
Sweet Potato	25 Oct	158	90	0.33	R	40
Squash	1 Nov	195	60	0.33	R	20
Small pumpkin	1 Nov	151	50	0.33	R or I	30
Water melon	1 Nov	139	50	0.33	I	40
Strawberry	5 Mar	301	30	0.33	I	40
Greenhouse crops[b]						
Tomato LC	8-Sep	297	10	0.33	I	300
Tomato A	01-feb	149	10	0.33	I	140
Tomato S	15-ago	138	10	0.33	I	180
Tomato LS	01-nov	241	10	0.33	I	230
Cucumber A	01-feb	150	10	0.33	I	100
Green beans S	01-ago	153	10	0.33	I	100
Sweet pepper	01-sep	302	10	0.33	I	150
Lettuce	15-jul	50	7	0.33	I	24.5
Chard A	01-feb	226	7	0.33	I	79.2
Chard S	01-sep	153	7	0.33	I	79.2
Celery A	01-mar	183	7	0.33	I	95
Celery S	01-oct	150	7	0.33	I	85.5

[a] I: Irrigated; R: Rainfed.
[b] LC: long cycle; A: Autumn; S: Spring; LS: Late Spring.

reduction factors (Table 4) for open field crops. We estimated water requirements for each crop and each dominant soil type of the 4 case study farms using a simulation model adapted from SUCROS2 (Van Laar et al., 1997), modified by Alliaume et al. (2016). The model estimates crop and soil water balances based on leaf area index (LAI), root growth, soil physical characteristics and local daily weather data. We used ten years of weather data (2004–2014) of the Faculty of Agronomy weather station in Progreso (Lat 34.362 – Long 56.130).

We calculated the yield reduction due to water deficit as the ratio of estimated actual and potential evapotranspiration (Dogliotti et al., 2004; Alliaume et al., 2016). In greenhouses, all crops were irrigated to avoid water deficit, and it was assumed that the effect of crop frequency on yield reduction was avoided by soil solarization at least once every three years combined with disinfection of the greenhouse structures.

In open field crop rotations, cover crops were included every time the inter-crop period was long enough, i.e. exceeded 90 days. We included the application of chicken manure for the most profitable crops. Without chicken manure, crop yields were assumed to be reduced by 5% even when they were preceded by a green manure crop (García and Reyes, 2001; Docampo and García, 2000; Peñalva and Calegari, 2000). In greenhouse rotations, we included an annual application of compost designed to increase soil organic matter. Fertilization and water requirements for irrigation were calculated to ensure yield was not limited by nutrients or water, based on expert knowledge and locally available data.

Soil erosion in open field rotations was estimated using the Revised Universal Soil Loss Equation (RUSLE) adapted to Uruguay (Mancassola et al., 2016; Renard et al., 1997; García and Clerici, 1996).

To estimate the effect of crop rotations on long-term soil organic matter (SOM) balance, we used the model developed by Dogliotti et al. (2004). This model combines the approach of Kortleven (1963) to estimate the decomposition of the initial SOM with the model of Yang and Janssen (2000) to estimate the decomposition of all organic residues added to the soil after the start of the simulation period.

To calculate the cost of operating different machines and tools, we standardized soil and crop management for each crop and calculated the inputs needed; diesel, lubricants, and reparation and depreciation costs for all the interventions. Labour requirements were estimated from interviews carried out during the characterization stage of co-innovation.

Calculations of feed requirements for beef-cattle production activities were based on the targeted body weight gain per day. Energy, crude protein and fibre demands were estimated based on initial live weight and the targeted daily gain. NRC tables were used to estimate metabolizable energy (ME) and maximum intake (NRC 1984, 2000). Crude protein requirements were calculated for each animal category, and minimum neutral detergent fibre (NDFI) requirement was set at 22% of maximum potential intake. This criterion for animal feed decreases the risk of digestive or metabolic disorders, and it eases animal management (Aguerre et al., 2014).

Data series of vegetable and animal product prices and costs of inputs up to December 2017 were used to calculate the economic performance of each production activity. The monthly market price for each product was derived by averaging data from a four-year price series (January 2014 to December 2017), including only the months where farmers usually sold their products.The average prices were used to calculate the average price of vegetables (U\$ kg-1) produced on the farm. Increases in the average price reflect the diversity and crop choice.

2.3.4. *Farm scale design and model runs*

FarmIMAGES is a whole-farm multi-objective mixed-integer linear programming model that allocates production activities to land units of a farm to maximize or minimize objectives, subject to constraints at farm level (Dogliotti et al., 2005). An overview of the model is given in supplementary material (see supplementary materials 2). FarmIMAGES considers the resource availability of the farm, i.e., suitable soil area, labour, irrigation, capital, machinery, and the limitations imposed by the complexity of the cropping system and the farmer's management skills. Aguerre et al. (2014) extended FarmIMAGES by including beef-cattle production activities and several types of feed supplements, and by taking into account monthly energy, protein and fibre balances. In this study, we further extended the model to include greenhouse vegetable production.

The model has seven objective functions, which can be optimized one at a time. When one of the objective functions is optimized, the others can be used as constraints. Besides farm level constraints related to the availability of land, labour, irrigation and capital, there are also constraints related to farming system complexity and farmer's preferences. The latter refer to the maximum number of different rotations per farm, the maximum number of different crops, minimum field area to be cultivated and the maximum number of beef-cattle activities (Dogliotti et al., 2005) (Table 5).

2.3.5. *Design of model-based explorations*

Model explorations were oriented to bring out more sustainable farming systems, thus revealing the room for improving family income without increasing family labour while constraining erosion, N surplus and rate of change of SOM. Since the purpose was to explore attainable farm performance based on resources and main structural farm characteristic at ImpFP, we maximized family income in each run and set the parameters according to current resource availability of each farm (Tables 1 and 5). We did not enable greenhouse activities for farms 3 and 4, in agreement with the short time horizon of the study. Minimum plot size was defined for each farm according to the farm's layout resulting from the co-innovation project. As maximum crop area, we used total arable land per farm. We restricted the area of melon to 1 ha, due to limitations on the amount of product farmers can sell. We constrained external supplements for animal feeding to 15% of the total feed requirements, since current systems use mainly on-farm-produced forage. We set the use of family labour to a minimum of 70% of family labour availability. For environmental parameters, we imposed an upper bound of 100 kg ha^{-1} on N surplus. Maximum soil erosion rate was set according to the tolerance level of each soil type (Puentes, 1981) (Table 5). For SOM balance, we established a lower bound of 0 kg ha^{-1} yr^{-1} except for farm 4, where it was not possible to design crop rotations with positive SOM balance (see supplementary materials 3.).

3. Results

3.1. *Farm characterization and diagnosis: IniFP*

During the diagnosis phase of co-innovation, we identified several problems common among the farms. All farms achieved low family income due to low vegetable and meat production levels. Vegetable production accounted for 80% of total farm gross product on farm 4 and more than 80% on the other farms. At IniFP crop yields were low: farmers obtained between 45 and 65% of attainable crop yields defined

Table 5
Constraints used to explore attainable farm performance for each of the 4 pilot farms.

	1	2	3	4
Maximum family labour (h)	4000	4400	5600	5600
Maximum hired labour (h)	1000	2000	1500	2000
Maximum irrigation volume (m^3)	4000	5000	6000	6000
Maximum area for crop rotation (ha)	8	12.7	12	80
Maximum erosion (MG ha^{-1} yr^{-1})	5	5	7	7
Maximum number of different rotations	5	6	3	3
Maximum number of different crops	23	23	11	11
Minimum plot size for vegetables (ha)	0.1	0.1	0.1	0.1
Minimum plot size for forage crops	0.1	0.2	0.1	0.2
Minimum size greenhouse (ha)	0.05	0.05		
Maximum number of animal activities	1	1	1	2

as maximum yield obtained by farmers in the region with similar resource endowment (Fig. 3). In addition to low crop yields, vegetable production on farm 1 was low due to a small cultivated area.

Meat production ranged from 100 to 200 kg per hectare. These values are low for production systems based on sown, fertilized pastures and short duration forage crops, which are associated with a high feed cost compared to natural grasslands-based production systems predominant in other regions of the country. An estimation using Farm-IMAGES showed that meat production could be increased to 320 to 800 kg ha $^{-1}$, depending on the beef-cattle raising alternative (Table 3, Aguerre et al., 2014). High feed costs and low meat production, plus high costs of rented land resulted in negative economic results in Farm 4. Soil erosion greatly exceeded the tolerance threshold: 43 Mg ha^{-1} year^{-1} for farms 1 and 3, and 25 and 31 Mg ha^{-1} year^{-1} for farms 2 and 4. Soil organic matter balance was negative in three farms (Fig. 3).

Farm re-design plans included changes in farm organization: forage-crop rotation and re-allocation of resources among activities. Changes were proposed in the areas and choice of crops, pastures and forage crops in the four farms, the inclusion of greenhouse production in farm 2, and finally changes in crop and animal management in all farms. Each farm re-design plan included improvements in soil management and general crop management. Farms 1 and 3 increased water availability for irrigation during co-innovation, which allowed increasing crop area and improving crop yields.

3.2. Farm performance after co-innovation: ImpFP

The degree to which re-design plans were implemented and the impact on sustainability indicators differed between farms. Farm 3 implemented successfully almost all planned changes, Farms 1 and 2 implemented around 75%, while Farm 4 implemented 50% of the plan. The re-design plans proposed similar technologies to improve soil quality and crop yields. Still, the strategies were significantly different between farms regarding re-allocation of resources among activities and spatio-temporal land use, including areas and choice of crops, and share of animal production.

After three years of co-innovation, family income improved in all farms by 16 to 350%, along with an increase in labour productivity (FIh) of 18, 54, 11 and 214% in farms 1 to 4, respectively. Farms 1 and 3 increased vegetable production as a consequence of a larger area of vegetables and increasing yields. Farm 2 reduced the area of open-field vegetable crops to half of the initial area but introduced 2350 m^2 of greenhouse crops maintaining the volume of vegetable products and increasing farm gate price by 50% (Table 6). Yield increase was due to improvements in soil management (crop rotation, green and animal manuring), the timing of management operations, plant density and fine tuning of crop nutrition and crop protection. In farm 4 production costs remained high. The amount of meat produced at the end of co-innovation decreased sharply compared to the initial situation due to a planned reduction of animal stock that led to capital reduction. In this farm, the improvement in FI and FIh was mainly due to the addition of contract work as a new economic activity. Nevertheless, the economic performance after co-innovation remained low (Table 6, Fig. 2).

Environmental parameters improved throughout co-innovation. Soil erosion decreased on all farms, least on farm 2 (20%) and most on farm 3 (79%). Despite these significant decreases, soil erosion remained high in comparison with threshold levels, 5 Mg ha^{-1} yr^{-1} for Typic Argiudoll and 7 Mg ha^{-1} yr^{-1} for Typic hapluderts (Puentes, 1981). SOM increased in the four farms (Fig. 2), but remained negative in Farms 1 and 4. The N surplus remained below the allowed threshold (Fig. 3).

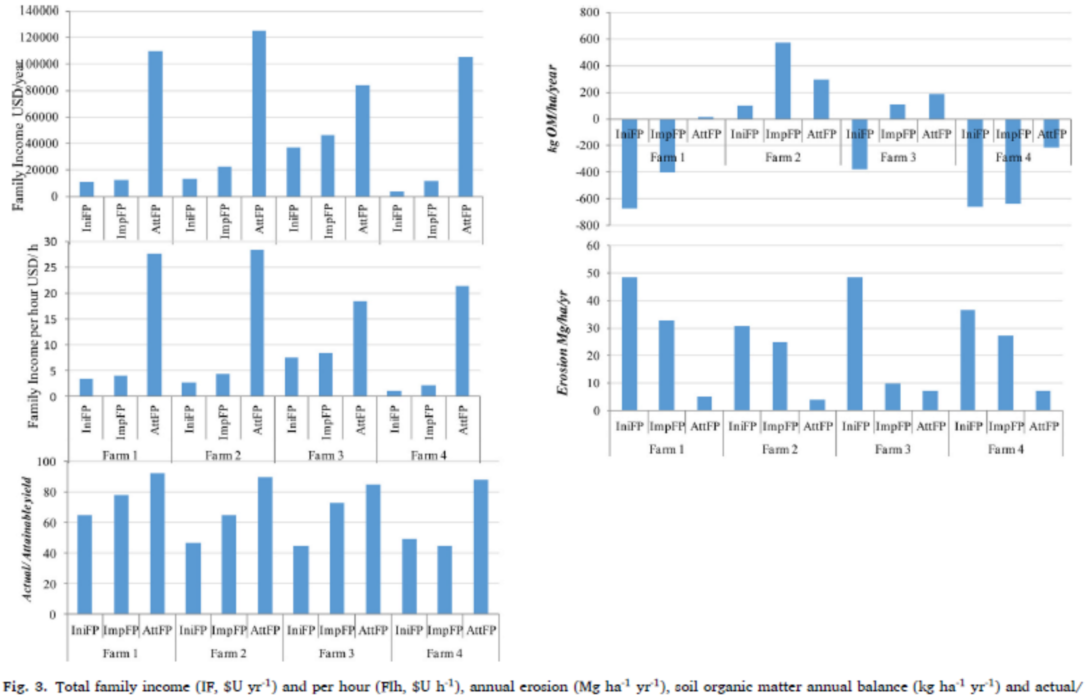

Fig. 3. Total family income (IF, $U yr^{-1}) and per hour (FIh, $U h^{-1}), annual erosion (Mg ha^{-1} yr^{-1}), soil organic matter annual balance (kg ha^{-1} yr^{-1}) and actual/attainable yield for initial, final and attainable farm performance. Currency is Uruguayan pesos. Actual/attainable yield of all crops weighted for their contribution 0 to cultivation area.

Table 6
Total production (beef and vegetables), prices, total costs and actual/attainable yields for initial, final and attainable farm performances. Currency is Uruguayan pesos ($U).

	Farm 1			Farm 2			Farm 3			Farm 4		
	IniFP	ImpFP	AttFP	IniFP	ImpFP	AttFP	IniFP	ImpFP	AttFP	IniFP	ImpFP	AttFP
Vegetable production (kg)	15,913	23,712	101,899	61,866	60,124	200,076	82,656	141,921	135,490	89,712	61,556	184,680
Average price vegetables ($U/kg)[a]	30.5	24.8	34.4	16	24	32.7	21	15	23	16	12	25.6
Meat production (kg)	1946.0	1853.0	1328	3467	2825	…	241	666	684	11,134	5807	6498
Average price cattle ($U/kg)	31.0	25.2	52	36	56	…	33	93	52	42	89	52
Total costs	265.3	301.1	946.4	766.9	941.6	1334.4	765.2	1077.4	654	2557.9	2685.1	1474.4

[a] The average price of vegetables was calculated as the ratio between the vegetables gross product ($) and the amount of vegetables sold (Kg).

3.3. *Attainable farm performance: AttFP*

We designed 435 and 919 production activities for farms 1 and 2, respectively, and 563 for farms 3 and 4. The activities varied widely in soil erosion, gross margin, labour and water requirements, production costs, and soil organic matter balance (Fig. 4).

For each farm, we were able to design an alternative farm system with significantly higher FI and FIh than ImpFP, while maintaining soil erosion below the tolerance level and improving SOM balance. At AttFP, FI was about 8.8, 5.5 and 8.8 times greater than at ImpFP, and labour productivity (FIh) at AttFP was about 6.9, 6.6 and 9.5 times greater than the value at the end of the co-innovation project for Farms 1, 2 and 4, respectively (Table 6, Fig. 3). Soil erosion could be reduced by a factor 6.6, 6.4 and 3.9 compared to ImpFP in Farms 1, 2 and 4, respectively. Differences between ImpFP and AttFP for Farm 3 were significantly lower. On this farm FI and FIh could be increased 82 and 120%, respectively, while soil erosion could be reduced by 42%. Compared to the other farms, Farm 3 performed best, i.e. had the greatest ImpFP at the end of the co-innovation project (Fig. 3, Table 6).

The strategy suggested by the model explorations to improve farm performance was different for each farm (Table 7). For Farm 1 the model allocated most of the resources to increasing the greenhouse and open field vegetable crops areas, resulting in 2.8 and 1.8 fold increases, respectively. For AttFP, Farm 1 maintained the diversity of greenhouse crops but reduced the variety of open field crops, increasing the area of sweet potato and introducing autumn potato as a new crop onto the farm. The increase in vegetable area, combined with decreases in relative yield gaps of the various crops from on average 22% to 8%, explained the estimated 4.3 fold increase in vegetable production. The model estimated a rise in the average price of sold vegetables of 39%, mainly due to the relative increase of greenhouse crops, which fetch a higher price. Forage crop area increased by 54%, while meat production (kg) decreased by 28%. Production and sales of hay bales were introduced as a new farm activity. Animal production involved fattening calves in a 17-month fattening cycle, i.e. animal production activity 1 (Table 3). This strategy resulted in a 300% increase in total costs. The area of greenhouse crops was limited by water and labour availability. The area of open field vegetable crops was additionally limited by soil erosion.

Also in farm 2 vegetable production (kg) increased significantly, by a factor 3.3, explained mainly by a 3.9 time increase in the area of greenhouse vegetable crops, while the area of open field vegetables decreased. The average relative yield gap of main crops was reduced from 35% to 10%. Similar to Farm 1, the model estimated a 36% increase in the average price of sold vegetables. The diversity of vegetable crops increased as a result of introducing several new crops to the farm. The area of forage crops and the total cultivated area were reduced by 90 and 75%, respectively (Table 7). Animal production was removed from the farm system, and the production and sales of hay bales were introduced. These changes required a 42% increase in total costs. Labour and water were constraining resources (Table 8).

In Farm 3, vegetable production and vegetable crop area were reduced by 5 and 35%, respectively. The average relative yield gap of main crops decreased from 27% to 15%. The improvements in FI and FIh were explained by an increase in the average price of vegetables of 53% and a reduction in total costs of 39%. The area of forage crops decreased by 49%, but crop diversity increased. Animal production remained almost the same, at a very low level. Labour and land availability were limiting resources (Table 8).

In farm 4, vegetable production tripled while the area of vegetable crops almost halved. The average relative yield gap of the main crops decreased from 55 to 12%. High yielding and more valuable new vegetable crops were introduced, slightly increasing crop diversity. This farm was the one achieving the smallest increase in average vegetable product prices at ImpFP (113%). The area of forage crops decreased by 65%, but crop diversity increased, and so did animal production. The animal production activity selected in farm 4 involved fattening steers for six months (i.e. activity 3, Table 3). Decreases in both vegetable and

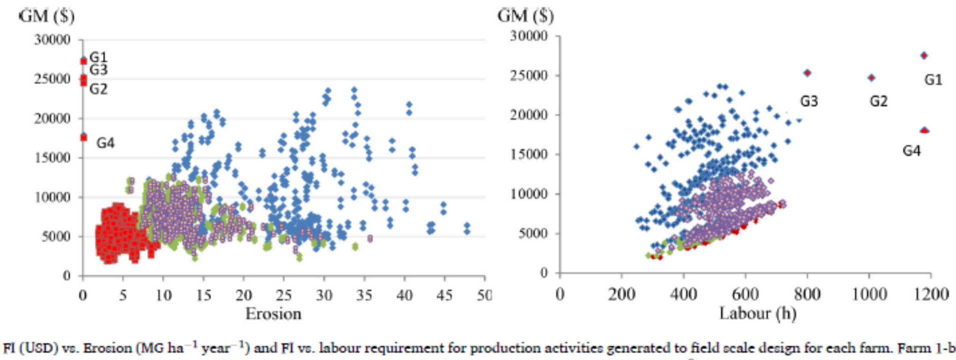

Fig. 4. FI (USD) vs. Erosion (MG ha^{-1} year^{-1}) and FI vs. labour requirement for production activities generated to field scale design for each farm. Farm 1-blue; Farm 2-red; Farm 3-green; Farm 4-violet. Labour and GM for greenhouse options (G1 to G4) are calculated for 1000 m^2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 7
Land use at ImpFP and AttFP.

Crop/area	Farm1		Farm2		Farm3		Farm4	
	ImpFP	AttFP	ImpFP	AttFP	ImpFP	AttFP	ImpFP	AttFP
Onion	–	–	0.80	0.11	2.50	1.10	2.00	1.17
Melon	–	–	–	–	0.30	–	–	0.33
Squash	–	–	0.60	–	–	–	4.50	–
Small pumpkin	0.20	–	–	0.70	1.70	0.81	–	–
Zucchini	0.10	–	–	–	0.10	–	–	–
Sweet potato	0.10	0.60	0.90	0.70	1.00	1.10	–	1.50
Spring potato	–	–	–	0.47	–	0.41	–	0.33
Autumn potato	–	0.30	–	–	–	0.70	1.30	1.17
Strawberry	–	–	–	–	–	–	–	–
Other	0.10	–	0.10	–	0.80	–	0.30	–
Sub total OFC[a]	0.50	0.90	2.40	1.99	6.40	4.12	8.00	4.50
Autumn tomato	0.04	0.11	0.07	0.15	–	–	–	–
Spring tomato	0.04	0.11	0.07	0.15	–	–	–	–
Autumn cucumber	0.04	0.11	–	0.15	–	–	–	–
Spring green pods	0.04	0.11	–	0.15	–	–	–	–
Sweet pepper	0.04	0.11	0.09	0.15	–	–	–	–
Lettuce	0.04	0.11	–	0.15	–	–	–	–
Sub total GC[a]	0.23	0.65	0.23	0.90	0.00	0.00	0.00	0.00
Pasture	1.90	3.73	7.71	0.95	–	2.20	–	11.86
Alfalfa	1.30	1.20	–	0.46	4.83	1.10	38.00	1.17
Oat	0.50	0.93	2.60	0.00	3.80	4.04	–	2.97
Moha	0.72	0.93	4.45	0.00	–	0.54	16.00	2.97
Sub total forage	4.42	6.80	14.76	1.41	8.63	7.88	54.00	18.97
Total cultivated	5.15	8.36	17.39	4.29	15.03	12.00	62.00	23.47

[a] OFC = open field crops. GC = greenhouse crops.

Table 8
Relative use of resources in the optimal model solution, estimated as the ratio between the amount of each resource used in the solution and its availability.

Resource/farm	1	2	3	4
Family labour	1.00	1.00	0.93	0.89
Hired labour	0.99	1.00	1.00	1.00
Land	1.00	0.47	1.00	0.31
Water	1.00	1.00	0.87	0.97

forage crop areas resulted in a 45% decrease in total costs. Labour and water were constraining resources (Table 8).

4. Discussion

Improving the sustainability of family farm systems can be seen as an evolutionary process composed of continuous learning cycles (Groot and Rossing, 2011). In this study, we presented two interdependent learning cycles developed to improve the sustainability of mixed vegetable-beef farm systems in south Uruguay. The first one involved farmers, extension agents and scientists in a co-innovation process that deployed systems analysis tools to facilitate knowledge exchange and improve understanding of systems structure and functioning by all participants (Reed et al., 2013). This first learning cycle resulted in significant improvements in farms systems performance. In the second learning cycle, we used the knowledge and understanding gained during the first cycle to adjust, parameterize and calibrate a bio-economic whole-farm model to explore the space to continue improving farms systems performance. The second learning cycle aimed to inform solution-oriented discussions among participants in a new co-innovation process.

In this section, we discuss the strategies identified in each learning cycle to improve farm sustainability, and how farm resource availability constrains the options for sustainable development of family farms. We also discuss how the approaches deployed in the learning cycles complement each other to enhance knowledge exchange and co-learning among participants in a transition process towards more sustainable farming systems.

4.1. Impact of co-innovation

Despite the differences in farm resource endowment among the four case study farms we found similar problems, echoing the problems of many family farms in the world: low family income and labour productivity, and soil degradation as main sustainability problems (Tittonell and Giller, 2013; Dogliotti et al., 2014; Paresys et al., 2018). Low income and low labour productivity were caused by low vegetable yields and low meat production. In farm 4 high total costs were another important cause. Soil degradation resulted from high soil erosion rates and negative soil organic matter balances. Consequently, re-design plans focused on introducing technologies to reduce soil erosion through crop rotations with pastures, cover crops and manure applications; to increase crop yields by improving the timing of operations, adjusting plant densities, crop nutrition and irrigation, and weed, pest and diseases management; and to improve the allocation of available resources among production activities. In animal production, we focused on cost reduction, on-farm feed production and stocking rate adjustment.

As observed in previous co-innovation projects in the region (Dogliotti et al., 2014; Albicette et al., 2017), the degree of implementation of the re-design plans varied among farms, which influenced the impact on farm performance. At the end of the co-innovation project, Farm 3 achieved the highest FI and FIh among the four farms, with the lowest soil erosion rate and highest soil organic matter balance (Fig. 3). This farm was the best performing farm in terms of FI and FIh at the beginning of the co-innovation project. Even though the average price of vegetables was reduced by almost 30% over the project period due to market fluctuation, the farm increased vegetable production by 72%, caused by a 40% increase in vegetable area and a 62% increase in crop yields. Total cost grew by 40% due to the increase in the vegetable area. Meat production and meat price also increased significantly in this farm, but still contributed little to FI. Farm 1 increased FI and FIh by 16 and 17%, respectively, in a similar context of decreasing vegetable prices. This farm increased vegetable production by 49% due to almost doubling the area of vegetables, increasing the greenhouse area from 756 to 1500 m^2, and increasing crop yields by 20%. Meat production remained nearly the same but fetched a lower price, resulting in a lower contribution to FI.

Farm 2 showed a significant impact of co-innovation on FI and FIh, which increased by 73 and 54%, respectively. In this farm, the area of vegetable crops decreased by 44%, but vegetable production remained the same, as crop yields increased by 38%. Greenhouse production on 2250 m^2 was introduced onto the farm, changing the type of vegetables produced, which contributed to a 50% increase in average vegetable price. Animal gross product increased by 27% but represented less than 10% of the total gross product.

Farm 4 showed the most significant changes in FI and FIh with 353 and 213%, respectively, but not due to implementation of the re-design plan. This farm re-allocated its resources to become machinery contractor providing services to other farmers, which became the main source of incomem. Farm 4 reduced its gross product by 31%, decreasing both vegetable crops area and animal production. All farms, and especially so Farm 3, decreased average soil erosion rates due to increased areas of pasture and cover crops. Soil organic matter balance increased in Farms 1 and 3 due to increased organic matter applications and reduced tillage during the pasture phase of crop rotations. At the same time, it remained unchanged in Farm 4 and decreased in Farm 2. Farm 4 had high initial soil organic matter content (5.7%, Table 1), which required huge inputs of fresh organic matter to maintain under tilled cropping.

These results advocate a farm systems innovation perspective where every farm and farm family is different, and consequently in need of a tailor-made farm management strategy. Farmers should be involved in selecting the required technologies or artefacts that bring about performance improvements (Neef and Neubert, 2011; Darnhofer et al., 2012; Dogliotti et al., 2014). The strategies unveiled by the model are consequently location-specific and need to be adjusted for each particular context.

4.2. Strategies to close the sustainability gap

Even though significant improvements in farm performance in three out of four farms were achieved after three years of co-innovation, FI and FIh were still low compared with the average income per capita in the rural areas (INE, 2020). At the end of the co-innovation project, farms 1 to 4 obtained 0.34, 1.24, 1.26 and 0.26 of the average rural income per capita, respectively. Erosion rates were higher than tolerance levels. We explored the room for further improvement of farm systems performance using FarmIMAGES. Model explorations showed that significant gains in productive, economic and environmental performance were possible, but the strategies to do so were different among farms. Similar to previous studies, different strategies were related to technological options available for each farm depending on farm resource endowment (e.g. Michalscheck et al., 2018; Dogliotti et al., 2006).

For Farms 1 and 2, the model explorations supported the existing farmers' strategies of increasing greenhouse area and vegetable production. Greenhouse vegetable crops achieve higher yields, higher labour productivity (Colnago and Dogliotti, 2020) and do not contribute to soil erosion. However, they increase production costs which were not considered as a limiting factor in our model explorations. The area of greenhouse crops was limited by water availability in both farms. Areas of open-field vegetable crops were reduced in farms 2, 3 and 4 mainly to keep soil erosion under the tolerance level, but also due to water and labour constraints. Nevertheless, vegetable production was increased or maintained, due to a significant reduction of vegetable crop yield gaps in all farms. Similar to previous studies in the region, (Dogliotti et al., 2005; Dogliotti et al., 2014; Scarlato et al., 2017; Berrueta et al., 2019) closing of yield gaps was achieved mainly by improving crop management such as sowing dates, planting densities, variety choice, crop rotation, soil management and timing of operations, without increasing inputs.

Increasing crop diversity and changing crop choice and allocation of resources to production activities explained simulated performance improvements in all farms. Diversifying the system and modifying crop choice allowed optimizing the use of available resources throughout the year and increased average farmgate product prices. Product prices are highly variable in the context of current market chain arrangements and require collective actions by farmers' organizations to secure better trade conditions (Kormelinck et al., 2019).

In previous studies (Dogliotti et al., 2005; Aguerre et al., 2014), increases of pasture area and introduction of animal production were proposed as a strategy to reduce soil loss below the tolerance level, and increase soil organic matter balance, as found elsewhere (Díaz-Zorita et al., 2002; García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009). Pastures could be used to produce hay bales for sale or for grazing beef cattle. Vegetable production (greenhouse and open field crops) achieved higher labour productivity than beef cattle. Therefore, since labour availability was a constraining factor in all farms, fewer resources were allocated to animal production. In farms 2 and 4 part of the land was even left unused since no labour was available to produce forage crops rotation and keep beef cattle.

For all farms, the model explorations were able to find a solution that reduced soil erosion below the tolerance level and a positive SOM balance, except for Farm 4. Farm 4 rented some land with no cropping history and a soil organic matter content of 5.78%, close to 6.38% found under undisturbed conditions (Durán and García-Prechác, 2007). Even a pure pasture and forage crops rotation showed a SOM balance of -13 kg ha^{-1} yr^{-1}, which is almost at equilibrium. Still, no rotation that included vegetable crops was close to the equilibrium level. Alternative technologies not considered in this study such as no-till vegetables and forage crop production (Alliaume et al., 2014), plus larger inputs of off-farm organic amendments might be able to maintain farm 4's high SOM level under vegetable production, but likely only at significant production costs.

4.3. Farm resource constraints

For the model explorations, we used the resource availability on each farm at the end of the co-innovation project and put no limits to total costs. Labour and water were the most limiting factors to increase farm productivity. At the regional level, agriculture is facing competition for available labour by other industries that offer employment stability and better salaries. Given the attainable FIh resulting from model explorations, vegetable production would be able to afford competitive salaries. However, employment stability along the year might be a problem to be addressed at the farm level. Several governmental development programs supported farmers wanting to increase their water reservoirs and establish drip irrigation systems during the last 15 years. Reservoirs collect surface water run-off, and their capacity is limited by topographic location and characteristics of each farm. Ground-water is scarce, and its quality for irrigation poor (Barreto et al., 2017). Possibilities to further increase water availability for irrigation, therefore, are different between farms and limit the expansion of the greenhouse area, which steadily increased during the last 15 years (DIEA-MGAP, 2015).

Increasing greenhouse production might have side effects not considered in this study. Increasing use of different types of plastic materials for greenhouse covers and drip irrigation systems require developing a local collection of waste and recycling facilities which are still not available, posing a serious concern for the environment. Increasing regional production might lead to a decrease of relative prices offsetting to a certain extent, the effect of farm system re-design on economic performance.

4.4. Enhancing knowledge exchange and co-learning among participants in the transition towards more sustainable farm systems

During the first learning cycle of this study farmers, extension agents and scientists engaged in a co-innovation process that resulted in improved understanding of farm systems by all participants and in changes in resource allocation and crops and animal management that improved farm performance. The systems analysis tools used as boundary objects during co-innovation (sustainability diagnosis tables, problem trees and farm re-design plans) allowed participants to translate trans-disciplinary knowledge into concrete actions to improve farm systems sustainability. During the second learning cycle, enhanced understanding of farm systems gained during co-innovation was used to design alternative production activities, quantify their inputs and outputs and enable quantification of the gap to attainable farm performance. The findings revealed opportunities for stakeholders' involvement in a new cycle of joint innovation.

The use of systems analysis and modelling tools helped to explain current farm performance and to explore alternative farm configurations. The results opened a space for a dialogue among the different stakeholders. The results contribute to the evidence base the National Committee for Rural Development (CNFR)could use in their engagement with policymakers about the need for a more systemic approach to extension. The local government and the national agency of rural development (DGDR) deliver programs to support family farmers; this type of research could inform e.g. discussions to build a national extension service or which could be the possible contributions of family farms to the National Plan for Agroecology. And finally, we gained new insights on processes and further research questions to orient future research projects. An example is how to maintain organic carbon in soils with a high organic matter content. In this way, improvements in agroecosystems management are fostered by cycles of research and redesign like an "evolutionary" adaptation process in which the primary outcome is learning by all participants (Groot and Rossing, 2011; Klerkx et al., 2012). At the farm level, innovation requires not only an improved understanding by farmers, extension agents and scientists but also tools that inform exploratory processes and solution-oriented discussions (Ditzler et al., 2018; Sterk et al., 2011). Both trust-building among participants, and model results underpinning the strategies suggested and implemented during on-farm work (Sterk et al., 2009; Ditzler et al., 2018), contribute to the symbolic role of whole-farm model explorations as input to inform discussions and further actions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.103017.

References

Ackermann, N., 2016. Anuario OPYPA. Available in. https://descargas.mgap.gub.uy/OPYPA/Anuarios/Anuario%202016/anuario_opypa_2016_en_baja.pdf.
Aguerre, V., Chilibroste, P., Casagrande, M., Dogliotti, S., 2014. Exploración de alternativas para el desarrollo sostenible de sistemas de producción hortícola-ganaderos familiares en el sur de Uruguay Exploring Alternatives for Sustainable Development of Mixed Vegetable Beef-cattle Family Farm Systems in Southern Urugu. Agrociencia Uruguay 18, 24–40.
Albicette, M.M., Leoni, C., Ruggia, A., Scarlato, S., Albín, A., Aguerre, V., 2014. A Co-Innovation Approach in Family-Farming Livestock Systems in Rocha - Uruguay : A Three-Year Learning Process, pp. 1–13.
Albicette, M.M., Leoni, C., Ruggia, A., Scarlato, S., Blumetto, O., Albín, A., Aguerre, V., 2017. Co-innovation in family-farming livestock systems in Rocha, Uruguay: a 3-year learning process. Outlook Agric. 46, 92–98. https://doi.org/10.1177/0030727017707407.
Alliaume, F., Rossing, W.A.H, García, M., Giller, K.E., Dogliotti, S., 2013. Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms. European Journal of Agronomy 46, 10–19. https://doi.org/10.1016/j.eja.2012.11.005.
Alliaume, F., Rossing, W.A.H, Tittonell, P., Dogliotti, S., 2016. Modelling soil tillage and mulching effects on soil water dynamics in raised-bed vegetable rotations. European Journal of Agronomy 82, 268–281. https://doi.org/10.1016/j.eja.2016.08.011.
Alliaume, F., Rossing, W.A.H, Tittonell, P., Jorge, G., Dogliotti, S., 2014. Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agriculture, Ecosystems and Environment 183, 127–137.
Barreto, P., Dogliotti, S., Perdomo, C., 2017. Surface water quality of intensive farming areas within the Santa Lucia river basin of Uruguay. Air Soil Water Res. 10, 1–8.
Berrueta, C., Borges, A., Giménez, G., Dogliotti, S., 2019. On-farm diagnosis for greenhouse tomato in South Uruguay: explaining yield variability and ranking of determining factors. Eur. J. Agron. 110 https://doi.org/10.1016/j.eja.2019.125932 (ISSN 11610301).
Colnago, P., Dogliotti, S., 2020. Introducing labour productivity analysis in a co-innovation process to improve sustainability in mixed family farming. Agric. Syst. 177, 102732. https://doi.org/10.1016/j.agsy.2019.102732.
Darnhofer, I., Strauss, A., 2010. Diversification Diversity as Key to Resilience, pp. 1777–1787.
Darnhofer, I., Gibbon, D., Dedieu, B., 2012. Farming systems research: an approach to inquiry. P 3-31. In: Darnhofer, Ika, Gibbon, David, Dedieu, Benoit (Eds.), Farming Systems Research into the 21st Century:The New Dynamic. Springer Dordrecht Heidelberg, New York London. https://doi.org/10.1007/978-94-007-4503-2. ISBN 978-94-007-4502-5 ISBN 978-94-007-4503-2 (eBook).
Darnhofer, I., Lamine, C., Strauss, A.M.N., 2016. The resilience of family farms: towards a relational approach. J. Rural. Stud. 44, 111–122. https://doi.org/10.1016/j.jrurstud.2016.01.013.
Diaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soilmanagement for sustainable crop production in the subhumid and semiaridPampas of Argentina. Soil Tillage Res. 65, 1–18.
DIEA-MGAP, 2015. Encuestas Horticolas 2015–2016 - Zonas Sur y Litoral Norte (N° 344). https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/datos-y-estadisticas/estadisticas/encuestas-horticolas-2015-2016-zonas-sur-litoral-norte-344.
Ditzler, L., Klerkx, L., Chan-Dentoni, J., Posthumus, H., Krupnik, T.J., Ridaura, S.L., Andersson, J.A., Baudron, F., Groot, J.C.J., 2018. Affordances of agricultural systems analysis tools: a review and framework to enhance tool design and implementation. Agric. Syst. 164, 20–30. https://doi.org/10.1016/j.agsy.2018.03.006.
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 smallholder vegetable growers 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. https://doi.org/10.1016/j.agsy.2004.08.002.
Dogliotti, S., Van Ittersum, M.K., Rossing, W.A.H., 2006. Influence of Farm Resource Endowment on Possibilities for Sustainable Development : A Case Study for Vegetable Farms in South Uruguay, 78, pp. 305–315. https://doi.org/10.1016/j.jenvman.2005.04.025.
Docampo, R., García, C., 2000. Sistemas de cultivos para la producción hortícola sostenible en la región sur. Proyecto PRENADER 35.
Dogliotti, S., García, M.C., Peluffo, S., Dieste, J.P., Pedemonte, A.J., Bacigalupe, G.F., Scarlato, M., Alliaume, F., Alvarez, J., Chiappe, M., Rossing, W.A.H., 2014. Co-innovation of family farm systems: a systems approach to sustainable agriculture. Agric. Syst. 126, 76–86. https://doi.org/10.1016/j.agsy.2013.02.009.
Doré, T., Makowski, D., Malézieux, E., Munier-jolain, N., Tchamitchian, M., Tittonell, P., 2011. Facing up to the Paradigm of Ecological Intensification in Agronomy : Revisiting Methods , Concepts and Knowledge, 34, pp. 197–210. https://doi.org/10.1016/j.eja.2011.02.006.
Durán, A., García-Precháс, F., 2007. Suelos del Uruguay: Origen, Clasificación. Manejo y Conservación, 4th. Durán, A., García-Precháс, F., 2007. Suelos del Uruguay: Origen, Clasificación. Manejo y Conservación, Montevideo, Hemisferio Sur, p. 358. FAO, 2006. Guidelines for Soil Description. 4th ed., Rome, pp. 1–358. In press.
Ernst, O., Siri-Prieto, G., 2009. Impact of perennial pasture and tillage systems oncarbon input and soil quality indicators. Soil Tillage Res. 105 (2), 260–268. https://doi.org/10.1016/j.still.2009.08.001.
Furest, F., 2008. Estadisticas agroclimtológicas mensuales 1971–2000. INIA Las Brujas.
García, F., Clerici, C., 1996. The use of the RUSLE model in Uruguay. In: Annals of the XIII Congreso Latinoamericano de la Ciencia del Suelo, August 4–8, Aguas de Lindoia, Brasil.
García De Souza, M., Alliaume, F., Mancassola, V., Dogliotti, S., 2011. Carbono orgánico y propiedades físicas del suelo en predios hortícolas del sur de Uruguay. Agrociencia Uruguay 15, 70–81.
García, M., Reyes, C, 2001. Estudio de la respuesta de una sucesión de cultivos hortícolas a diferentes abonos orgánicos. VIII Congreso Nacional de Horticultura; 29.
García-Préchac, F., Ernst, O., Siri-Prieto, G., Terra, J.A., 2004. Integrating no-till intocrop and pasture rotations in Uruguay. Soil Tillage Res. 77, 1–13. https://doi.org/10.1016/j.eja.2008.10.005.
Graeub, B.E., Chappell, M.J., Wittman, H., Ledermann, S., Kerr, R.B., Gemmill-Herren, B., 2016. The state of family farms in the world. World Dev. 87, 1–15. https://doi.org/10.1016/J.WORLDDEV.2015.05.012.

Groot, J.C.J., Rossing, W.A.H., 2011. Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. Methods Ecol. Evol. 2, 643–650.

IDB, 2015. Documento de enfoque. Uruguay 2010-2015. Evaluación Del Programa Del País. Avialable in. https://publications.iadb.org/publications/spanish/document/Documento-de-Enfoque-Evaluaci%C3%B3n-del-Programa-de-Pa%C3%ADs-Uruguay-2010-2015.pdf.

IFAD, 2011. Rural Poverty Report.New Realities, New Challenges: New Opportunities for Tomorrow's Generation, IFAD.

INE, 2020. Instituto Nacional de Estadistica. Ingreso de los hogares y de las personas. Boletín técnico. Montevideo 1–10.

Klerkx, L., van Bommel, S., Bos, B., Holster, H., Zwartkruis, J.V., Aarts, N., 2012. Design process outputs as boundary objects in agricultural innovation projects: functions and limitations. Agric. Syst. 113, 39–49.

Kormelinck, G., Bijman, J., Trienekens, J., 2019. Characterizing producer organizations: the case of organic versus conventional vegetables in Uruguay Annemarie. J. Rural. Stud. 69, 65–75. https://doi.org/10.1016/j.jrurstud.2019.04.012.

Kortleven, J., 1963. Quantitative aspects of humus accumulation and decomposition. In: Verslagen Landbouwkundige Onderzoekingen 69:1, Pudoc, Wageningen.

Le Gal, P.-Y., Merot, A., Moulin, C.-H., Navarrete, M., Wery, J., 2010. A modelling framework to support farmers in designing agricultural production systems. Environ. Model. Softw. 25, 258–268. https://doi.org/10.1016/j.envsoft.2008.12.013.

Le Gal, P.Y., Merot, A., Moulin, C.H., Navarrete, M., Wery, J., 2010. A modelling framework to support farmers in designing agricultural production systems. Environ. Model. Softw. 25, 258–268. https://doi.org/10.1016/j.envsoft.2008.12.013.

Lipton, M., 2005. In a Globalizing World The Role of Crop Science in Alleviating Poverty.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34, 179–204. https://doi.org/10.1146/annurev.environ.041008.093740.

Lowder, S.K., Skoet, J., Raney, T., 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev. 87, 16–29. https://doi.org/10.1016/J.WORLDDEV.2015.10.041.

Mancassola, V., Hill, M., Clérici, C., Sánchez, G., 2016. Estimación de la relación de pérdida de suelo (RPS) para cultivos hortícolas en el sur de Uruguay Estimation of Soil Loss Ratio (SLR) for Horticultural Crops in Southern Uruguay, 4, pp. 95–108.

Mandryk, M., Reidsma, P., Kanellopoulos, A., Groot, J.C.J., van Ittersum, M.K., 2014. The role of farmers' objectives in current farm practices and adaptation preferences: A case study in Flevoland, the Netherlands. Regional Environmental Change 14, 1463–1478. https://doi.org/10.1007/s10113-014-0589-9.

Martin, G., 2015. A conceptual framework to support adaptation of farming systems-development and application with Forage Rummy. Agric. Syst. 132 https://doi.org/10.1016/j.agsy.2014.08.013.

MGAP, 2004. Dirección General de Recursos Naturales Renovables. División de suelos y agua.Montevideo, PN41-PRENADER.

Michalscheck, M., Groot, J.C.J., Kotu, B., Hoeschle-Zeledon, I., Kuivanen, K., Descheemaeker, K., Tittonell, P., 2018. Model results versus farmer realities. Operationalizing diversity within and among smallholder farm systems for a nuanced impact assessment of technology packages. Agric. Syst. 162, 164–178. https://doi.org/10.1016/j.agsy.2018.01.028.

Neef, A., Neubert, D., 2011. Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making. Agric. Hum. Values 28, 179–194. https://doi.org/10.1007/s10460-010-9272-z.

Nye, C., 2018. The 'blind spot' of agricultural research: labour flexibility, composition and worker availability in the south west of England. Cah. Agric. 27, 35002. https://doi.org/10.1051/cagri/2018018.

Paresys, L., Saito, K., Dogliotti, S., Malézieux, E., Huat, J., Kropff, M.J., Rossing, W.A.H., 2018. Feeding the world while reducing farmer poverty? Analysis of rice relative yield and labour productivity gaps in two Beninese villages. Eur. J. Agron. 93, 95–112. https://doi.org/10.1016/j.eja.2017.10.009.

Peñalva, M., Calegari, A., 2000. Uso de abonos verdes en sistemas de producción hortícola. Editorial Peri. Montevideo, Uruguay.

Puentes, R., 1981. A Framework for the Use of the Universal Soil Loss Equation in Uruguay. M.Sc. Thesis. Texas A&M University.

Reed, M.S., Fazey, I., Stringer, L.C., Raymond, C.M., Akhtar-Schuster, M., Begni, G., Bigas, H., Brehm, S., Briggs, J., Bryce, R., Buckmaster, S., Chanda, R., Davies, J., Diez, E., Essahli, W., Evely, A., Geeson, N., Hartmann, I., Holden, J., Hubacek, K., Ioris, A.A.R., Kruger, B., Laureano, P., Phillipson, J., Prell, C., Quinn, C.H., Reeves, A. D., Seely, M., Thomas, R., van der Werff Ten Bosch, M.J., Vergunst, P., Wagner, L., 2013. Knowledge management for land degradation monitoring and assessment: an analysis of contemporary thinking. Land Degrad. Dev. 24, 307–322.

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.

Renting, H., Rossing, W.A.H., Groot, J.C.J., Van Der Ploeg, J.D., Laurent, C., Perraud, D., Stobbelaar, D.J., Van Ittersum, M.K., 2009. Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. J. Environ. Manag. 90, S112–S123. https://doi.org/10.1016/j.jenvman.2008.11.014.

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.

Scarlato, M., Gimenez, G., Lenzi, A., Borges, A., Bentancur, O., Dogliotti, S., 2017. Análisis y jerarquización de factores determinantes de las brechas de rendimiento del cultivo de frutilla en el sur del Uruguay. Agrociencia Uruguay 43–57.

Sterk, B., Leeuwis, C., van Ittersum, M.K., 2009. Land use models in complex societal problem solving: plug and play or networking? Environ. Model. Softw. 24, 165–172.

Sterk, B., van Ittersum, M.K., Leeuwis, C., 2011. How, when, and for what reasons does land use modelling contribute to societal problem solving? Environ. Model. Softw. 26, 310–316. https://doi.org/10.1016/j.envsoft.2010.06.004.

Tittonell, P., 2014. Ecological intensification of agriculture-sustainable by nature. Curr. Opin. Environ. Sustain. 8, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006.

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. F. Crop. Res. 143, 76–90. https://doi.org/10.1016/J.FCR.2012.10.007.

Tittonell, P., Van Wijk, M.T., Herrero, M., Rufino, M.C., De Ridder, N., Giller, K.E., 2009. Beyond resource constraints – Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agricultural Systems 101, 1–19. https://doi.org/10.1016/j.agsy.2009.02.003.

Tittonell, P., van Wijk, M.T., Rufino, M.C., Vrugt, J.a., Giller, K.E., 2007. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. Agric. Syst. 95, 76–95. https://doi.org/10.1016/j.agsy.2007.04.002.

Van Laar, H.H., Goudriaan, J., Van Keulen, H., 1997. SUCROS97: Simulation of Crop Growth for Potential and Water-Limited Production Situations. Quantitative Approaches in Systems Analysis n° 14. AB-DLO, C.T. de Wit Graduate School for Production Ecology, Wageningen, The Netherlands.

Woodhouse, P., 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. ttp://dx.doi.org/10. 1111/j.1471-0366.2010.00278.x. J. Agrar. Chang. 10, 437–543. https://doi.org/10.1111/j.1471-0366.2010.00278.x.

Woodward, S.J.R., Romera, A.J., Beskow, W.B., Lovatt, S.J., 2008. Better simulation modelling to support farming systems innovation: Review and synthesis. New Zeal. J. Agric. Res. 51, 235–252. https://doi.org/10.1080/00288230809510452.

Yang, H.S., Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. Eur. J. Soil Sci. 51, 517–529.

5

DISCUSIÓN GENERAL

El propósito de esta investigación fue contribuir al desarrollo sostenible de los sistemas de producción familiar mediante la comprensión de las brechas entre la productividad actual y alcanzable de la tierra, la mano de obra, y el impacto ambiental de predios hortícola-ganaderos en el sur de Uruguay, y explorar opciones para reducirlas.

El diagnóstico realizado en los 14 sistemas de producción hortícola-ganaderos re-afirma la insostenibilidad de las prácticas actuales que llevan al deterioro de los recursos naturales y a comprometer la calidad de vida de las familias productoras. Estos problemas fueron consistentes con lo reportado en antecedentes en Uruguay (Albicette et al. 2017, Dogliotti et al. 2014) y con lo citado internacionalmente para productores familiares a nivel global (IFAD 2011, Keating et al. 2010, Lipton 2005, Lobell et al. 2009).

5.1 PRODUCTIVIDAD DE LA TIERRA Y EL TRABAJO COMO FACTORES CLAVE EN LA SOSTENIBILIDAD DE LA PRODUCCIÓN FAMILIAR

El deterioro de la calidad del suelo, diagnosticado a través del porcentaje de carbono mineralizable actual sobre el original se situó en promedio en 38% (en base a 76 análisis de suelos realizados durante la caracterización de los 14 predios). El ingreso medio per cápita en zonas rurales es menor que en las ciudades y se sitúa 17% por debajo del ingreso medio nacional (INE, 2014, 2015). Para el conjunto de los predios analizados el ingreso familiar fue 40% menor al promedio para zonas rurales del departamento de Canelones (INE, 2014, 2015). El bajo ingreso familiar dificulta la re-inversión y en algunos casos lleva a la necesidad de búsqueda de oportunidades y fuentes de trabajo fuera del predio. La productividad del trabajo (PT) para el conjunto de predios fue 85\$U h^{-1}, con un rango de 22\$U h^{-1} a 171\$U h^{-1}(información en base al diagnóstico realizado para el ejercicio 2013-2014), situándose por debajo del costo de oportunidad (estimado como el equivalente al pago del trabajo asalariado por hora; 100$U h^{-1}) en 10 de los 14 predios lo que lleva a una alta carga de trabajo para mejorar los ingresos prediales.

El rendimiento obtenido en los cultivos principales fue, en promedio, 47% del rendimiento alcanzable y solo 3 predios superaron el 50% (Capítulo 2, cuadro 2).

Los problemas encontrados se ordenaron y jerarquizaron identificando sus principales causas y las consecuencias que éstos generan (Capítulo 2, figura 1). Se identificaron factores estructurales (relacionados con limitaciones de recursos) y factores funcionales (organización y asignación de recursos) vinculados a los problemas principales.

Existe una pobre interacción entre la producción hortícola y la ganadera, explicada en parte por la limitación de infraestructura como la disponibilidad de alambrados o el alcance y diseño de los sistemas de riego. El beneficio potencial de integrar estas actividades en rotaciones de largo plazo para disminuir la erosión y aumentar el balance de materia orgánica del suelo (Díaz-Zorita et al. 2002, García-Préchac et al. 2004, Ernst y Siri-Prieto 2009), es en general desaprovechado.

Las hipótesis planteadas en el capítulo 1, postulaban que: 1) *existe una brecha importante entre los resultados que actualmente se obtienen en los sistemas de producción y los que se podrían obtener en términos de productividad, eficiencia del uso de los recursos e impacto ambiental con los recursos actuales disponibles en los predios, y 2) la productividad de la tierra y del trabajo son factores clave para aumentar la sostenibilidad de los predios familiares. Es posible aumentar significativamente las dos a través de una mejor asignación de los recursos mejorando la eficiencia de su uso, sin incrementar el uso de insumos externos y reduciendo el impacto ambiental.*

Los impactos obtenidos fueron consistentes con antecedentes de proyectos de co-innovación; luego de dos ciclos de re-diseño e implementación de propuestas, el aumento del ingreso familiar fue en promedio 32% y el ingreso familiar por hora de trabajo aumentó en un 22% (Capítulo 2, tabla 5). Aunque la carga de trabajo general se mantuvo alta, fue menor que la informada por Dogliotti et al. (2014). Las mejoras logradas se relacionaron con el grado de implementación de los planes de rediseño. El impacto logrado resultó de cambios en varios componentes y sus interacciones basadas en una mejor gestión y control sobre los procesos biológicos internos, mejorando las habilidades de gestión y sin inversiones importantes (Dogliotti et al. 2014, Albicette et al. 2017).

Los cambios constatados a través del proceso de co-innovación (capítulo 2), permiten afirmar que en el contexto actual en el que los sistemas de producción están inmersos, existe un espacio importante para la mejora.

En las hipótesis planteadas se señala a la PT como clave en la mejora de la sostenibilidad. En los antecedentes (Capítulo 1) se planteó que la baja PT era una de las principales causas que afectan la sostenibilidad de los predios familiares (Bendahan et al. 2018, Komarek et al. 2018, Paresys et al. 2018, Parodi 2018) y que varios de los problemas de la producción familiar están asociados al trabajo: la sobrecarga de trabajo, la falta de tiempo libre y problemas de salud asociados al trabajo (Dogliotti et al., 2014).

Los valores de PT hallados en nuestra investigación no permiten generar excedentes que puedan ser re-invertidos en los predios para mejorar o al menos mantener los recursos e infraestructura productiva. Esto confirma que la PT es una de las mayores causas que compromete la sostenibilidad de predios familiares y que sea clave su análisis para pensar en propuestas de mejoras prediales.

Para estudiar la PT se propuso un método que permitió desagregar entre las distintas actividades productivas (horticultura, ganadería y otras) e identificar distintos coeficientes técnicos. La PT fue baja en la horticultura y en la ganadería, en promedio para los 14 predios fue de 114\$U h^{-1} y 47\$U h^{-1} respectivamente.

En proyectos anteriores, se encontró que los predios que combinaban horticultura y ganadería tenían mejor PT (Dogliotti et al 2014) bajo el supuesto de que la ganadería insumía poco trabajo y generaba un ingreso complementario a la horticultura. En esta investigación, la PT en ganadería fue menor que la PT en horticultura y estuvo fundamentalmente explicada por los altos costos incurridos en la producción de carne (capítulo 3).

Esto haría repensar el rol de la ganadería en estos sistemas. En la última década hubo un incremento importante en la cantidad de vacunos en Canelones. Este cambio fue impulsado por la disminución de precios en la horticultura, por el incremento de sus costos (insumos en moneda extranjera) y al mismo tiempo debido al estímulo de altos precios de venta de la carne. Por otro lado se trata de un producto que genera la oportunidad de venta en distintos momentos, oficiando de caja de ahorro o generando ingresos en momentos clave donde es necesario contar con dinero circulante para pagar costos de cultivos, o afrontar un nuevo año agrícola. Este aumento en la cantidad de vacunos en cada predio se produjo por retención de las terneras, aumentando el número de vientres pero sin planificación ni propósito concreto. El análisis de la PT permitió evidenciar que esta actividad consume mucho tiempo debido al trabajo de rutina que insume, que es relativamente independiente del número de animales (dentro de cierta escala). A su vez ese tiempo se incrementa debido a las carencias constatadas en la infraestructura disponible. Paralelamente, los indicadores productivos no son buenos (% de preñez, de destete, intervalo inter-partos) por falta de conocimiento y experiencia en la ganadería como actividad económica, lo que lleva a deficiencias en el manejo. La estrategia de producción de forraje dominante es la siembra de verdeos o de praderas de alfalfa, incrementando los costos de producción.

La elaboración de árboles de problemas para este indicador permitió identificar distintas vías de mejora para cada sistema de producción. Para poder traducir esto en propuestas de re-diseño que contemplen los principales problemas hallados es necesario conocer cuáles son los criterios y reglas de decisión implementados por cada familia. El análisis realizado nos permitió profundizar en estos criterios así como obtener información sobre la carga global de trabajo y su distribución a lo largo del año.

A través del método desarrollado identificamos y cuantificamos que la brecha de rendimiento de los cultivos, la asignación de tiempo de trabajo entre actividades productivas y su eficiencia, y los precios, son los factores que explican la PT. Si bien los factores son comunes, cobran diferente relevancia según el predio, lo que justifica la necesidad de un análisis en profundidad para diseñar estrategias apropiadas a cada caso (Capítulo 3).

Ajustar la selección y áreas de cultivos, y balancear mejor la oferta y demanda de mano de obra, permitió utilizar los recursos de manera más eficiente. Las proyecciones hechas en el escenario 1 -cuantificación ex ante del impacto de las propuestas de re-diseño-, estuvieron basadas en los cambios acordados con los productores y proyectando rendimientos posibles de obtener (Capítulo 3, figura 2).

La mejora de PT proyectada en el escenario 2 mecanizando algunas tareas, varió fuertemente dependiendo del grado de mecanización inicial en cada predio, del tiempo de trabajo que se ahorra y del incremento de los costos debido a la amortización. Además de su impacto en la mejora de PT, hay un efecto cualitativo vinculado a la calidad de vida. La mecanización aliviana algunas tareas y el ahorro de trabajo libera tiempo para el descanso o para su asignación a otras tareas.

Incorporar el análisis de PT constituyó una contribución metodológica que enriquece el desarrollo de la co-innovación como enfoque sistémico ya que permite considerar esta variable de forma explícita en las propuestas de re-diseño, mejorando su pertinencia e impacto. Se demostró la hipótesis de que es posible aumentar significativamente este indicador generando cambios en la asignación de los recursos (tierra, trabajo y capital) entre actividades productivas (distintos cultivos y producción animal) y mejorando el manejo, sin aumentar el uso de insumos (Capítulo 3- figura 2).

5.2. BRECHAS DE SOSTENIBILIDAD A NIVEL PREDIAL; ¿CUÁNTO ES POSIBLE MEJORAR?

La distancia entre el valor medido para los indicadores de sostenibilidad al final de la co-innovación y los resultados obtenidos por los productores al inicio del proyecto evidencian una brecha que pudo ser reducida mejorando la asignación de recursos y el manejo de cultivos y animales. Después de tres años de co-innovación (ImpFP), el

IF mejoró en los cuatro predios analizados en el Capítulo 4, entre 16% y 350%, mientras que la PT aumentó entre 11% y 214%. Si bien se logró reducir la erosión los valores estimados continuaban superando el umbral de tolerancia (5-7Mg $ha^{-1}año^{-1}$ de acuerdo al tipo de suelo).

Las preguntas emergentes fueron ¿cuánto más puede mejorar el ingreso familiar y la productividad del trabajo, manteniendo la calidad del suelo y reduciendo otros impactos ambientales, dadas las restricciones impuestas por la dotación de recursos propia de cada predio? y ¿cuáles podrían ser estrategias prometedoras para seguir mejorando la sostenibilidad de sistemas de producción hortícola-ganaderos?

La tercera hipótesis (Capítulo 1) plantea que *"las estrategias y opciones tecnológicas para reducir estas brechas dependen fuertemente de la disponibilidad de recursos de cada sistema de producción"*.

Para contestar estas preguntas y discutir esta hipótesis se seleccionaron 4 de los 14 predios con recursos contrastantes. En comparación con el predio 1, los predios 2, 3 y 4 tenían un 10%, 40% y 32.5% más de disponibilidad de mano de obra y 50%, 33% y 9.5 veces más tierra, respectivamente. También diferían en el nivel de mecanización (de acuerdo a la clasificación propuesta del nivel 1 al 5, oscilaron entre 2 y 5) y en la disponibilidad de agua; 25% más en el predio 2 y 50% en los predios 3 y 4 en comparación con el predio 1 (Capítulo 4, cuadro 5). Se estimó una brecha definida como la distancia entre los resultados obtenidos al término del proyecto de co-innovación (ImpFP) y los resultados alcanzables, estimados con el modelo de simulación FarmImages (AttFP). Los datos obtenidos durante el proceso de co-innovación se utilizaron para parametrizar el modelo.

Las simulaciones con el modelo permitieron diseñar una configuración alternativa para cada predio que llevó a una mejora significativa adicional en los resultados socioeconómicos manteniendo la erosión del suelo por debajo del nivel de tolerancia y mejorando el balance de la MOS.

El IF estimado con el modelo fue entre 5.5 y 8.8 veces mayor que en ImpFP, y la PT fue entre 6.6 y 9.5 veces mayor que el valor al final del proyecto para los predios 1, 2 y 4, (Capítulo 4, Tabla 6, Figura 3). La erosión podría reducirse en un factor de 3.9 y

6.6 en comparación con ImpFP en estos mismos predios. Para el predio 3, las diferencias entre ImpFP y AttFP fueron significativamente menores; 82 y 120% para el IF y la PT respectivamente, mientras que la erosión del suelo podría reducirse en un 42%. En comparación con los otros predios, los resultados obtenidos en este predio al final del proyecto de co-innovación eran superiores (Capítulo 4, Tabla 6, Figura 3).

5.2.1. Recursos que condicionan las estrategias

Las estrategias para obtener estas mejoras difirieron entre predios y se relacionaron con las opciones tecnológicas disponibles en función de la dotación de recursos de cada predio (Dogliotti et al. 2006, Michalscheck et al. 2018). Para las exploraciones se utilizó la disponibilidad de recursos que cada predio tenía al final del proyecto de co-innovación y no se restringieron los costos totales.

Para los predios con invernáculos (predios 1 y 2, Capítulo 4), los resultados de la simulación reafirman la estrategia actual de los productores de aumentar el área de invernáculos. Los cultivos que se producen en invernáculos alcanzan mayores rendimientos y mayor PT (Colnago y Dogliotti, 2020) y no tienen riesgo de erosión del suelo. Sin embargo, aumentan los costos de producción que no se consideraron como un factor limitante en las exploraciones. El área de cultivos estuvo limitada por la disponibilidad de agua. Las áreas de cultivos de campo se redujeron en tres de los predios principalmente para mantener la erosión del suelo por debajo del nivel de tolerancia, pero también debido a las limitaciones de agua y mano de obra. Sin embargo, la producción de hortalizas aumentó o se mantuvo debido a una reducción significativa de la brecha de rendimiento en todas las explotaciones (reducción entre el 10 y 55% dependiendo del cultivo y del predio). De manera similar a estudios previos en la región (Berrueta et al. 2020, Dogliotti et al. 2014, 2005, Scarlato et al. 2017) el cierre de las brechas de rendimiento se logró principalmente mediante la mejora del manejo de cultivos como fechas y densidades de siembra, elección de variedades, rotación de cultivos, manejo del suelo y calendario de operaciones, sin aumentar los insumos.

En estudios previos (Aguerre et al. 2014, Dogliotti et al. 2005), se propusieron incrementos del área de forraje y la introducción de producción animal como una estrategia para reducir la pérdida de suelo por debajo del nivel de tolerancia y aumentar el balance de materia orgánica del suelo (Díaz-Zorita et al. 2002, García-Préchac et al. 2004, Ernst y Siri-Prieto, 2009). En las simulaciones realizadas, la producción de hortalizas logró mayor PT que la ganadería. Por lo tanto, dado que la disponibilidad de mano de obra fue un factor limitante en todos los predios, se asignaron menos recursos a la producción animal. En dos de los predios se dejó sin utilizar parte de la tierra ya que no se disponía de mano de obra para implementar una rotación forrajera y criar ganado. El trabajo y el agua fueron en todos los casos, los factores más limitantes.

A nivel regional, la agricultura se enfrenta a la competencia por la mano de obra por parte de otras industrias que ofrecen estabilidad laboral y mejores salarios. El IF potencialmente alcanzable (AttFP) permitiría otorgar a la producción hortícola salarios competitivos. Sin embargo, la estabilidad del empleo a lo largo del año podría ser un problema a abordar a nivel de las explotaciones.

El agua subterránea en Canelones es escasa y su calidad para el riego es deficiente (Barreto et al., 2017). Las reservas de agua de escorrentía tienen capacidad limitada por la ubicación topográfica y las características de cada predio. Por lo que las posibilidades de incrementar aún más la disponibilidad de agua para riego difiere entre predios y limitan la expansión del área de invernáculos, que aumentó de manera constante durante los últimos 15 años (MGAP-DIEA, 2015).

5.2.2. Nuevas preguntas que surgen a partir de las exploraciones con modelos

Las exploraciones del modelo pudieron encontrar una solución que redujo la erosión del suelo por debajo del nivel de tolerancia y un balance MOS positivo, excepto para el predio 4. El suelo utilizado para la simulación en este predio tenía un contenido de materia orgánica de 5.78%, cercano al 6.38% encontrado en condiciones inalteradas (Durán y García-Prechác, 2007). Incluso la rotación puramente forrajera mostró un balance de MOS de -13 $kg.ha^{-1}año^{-1}$, cercano al equilibrio. Sin embargo, ninguna rotación que incluyera cultivos hortícolas se acercó al nivel de equilibrio. Esto hace pensar en la necesidad de tecnologías alternativas no consideradas en este estudio, como el mínimo laboreo en la horticultura (Alliaume et al., 2013) o mayor incorporación de enmiendas orgánicas. Existen trabajos promisorios a nivel de estación experimental (García de Souza et al. 2011, Alliaume et al. 2014) que deben validarse a nivel predial.

El aumento de la producción de invernadero puede tener efectos secundarios no considerados en este estudio. El uso del polietileno como cubierta y en los sistemas de riego por goteo, requiere el desarrollo de una recolección local de residuos e instalaciones de reciclaje que aún no están disponibles. Por otro lado el aumento de la producción podría conducir a una disminución de los precios relativos que disminuyan en cierta medida el efecto del rediseño del sistema en los resultados económicos.

5.3. CONSIDERACIONES FINALES

El trabajo de investigación presentado integra un enfoque sistémico, co-innovación, con exploraciones basadas en modelos, generando un aporte metodológico que contribuye a conectar conocimientos científicos con su contextualización práctica, para cerrar las brechas de sostenibilidad en predios.

En la investigación vinculamos dos ciclos de aprendizaje interdependientes desarrollados para mejorar la sostenibilidad de los sistemas hortícola-ganaderos en el sur de Uruguay. El primero involucró a productores, agentes de extensión e investigadores en un proceso de co-innovación que implementó herramientas de análisis de sistemas para facilitar el intercambio de conocimientos y mejorar la comprensión de la estructura y el funcionamiento predial por parte de todos los participantes (Reed et al., 2013). Este primer ciclo de aprendizaje resultó en mejoras significativas en los resultados prediales. En el segundo ciclo de aprendizaje, utilizamos el conocimiento y la comprensión adquiridos durante el primer ciclo para ajustar, parametrizar y calibrar un modelo bioeconómico y explorar el espacio para continuar mejorando la performance predial. Este ciclo tuvo como objetivo aportar elementos para discusiones orientadas a la solución de problemas y al diseño de estrategias entre distintos tomadores de decisión.

Los problemas complejos son difíciles de identificar y requieren soluciones complejas (Farrell et al. 2008, Pacín y Oesterheld, 2015). Existe tecnología generada para la pequeña y mediana escala que podría resolver varios de los desafíos productivos que los productores tienen. Sin embargo los sistemas de transferencia tecnológica y de asesoramiento técnico no han sido exitosos en revertir estas tendencias. El diseño de políticas de apoyo a la producción familiar ha priorizado el abordaje por componentes, ofreciendo financiamiento y asesoramiento técnico para mejoras en cultivos de interés o planes de negocio. Estos apoyos, si bien necesarios, son insuficientes en lograr cambios que impacten en los resultados globales del predio.

Durante el proceso de co-innovación, las tecnologías implementadas fueron similares entre los predios pero las estrategias diferían ampliamente, lo que evidencia la necesidad de tener un enfoque sistémico en la construcción de las propuestas y que integre la participación de los productores (Darnhofer et al. 2016, Dogliotti et al. 2014, Neef y Neubert 2011). La estrategia seguida utilizando diferentes herramientas de análisis de sistemas para promover el aprendizaje -informes de diagnóstico, árboles de problemas, tablas de puntos críticos, planes de rediseño, días de campo y talleres de reflexión- facilitó la comunicación efectiva entre diferentes actores (agricultores, asesores, equipo de investigación, actores del gobierno local) permitiendo que la innovación tuviera lugar (Clark et al. 2016, Ditzler et al. 2018, Farrell et al. 2008, Reed et al. 2010).

La mejora continua de los sistemas de producción, buscando “soluciones a medida” que permitan posicionar a los sistemas de producción familiar como innovadores, donde la tecnología implementada refleje un uso intensivo del conocimiento mejorando *la agronomía,* debe ser una aspiración y desafío permanente para los investigadores y profesionales del agro.

6

BIBLIOGRAFÍA GENERAL

Ackermann N. 2016. Horticultura: situación y perspectivas. Anuario OPYPA (Oficina de Programación y Política Agropecuaria). (En línea). Consultado 10 de noviembre de 2020. Disponible en: https://descargas.mgap.gub.uy/OPYPA/Anuarios/Anuario%202016/anuario_opypa_2016_en_baja.pdf

Aguerre V, Chilibroste P, Casagrande M, Dogliotti S. 2014. Exploración de alternativas para el desarrollo sostenible de sistemas de producción hortícola-ganaderos familiares en el sur de Uruguay. Agrociencia Uruguay 18: 24–40.

Albicette MM, Leoni C, Ruggia A, Scarlato S, Blumetto O, Albín A, Aguerre V. 2017. Co-innovation in family-farming livestock systems in rocha, Uruguay: A 3-year learning process. Outlook on Agriculture. 46: 92–98. doi:10.1177/0030727017707407

Alliaume F, Rossing WAH, Tittonell P, Jorge G, Dogliotti S. 2014. Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems. Agriculture, Ecosystems and Environment 183: 127–137.

Alliaume F, Rossing WAH, García M, Giller KE, Dogliotti S. 2013. Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms. European Journal of Agronomy. 46: 10–19. doi:10.1016/j.eja.2012.11.005

Barreto P, Dogliotti S, Perdomo C. 2017. Surface water quality of intensive farming areas within the Santa Lucía river basin of Uruguay. Air, Soil and Water Research. 10:1-8.

Bendahan AB, Poccard-Chapuis R, De Medeiros RD, De Lucena Costa N, Tourrand JF. 2018. Management and labour in an integrated crop-livestock-forestry system in Roraima, Brazilian Amazonia. Cahiers Agricultures. 27(2) 25005. doi:10.1051/cagri/2018014

Berrueta C, Heuvelink E, Giménez G, Dogliotti S. 2020. Estimation of tomato yield gaps for greenhouse in Uruguay. Scientia Horticulturae. 265, 109250. doi:10.1016/j.scienta.2020.109250

Clark WC, Van Kerkhoff L, Lebel L, Gallopin GC. 2016. Crafting usable knowledge for sustainable development. Proceedings of the National Academy of Sciences 113: 4570–4578. doi:10.1073/pnas.1601266113

Colnago P, Dogliotti S. 2020. Introducing labour productivity analysis in a co-innovation process to improve sustainability in mixed family farming. Agricultural Systems. 177: 102732. doi:10.1016/j.agsy.2019.102732

Darnhofer I, Lamine C, Strauss A, Navarrete M. 2016. The resilience of family farms: Towards a relational approach. Journal of Rural Studies. 44: 111–122. doi:10.1016/j.jrurstud.2016.01.013

Darnhofer I. 2010. Strategies of family farms to strengthen their resilience. Environmental Policy and Governance 20: 212–222

Darnhofer I, Strauss A. 2010. diversification Diversity as key to resilience 1777–1787, in 11th European IFSA Symposium, on “Farming systems facing global challenges: Capacities and strategies”. Berlin,www.ifsa-europe.org

Díaz-Zorita M, Duarte GA, Grove JH. 2002. A review of no-till systems and soilmanagement for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil and Tillage Research. 65: 1–18.

D’Souza F, Ikerd J. 1996. Small farms and sustainable development: is small more sustainable? Journal of Agricultural and Applied Economics 28(1): 73-83.

Ditzler L, Klerkx L, Chan-Dentoni J, Posthumus H, Krupnik TJ, Ridaura SL, Andersson JA, Baudron F, Groot JCJ. 2018. Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation. Agricultural Systems. 164: 20–30. doi:10.1016/j.agsy.2018.03.006

Dogliotti S, García MC, Peluffo S, Dieste JP, Pedemonte AJ, Bacigalupe GF, Scarlato M, Alliaume F, Alvarez J, Chiappe M, Rossing WAH. 2014. Co-innovation of family farm systems: A systems approach to sustainable agriculture. Agricultural Systems. 126: 76–86. doi:10.1016/j.agsy.2013.02.009

Dogliotti S, Colnago P, Favretto G, Fernández JL, Morales G, Riet L, Sierra F, Vieta

A. 2012. Co-innovando para una agricultura más sostenible: apoyando el desarrollo de un sistema de extensión para la agricultura familiar. En: 1er congreso de ciencias sociales agrarias. "Desafíos y contribuciones para el desarrollo rural"'(1º, 2012, Montevideo-Uruguay). 16p

Dogliotti S, van Ittersum MK, Rossing WAH. 2006. Influence of farm resource endowment on possibilities for sustainable development: A case study for vegetable farms in South Uruguay. Journal of Environmental Management 78: 305–315. doi:10.1016/j.jenvman.2005.04.025

Dogliotti S, van Ittersum MK, Rossing WAH. 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agricultural Systems. 86: 29–51. doi:10.1016/j.agsy.2004.08.002

Doré T, Makowski D, Malézieux E, Munier-jolain N, Tchamitchian M, Tittonell P. 2011. Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. European Journal of Agronomy. 34: 197–210. doi:10.1016/j.eja.2011.02.006

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

Ernst O, Dogliotti S, Cadenazzi M, Kemanian A. 2018. Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. Field Crops Research. 217: 180-187. doi: 10.1016/j.fcr.2017.11.014

Ernst O, Siri-Prieto G. 2009. Impact of perennial pasture and tillage systems on carbon input and soil quality indicators. Soil and Tillage Research. 105 (2): 260–268,http://dx.doi.org/10.1016/j.still.2009.08.001.

Farrell M, Mcdonagh J, Mahon M. 2008. The Options for Farm Families Programme: Rhetoric and Reality of Change Maura. The Journal of Agricultural Education and Extension. 15: 39–58.

Foley JA. 2011. Can we feed the world & sustain the planet? Scientific American. 305: 60–65. doi:10.1038/scientificamerican1111-60

Foley JA, De Fries R, Asner GP, Barford C, Bonan, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik

CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK. 2005. Global consequences of land use. Science. 309: 570–574. doi:10.1126/science.1111772

García De Souza M, Alliaume F, Mancassola V, Dogliotti S, 2011. Carbono orgánico y propiedades físicas del suelo en predios hortícolas del sur de Uruguay. Agrociencia Uruguay. 15 (1): 70–81.

García-Préchac F, Ernst O, Siri-Prieto G, Terra JA. 2004. Integrating no-till intocrop and pasture rotations in Uruguay. Soil and Tillage Research. 77: 1–13. doi.org/10.1016/j.still.2003.12.002

Graeub BE, Chappell MJ, Wittman H, Ledermann S, Kerr RB, Gemmill-Herren B. 2016. The State of Family Farms in the World. World Development. 87: 1–15. doi.org/10.1016/j.worlddev.2015.05.012

Hostiou N, Tourrand JF, Bastos da Veiga J, Negreiros A, Barbosa T. 2006. The labour organization of small-scale breeders in the Brazilian Amazon is a key point for sustainable development. En: Langeveld H, Röling N. (Eds.), Changing European farming systems for a better future. Wageningen Academic Publishers. 247-251.

IFAD (International Fund for Agricultural Devolopment), 2011. Rural Poverty Report.New realities, new challenges: new opportunities for tomorrow's generation (En línea). Consultado 10 de noviembre de 2019. Disponible en: 2020https://reliefweb.int/sites/reliefweb.int/files/resources/0761B50B87EC879BC12577F10051867C-IFAD_Dec2010.pdf

INE (Instituto Nacional de Estadística). 2014, 2015. Ingreso de las personas y hogares (En línea). Consultado 10 de noviembre de 2020. Disponible en: https://www.ine.gub.uy/web/guest/gastos-e-ingresos-de-las-personas-y-los-hogares

Keating BA, Carberry PS, Bindraban PS, Asseng S, Meinke H, Dixon J. 2010. Eco-efficient agriculture: Concepts, challenges, and opportunities. Crop Science. 50:109-119. doi:10.2135/cropsci2009.10.0594

Komarek AM, Koo J, Haile B, Msangi S, Azzarri C. 2018. Trade-offs and synergies between yield, labor, profit, and risk in Malawian maize-based cropping systems. Agronomy for Sustainable Development. 38(32). doi:10.1007/s13593-

018-0506-6

Lipton M. 2005. The family farm in a globalizing world: The role of crop science in alleviating poverty. 2020 Discussion Paper No. 40. International Food Policy Research Institute (En línea). Consultado 10 de noviembre de 2019.Disponible en: http://cdm15738.contentdm.oclc.org/utils/getfile/collection/p15738coll2/id/59428/filename/59429.pdf

Lobell DB, Cassman KG, Field CB. 2009. Crop yield gaps: their importance, magnitudes, and causes. Annual Review of Environment and Resources. 34: 179–204. doi:10.1146/annurev.environ.041008.093740

Lowder SK, Skoet J, Raney T. 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Develpment. 87: 16–29. doi:10.1016/J.worlddev.2015.10.041

Madelrieux S, Dedieu B. 2008. Qualification and assessment of work organisation in livestock farms. Animal 2: 435–46. doi:10.1017/S175173110700122X

MGAP-DIEA.Ministerio de Ganadería, Agricultura y Pesca. Dirección general de encuestas agropecuarias. 2020. Censo General Agropecuario 2011. (En línea). Consultado 20 de noviembre de 2020. Disponible en: https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/datos-y-estadisticas/estadisticas/censo-general-agropecuario-2011

MGAP-DIEA.Ministerio de Ganadería, Agricultura y Pesca. Dirección general de encuestas agropecuarias. 2015. Encuestas Hortícolas 2015-2016 - Zonas Sur y Litoral Norte (En línea). Consultado 1 de abril de 2020. Disponible en: https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/datos-y-estadisticas/estadisticas/encuestas-horticolas-2015-2016-zonas-sur-litoral-norte-344

Michalscheck M, Groot JCJ, Kotu B, Hoeschle-Zeledon I, Kuivanen K, Descheemaeker K, Tittonell P. 2018. Model results versus farmer realities. Operationalizing diversity within and among smallholder farm systems for a nuanced impact assessment of technology packages. Agricultural Systems 162: 164–178 https://doi.org/10.1016/j.agsy.2018.01.028

Moraru A, Munteanu RF. 2015. "Workforce deruralization ” - a consequence of migration with implication over agriculture. Lucrari Stiintifice. Seria Agronomie 58: 277–281.

Naresh RK, Prakash S, Singh M. 2012. Role of conservation agriculture and agricultural mechanization on productivity sustainability and income generation in north west India. International Journal of Agricultural Engeneering. 5 (1): 103-113.

Neef A, Neubert D. 2011. Stakeholder participation in agricultural research projects: A conceptual framework for reflection and decision-making. Agriculture and Human Values 28: 179–194. doi:10.1007/s10460-010-9272-z

Nye C. 2018. The ‘blind spot’ of agricultural research: Labour flexibility, composition and worker availability in the South West of England. Cahiers Agricultures. 27: 35002. doi:10.1051/cagri/2018018

Pacín F, Oesterheld M. 2015. Closing the technological gap of animal and crop production through technical assistance. Agricultural Systems 137: 101–107. doi:10.1016/j.agsy.2015.04.007

Paresys L, Saito K, Dogliotti S, Malézieux E, Huat J, Kropff MJ, Rossing WAH. 2018. Feeding the world while reducing farmer poverty? Analysis of rice relative yield and labour productivity gaps in two Beninese villages. European Journal of Agronomy. 93: 95–112. doi:10.1016/j.eja.2017.10.009

Parodi G. 2018. Agroecological transition and reconfiguration of horticultural work among family farmers in Buenos Aires, Argentina. Cahiers Agricultures 27(3):35003. doi: 10.1051/cagri/2018020

Petit S, Dobremez L, Fleury P. 2006. Working conditions: A challenge for sustainability of mountain family farming systems diagnosis at farm level and responses designed by farmers in the Alps. En: Langeveld H, Röling N. (Eds.). Changing European farming systems for a better future. Wageningen Academic Publishers. 272-277.

Prasad S. 2014. MGNREGA: a strategy to overcome labour shortage in agriculture. International Journal of Agricultural Extension 02(01): 57–64.

Reed MS, Fazey I, Stringer LC, Raymond CM, Akhtar-Schuster M, Begni G, Bigas

H, Brehm S, Briggs J, Bryce R, Buckmaster S, Chanda R, Davies J, Diez E, Essahli W, Evely A, Geeson N, Hartmann I, Holden J, Hubacek K, Ioris AAR, Kruger B, Laureano P, Phillipson J, Prell C, Quinn CH, Reeves AD, Seely M, Thomas R, van der Werff, Ten Bosch MJ, Vergunst P, Wagner L. 2013. Knowledge management for land degradation monitoring and assessment: an analysis of contemporary thinking. Land Degradation & Development. 24(4): 307–322. https://doi.org/10.1002/ldr.1124

Reed MS, Evely A.C, Cundill G, Fazey I, Glass J, Laing A, Newig J, Parrish B, Prell C, Raymond C, Stringer LC. 2010. What is social learning? Ecology and Society. 15(4), 1-10 doi:10.5751/ES-03564-1504r01

Renting H, Rossing WAH, Groot JCJ, Ploeg JD, Van Der Laurent C, Perraud D, Stobbelaar DJ, Van Ittersum MK. 2009. Exploring multifunctional agriculture . A review of conceptual approaches and prospects for an integrative transitional framework. Journal of Environmetal Management. 90(2):112–123. doi:10.1016/j.jenvman.2008.11.014

Rossi V. 2011. Aportes metodológicos para el asesoramiento técnico y la extensión rural. Cangüé. 31: 51–60.

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

Scarlato M, Gimenez G, Lenzi A, Borges A, Bentancur O, Dogliotti S. 2017. Análisis y jerarquización de factores determinantes de las brechas de rendimiento del cultivo de frutilla en el sur del Uruguay. Agrociencia Uruguay. 21(1):43-57.

Tilman D, Reich PB, Isbell F. 2012. Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. Proceedings of the National Academy of Sciences.109:10394–10397. doi:10.1073/pnas.1208240109

Tittonell P. 2014. Ecological intensification of agriculture-sustainable by nature. Current Opinion in Environmental Sustainability. 8: 53–61.

doi:10.1016/j.cosust.2014.08.006
Tittonell P, Giller KE. 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research. 143: 76–90. doi:10.1016/J.FCR.2012.10.007
Tittonell P, Shepherd KD, Vanlauwe B, Giller KE, 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. Tropical Agriculture. 123: 137–150. doi:10.1016/j.agee.2007.05.005
Woodhouse P. 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. Journal of Agrarian Change. 10: 437–453. doi:10.1111/j.1471-0366.2010.00278.x
World Food Programme, 2013. The World Food Programme' s Achievements in 2013 (En línea). Consultado en agosto 2019. Disponible en: https://publications.wfp.org/en/apr/2013/

7

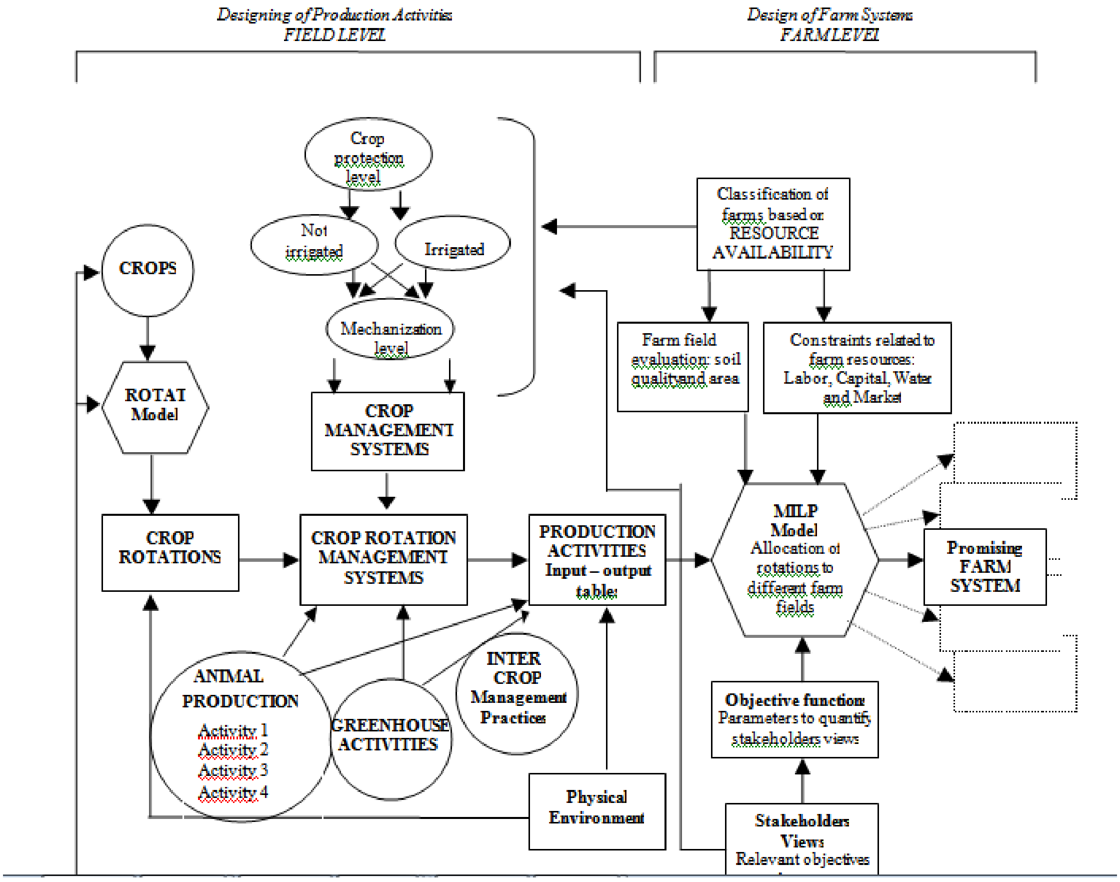
ANEXOS

7.1. SUPPLEMENTARY MATERIALS FOR CHAPTER 4

7.1.1. Main data sources of information used as inputs for FarmIMAGES model

Data	Farmers interviews	Farmers records	Measures (samples)	Direct observations
Family members, roles, decision making	x			
Labour availability	x			
Cattle stock		x		
Cattle sales and purchases		x		
Inputs used and prices		x		
Areas of vegetable and forage crop and pastures			x	x
Land use history (crop rotation before the project)	x			
Machinery and tools inventory				x
Water sources and availability			x	x
Soils types and quality			x	x

7.1.2. Model overview



Adapted from Dogliotti et al. 2006

7.1.3. Production activities for model exploration

Minimum and maximum Gross Margin (GM, \$), cost (\$), labour required (h), labour productivity (\$ h^{-1} yr^{-1}), water required (m^3 yr^{-1}), erosion (Mg ha yr^{-1}), N surplus and SOM balance (kg ha yr^{-1}) for production activities generated for open air and greenhouse for each farm. Currency is USD (U\$S).

	Farm1		Farm2		Farm3		Farm4	
	Min	Max	Min	Max	Min	Max	Min	Max
GM	3378	23620	1891	8889	2148	12671	2801	12707
Cost	991	2844	924	3234	1019	2787	1016	2752
Erosion	2.8	47.8	2.8	9.4	2.8	33.9	2.8	35.7
Labour	248	773	285	713	286	723	317	723
Labour productivity [1]	10	64	6	14	7	24	9	24
Water use	0	2899	0	2374	0	2593	0	2447
SOM	-608	499	-39	353	-293	549	-812	-13
N surplus	9	128	27	157	7	140	61	185
Greenhouse activities								
GM[1]	179072	259589	175610	272707				
Cost[1]	50394	61223	50394	61223				
Labour	8005	11791	8005	11791				
Labour productivity	15	32	15	31				
Water	10000	10971	10000	10971				
SOM	-143	551	620	1299				
N surplus	51	115	53	107				

[1]Labour productivity was estimated as the ratio between Gross Margin (\$U) and labour demand (h)