Regenerating degraded soils and increasing efficiency of water use on vegetable farms in Uruguay through ecological intensification

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Abstract

This thesis investigated alternative soil management strategies for vegetable crop systems and their hypothesized effects on increasing systems resilience by sequestering soil carbon, increasing the efficiency of water use, and reducing erosion. The goal was to contribute knowledge on and tools for the integrated assessment of soil management strategies for the ecological intensification and small-scale production systems sustainability in South Uruguay.

We performed a baseline assessment of key soil properties on cropped fields, and evaluated the impact of implementing different soil management strategies after re-design of systems in a co-innovation project. We showed evidence that even under smallholder conditions, it was possible to reverse the soil degradation. However, it was not possible to reduce erosion in cases that a pasture could not be included in the rotation. We evaluated reduced tillage and cover crop management in an experiment. In-situ grown mulching increased water capture by 9.5% and reduced runoff by 37% on average, leading to less erosion risk and greater plant available water. We also collected enough data to develop a simple, generally applicable, locally parameterizable mathematical model that accounts for the effect of soil cover on soil water dynamics. Exploration with 10 years of weather data showed that reduced tillage and mulching (*RTmulch)* would decrease water requirements for irrigation by 37% on average.

Finally, we scaled up the results to study the impact of *RTmulch* on two small horticultural family farms with different resource availabilities. By combining process-based simulation models with empirical data and expert knowledge, we quantified inputs and outputs of production activities. Adoption of *RTmulch* was associated with improvements of the economic and/or environmental performances. It was possible to design production activities with erosion rates below the tolerable level without sacrificing the family income too much. Average water savings of 775 m^3 ha^{-1} yr^{-1} (fully irrigated rotations) to 452 (irrigating only the most profitable vegetable crops) were obtained under *RTmulch* compared with conventional tillage.

Reduced tillage and mulching have potential for increasing water infiltration, reducing runoff and erosion, and achieving greater efficiency of water use for vegetable crops grown in raised bed systems. These aspects are especially relevant under conditions of high rainfall variability, limited access to irrigation and high soil erosion risk. For future research, we suggest combining long-term experiments with on- farm research to capture the benefits of improving soil quality on soil productivity, while adjusting the technology to solve limitations that arise in the process. This study provides ground for testing the proposed changes on pilot farms, using a co-innovation approach combining scientific insights with farmers' knowledge of their farms.

Keywords: minimum tillage, tillage systems, organic mulch, degraded soils, soil conservation, soil water modelling, infiltration, soil water capture.

A Micaela y Manuel, mis hijos, que nunca se les acaben los "porqué?";

y a Mª del Carmen y Carlos, mis padres,

que nos dieron la posibilidad de elegir ser quienes somos

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Chapter 1

General introduction

1. Ecological intensification and sustainability

Current agricultural farming systems are mainly based on a model that has proved to be socially and biophysically unsustainable, unable to feed the world effectively and to maintain biodiversity, and harmful to the environment (Tittonell, 2014, D´Odorico et al., 2013, United Nations, 2013, Altieri et al., 2012, Tillman et al., 2012). Ecological intensification (EI) emerged as a new paradigm that gave a framework to transit towards agricultural models able to feed the world in a more sustainable and equitable way. Bases of EI include a landscape approach, the use of natural ecosystems functionalities, the importance of local resource and indigenous knowledge, a decrease of external and non-renewable inputs use, and optimizing the use of water and energy (Doré et al., 2011, Godfray et al., 2010).

Soils play a crucial role in meeting the needs of future generations and in the realization of the United Nations sustainable development goals (Keesstra et al., 2016). "Healthy soils for a healthy life" was the motto coined for the international year of soils by FAO, who declared that "The promotion of sustainable soil and land management is central to ensuring a productive food system, improved rural livelihoods and a healthy environment." (FAO, 2014). Farming systems sustainability depends on maintaining healthy soils, which is the ability of soils to sustain biological productivity, environmental quality and promote animal and plant health (Doran and Zeiss, 2000). The capability of soils to produce food, store and provide clean water, protect biodiversity, sequester carbon and nutrients, and provide ecosystem services are influenced by soil management (e.g. Costa et al., 2015, Andrews et al., 2004). The development of local-specific soil management strategies that enhance ecosystem services, reduce the dependency on external inputs and prevent further land degradation is central to improve the sustainability of vegetable family farms in south Uruguay.

2. Un-sustainability of vegetable systems in South Uruguay: implications for and causes from land degradation

The area dedicated to horticulture decreased by 14% in the period 1990-2000, and by 52% in the period 2000-2010 (DIEA, 2015). The number of farms dedicated to horticulture with field-grown crops decreased from 6,950 in 2000 to 3,155 in 2011, and the number of farms with greenhouses decreased from 1,125 to 962 (Ackermann, 2014). Located on originally fertile soils and concentrated in the south of the country, these production systems feature high external input use and continuous cropping of high value commodities (Dogliotti et al., 2003). These practices, together with a long history of agriculture with no soil conservation strategy resulted in 60-70% of the area classified as moderately to severely eroded (MGAP, 2004).

Fine textured soils (Mollic Vertisols and Luvic/Vertic Phaeozems Pachic/Abruptic/Oxyaquic; IUSS Working Group WRB, 2006) are dominant in the region (Fig. 1.1). Vegetable crops are grown on raised beds in order to both increase the volume of soil easily explored by roots, and to improve surface drainage after heavy rainfall. The presence of argillic B horizons close to soil surface in combination with intense rainfall events leads to rapid saturation of the topsoil, exacerbating surface runoff. In addition, soil physicochemical quality deteriorates severely under vegetable farming due to intense tillage, poor soil cover, low organic carbon inputs, and frequent cultivation (Altieri, 1992; Yan et al., 2012). Decline of soil organic carbon (SOC), resulting in crust formation, reduced water holding capacity and poor soil aeration, constitute the production situation of vegetable crops (Terzaghi and Sganga, 1998). Low water holding capacity affects resilience and stability of production systems in the face of an increased frequency of extreme weather events (Giménez and Lanfranco, 2012; Marengo et al., 2012), and limited availability of water for irrigation; most farmers in south Uruguay can only irrigate a 48% of the vegetable crop area (DIEA, 2014).

From 1992 to 2004 average vegetable prices in Uruguay decreased by 50% and farmers had to produce more, cheaper and better quality products to keep the same income. Farmers in

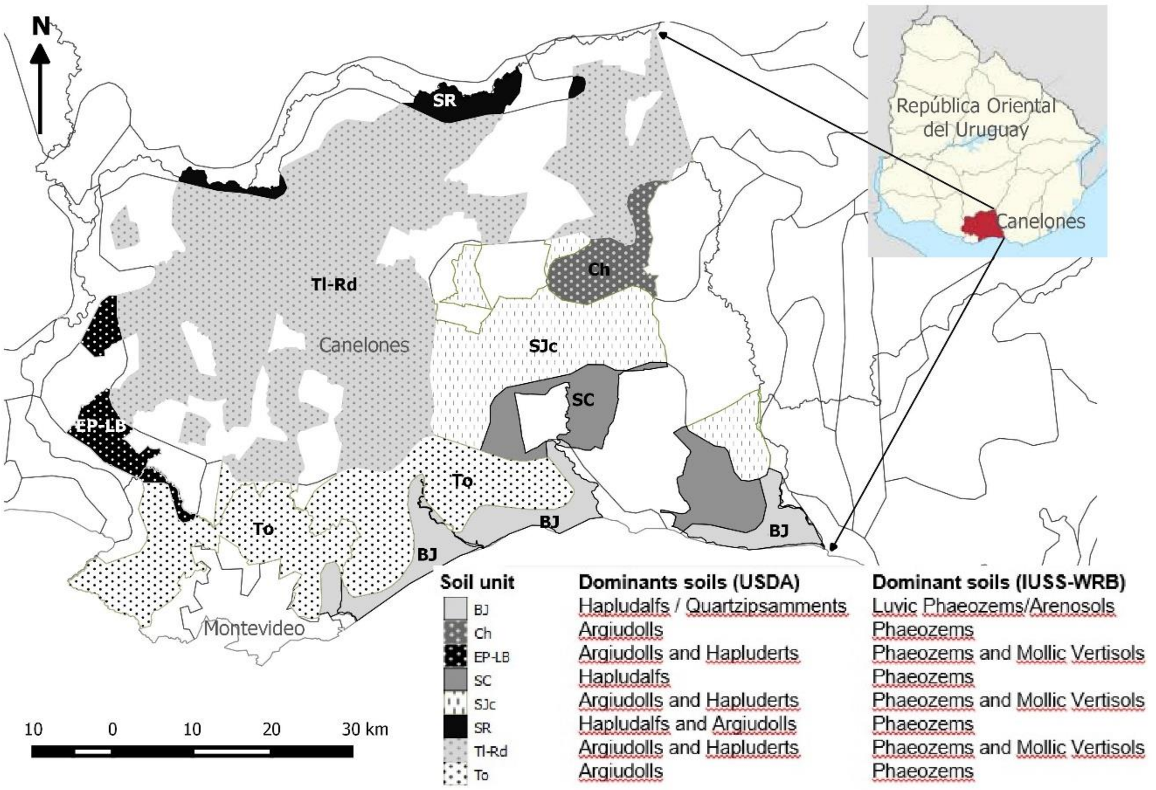

Figure 1.1. Soil units (mapped at 1:1,000,000 according to USDA Soil taxonomy) for those census units with more than 50 ha of horticulture in Canelones and Montevideo. Elaborated based on soil map (MGAP – DSF, 1976), and census 2011 (DIEA, 2014)

south Uruguay responded by increasing the area of vegetables, reducing the variety of crops and increasing the amounts of inputs and irrigation (Dogliotti, et al., 2004). These strategies put even more pressure on the already degraded soils, driving these systems into a downward spiral of environmental degradation, and feeding what it is called an unsustainability spiral (Dogliotti, 2003).

Demand for vegetables is expected to increase due to rising standards of living and supported by health-promoting initiatives such as the Fruit and Vegetable Promotion Initiative by the World Health Organization (Tittonell et al, 2016). Satisfying the growing demand for vegetables in a sustainable way requires more knowledge on how to improve environmental performance of vegetable cropping systems, while maintaining or improving their productivity.

Strategies to increase water productivity with reduced environmental impact, while maintaining or increasing crop yields are urgently needed.

3. Opportunities for soil degradation reversal

In a model-based exploratory study, Dogliotti et al. (2005) identified different farm systems that performed better than the original farms in both economic and environmental indicators. The improved systems followed ecological intensification principles (Doré et al., 2011) by relying on ecosystems functions provided by green manures and other non-vegetable crops in the rotation, re-introduction of pasture phases combined with beef cattle when allowed by farm size, and use of animal manures available in the area. The hypothesis that these changes would improve system sustainability was put to the test in an on-farm re-design project with 16 pilot farms.

Systems re-design that implies alternating phases of description, explanation, exploration and design was applied following a co-innovation approach (e.g. Rossing et al., 2010; Giller et al., 2008). This approach combines complex systems theory, social learning and dynamic project monitoring and evaluation to re-orientate and re-design plans for individual farms. In the mentioned project, the farmers and other stakeholders were involved from the beginning and in every phase of the re-design process, contemplating individual priorities and resource availabilities (Dogliotti et al., 2014). This process was key to developing local solutions in the search of sustainable farming, which is part of the essence of the ecological intensification process, rather than global solutions (Titonell, 2014). The drawback of this approach is that it is impossible to elucidate cause-effect relations without additional experimentation (e.g. Debaeke et al., 2009). An advantage is that it reveals opportunities at the relevant scale of complexity, both biophysically and socio-economically, and provides an agenda for salient component-oriented research.

An important component of the re-design plans for soil conservation on large farms was the inclusion of a pasture phase. As pastures do not result in important financial returns in the short-term, pasture phases were not feasible on smaller farms. On small farms, reduced tillage in combination with mulching on the raised beds was thought to be a viable option to improve soil structure and water infiltration, and to reduce runoff and soil erosion. These improvements may lead to greater water use efficiency, which is especially needed under conditions of high variability of rainfall and limited access to irrigation, such as those in south Uruguay.

Reduced tillage combined with cover crops and raised beds was shown to improve soil quality in vegetable production systems (Johnson and Hoyt, 1999). Scopel et al. (2004) showed that mulching under semi-arid and humid tropical conditions increased water infiltration, reduced soil evaporation losses by ca. 52% and increase rain-water storage by ca. 50%. In Mediterranean orchards, an addition of 75 gm^{-2} straw cover reduced water losses from 60 to 13% of total rainfall, and drastically reduced erosion rates (Cerdà et al., 2016). Permanent beds with partial or complete retention of crop residues improved infiltration, aggregate stability and soil microbial biomass (Verhulst et al., 2011). In a permanent bed system with organic mulch in a Mediterranean climate, it was possible to reduce erosion (Boulal et al., 2008) and increase surface carbon stocks (Cid et al., 2014), with possible positive consequences for climate change mitigation (Lal, 2010). In an arid region permanent beds and retention of residues increased water productivity by about 30% for wheat and 80% for maize, with 11% to 23% reduction in the amount of water applied (Davkota et al., 2013). Similar management in a Mediterranean climate did not improve water use efficiency and did not change the yields (Boulal et al., 2012), but resulted in a more timely and efficient use of available water and nitrogen resources for growth.

However, results were not consistently positive. Poor crop establishment and lower initial LAI was observed by Boulal et al. (2012), and the impact on yield was variable (Boulal et al., 2012; Gilsanz et al., 2004; Luna et al., 2012). Soil compaction and difficulties in managing large amounts of residues was also reported as a limiting factor for the adaptation of irrigated permanent bed system for cereals in the Mediterranean (Gómez-Macpherson et al., 2009). Preliminary studies in Uruguay comparing minimum tillage with conventional tillage in vegetable production showed benefits in terms of soil quality and soil moisture accumulation, while yields were not affected (Arboleya et al., 2012).

4. Modeling to support systems re-design

Models able to evaluate alternative strategies for farm design can show ex-ante if there is room for improvement, and therefore are useful tools in the re-design process. A mixed integer linear programming model (MILP), named Farm Images was developed by Dogliotti et al. (2005) specifically for vegetable farm systems of south Uruguay. The model selects the production activities that optimize the objective function, such as maximizing family income or minimizing soil erosion at farm level, while satisfying constraints on resources. Quantification of inputs and outputs of the production activities at field level that are input to Farm Images, is based on a combination of field measurements, expert knowledge, and outputs from other models. Particularly, the water requirements resulted from each production activity is estimated from a water balance model.

Several mechanistic and empirical methods have been proposed worldwide to estimate the amount of water infiltrating into the soil after a rainfall event. Most of these models have focused on sandy to loam soils (Bonfante et al., 2010). There is yet little information available for clayey soils or raised bed systems, in combination with crop residue management strategies. Holland et al. (2012) evaluated the influence of raised beds on water runoff on layered soils cropped with grains or oilseeds, but did not consider mulching. Scopel et al. (2004) updated the STICS soil-crop model with an empirical module that accounts for effects of surface residue on soil water balance. The module depends on local parameters and was tested on soils without an argillic horizon. Jones et al. (2014) simulated soil water dynamics using the DSSAT model under drip-irrigated plastic-mulched raised-bedded production systems on a fairly homogeneous sandy soil. The authors point out that simulations for highly layered soils should be considered with caution.

We did not find a model with satisfactory performance to simulate water dynamics for the conditions of southern Uruguay. Therefore, a tool was needed which was low demanding in input data, and able to predict how alternative soil management strategies affect irrigation water needs.

5. Objective of this study

The goal of this thesis was to contribute knowledge on and tools for the integrated assessment of alternative soil management strategies for the ecological intensification and soil degradation reversal in small-scale vegetable production systems in the south of Uruguay. To achieve this goal, four objectives were defined.

1. To assess the impact of different soil management strategies involving, organic matter addition and cover crops, on soil properties after two to five years of

implementing them in a co-innovation project where systems were re-designed;

2. To evaluate the effect of reduced tillage plus mulching, cover crops and organic matter addition on water runoff, vulnerability to soil erosion, soil moisture supply capacity and crop yield;
3. To develop a simple, generally applicable, locally parameterizable mathematical model that accounts for the effect of soil management alternatives on soil water dynamics, to be able to perform an ex-ante evaluation of the possible impact on water productivity of implementing alternative soil management technologies;
4. To analyze to what extent soil management alternatives impact on the family income, water productivity and erosion risk of small horticultural family farms in south Uruguay.

6. Outline of the thesis

Chapter 2 characterizes the soils and soil quality in 16 farms at the beginning of a co-innovation project where vegetable family farm were re-designed, and assess the impact of re-design in terms of soil quality achievements. We also propose a model to estimate topsoil SOC change in those systems based on the amount of incorporated organic amendments, the initial amount of SOC, and the clay content, based on data of 69 fields.

In Chapter 3, we present experimental results to quantify the impact of tillage and crop residue management on runoff, water dynamics, soil erosion, and productivity of a tomato - oat rotation. Experiments were carried out on raised beds on a fine-textured, moderately well-drained soil, representative of soils used for horticulture in the region.

In Chapter 4 we use 4 years of experimental data to develop and parameterize a novel combination of empirical models on water interception and infiltration with a soil-water balance model. The new model was used to evaluate the impacts that the alternative soil management of soil cover, reduce tillage plus mulch may have in saving irrigation water.

A scaling up from field to farm level is presented in Chapter 5 where we explore the effect of the different soil management strategies developed in Chapters 2, 3 and 4 in terms of family income, erosion risk and SOM change for two case study farms. The data of these farms were collected in the co-innovation project presented in Chapter 2. By integrating the water balance model developed in Chapter 4 with tools that facilitate scaling up results at the farm level, we explore for opportunities for more sustainable systems on vegetable farms in South Uruguay.

In Chapter 6 we discuss the contribution made by this study to the development of more sustainable soil management practices. We give insight in the potential contribution that proposed practices and technologies may have in adapting to and mitigating climate change. The Chapter also discusses the potential use of models developed in the study for integration in a farm design and evaluation tool. Finally, we discuss the implications of research for family farm sustainability and the impacts for the society as a whole, and we provide ideas for future research. The flow of information among Chapters is shown in Fig. 1.2.

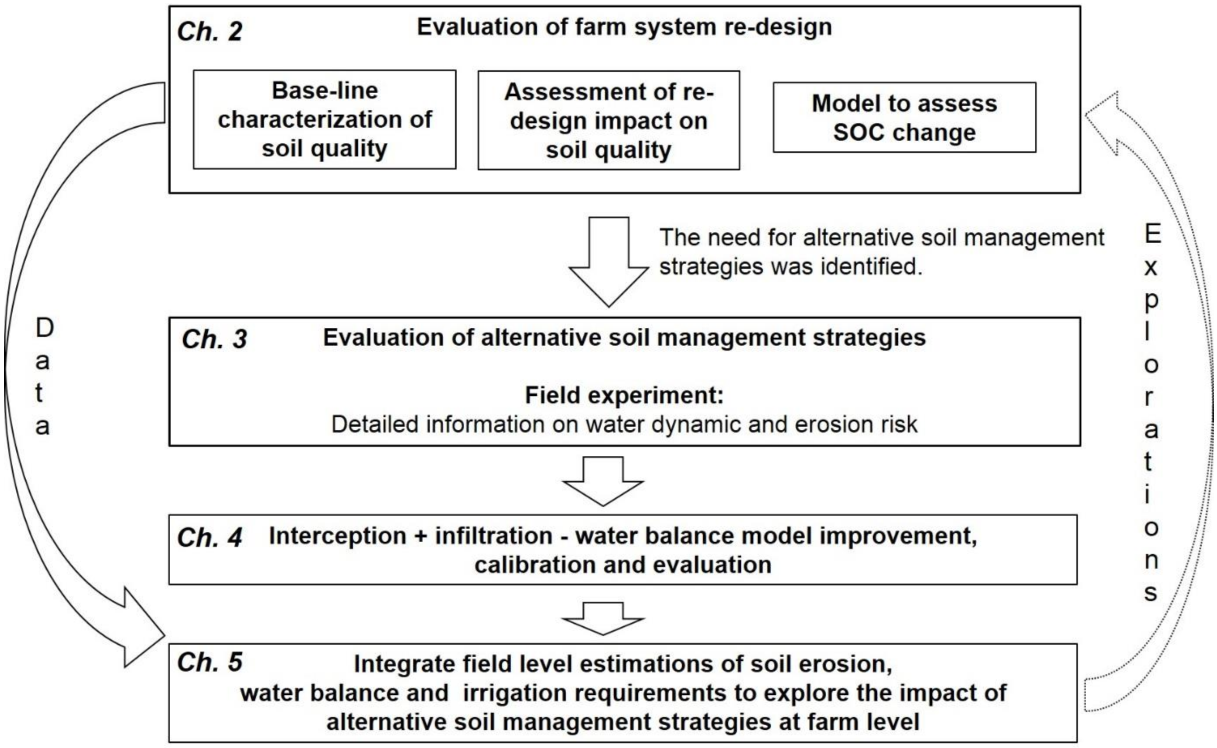

Figure 1.2. Connectivity and flows of information showing the research strategy followed in this thesis

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Chapter 2

Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms

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Abstract

Loss of ecological functions due to soil degradation impacts viability of crop production systems world-wide, particularly in vegetable cropping systems commonly located in the most productive areas and characterized by intensive soil cultivation. This paper reports soil degradation caused by intensive vegetable farming, and its reversibility after two to five years of drastic changes in soil management on 16 commercial vegetable farms in south Uruguay. Changes in soil management included addition of green manures and pastures in rotations of vegetable crops, use of animal manure, and erosion control support measures (terracing, reducing slope length, re-orientation of ridges). Soil degradation caused by vegetable farming was assessed by comparing soil properties in 69 vegetable fields with values at reference sites located close to the cropped fields. Effects of the changes in soil management in the 69 fields were assessed by comparing soil properties at the start and to those at the end of the project. Compared to the on-farm reference sites, the vegetable fields contained 36% less SOC, 19% less exchangeable potassium, water stable aggregates with an 18% smaller geometric mean diameter, and 11% lower plant-available soil water capacity. Phosphorus availability was 5 times higher under vegetable cropping compared to the on-farm reference. Phaeozems (Abruptic) revealed greater degradation (44% less soil organic carbon (SOC)) than Vertisols (24% less SOC) and Phaeozems (Pachic) (21% less SOC). After two to five years of improved soil management, SOC concentration in the upper 20 cm increased by on average 1.53 g kg^{-1} (12%) in the Phaeozems (Abruptic) and 1.42 g kg^{-1} (9%) in the Phaeozems (Pachic). SOC in Vertisols increased only by 0.87g kg^{-1}, most likely due to their greater initial SOC concentration. Topsoil carbon sequestration was on average 3.4 Mg ha^{-1} in the Phaeozems. Multiple linear regression showed the quantity of incorporated amendments, the initial amount of SOC and the clay content to explain 77% of the variability in yearly changes of SOC. Available water capacity increased significantly with SOC particularly due to more water retention at field capacity, resulting in an increase in available water capacity in the first 20 cm of soil of 8.4 mm for every 10 g kg^{-1} of SOC increase. Results are discussed in relation to perspectives of soil degradation reversal in the long term.

Key words:

Soil rehabilitation; Soil organic carbon; Organic amendments; Soil management; Horticulture; Available water capacity

1. Introduction

Land degradation, which involves soil erosion and compaction, decreases in soil moisture supply capacity and fertilizer use efficiency, and loss of productivity is a major concern worldwide (Lal, 2011). Research on extent, causes and solutions focuses on soil management in broad-acre cropping systems, and little information is available on management options in vegetable cropping systems. Traditionally located on originally fertile soils these production systems typically feature high external input use and continuous cropping of high value commodities (Altieri, 1992; Yan et al., 2012). Decline of soil organic carbon (SOC) results in crust formation, reduced water holding capacity and poor soil aeration, which constitute important yield-limiting factors for vegetable crops (Terzaghi and Sganga, 1998). Lower water holding capacity furthermore affects resilience and stability of production systems in the face of an increased frequency of extreme weather events as predicted in climate change scenarios (Giménez and Lanfranco, 2012), with negative consequences for the many smallholder family-based farms around the world, as well as for vegetable prices on local markets. Demand for vegetables is expected to increase due to rising standards of living and supported by health-promoting initiatives such as the Fruit and Vegetable Promotion Initiative by the World Health Organization (FAO, 2003). Vegetable production worldwide increased by 9 million hectares from 1999 to 2009 (FAO, 2010). Satisfying the growing demand for vegetables in a sustainable way requires more knowledge on how to improve environmental performance of vegetable cropping systems, while maintaining or improving their productivity.

Systems re-design can be seen as part of an application-oriented research cycle, consisting of alternating phases of diagnosis and testing and improving of systems (e.g. Rossing et al., 2010). Giller et al. (2008) refined the representation of the application-oriented research cycle by distinguishing four consecutive phases, including description, explanation, exploration and design. Such systems re-design may take place on-station, mimicking factorial experimentation as much as possible by having replicated treatments that vary in a small number of factors, while keeping all other attributes constant (e.g. Drinkwater, 2002; Vereijken, 1997). This approach is associated with practical problems particularly when the aim is to re-design entire farm systems, often lacks salience for farmers and therefore risks lack of uptake. An alternative approach, which has been called prototyping (Vereijken, 1997) is to develop re-design plans for individual farms together with the farmers and monitor the evolution of individual farms following re-design. Drawback of this approach is that it is impossible to elucidate cause-effect relations without additional experimentation (e.g. Debaeke et al., 2009). Advantage is that it reveals opportunities at the relevant scale of complexity, both biophysically and socio-economically, and provides an agenda for salient component-oriented research.

In Uruguay soil degradation has affected especially the vegetable production area in the southern part of the country, where 60-70% of the area is classified as moderately to severely eroded (MGAP, 2004). From 1992 to 2004 average vegetable prices decreased by 50% and farmers had to produce more, cheaper and better quality products to keep the same income. Farmers in south Uruguay responded by increasing the area of vegetables, reducing the variety of crops and increasing the amounts of inputs and irrigation (Dogliotti, et al., 2004). In a model-based exploratory study, Dogliotti et al. (2005) identified different farming systems which performed better in both economic and environmental indicators. These systems were based on reducing the area of vegetables in the farm, including green manures and other non-vegetable crops in the rotation, re-introduction of pasture phases combined with beef cattle when allowed by farm size, and use of animal manures available in the area. The hypothesis that these changes would improve system sustainability was put to the test in a research project with 16 pilot farms. Following a diagnostic phase of about one year resulting in the identification of key weaknesses in the production systems of each individual farm, the research team and the farm families agreed on implementation of innovative farm plans aiming to improve both family income and soil quality. The plans were then implemented and consequences for various variables were monitored on each farm during 2 to 5 years, depending on the moment of implementation. This paper focuses on changes in soil quality parameters resulting from the farm systems redesign.

The purpose of this study is to characterize soil degradation in smallholder vegetable production systems in southern Uruguay at the outset of farm systems redesign and to assess the impact of changes in soil management practices after two to five years of implementation. We hypothesized that at the start of the project soil quality in vegetable fields was inferior to soil quality at relatively undisturbed on-farm reference sites. We furthermore hypothesized that systems redesign positively affected soil quality parameters over a two to five year time horizon. Results are discussed in relation to perspectives of soil degradation reversal in the long term, its implications for soil moisture supply capacity (SMS), and resource use efficiency at the farm level.

2. Materials and methods

2.1 Approach and pilot farms

Data on soil quality were obtained by sampling on a total of 69 fields of 16 ‘pilot’ farms that participated in a project aimed at improving farming systems performance, based on hypotheses put forward by Dogliotti et al. (2005). For each farm, the project developed and implemented farm-specific plans which constituted a balance among economic and environmental considerations, negotiated between the research teams and the farm families.

Details of the project and its co-innovation approach are provided by Dogliotti et al. (2012) and Rossing et al. (2010).

The 16 pilot farms were situated within a radius of approximately 60 km from Montevideo city (34º 55' S, 56º 09' W; 15 to 60 m asl) in southern Uruguay. Farms were selected to represent the variation in existing vegetable production systems. Selection criteria included availability of production resources (farm area, degree of mechanization, labour availability), geographic spread in the region, diversity of production systems (mainly type of crops), and interest of farmers to participate and discuss strategic decisions. Nine of the pilot farms belonged to 3 farm types that together account for 78% of the specialized vegetable farms in South Uruguay (Righi et al., 2011). The remaining 7 pilot farms represented 4 farm types that account for 87% of the mixed vegetable – beef cattle farms in South Uruguay.

Climate in the area is temperate sub-humid with a mean annual temperature of 16.4ºC. Mean annual precipitation is 975 mm, fairly evenly distributed throughout the year, but with major variation between years (Furest, 2008). Water deficits occur frequently between October and March and water surpluses between May and August. Geomorphology ranges from very gently undulating to undulating (slopes 0-6%), including some flat valleys. Soils were described on each farm following the FAO (2006) guidelines, and classified as Mollic Vertisols (Hypereutric), Luvic/Vertic Phaeozems (Pachic), and Luvic Phaeozems (Abruptic/Oxyaquic) (IUSS Working Group WRB, 2006). We will refer to these soils as Vertisols, Phaeozems (Pachic) and Phaeozems (Abruptic). Topsoil texture ranged from silty clay loam to clayey (Table 2.1).

2.2 Soil use and management changes

Before the start of the project continuous vegetable production occasionally alternated with bare fallows was the dominant form of soil use on the 16 farms. Standard practices included 4 to 8 tillage operations annually. The changes in soil management proposed by the project included erosion control support measures such as terracing, reducing slope length, re-orientation of ridges along the slope; changing crop sequences to include grass and legume pastures if total farm area was large enough; inclusion of cover crops in rotation with vegetable crops; and incorporation of plant residues and green and animal manures. In Table 2.3 we present details of the main management changes that were actually implemented on each of the 16 farms.

Above-ground biomass of crop residues and green manures was determined before incorporation into the soil by harvesting, drying and weighing 0.16 m^2 in three replicates in each of the 69 fields. Animal manure was sampled from different parts of the piles prior to incorporation using a gauge auger. Plant and manure samples were dried at 60°C until constant weight. Total dry plant biomass was estimated assuming that below-ground gramineous biomass was 25% of total biomass, which is a conservative estimate (Bolinder et al., 1997). Nitrogen content was determined by the Kjeldahl method. Carbon concentration in plant tissues was assumed to be 40%, which is known to be a conservative quantity (Bolinder et al., 1997). Carbon concentrations in animal manures were determined according to Nelson and Sommers (1996). Averages and ranges of organic matter and carbon incorporated in the fields are shown in Table 2.2. In the course of the project participating farmers incorporated on average 3.9 Mg DM ha^{-1} of green manure annually (Table 2.2).

Table 2.1. General properties for the three soil types under study

Horizon	Bottom depth (cm)	pH (H_2O)	Sand (%)	Silt (%)	Clay (%)	Texture[a] class	SOC (g kg^{-1})	CEC[b] pH 7 (cmol+ kg^{-1})	BS[c] pH7 (%)
Mollic Vertisols (Hypereutric) (fineTypic Hapluderts) (33 fields)									
Ap	15-30	6.5-7.0	17-23	35-45	35-48	ClL - Cl	19-37	30-33	95-100
Bt(A1,A2)	60-70	6.8-7.5	13-20	30-38	45-51	Cl	10-15	35-42	95-100
Ck	75-100+	8.0-8.5	12-15	33-40	50-54	Cl - SiCl	2-5	29-31	100
Luvic/Vertic Phaeozems (Pachic) (fine- silty Pachic (Vertic) Argiudolls) (21 fields)									
Ap	10-30	5.0-6.0	18-31	40-50	28-42	ClL(gv)-SiClL	20-27	17-29	80-90
Bt(Bt1, Bt2)	40-70	6.0-7.0	12-20	25-40	46-59	Cl	7-15	30-46	90-100
Ck	50-100+	7.0-8.5	15-35	30-45	35-47	Cl-SiCl	1-6	25-30	100
Luvic Phaeozems (Abruptic/Oxyaquic) (fine –silty Abruptic Argiudolls) (15 fields)									
Ap	10-30	4.8-6.3	10-42	45-65	20-27	L - SiL	9-17	12-19	75-90
Bt	20-30	6.0-7.2	10-28	35-48	43-45	Cl - SiCl	6-9	20-30	85-90
BC	20	5.7-7.0	6-20	35-50	45	Cl - SiCl	4-6	20-31	99
Ck	50-80+	7.0-8.0	7-21	39-51	39-42	Cl - SiCl	1-5	20-25	100

[a] L: loam; Cl: clay; gv: with gravels; Si: silt. [b] CEC: cation exchange capacity. [c] BS: base saturation.

Table 2.2. Averages and [ranges] of organic dry matter, its C/N ratio, and the associated amount of C incorporated annually into the soil during the 2-4 year study period

Material	Dry matter (Mg ha^{-1} $year^{-1}$)	C/N	Carbon (Mg ha^{-1} $year^{-1}$)
Green manure + crop residue	3.9 [0 - 19.0]	39.0 [19.0 - 51.0]	1.6 [0 – 7.6]
Chicken manure mixed with rice husk	3.2 [0 - 13.3]	15.9 [7.0 - 32.4]	0.9 [0 – 4.1]
Total	7.1 [0 - 24.9]		2.4 [0 – 9.5]

Table 2.3. Land use and management changes implemented per farm as part of a soil management project in south Uruguay

Farm-Syst.[a]	N° years impl.[b]	Total area (ha)	Initial cropped area (%)	Final cropped area (%)	Change size or slope of plots	Green manure	Animal manure	Planned crop rotation	Rotation with pastures or alfalfa	Change in crop surface	Change in crop manage-ment	Main crops / animal products
1- M c	5	48	5	5	√	√	√	√	√	√	√	onion, garlic, sweet pepper, tomato, calves
2- M c	2	38	13	12			√					onion, sweet potato, pumpkin, calves
3- M c	3	29	51	41		√	√	√		√	√	onion, seed onion, garlic, potato, calves
4- M c	2	26	34	17	√	√	√	√		√	√	onion, tomato, sweet pepper, calves
5- M c	2	20	25	10	√	√	√	√		√	√	onion, industry tomato, pork
6- M c	5	13	12	10	√	√	√	√	√	√	√	onion, tomato, pumkin, heifers
7- M o	3	25	29	16		√	√		√	√	√	pumpkin, strawberry, heifers
8- V c	2	59	42	30	√	√		√	√	√	√	carrot, onion, pumkin
9- V c	5	15	80	80		√	√	√		√	√	broccoli, spinach, celery
10-V c	3	12	37	31	√		√				√	sweet potato, tomato, sweet pepper, eggs
11-V c	3	6	63	42		√	√	√	√	√	√	tomato, onion
12-V c	5	6	45	51		√	√	√	√	√	√	onion, tomato, seed onion
13-V c	5	4	64	64	√	√	√	√		√	√	onion, tomato, garlic
14-V o	3	19	17	14	√	√	√	√		√	√	carrot, spring onion, onion
15-V o	2	11	26	16	√	√	√	√	√		√	potato, garlic, lettuce, strawberry
16-V o	2	8	26	26	√	√	√			√		spinach, potato, pumpkin
Average	3	21	36	29	63%	88%	94%	75%	44%	81%	88%	

[a] Farm - System: M, Mixed vegetable + cattle production; V, specialized Vegetable production; c, conventional; o, organic.

[b] N° years impl.: number of years t

Green manures included oats (*Avena sativa* L.; 50% of cases), wheat (*Triticum aestivum* L.; 30% of cases), foxtail millet (Setaria italica L.; 13% of cases), sorghum sudangrass (*Sorghum* × *drummondii* (Steud.) Millsp. & Chase), and maize (*Zea mays* L.). Average yearly incorporation of animal manure was 3.2 Mg DM ha^{-1}. The majority of animal manure applications were chicken litter (chicken manure mixed with rice husk) with 26.6% C on average, and the remainder was hen manure with 22.5% C on average.

2.3 Soil sampling and analysis

At the beginning and at the end of the project, composite samples each consisting of 20 subsamples were taken from each of the 69 fields under investigation (Table 2.1). For each soil type found on a farm, a relatively undisturbed site on the same farm was selected to act as reference for the soil quality variables and sampled. Further soil quality comparisons were made with SOC data obtained from soil surveys done in the 1970s. For each of the three soil types we collected information from the database of the Soil Survey Staff of the Soil Directory of the Ministry of Agriculture and Fishery. Only a small part of this data has been published as Series “Santa Rosa”, Series “El Colorado” and Series “Pando” (DS-MGAP, 1982).

On-farm sampling served two purposes: a baseline assessment of soil quality at the onset of the systems redesign, and an assessment of soil quality changes after two to five years of implementation of the re-design.

2.3.1 Baseline assessment

At the start of systems redesign in the autumn of 2005 (6 farms) and 2007 (10 farms), composite samples of the upper 20 cm soil of 69 cropped fields on the 16 farms were collected. For each of the soil types found on a farm, a reference site was selected and sampled. Potential locations for reference sites included soils under fences or on uncultivated land. Farmers were asked about land use history and only sites which had not been cultivated for at least 20 years were selected. Next, the soil type at the potential reference locations was described. A location was designated a reference site when soil type was identical to one of the soil types in the sampled cropped field. Composite samples were formed by 20 subsamples collected using a gauge auger, and sampling sites were geo-referenced using a GPS for end-of-project sampling.

After air-drying the soil samples and passing through a 2 mm sieve the following analyses were made: soil pH (1:2.5 soil:water and soil:KCl ratio); soil texture (Gee and Bauder, 1986); SOC (Nelson and Sommers, 1996); available P (Bray and Kurtz, 1945); exchangeable K (atomic absorption spectrophotometry following ammonium acetate extraction); and cation exchange capacity (CEC) in ammonium acetate at pH 7 (Rhoades, 1982).

Undisturbed samples at 5-10 cm depth were collected in triplicate using 5 cm wide and 3 cm tall metal rings and take to the laboratory. There, the samples were placed on a suction table and tensions of 1 kPa and 6 kPa were applied. Samples where then transferred to a pressure plate for readings at soil tensions of 10, 30 and 100 kPa. Bulk density was estimated after oven drying the samples. Porosity was estimated as one minus the ratio between bulk density and real density (taken as 2.65 Mg ha^{-1}). Gravimetric water content at permanent wilting point (ϴw, pwp) was estimated using an empirical relation obtained by Fernández (1979) based on 283 samples from a wide range of Uruguayan soils:

$$\Theta_{w\,pwp} = -58.1313 + 0.3718\,(SOC \times 1.724) + 0.5682\,(sand) + 0.6414\,(silt) + 0.9755\,(clay)$$
$$r^2 = 0.864 \qquad [1]$$

Where ϴw pwp is weight percentage of water content at 1500 kPa. All variables in percentage.

Samples for estimating aggregate stability were taken at least two months after the last tillage operation. Duplicate samples of soil clods at 0–20 cm depth were collected with a spade. Aggregate stability was assessed by wet sieving through multiple sieves and calculating the geometric mean diameter index (Kemper and Chepil 1965):

$$GMD = \exp\left\{\frac{\sum w_i \ln x_i}{\sum w_i}\right\} \qquad [2]$$

where *GMD* is geometric mean diameter, w_i is the weight of the aggregates of size class *i* (g) and ln x_i is the natural logarithm of the mean diameter of size class *i*.

2.3.2 Impact of farm systems re-design

In autumn 2010 we repeated the sampling procedure at the same (geo-referenced) locations. Soil analyses included pH, SOC, available P, and exchangeable bases using the same analytical procedures as described previously.

2.4 Statistical analysis

The effects of soil type and land use history (cropped – non cropped) on soil properties were tested with a mixed linear model:

$$y_i = \mu + s_t + u_h + su_{th} + \varepsilon_i \qquad [3]$$

where the fixed part of the model consists of: grand mean µ, main effect of soil type t s_t, main effect of land use history h u_h, and interaction of s_t and u_h su_{th}. The random model term is ε_i, a random error term representing field effects since field is the smallest experimental unit.

Effects were estimated using residual maximum likelihood (REML) in Genstat 14th Edition (VSN International Ltd., Lawes Agricultural Trust, UK). A Wald test was applied to determine the significance of main effects. Treatment means of significant variables were separated using least significant differences (LSD, $P \leq 0.05$). Pearson correlation coefficients were calculated between SOC and volumetric water content at -10 kPa and -1500 kPa, and data were plotted.

Comparisons of soil properties at the beginning and at the end of the project was made by paired Student t-test using Infostat software (Di Rienzo et al., 2008), which allows partitions to analyse the data per soil type.

To explore the effect of the initial amount of SOC in the observed SOC change, we used the boundary line approach as used by Fermont et al (2009). After sorting the initial SOC in ascending order, we identified the maximum and minimum increase and decrease in SOC for different levels of initial SOC. These boundary points (Schnug et al.,1996) were used to fit the maximum and minimum boundary lines that represented the maximum and minimum annual SOC change as a function of the initial SOC value. Two logistic models resulted in the best fits for the boundary points based on minimizing the root mean squared error (RMSE). These models were used to assess the thresholds for initial SOC values beyond which we could expect a SOC increment.

A multiple linear regression equation was fitted to estimate annual increase in SOC as a function of: initial SOC, annual amounts of animal and green manures incorporated, clay percentage, silt percentage, number of soil tillages per year, and number of years under re-design, using Genstat's 14th Edition. A stepwise (backward) procedure was followed, removing those variables not satisfying $p<0.05$.

3. Results

3.1 Baseline assessment

3.1.1 Chemical properties

On average SOC was 36% greater at the reference sites than in the cropped fields ($P \leq 0.05$, Table 2.4). SOC depletion due to cropping was greater in Phaeozems (Abruptic) (43%) than in both Vertisols and Phaeozems (Pachic) (32% on average). Exchangeable K decreased and available P increased in cropped fields compared to the reference sites (Table 2.4). Land use history did not affect concentrations of exchangeable calcium, magnesium, total exchangeable bases or pH (Table 2.4). As expected there were differences among soil types, with the coarser textured Phaeozems (Abruptic) having the smallest values for all variables, and Vertisols the largest.

Table 2.4. Mean soil chemical properties for two different land use histories and three soil types at 0–20 cm depth. For description of the variables see text.

Soil type	Vertisols	Phaeozems (Pachic)	Phaeozems (Abruptic)	Average	S.E.D.[a] (land use)
Land use	SOC (g kg^{-1})				
Reference	24.84	21.34	20.01	22.07 a	1.31
Crop field	16.51	14.71	11.31	14.18 b	
Average	20.68 A	18.03 AB	15.66 B		
S.E.D. (soil type)	1.61				
	K ($cMol_c$ kg^{-1})				
Reference	0.89	0.74	0.92	0.85 a	0.07
Crop field	0.78	0.69	0.60	0.69 b	
	P (mg kg^{-1})				
Reference	15.02	8.87	19.00	14.30 b	13.72
Crop field	71.19	66.87	86.55	74.87 a	
	Exch. bases ($cMol_c$ kg^{-1})				
Reference	32.55	21.03	15.19		
Crop field	34.74	17.51	13.87		
Average	33.64 A	19.27 B	14.53 C		
S.E.D. (soil type)	2.52				
	Ca ($cMol_c$ kg^{-1})				
Reference	26.99	15.43	10.97		
Crop field	29.63	12.50	9.46		
Average	28.31 A	13.96 B	10.22 B		
S.E.D. (soil type)	2.44				
	Mg ($cMol_c$ kg^{-1})				
Reference	4.37	4.33	3.03		
Crop field	3.99	3.95	3.25		
Average	4.18 A	4.14 A	3.14 B		
S.E.D. (soil type)	0.38				
	pH (1:2.5 soil:H_2O)				
Reference	6.91	6.34	6.05		
Crop field	7.04	6.15	6.48		
Average	6.97 A	6.24 B	6.26 B		
S.E.D. (soil type)	0.23				

[a] S.E.D.: average standard error of the difference

Note**:** Different lower case letters indicate significant differences between land uses (within a column). Different upper case letters indicate differences among soils (within a row) (REML analysis, $P < 0.05$).

3.1.2 Soil aggregation, porosity and moisture release curves

Soil aggregation was less under cropped fields than at the reference sites. The difference in the geometric mean diameter of aggregates (GMD) between reference sites and cropped fields was 0.8, 0.28 and 0.31 mm in Vertisols, Phaeozems (Pachic) and Phaeozems (Abruptic), respectively (Table 2.5).

Table 2.5. Porosity, bulk density, available water capacity and geometric mean diameter of aggregates, from undisturbed samples of reference sites and crop fields in three soils

Soil type	Vertisols	Phaeozems (Pachic)	Phaeozems (Abruptic)	Average	S.E.D.[a] (land use)
	Geometric mean diameter of aggegates[b] (mm)				
Reference	2.85 ab	2.66 b	2.95 a		
Crop field	2.05 d	2.38 c	2.64 b		
S.E.D. (soil type x land use)		0.013			
Land use	Total porosity (%)				
Reference	59.8 b	52.7 d	53.7 cd		
Crop field	63.7 a	56.0 c	52.8 d		
S.E.D. (soil type x land use)		1.7			
	Bulk density (Mg ha^{-1})				
Reference	1.07 c	1.28 a	1.25 a		
Crop field	0.96 d	1.15 bc	1.21 ab		
S.E.D. (soil type x land use)		0.06			
	Macroporosity (%)				
Reference	13.7	14.9	17.8	15.5 a	2.2
Crop field	21.4	23.8	20.3	21.9 b	
	Available water capacity (mm 10 cm^{-1})				
Reference	26.3	18.5	21.6	22.1 a	1.5
Crop field	23.5	17.1	18.7	19.8 b	
Average	24.9 A	17.6 C	20.1 B		
S.E.D. (soil type)	1.5				

[a] S.E.D.: average standard error of the difference

[b] GMD estimated through equation 3 explained in the text, section 2.3.1.

Note**:** Different lower case letters indicate significant differences between land uses or between land uses x soils. Different upper case letters indicate differences among soils (within a row) (REML analysis, $P < 0.05$).

The volumetric water content at 10 to100 kPa (pF 2 to pF 3) was larger at reference sites than in the cropped fields for all three soil types (Fig. 2.1). Available water capacity (AWC) at the reference sites was on average 2.3 mm 10 cm^{-1} more than in the cropped fields (Table 2.5 and Fig. 2.1).

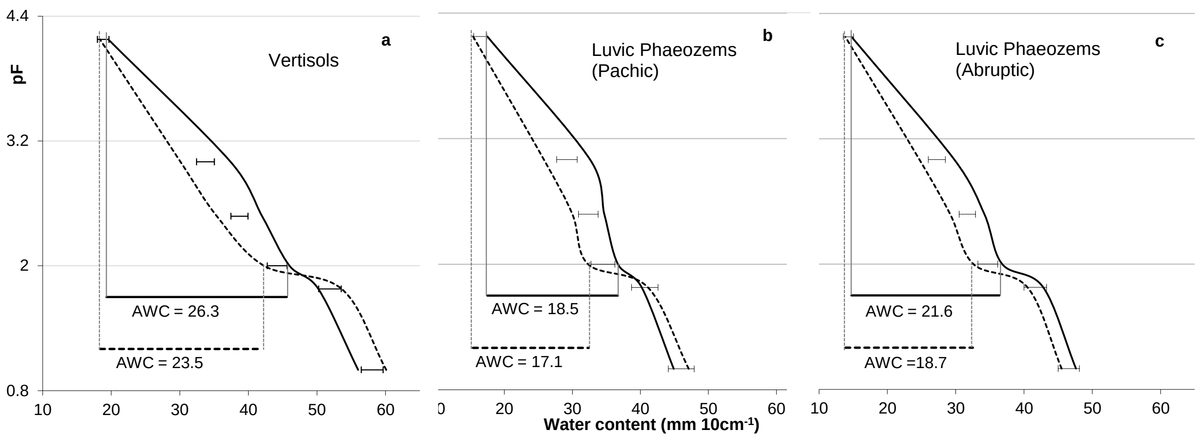

Figure 2.1. Averaged soil water release curves for reference sites (——) and cropped fields (- - -) for Vertisol (a), Phaeozems (Pachic) (b), and Phaeozems (Abruptic) (c). Drawn lines refer to on-farm reference sites, dotted lines refer to crop fields. Available water capacity (AWC), mm 10cm^{-1}) is indicated as the difference in water content between pF2 and pF4.2. Error bars indicate the least significant difference ($p < 0.05$).

We found a positive correlation between SOC and available water capacity (Pearson correlation r = 0.59, P < 0.0001). From the difference in slopes of the linear regressions of water content at field capacity and at wilting point (Fig. 2.2) an increase of 4.2 mm 10 cm^{-1} of water for every 10 g kg^{-1} additional SOC is inferred.

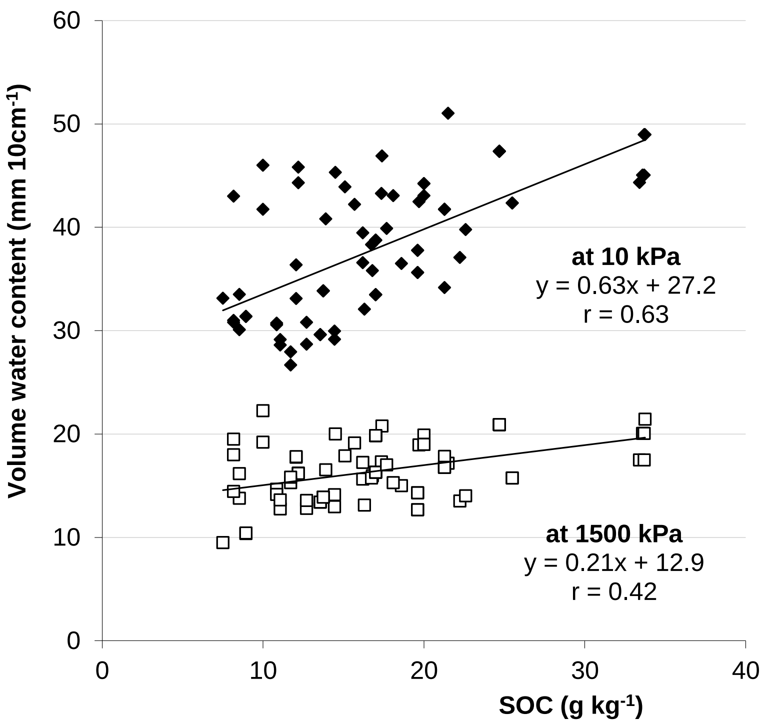

Figure 2.2. Volumetric water content at field capacity (10 kPA, ♦) and wilting point (1500 kPA, □) as a function of SOC content.

3.2 Impact of farm systems re-design

Two to five years of improved soil management practices, including uptake of pasture in rotations, green and animal manures, and incorporation of plant residues resulted in a pronounced increase of SOC in the first 20 cm of the Phaeozems (1.42 and 1.53 g kg^{-1}), and a slight, non- significant increase in the Vertisols (0.87 g kg^{-1}) (Table 2.6). The pH increased in Vertisols and Phaeozems (Abruptic), and the available P and exchangeable bases increased in Phaeozem (Abruptic) (Table 2.6). The average carbon addition rate of 2.4 Mg ha^{-1} $year^{-1}$ combined with the other soil management changes (Table 2.2) resulted in an average SOC increment of 0.8 Mg ha^{-1} $year^{-1}$ in the Phaeozems (Pachic) and 1.2 Mg ha^{-1} $year^{-1}$ in the Phaeozems (Abruptic).

The change in SOC between start and end of the re-design was plotted against the initial amount of SOC (Fig. 2.3a). Although variability was substantial, consistent increase in SOC was associated with initial SOC levels below 10 g kg^{-1} at which point the lower boundary line crossed the x axis, and consistent decrease in SOC over the re-design period was associated with initial SOC levels exceeding 22 g kg^{-1}, where the upper boundary line cross the x axis.

Table 2.6. Changes in SOC, pH and exchangeable bases in cropped fields as a result of the implementation of improved cropping systems.

Variable/Soil type	Mean of 2010	Mean at start of syst. redesign	S.D.[a] of the difference	*P* two-sided
SOC (g kg^{-1})				
Vertisol	17.38	16.51	3.64	0.1871
Phaeozems (Pachic)	16.13	14.71	2.60	0.0199
Phaeozems (Abruptic)	12.84	11.31	2.00	0.0102
pH (H_2O)				
Vertisol	7.41	7.04	0.41	0.0014
Phaeozems (Pachic)	6.21	6.15	0.50	0.1801
Phaeozems (Abruptic)	6.70	6.48	0.46	0.0014
P (mg kg^{-1})				
Vertisol	62.72	72.11	59.21	0.3693
Phaeozems (Pachic)	65.35	56.77	35.44	0.2924
Phaeozems (Abruptic)	99.90	82.25	27.31	0.0253
Exch. bases ($cMol_c$ kg^{-1})				
Vertisol	38.78	35.06	10.40	0.0561
Phaeozems (Pachic)	18.12	16.82	3.26	0.1084
Phaeozems (Abruptic)	15.46	13.60	2.32	0.0077

[a] S.D.: standard deviation.

During backward stepwise regression analysis silt and sand contents, number of annual tillage operations, and number of years that the fields had been under re-design were discarded at the p=0.05 level. The regression equation (4) showed that in addition to a negative effect of initial SOC content, increases in SOC were associated with greater rates of application of green and animal manures and larger soil clay content:

$$\Delta SOC \text{ (Mg ha yr}^{-1}\text{)} = -\ 3.00 \times 10^{-1} - 3.92 \times 10^{-2}\ (9.8 \times 10^{-3}) \times SOC_i + 2.50 \times 10^{-4}\ (2.72 \times 10^{-5}) \times GM + 1.33 \times 10^{-4}\ (2.22 \times 10^{-5}) \times AM + 2.48 \times 10^{-2}\ (1.11 \times 10^{-2}) \times Cl \qquad [4]$$

$P<0.001$, $r^2 = 76.8$, SE = 0.73, RMSE = 0.73 Mg ha yr^{-1}

where ΔSOC is the difference between SOC contents at the end and the start of the redesign period, averaged per year (Mg ha^{-1} yr^{-1}), SOC_i is the initial amount of SOC (Mg ha^{-1}), *GM* is the amount of green manure added (kg ha^{-1} yr^{-1}), *AM* is the amount of animal manure added (kg ha^{-1} yr^{-1}), and *Cl* is the concentration of clay (%). The numbers between parentheses indicate the standard error for the parameters.

The estimated and observed changes in SOC were plotted in Fig. 2.3b, distinguishing fields with different number of years under redesign by different symbols.

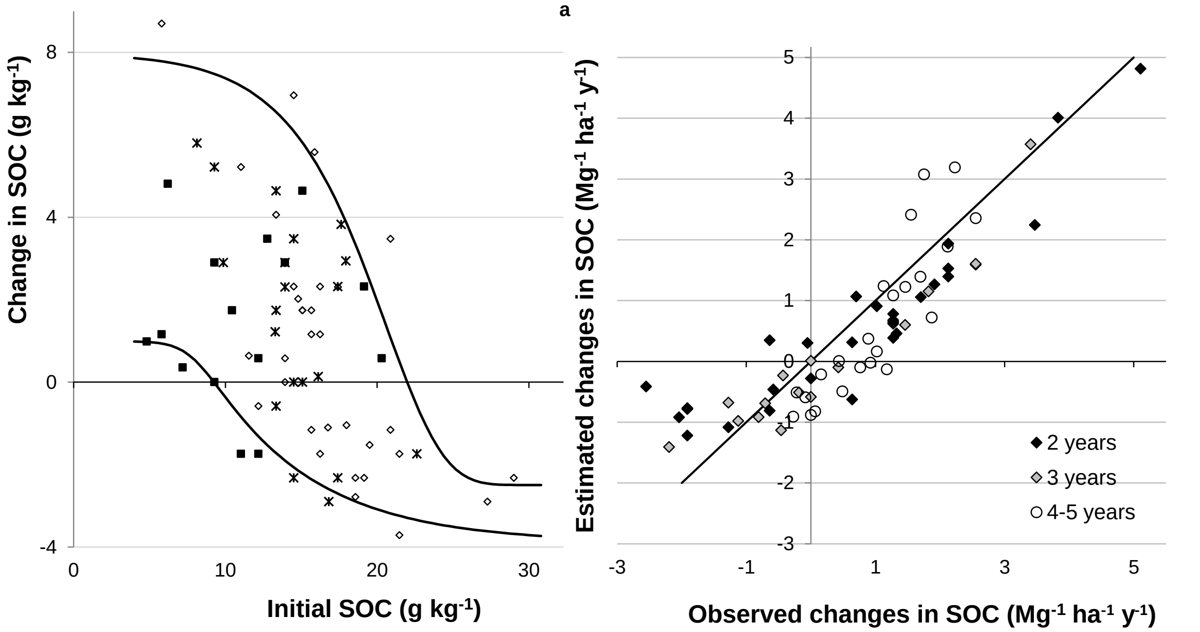

Figure 2.3. Change in SOC on cropped fields as a function of the initial SOC in Phaeozems (Pachic) (ж), Phaeozems (Abruptic) (■), and Vertisols (◊). Upper and lower boundary lines for the observed SOC change were drawn (a). Predicted using equation 4 and observed annual changes in SOC as a function of the initial SOC content, annual additions of green and animal manures and clay content. Different symbols indicate the number of years that each field has been re-designed (b). For description of the regression equation (4), see text section 3.2.

Total SOC for the three soil types was 29, 11 and 4% less at the on-farm reference sites than for historical references for Vertisols (Fig. 2.4a), Phaeozems (Pachic) (Fig. 2.4b) and Phaeozems (Abruptic) (Fig. 2.4c) respectively. Statistical inferences cannot be made due to lack of variability estimates in the historical data.

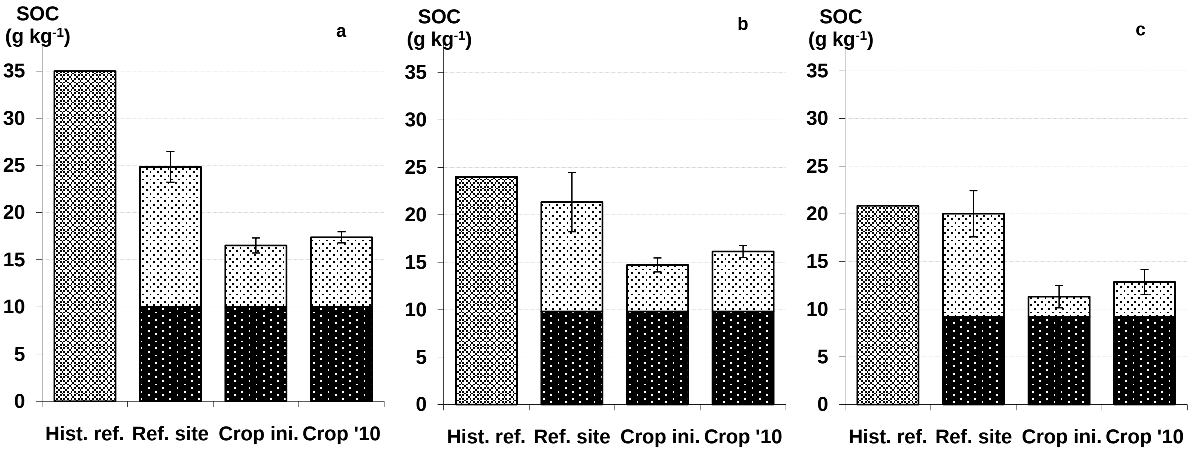

Figure 2.4. Total soil organic carbon (SOC, g kg^{-1}) at the historical reference site (Hist. ref.), and unstable (light shading) and stable (dark shading) soil organic carbon as calculated by equation (5) at on-farm reference sites (Ref. site) and in cropped fields at the beginning (Crop ini.) and at the end of the systems redesign (Crop '10), for (a) Vertisols, (b) Phaeozems (Pachic), and (c) Phaeozems (Abruptic). Error bars indicate the standard errors in total SOC.

4. Discussion

The results of the study show that intensive and participatory re-design including researchers and farmers was able to significantly improve average SOC after only 2 to 5 years. Farmers participated voluntarily as they saw benefits from the changes and no financial remuneration was provided. The results are novel as they demonstrate that even under smallholder conditions producing for competitive markets improvements of the soil resource base are possible with targeted redesign approaches. Below we discuss the state of the soils at the start and the end of redesign, reflect on the prototyping methodology and assess the perspective of further improvements in soil quality.

4.1 Baseline assessment

The results support our initial hypothesis that soil quality in vegetable fields was significantly poorer than at relatively undisturbed on-farm reference sites. Twenty and more years of vegetable production had caused a decline in SOC stocks in the first 20 cm of soil, a decline in K concentration, a fivefold increase in P concentration, and a decline in available water capacity of 2.3 mm per 10 cm of soil on average.

When compared to historical data, it seems that the on-farm reference sites for the heavier soil types may have been degraded by livestock grazing and cropping even before the advent of vegetable production (Fig. 2.4). The higher SOC depletion compared to the on-farm reference site on Phaeozems (Abruptic) (Table 2.4) is explained by the lesser capacity of coarser textured soils to protect SOC (Hassink et al. 1997) and their higher susceptibility to erosion. This result indicates the need for extra attention for improved soil management techniques on this coarser textured soil.

Over the years, negative K balances resulted in depletion of soil K reserves in cropped fields compared to the reference sites (Table 2.4). Amounts of K taken up by vegetable crops are on average 3.5 kg Mg^{-1} of fresh harvested product, which is 4 to10 times greater than uptake and removal of P (Ciampitti and García, 2008). Nevertheless, farmers in the area apply more P than K in fertilizer because the soils are known to be naturally rich in K and poor in P. Phosphorus accumulation together with potassium depletion points to the need for extra attention to fertilization practices.

Larger aggregates are indicative of greater soil structure stability. The reduction in soil structure stability in cropped fields compared to the reference sites may increase soil erodability and diminish the infiltration and porosity over time. Larger macro-porosity and lower bulk density found in cropped fields is most likely due to tillage operations 2-3 months before measurements, which temporarily loosened the soil. These findings are in accordance with results of a meta-analysis of field experiments that showed that bulk density and cone penetration resistance were larger under reduced tillage than under conventional tillage systems in the Argentine Pampas (Alvarez and Steinbach, 2009). Vegetable crops strongly depend on maintaining an adequate soil macro-porosity, so cropping with reduced or no tillage is a major management challenge.

We found that the loss of SOC in cropped fields had a pronounced effect on the volumetric water content at different tensions (Fig. 2.1), resulting in steeper moisture-retention curves for cropped fields than for reference sites in the range of pF 2 - 4.2 that determines the available water capacity (AWC). The volumetric water content increased by 6.3 mm 10 cm^{-1} and 2.1 mm 10 cm^{-1} with a 10 g kg^{-1} increase in SOC content at field capacity and wilting point, respectively (Fig. 2.2). Our measurements are in agreement with Hudson (1994) who found that in soils including different textural groups responses were 6.2 mm 10 cm^{-1} and 1.2 mm 10 cm^{-1} increase in volumetric water content per 10 g kg^{-1} increase SOC at field capacity and wilting point, respectively. Rawls et al. (2003) and Tomer et al. (2006) arrived at similar conclusions about the role of SOC on AWC.

4.2 Impact of farm systems re-design

The SOC increases obtained after systems redesign support our hypothesis that it is possible to improve soil quality on commercially operating vegetable farms. Topsoils sequestered an average of 3.4 Mg ha^{-1} of carbon in Phaeozems (Pachic and Abruptic) after two to five years of re-design involving average annual carbon incorporations of 2.4 Mg ha^{-1} y^{-1}. Effects of organic additions on SOC reported for other regions are highly variable due to variation in soil types, climate, initial SOC values, tillage and field history. In a three year study in a Mediterranean intensive vegetable crop system, no change in SOC was detected following applications of food waste and yard trimmings of up to 45 Mg ha^{-1} yr^{-1} (Lovieno et al., 2009). In a granitic sandy soil a single application of 37.5 Mg ha^{-1} yr^{-1} of cattle manure resulted in a 38% increase in SOC in the first 10 cm of soil after three years (Nyamangara et al., 2001). After 10 years of manuring a Mollisol at application rates similar to our study (7.5 Mg ha^{-1} $year^{-1}$) in a temperate agro-ecosystem in China, Ding et al. (2012) found that the carbon stocks in the top 20 cm increased by 12.5% from an initial value of 26.9 g kg^{-1}.

The capacity of a soil to integrate and protect new additions of organic matter increases when its total SOC content is closer to the stable SOC content (Hassink et al., 1997). Consequently, we could expect higher rates of SOC increase in soils where stable SOC constitutes a larger fraction of the total SOC. Theoretical "stable" organic carbon can be estimated from silt and clay contents using an equation proposed by Rühlmann (1999):

$$\textit{Stable SOC} = [0.017 \times (\textit{clay} + \textit{silt})] - [0.001 \times \exp(0.075 \times (\textit{clay} + \textit{silt})] \quad r^2 = 0.96 \qquad [5]$$
(all variables in percentage)

The above equation is based on data from 106 different soils from long term experiments under bare fallow treatments during 13 to 100 years .The database included 13 locations in temperate, arid and tropical areas of the world. We calculated what we refer to as the "unstable" soil organic carbon by subtracting the estimated "stable" SOC from the measured total SOC. The unstable SOC (Fig. 2.4) at the on-farm reference sites was 64, 53 and 51% of total SOC for Vertisols, Phaeozems (Pachic) and Phaeozems (Abruptic) respectively, compared to 39, 33 and 19% for the associated cropped fields before starting the implementation of systems redesign, and 42, 39 and 28% after the re design. In agreement with what was expected, we found that SOC increments were greatest in Phaeozems (Abruptic), which contained highest levels of stable SOC relative to initial total SOC (81%; Fig. 2.4).

From Fig. 2.3 we deduced that below an initial SOC content of 10 g kg^{-1} soils could be easily improved, while above 22 g kg^{-1} SOC decreased with the practices used during re-design. This was corroborated by equation (4), in which we implicitly assumed that the change in

SOC is linear in time. This assumption is reasonable for short periods of time (Hassink and Whitmore, 1997) such as the 2-5 years in this research. This conclusion is confirmed by the fact that the number of years under re-design did not significantly explain annual SOC change. Over the next years, it is likely that currently positive and negative rates of SOC change will tend to zero and a new dynamic equilibrium will establish based on new rates of organic matter addition (Stewart et al., 2007).

We observed an increase in pH and exchangeable bases (Table 2.6), which may be attributed to the addition of organic matter and of large amounts of alkaline cations in manure. Soil pH increases were reported by Sharpley et al. (1993) after 12 years of poultry litter applied at 6 Mg ha^{-1} yr^{-1} and by Whalen et al. (2000) after incorporation of cattle manure in acid soils. In our study, initial soil pH values were around 6 in the top 20 cm (Table 2.6), and farmers incorporated on average 3.2 Mg DM ha^{-1} of animal manure with an average pH (H_2O) of 7.3. Given the average amounts of animal manures added to the vegetable fields (Table 2.3) and the contents of cations reported in chicken litter in Uruguay (Barbazán et al., 2011) we estimated that 43 kg ha^{-1} yr^{-1} of P and 125 kg ha^{-1} yr^{-1} of bases (75 kg ha^{-1} $yr^{-1}Ca^{++}$; 30 kg ha^{-1} $yr^{-1}K^{+}$; 12 kg ha^{-1} $yr^{-1}Mg^{++}$, and 8 kg ha^{-1} $yr^{-1}Na^{+}$) were added to the soil on average. This could explain part of the observed increase in P and soil exchangeable bases (Table 2.6). Another source of cations for many fields could have been the irrigation water, which in most cases was rich in Ca (Dogliotti et. al., 2012).

In vegetable farms of south Uruguay access to irrigation water poses a major constraint. One of the main causes of reduced soil productivity for high value vegetable crops is the reduction in soil moisture supply capacity (SMS), defined here as the capacity of soils to store and supply adequate amounts of water for crops. An important concern of vegetable growers is resilience by increasing water infiltration in the face of increasingly erratic rainfall and thus reducing run-off and soil erosion, and by increasing the water storage capacity of the soils. Using equation (4), we estimated the SOC increase after five years of annual incorporation of 3.9 Mg ha^{-1} of green manures and 3.2 Mg ha^{-1} of animal manures for three different initial SOC values. SOC increased by 5.6, 2.9, and 2.2 Mg ha^{-1} (2.3, 1.2, 0.9 g kg^{-1}) for initial SOC contents of 10, 30, and 40 Mg ha^{-1} (4.2, 12.5, 16.7 g kg^{-1}) respectively, at clay contents of 20, 30 and 40% respectively. Based on the relations shown in Fig. 2.2 these increments in SOC would result in increments of 2.0, 1.0 and 0.8 mm in the first 20 cm of soil of additional available water capacity, what could result in savings of 8,000 to 20,000 L ha^{-1} of irrigation water. Further analysis of rainfall patterns in relation to crop demand is needed to assess what consequences are for yield.

How the available water capacity increase affects SMS would depend also on the effect of increases in SOC on water infiltration and run-off, root exploration, soil evaporation and drainage, which are all positively influenced by SOC content and soil aggregation (Carter, 2002).

4.3 Research methodology and implications

The prototyping approach to re-design farming systems precludes elucidation of the effect of individual changes in soil management on the overall change. Regression analysis (equation 4) showed the relative importance of initial SOC and clay content for changes in SOC that may be expected from applications of green and animal manures. It also indicated that the green manures (mainly gramineous species) were almost twice as effective in increasing SOC compared to animals manures. However, the relative role of parcel levelling for erosion control and changes in relative areas of crops at the whole-farm level cannot be disentangled from the other factors.

Elucidation of changes in yield on individual fields resulting from re-design would require a much larger set of farms to account for differences in cropping plans. Such set-up would be unwieldy in view of the labour demand for monitoring and negotiation associated with a prototyping approach. Nevertheless, results obtained at farm level showed that the improvements in soil quality described in this paper were accompanied by an average yield increase of the main vegetable crops (tomato, sweet pepper, onion, garlic and sweet potato) of 39%, and an increase in labour productivity of 53% (Dogliotti et al., 2012). These results support the win-win outcome that was hypothesized by Dogliotti et al. (2005) for improvements in both the economics and the resource base of farms in South Uruguay.

Further increases of SOC on the pilot farms would in many cases require organic matter applications exceeding the average rate applied in this study, 7.1 Mg ha^{-1} yr^{-1} (Table 2.3), which may not be feasible at a farm scale. Reduced tillage in combination with green manures or pastures offers scope for reducing the rates of animal manure input by reducing breakdown rates of organic matter and maintaining soil surface cover (Erenstein, 2002; Johnson and Hoyt, 1999; Scopel et al., 2004 and 2005). Although reduced tillage in vegetable production poses considerable technical and economic challenges (Boulala et al., 2012; Jackson et al., 2004), it might be a way to rebuild soil structure stability and to avoid sole reliance on animal and green manures to increase SOC.

Additional studies on infiltration and crop production are needed with a more classical factorial design in order to provide an assesment of the benefits in terms of productivity and reduction in soil erosion and/or run-off. Future studies could also explore the integration of organic amendments and green manures with the use of reduced tillage practices to overcome the impracticalities and environmental concerns associated with incorporation of large amounts of green and animal manures.

What do our results mean for other places? As redesigns differed between farms depending on farm-specific biophysical and socio-economic conditions, the results do not provide a dose-response relation for system change and system performance. Instead they show the magnitude of changes in soil quality that may be expected in the short term when agricultural scientists engage in a systems innovation effort under commercial smallholder farming conditions. In doing so, they support approaches put forward for more effective science – practice engagement (e.g. Blazy et al., 2009; Giller et al., 2008; Wery and Langeveld, 2010) with evidence of actual changes in the soil resource base.

Acknowledgments

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Chapter 3

Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems

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Abstract

Smallholder vegetable farmers tend to specialize and intensify their production to secure income. In south Uruguay, frequent tillage and little or no inputs of organic matter have resulted in soil degradation that threatens soil productivity and systems sustainability. This study aimed to quantify the impact of tillage, crop residue management, and organic matter incorporation on runoff, soil erosion, water dynamics, and productivity of a raised bed tomato- oat rotation system. A field trial was set up in 2010 and replicated in 2011 in a temperate climate on a fine textured soil including four soil management practices: reduced tillage with a cover crop left as mulch and chicken manure incorporation (*RTmulch*), conventional tillage with a cover crop used as green manure and chicken manure incorporation (*CTgm*), conventional tillage with chicken manure incorporation (*CTchm*), and conventional tillage system as control (*CT*). *RTmulch* decreased soil erosion and runoff by more than 50% compared with the three conventional tillage systems. We proposed a non-linear model to estimate the reduction in runoff due to stubble as a function of rainfall, with locally adjusted parameters. Yields under *CTchm* were the largest both years, and more than 50% greater than under *RTmulch*. Causes of low yields under *RTmulch* are most likely poor crop establishment under the organic cover in combination with N immobilization. Compared with *CTchm* water use efficiency under *RTmulch* was reduced by 43% during the first season, and by 35% under both *RTmulch* and *CTgm* during the second season. In a dry season, *RTmulch* increased soil water capture by 20% (45 mm) compared with conventional tillage treatments. This is of special interest in these systems as it may result in a larger cultivated area of irrigation-dependent crops on a farm, thus building resilience to climate change. Future research on soil and water conserving practices in vegetable production systems should particularly address crop establishment and N management to avoid yield penalties under reduced tillage.

Keywords: Mulching; Organic manure; Vegetable cultivation; Infiltration; Soil water supply; Conservation agriculture

1. Introduction

Soil quality deterioration and fertility decline caused by agriculture is a problem worldwide, threatening both quality of the environment and sustainability of farmers' livelihood. This is also the case for smallholder vegetable farmers in south Uruguay, who tend to specialize and intensify their production to secure income. In the region, fine textured soils (Vertisols and vertic Argiudols) are dominant, and vegetable crops are generally grown on raised beds in order to both increase the volume of the "A" horizon that can be easily explored by roots, and to improve surface drainage after a heavy rainfall. The presence of argillic B horizons close to soil surface in combination with intense rainfall events leads to rapid saturation of the topsoil, exacerbating surface runoff. In addition, soil physicochemical quality deteriorates severely under vegetable farming due to intense tillage, poor soil cover, low organic carbon inputs, and frequent cultivation (Alliaume et al., 2013; Dogliotti et al., 2003). Additionally, while the frequency of extreme events such as droughts and heavy rains has increased in the region (Giménez and Lanfranco, 2012), water for irrigation is a limiting factor and most farmers in south Uruguay can only irrigate a small fraction (48% on average) of their vegetable crops (Righi, 2011).

The implementation of practices to improve soil quality was a key element in two projects aimed at a systemic re-design of vegetable farm systems in south Uruguay. The recommended practices included crop rotations; inclusion of a pasture phase when the farm was large enough; introduction of cover crops and incorporation of organic manures; and erosion control practices such as terracing and reducing plot sizes to avoid steep slopes (Dogliotti et al., 2013). When implemented, these practices were found to contribute to reducing soil erosion and increasing topsoil carbon content (Alliaume et al., 2013). Particularly, the inclusion of a pasture phase reduced soil erosion estimates to levels below the threshold proposed for sustainable management of these soils, i.e. 7.0 Mg ha^{-1} $year^{-1}$ (Hill et al., 2010; Puentes and Szogui, 1983). A pasture phase, however, is not feasible for small farms as pastures do not result insufficient financial returns in the short-term. In these cases, reduced tillage in combination with mulching on the raised beds can be a viable alternative to reduce runoff and soil erosion, and to increase infiltration. In a laboratory experiment, the use of 2 to 4 Mg $ha^{-1}$of organic mulch strongly affected the infiltration, increasing soil moisture and reducing runoff and sediment transport (Montenegro et al., 2013).

A number of studies demonstrated that the use of minimum tillage combined with cover crops and raised beds can improve soil quality (Johnson and Hoyt, 1999) and reduce erosion (Boulal et al., 2008) in vegetable production systems. Scopel et al. (2004) showed that mulching under semi-arid and humid tropical conditions increased water infiltration, reduced soil evaporation losses by ca. 52% and increase drain water storage by ca. 50%. Permanent beds with partial or complete retention of residues improved infiltration, aggregate stability and soil microbial biomass (Verhulst et al., 2011). In an arid region permanent beds and retention of residues increased water productivity by about 30% for wheat and 80% for maize, with 11% to 23% reduction in the amount of water applied (Davkota et al., 2013). Similar management in a Mediterranean climate did not improve water use efficiency but delayed the water use by the maize crop until later in the season without changing the yields (Boulal et al., 2012). The delay may result in a more timely and efficient use of available resources for growth (water and nitrogen) and therefore, as the authors concluded, permanent beds with mulch have potential for reducing costs and increasing profitability. However, results were not consistently positive. Poor crop establishment and lower initial LAI was observed by Boulal et al. (2012), and the impact on yield has been variable (Boulal et al., 2012; Gilsanz et al., 2004; Luna et al., 2012). Preliminary studies in Uruguay comparing minimum with conventional tillage in vegetable production showed potential benefits in terms of soil quality and soil moisture accumulation, while yields were not affected (Arboleya et al., 2012).

Conservation agriculture (CA) has been widely adopted in broad-acre arable systems in Uruguay. Vegetable cropping systems, however, which use the land much more intensively, have continued to rely on conventional tillage. For a successful adoption of CA practices, they should be adapted to local conditions and to resource availability of smallholder vegetable farmers. Accordingly, we studied the effect of combinations of reduced tillage, mulching and organic matter addition on water capture and conversion efficiencies under vegetable crops grown on raised beds on fine textured soils. We hypothesise that reduced tillage in combination with a cover crop and addition of locally-sourced organic matter can substantially reduce runoff and soil erosion from raised beds as compared with current practices.

The aim of our study was to analyze the effect of reduced tillage, cover crops and organic matter addition on water runoff, soil erosion, soil moisture supply capacity and crop yield in raised bed systems on a fine-textured, moderately well-drained soil. We compared soil management practices that are readily available to local farmers, focusing on tomato as a major crop. We analyzed the first two years of transition from conventional to reduced tillage combined with organic mulching and the incorporation of cover crops and chicken manure. Runoff, soil moisture, cover and surface roughness were measured and used to calculate water-use efficiency, vulnerability to soil erosion through the Revised Universal Soil Loss Equation(RUSLE) (USDA-ARS, 2003), threshold rainfall at which runoff starts and the runoff/rainfall ratio across tillage systems.

2. Materials and methods

2.1 Study site, experimental design and soil management

The study was conducted at the South Regional Centre research station, Canelones, south Uruguay. Climate is temperate with a mean annual rainfall of 975 mm (Fig. 3.1). Weather variables were monitored with an automatic meteorological station situated at 630 m from the experimental site and a pluviometer next to the plot.

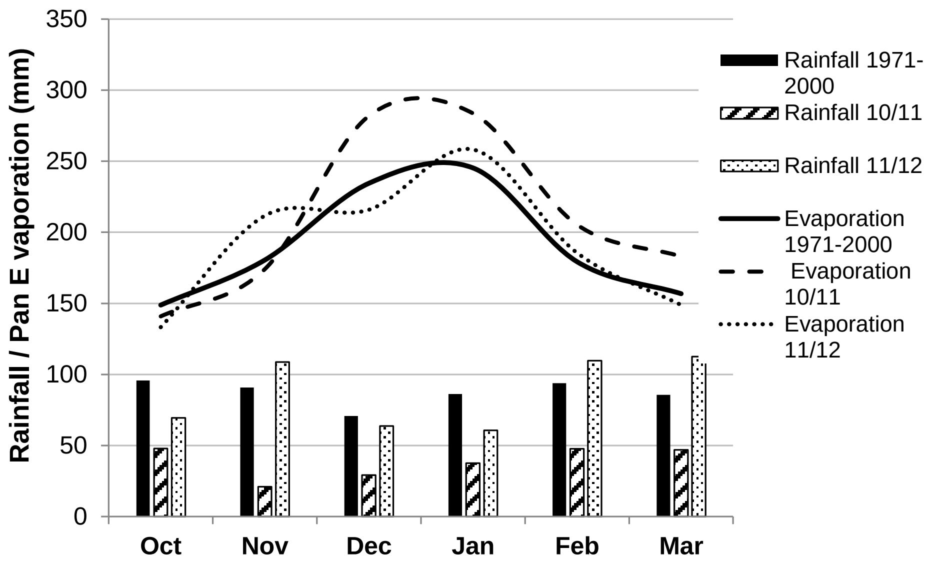

Figure 3.1. Monthly pan evaporation (lines) and precipitation (bars) from October to March at INIA Las Brujas meteorological station (Lat: 34° 40' S; Lon: 56° 20' W). Bars represent climate (1971-2000; black), cropping season 2010-11 (hatched) and cropping season 2011-12 (gray).

The soil at the experimental site is a Luvic Phaeozem according to the FAO system, with particle size distribution in the upper 20 cm soil layer of 140 g kg^{-1} sand, 625 g kg^{-1} silt, 235 g kg^{-1} clay, and 15 g kg^{-1} soil organic carbon (SOC). A sequence of black oat (*Avenastrigosa* L.; winter crop) - processing tomato (*Lycopersicon esculentum Mill.*; summer crop) was established during two subsequent years (2010-2012) in a field of 50 x 30 m as part of a rotation that also included the summer crops corn and onion. Black oat was sown in autumn and killed off with glyphosate at the end of the winter (20 August 2010 and 7 September 2011). Tomato was transplanted on 22 October 2010 and 1 December 2011 at a density of 26,667 plants ha^{-1}, and harvested weekly from 5 January to 17 February 2011, and from 8 February to 7 March 2012. Water was provided at transplanting and during the growing phase after several days of no rainfall.

Four treatments in three replicates were arranged in a complete random design in plots consisting of two contiguous raised beds, 1.5 m apart (Fig. 3.2). In three conventional tillage treatments, beds were re-built twice a year before each crop. The fourth treatment was based on reduced tillage where beds were re-built only before sowing black oat. The conventional tillage systems included a control system with only artificial fertilizer (*CT*), a system with a mixture of chicken manure and rice husk commonly used in the region (*CTchm*), and a system with both chicken manure and green manure consisting of black oat incorporated to the soil 20-70 days before planting the tomato crop (*CTgm*). In the reduced tillage treatment (*RTmulch*) chicken manure was incorporated during the re-building of the beds, and black oat was killed with glyphosate 40-105 days before planting the tomato crop and left as mulch on the soil surface. In each treatment the soil was tilled with a tandem disk and a disk hiller was used to re-build the beds in autumn. Details of the treatments and amounts of nutrients applied are given in Table 3.1. P was not applied since it was not a limiting nutrient (P-Bray I status in soil surface of the plots was 75 mg kg^{-1}).

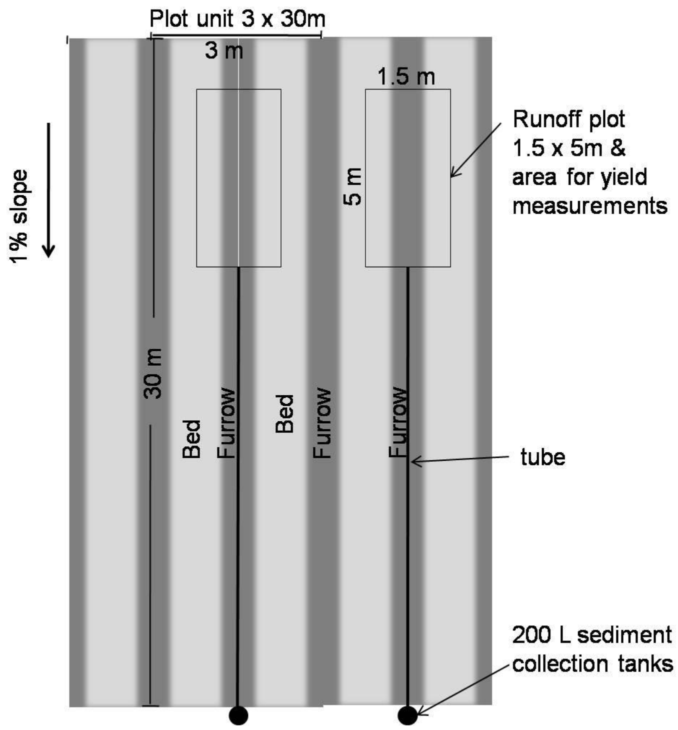

Figure 3.2. Schematic representation of the field experiment showing the layout of the raised beds, runoff plots, sediment collection tanks and tubes that conduct water from runoff plots to sediment collection tanks.

Table 3.1. Details of soil management operations in the four treatments.

Treatment	Chicken Manure[a] (Mg ha^{-1})	Oat sown[b]	Oat incorporated[c] (Mg ha^{-1})	Chicken manure[d] (Mg ha^{-1})	Base fertilization for tomato		Fertilization during growing season	
					type	(kg N ha^{-1})	type	(kg N ha^{-1})
2010/2011								
CT	-	-	-	-	Urea	18	Urea + KNO_3	42 + 18
CTchm	3.5	-	-	3.5	Urea	18	Urea + KNO_3	42 + 18
CTgm	3.5	Yes	8.5	3.5	Urea	18	Urea + KNO_3	42 + 18
RTmulch	7.0	Yes		-	Urea	18	Urea + KNO_3	42 + 18
2011/2012								
CT	-	-	-	-	Urea + KNO_3	25 + 25	Urea + KNO_3	92 + 18
CTchm	3.5	-	-	3.5	KNO_3	25	Urea + KNO_3	92 + 18
CTgm	3.5	Yes	9.9	3.5	Urea + KNO_3	40 + 25	Urea + KNO_3	92 + 18
RTmulch	7.0	Yes	-	-	Urea + KNO_3	40+ 25	Urea + KNO_3	92 + 18

Treatments: *CT*= Conventional Tillage; *CTchm*= Conventional tillage with Chicken manure *; CTgm*= Conventional Tillage with chicken manure and Green

Manure*; RTmulch*= Reduced Tillage with chicken manure and cover crop as mulch.

[a]Chicken manure was incorporated with the disk hiller immediately after the first tillage with tandem disk on3 March 2010 and 22 March 2011.

[b]Oat was seeded at 120 kg ha^{-1} on 3 March 2010 and 29 March 2011.

[c]Oat was incorporated with disc hiller on 6 October 2010 and 20 September 2011. In *RTmulch* oat was left as mulch.

[d]Chicken manure was incorporated with disc hiller on 3 March 2010 and 22 March 2011.

[e]Ferti- irrigation; KNO_3 at flowering, and urea from fruit set.

2.2 Runoff from rainfall events and mini rainfall simulations

Runoff plots, 1.5 m wide x 5 m long with 1% slope, were established in each treatment by inserting metal barriers 10 cm deep into the soil across two beds. This effectively created a runoff plot consisting of the inner halves of two adjacent beds and the furrow (Fig. 3.2). Each down-slope barrier contained 30 holes of 2.5 cm diameter at the level of the furrow soil surface and above, to channel the runoff water to a 25 m long and 5 cm diameter tube that ended in a 0.2 m^3 buried metal collector tank. The amount of water collected in the tank was measured after each rainfall event, both manually and automatically. Cumulative infiltration was calculated as the difference between rainfall plus applied water and runoff.

To predict runoff from rainfall in each event, we used a boundary line approach. After sorting the runoff data in order of decreasing rainfall, we identified the maximum runoff measured at each rainfall level and fitted an expo-linear function through these boundary points [Eq. 1] (Goudriaan and Monteith, 1990).

*Max runoff (mm) = a * ln (1 + exp (b * (rainfall - c)))* [1]

Parameters for Eq.1 were adjusted separately for conventional and for reduced tillage systems, taking into account whether soil water content to 1 m depth was above or below permanent wilting.

Scopel et al. (2004) developed a simple empirical relationship to estimate runoff from the amount of rainfall, as follows:

Maximum runoff (mm day^{-1}) = B x (rainfall – A) [2]

where *A* (mm day^{-1}) is the daily rainfall below which there is no water runoff, and *B*(-) is the proportion of water above threshold value that is lost through runoff once the infiltration process has started. We estimated parameter *A* as the x-intercept of the linear part of the expo-linear function, which corresponds to parameter *c* in Eq. 1, while parameter *B* corresponds to the slope of the linear part of the expo-linear function. As Eq. 2 is fitted to the set of maximum observed runoff values, it estimates the maximum runoff expected for any rainfall event under a given tillage system.

Rainfall simulations were performed using an Eijkelkamp mini-rainfall simulator (http://www.eijkelkamp.com/files/media/Gebruiksaanwijzingen/EN/m1-0906erainfallsimulat.pdf). Runoff volume and sediment loss produced by simulated rainfall events of 6 mm min^{-1}during 4 min on a 0.650 m^2 soil surface were measured in four replicates per treatment. The simulations were carried out in the second year of the experiment, in December at crop establishment and in February at the end of crop leaf area growth, coinciding with maximum soil cover.

2.3 Soil moisture, moisture-tension curve and bulk density

Soil moisture content was measured weekly, from 0 to 0.2 m depth with a time domain reflectometer (TDR), and from 0.2 to 1.0 m depth, with a neutron probe. We calibrated the two pieces of equipment with gravimetric samples corrected for bulk density. One access tube was installed per plot in the middle of a bed, and water content was measured at 15 cm intervals throughout the profile. The moisture-tension curve was calibrated on undisturbed samples (cores of 68.7 cm^3) using a tension table for tensions of 0.1 and 0.6 m, and a pressure plate for tensions of 1, 3, 10, and 30 m. Different models (van Genuchten, 1980; Logaritmic – Kosugi, 1996; and Brooks and Corey, 1964) were fitted to the measured soil water retention data (Seki, 2007) using the public domain software tool Soil Water Retention Curve (online at http://purl.org/net/swrc/). The Brooks and Corey model resulted in the best fit (n = 6 for each depth, average r^2 of 0.98). Saturated bulk density was determined by dividing the dry weight of the undisturbed samples by the volume of the cores (Blake and Hartge, 1986). Available water was calculated as the difference between the actual water content at each moment and water at wilting point for different depths.

2.4 Soil loss ratio, RUSLE-C factor and estimated annual erosion

From September 2010 to March 2012 we measured soil coverage and recorded the management parameters needed to estimate the soil loss ratio (SLR) used in the calculation of the Revised Universal Soil Loss Equation (RUSLE) - C factor according to USDA-ARS (2003):

$$SLR = Cc \times Gc \times Sr \times Rh \times Sb \times Sc \times Am \quad [3]$$

where the sub-factors are: *Cc*, canopy; Gc, ground cover; *Sr*, soil roughness; *Rh*, ridge height; *Sb*, soil biomass; *Sc*, soil consolidation; and *Am*, antecedent soil moisture.

Starting in September 2010 we took monthly measurements of soil surface roughness, canopy cover, plant height, and ground cover in three zones of the field (furrows, top of beds and slope of the beds). We calculated area-weighted averages of each sub-factor taking into account that furrows occupied 25% surface area, bed tops 45% and bed slopes 30%.We measured the surface covered by residues in 12 replicates of 1 m transects. Canopy cover was calculated as the fraction of vegetation cover present in samples every 5 cm along 1.6 m-transects. Soil surface roughness was measured with a 1.0 mm resolution on the same 1.6 m-transects with a PIN micro-relief meter. The device was leveled above the soil surface before readings were taken.

The ridge height sub-factor (*Rh*) was fixed as 1.7 following USDA-ARS (2003). Soil biomass (*Sb*) was estimated following the procedure described in Renard et al. (1997). Soil consolidation (*Sc*) fluctuated between 1 after a tillage operation and 0.93 after 12 months since the last tillage operation.

The antecedent soil moisture sub-factor (*Am*) was calculated as described in the manual (USDA- ARS, 2003).

We estimated the rainfall erosivity (R factor) for each rainstorm event during the second tomato crop growth period. The R factor, which depends on the intensity and amount of rainfall, and C factor (cropping management factor) which depends on the soil loss ratio(SLR), were estimated for each month following Renard et al. (1997). The predicted annual erosion for each management treatment was estimated using different combinations of length/slope, a K factor (soil erodability) of 0.33 estimated for the soil in the experimental plot using texture and SOC data (Puentes and Szogui, 1983), a P factor of 1, and an annual R factor of 400.

2.5 Biomass, LAI, foliar nitrogen and yields

Aboveground biomass of black oat was determined before incorporation into the soil by harvesting, drying and weighing 0.16 m^2 in three replicates in both *RTmulch* and *CTgm* plots. At the end of fruit set, 24 tomato plants were sampled to determine aboveground biomass and leaf area index (LAI, cm^2 of leavescm^{-2} of soil). Aboveground biomass was determined by cutting whole plants and drying at 60°C for 48 hours, and weighing separately the leaves, stems and fruits. A subsample of 24 fully developed leaves were scanned and specific leaf area (cm^2 g^{-1}) was determined using J-image public domain software (National Institute of Mental Health, Bethesda, Maryland, USA., http://rsb.info.nih.gov/ij) to measure the area of leaves and dividing by dry weight. Weekly marketable tomato yields were calculated from fresh weights harvested on 2 m within each runoff plot. Commercial and total yields were computed as the sum of weights of fresh fruit harvested in 6 weekly harvests each year. Twenty leaves opposite to fruit clusters were sampled at the beginning and at the middle of the fruit set period to determine total nitrogen by the Kjeldhal method (Bremner and Mulvaney, 1982).

2.6 Evapotranspiration, water demand satisfaction and water use efficiency

Potential evapotranspiration (ET_0) was calculated with the Penman Monteith – FAO equation (Allen et al., 2006). We estimated the crop evapotranspiration (ETc) by multiplying ET_0 by the crop-specific coefficient Kc (Allen et al., 2006). The actual evapotranspiration ETa was calculated as the sum of evapotranspiration (mm) between consecutive soil moisture content readings accumulated to 1 m depth, following the methodology described by Boulal et al. (2012). For each period, ET was calculated as the infiltration plus the difference in soil water storage. Soil moisture measured until 1 m depth was always below field capacity, thus we assumed that water losses by deep drainage were negligible. For each period, infiltration was calculated as the sum of rainfall plus effective irrigation minus runoff. Effective irrigation was calculated from the amount of water applied, multiplied by the efficiency of the system and the uniformity coefficient (Brower et al., 1989) measured in the field. From the fitted Brooks and Corey (1964) model parameters and the moisture content measurements we estimated the water potentials for each measurement date using Eq 4.

$$h = S_e^{(1/-\lambda)})*h_b, \qquad [4]$$
with $S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$

where h is capillary pressure (cm), S_e is effective saturation (-), λ is pore size distribution index, h_b is bubbling pressure (cm), θ is actual soil water content, θ_r = residual soil water content and θ_s = saturated soil water content (all in $cm^3\ cm^{-3}$).

Soil water capture was estimated as the sum of ETa during the growth period of tomato plus the available soil water at the end of harvest minus the available water at transplanting. Water demand satisfaction (WDS) was estimated as the percentage of the water demand ETc covered by the actual evapotranspiration ETa. ETa and WDS were calculated for the total tomato crop growth period and for different stages (to start of fruit set, to start of harvest and during harvest time). Water-use efficiency (WUE) was calculated as the ratio between total yield and total ETa.

2.7 Statistical analysis

The effects of treatments on runoff and sediment transport were estimated using a residual maximum likelihood (REML) model with treatments as fixed effect and replicates as random effect, since variances were not homogenous. The effects of treatments on soil moisture at different depths were assessed through analysis of variance for repeated measurements. Yield parameters, ETa, water deficit and WUE were subjected to general ANOVA with a split-plot design, where soil management was taken as the main factor and year as the splitting factor. When the F-test indicated significant ($P \leq 0.05$) treatment effects, means were compared using Fisher's protected least significant difference (LSD) test. Data were transformed, when necessary, to homogenize the variance. Statistical analyses were performed using Genstat 14th edition (VSN International Ltd., Lawes Agricultural Trust, U.K.).

3. Results

3.1 Runoff from rainfall events

Tillage method had a significant effect (p<0.001) on runoff from raised bed plots (Fig. 2.3).

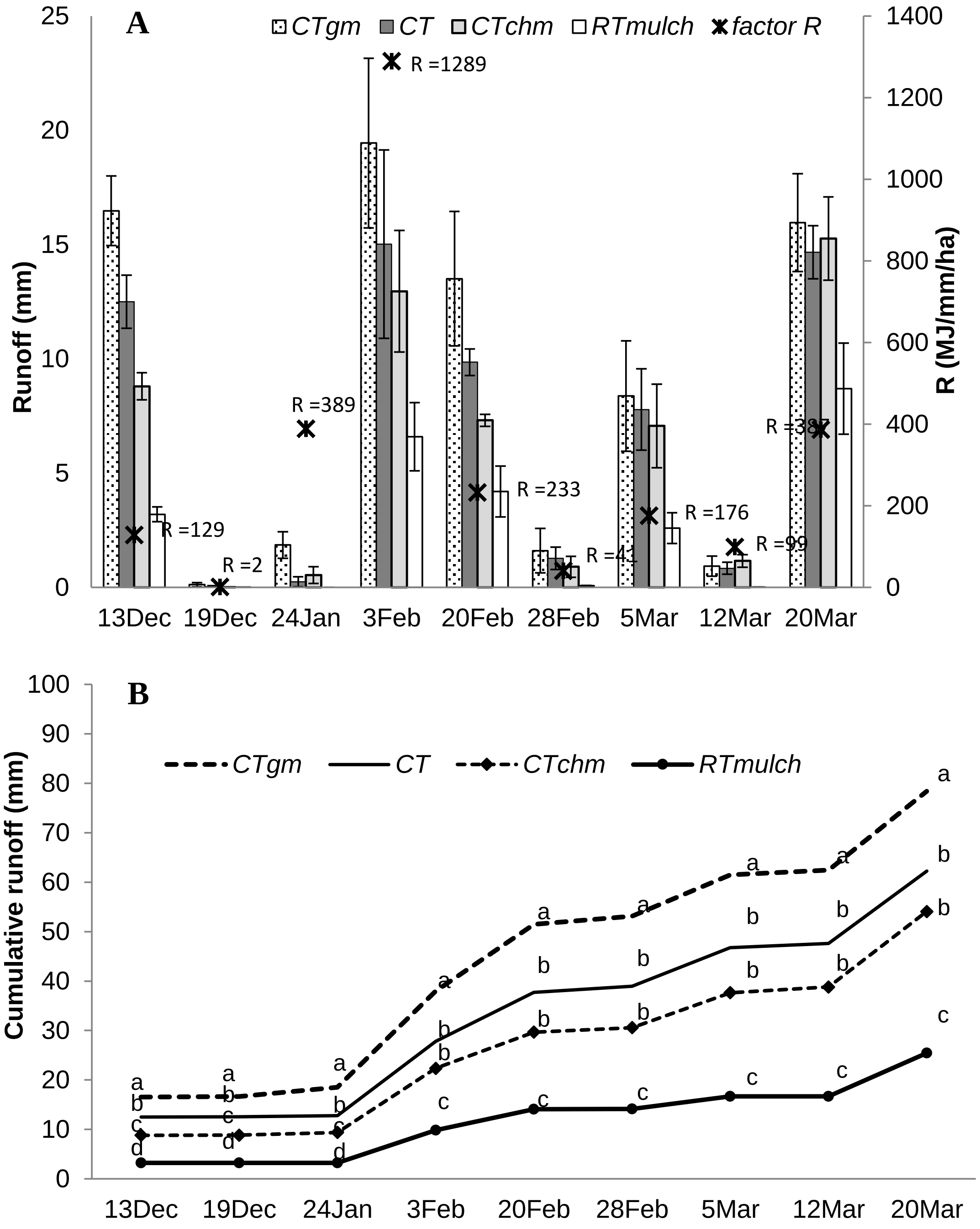

Figure 3.3. A) Runoff after rain events 2011-12 under four types of soil management. The asterisks and numbers represent the RUSLE R factor for each event; s.e. is standard error. B) Cumulative runoff under the four soil management types. Different letters within a date indicate differences between treatments (REML analysis, p < 0.05).

During the first tomato crop (from 22/10/2010 to 17/02/2011) the total amount of rainfall was abnormally low; rainfall plus effective irrigation totaled 138 mm and no runoff was detected. During the second tomato crop (from 01/12/2011 to 13/03/2012) the total amount of rainfall plus effective irrigation was 491 mm, and total runoff volume was 26 mm under reduced tillage (*RTmulch),* 54 mm under conventional tillage with chicken manure (*CTchm)*, 62 mm under conventional tillage (*CT)*, and 78 mm under conventional tillage with green manure (*CTgm)*. Total accumulated runoff under *RTmulch* was thus 37, 43, and 58% less than under *CTchm*, *CT* and *CTgm,* respectively (Fig. 3.3). The minimum, mean and maximum runoff/rainfall ratios across rainfall events were 0.0, 0.06 and 0.20 under *RTmulch*, 0.003, 0.13 and 0.34 under *CTchm*, 0.004, 0.15 and 0.35 under *CT,* and 0.03, 0.18 and 0.5 under *CTgm.* Fraction runoff and RUSLE factor R were positively correlated (Spearman correlation = 0.88; n=72; $p < 0.001$) when the measurements of 19 January and 1 February at which the soil to 1 m depth was at permanent wilting point (PWP) were excluded.

Parameters values for Eq.1, standard deviations and goodness of fit are shown separately for conventional and for reduced tillage systems in Table 3.2.

Table 3.2. Characteristics of the expolinear equations describing maximum runoff under conventional and reduced tillage on wet soil, i.e. soil above permanent wilting point to 1 m depth.

Tillage system and soil wetness	a (mm)	b (mm)	c (mm)	s.e.[b]	Variation accounted for (%)	RMSE
C [a] *wet*	2.32	0.43	24.10	1.93	95.1	1.9
RTmulch wet	2.41	0.44	35.35	1.46	92.0	1.4

[a]*C:* all conventional tillage treatments: *CT*, *CTchm* and *CTgm*.

[b] s.e.: standard error

The values of threshold parameter c (Eq. 1) from which we derived the parameter A of Eq. 2, were 24 (s.e. 1.9) mm day^{-1} of rainfall on average for the three conventional systems (*C*), and 35 (s.e. 1.5) mm day^{-1} for *RTmulch* when the soil was above PWP to 1 m depth. We could not reliably estimate A when the soil was below PWP since only two events were registered with such condition. However, from the runoff measurements during these two events we observed that the threshold rainfall values were greater than when the soil was wetter, about 44 mm on average for conventional tillage treatments and 55 mm for *RTmulch*. Parameter B (Eq. 2), the proportion of soil water above the threshold A lost through runoff was 0.95 for conventional tillage treatments and 0.94 for *RTmulch* when the soil was above PWP, and was deduced from the slopes of the linear part of the Goudriaan-Monteith fitted models. Again, we could not estimate parameter B for conditions drier than PWP; but from the data obtained, we observed much lower B values than when the soil was wetter, with the smallest B values under *RTmulch* (flattest slope, Fig. 3.4).

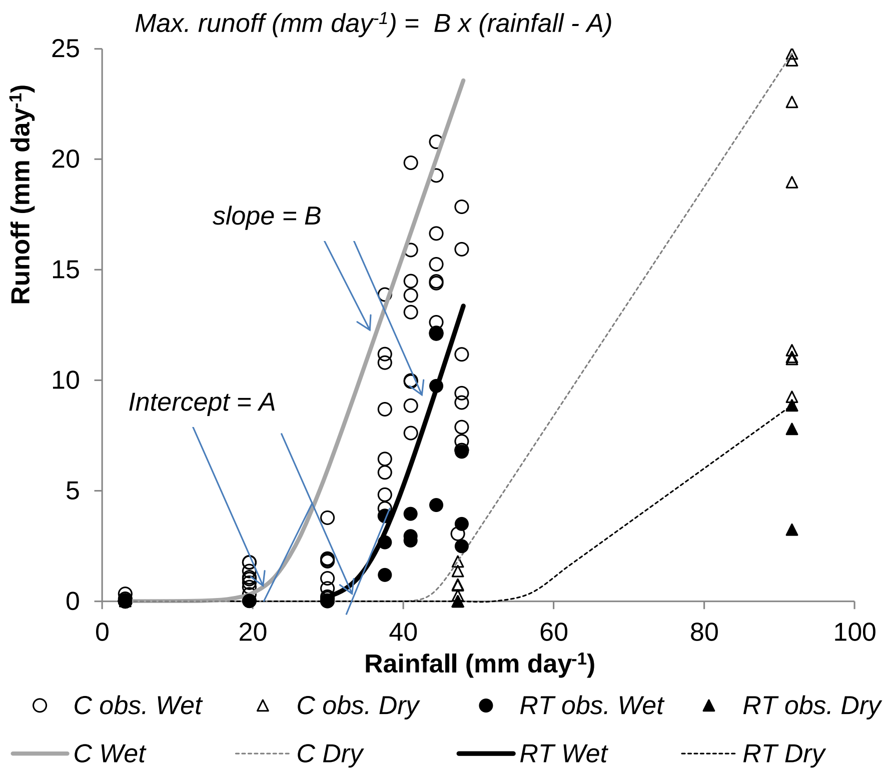

Figure 3.4. Runoff on runoff plots as a function of rainfall amount per event under all conventional tillage treatments (*C*, ○) and under reduced tillage plus mulch (*RT*, ●) with soil water content above permanent wilting point (pwp), and under all conventional treatments *C* (∆) and *RTmulch* (▲) with SWC below PWP. Expolinear models fitted for *C* (▬) and *RTmulch* (▬) (see Table 3.2 for parameters) represent the maximum runoff expected given a certain rainfall amount when the soil was above PWP.

3.2 Runoff and sediment transport from mini rainfall simulations

Runoff and sediment transport decreased in the sequence *CT>=CTchm>CTgm=RTmulch* (Fig. 3.5). Rainfall simulation during tomato establishment of the tomato crop resulted in less runoff and less sediment transport in the treatments *RTmulch* and *CTgm* than the treatments *CTchm* and *CT* without cover crop(p <0.001). Runoff and sediment transport at the end of crop growth showed the same tendency although the effect of the cover crop was not significant. Runoff as percentage of the total simulated rainfall was 54% at crop establishment and 34% at the end of crop growth for the treatments without cover crop, while it was around 6% at both times for treatments with cover crop. Median soil loss from the raised beds in the treatments with cover crop was reduced by more than 98% when compared to the treatments without cover crop, both at start and end of the tomato crop (p <0.001) (Fig. 3.5).

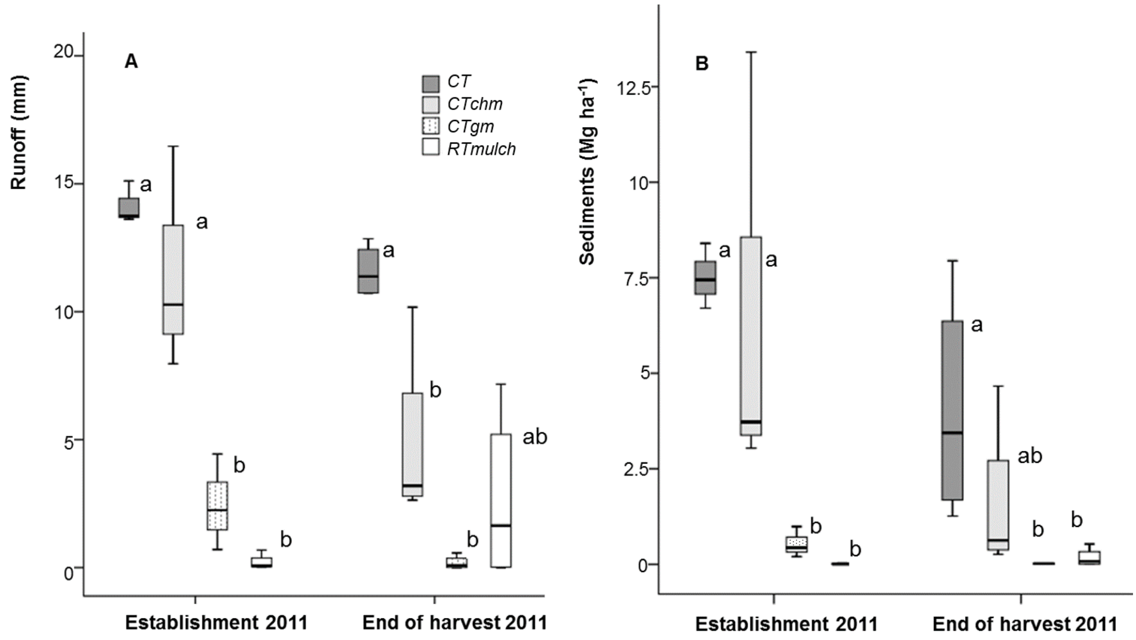

Figure 3.5. Boxplots of A) Amount of runoff water and B) sediments after rainfall simulation with 6 mm min^{-1} for 4 minutes on two dates. The line inside a box indicates the median. Boxes indicate the lower and upper quartiles and T-bars indicate the minimum and maximum values. Different letters per date indicate differences between treatments (REML analysis, $p < 0.05$).

3.3 C factor and soil loss ratio

The estimated values of the soil loss ratio (SLR) and the RUSLE C factor and sub-factors Cc and Gc from September 2010 until March 2012 under the four treatments are presented in Fig. 3.6. Under *RTmulch* and *CTgm,* greater soil cover by the crop and/or by crop residues during various periods led to considerably smaller values for the sub-factors Cc and Gc than under *CTchm* and *CT*. Soil roughness (Sr) and soil moisture (Am) did not differ greatly among treatments, while the soil biomass multiplier (Sb) was lower in treatments that did not include cover crops during some periods of the year.

Combining all sub-factors, SLR under *RTmulch* was close to 0 all along the year, *CTgm* varied between 0 and 0.4, and the treatments that did not include cover crops varied between 0 and 1 with greater values during late autumn, winter and early spring, i.e. the periods with precipitation surplus (Fig. 3.6). Soil moisture was below PWP during some months in summer, which strongly reduced SLR in all treatments. Annual C factors estimated from March to February were 0.04, 0.13, 0.38 and 0.43 for *RTmulch*, *CTgm*, *CTchm* and *CT*, respectively. Applying RUSLE we estimated that under *RTmulch* the annual erosion was below the locally used threshold of 7 Mg ha^{-1} for slopes ranging from 1.5 to 4.5% and for slope lengths up to 80 m. Under *CTgm* annual erosion was below 7 Mg ha^{-1} only for slopes up to 1.5% and 80 m slope length. Under *CTchm* and *CT* all combinations of slope gradient and slope length generated annual sediment losses above10 Mg ha^{-1} (Table 3.3).

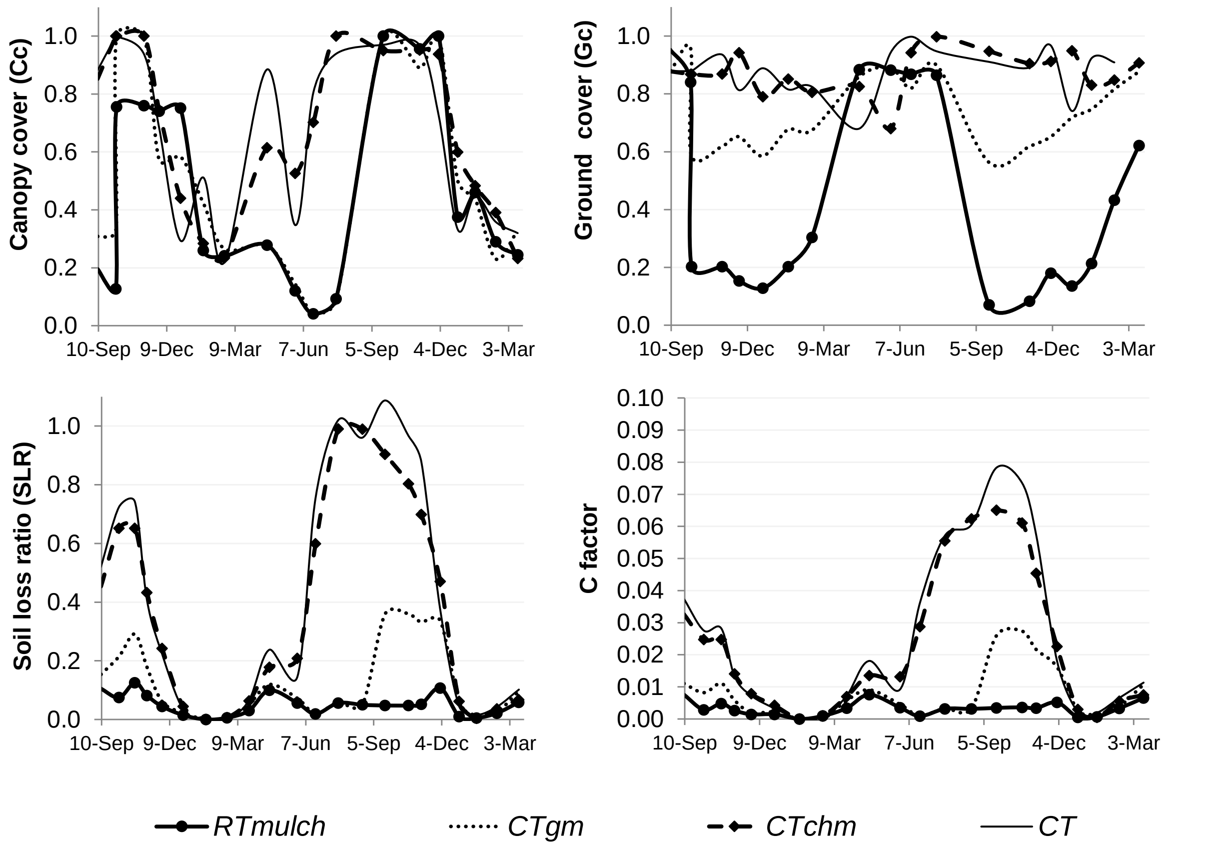

Figure 3.6. Dynamics of factors of the RUSLE equation: canopy cover (Cc), ground cover (Gc), soil loss ratio SLR, and cover factor C. Value for soil consolidation ridge sub-factor were estimated to be 1 and 1.7, respectively, for all treatments and dates. The plots represent area-weighted averages, with top of beds contributing 45%, slopes 30% and furrows 25%.

Table 3.3. Annual erosion (Mgha^{-1}) predicted using RUSLE for different soil conservation treatments at different combinations of slope and slope length on a fine Typical Hapludert.

Slope length (m)	30			50			80		
Slope (%)	1.5	3	4.5	1.5	3	4.5	1.5	3	4.5
Treatment									
CT	11.4	21.8	32.4	12.7	25.5	39.4	13.9	29.6	47.2
CTchm	10.1	19.2	28.7	11.2	22.6	34.8	12.3	26.1	41.7
CTgm	3.7	7.1	10.6	4.1	8.3	12.8	4.5	9.6	15.4
RTmulch	1.1	2.0	3.0	1.2	2.4	3.7	1.3	2.7	4.4

3.4 Soil water storage

Soil water dynamics exhibited contrasting patterns in the two experimental years due to the large differences in rainfall amount and distribution (Fig. 3.7.A). In each year, the largest differences in soil water content were observed between reduced and conventional tillage treatments, and during the first month after transplanting. The upper 20 cm of the soil contained 14 and 7 mm more water under *RTmulch* than under the other treatments in 2010 and 2011 respectively ($p = 0.003$) (Fig. 3.7.B). At transplanting in 2010 available water (AW) to 55 cm was 36 mm under *RTmulch*, 17 mm under *CTgm* and 2 mm under the two other treatments; and the AW to 1 m depth was 46 mm more under *RTmulch* than under the rest of the soil management treatments ($p = 0.012$). Soil water contents decreased rapidly during the season and were below PWP during most of the first year of tomato cropping. In 2011 AW to 55 cm was 14 mm under *RTmulch* , 7 mm under *CTgm* and *CT*, and 3 mm under *CTchm*. Soil moisture content showed greater variation than during the first year due to more frequent rainfall events, while the periods when the profile was below PWP were fewer and shorter than in the first year.

3.5 Crop productivity

Tomato yields under *RTmulch* did not differ significantly from those of *CTgm* or *CT* in both years ($p = 0.004$). During the first year, however, although large variability was observed within treatments, average *RTmulch* yields were about 20 to 30% lower than *CTgm* or *CT.* Greatest yields were obtained under *CTchm* in both years ($p = 0.004$; Table 3.4). Yield differences among treatments were explained by differences in the number of fruits per plant ($p = 0.005$) and not by fruit weight, which did not differ among treatments. Aboveground biomass under the *CTchm* treatment significantly exceeded that of the treatments that included a cover crop either incorporated or as mulch ($p = 0.09$). LAI at maturity tended to be smaller in the *RTmulch* treatment, but there was major variation among treatments.

At the beginning of each growing period, the tomato plants under *RTmulch* and *CTgm* showed symptoms of nitrogen deficiency. In the second year, total N content (Kjeldal method, Bremner and Mulvaney, 1982) of tomato leaves was analyzed at the beginning and middle of the fruit set period (34 and 49 days after transplanting). Treatment *RTmulch* had the lowest leaf N concentrations, with 27 mg kg^{-1} at the start of fruit set and 23 mg kg^{-1} at 50% fruit set, against 40 and 30 mg kg^{-1} under *CTchm* and *CT* for the first and second date respectively ($p = 0.05$, L.S.D. = 7.2 mg kg^{-1}). Under *CTgm* N concentrations were intermediate; 28 mg kg^{-1} at both times. The effect of the interaction date x treatment was not significant.

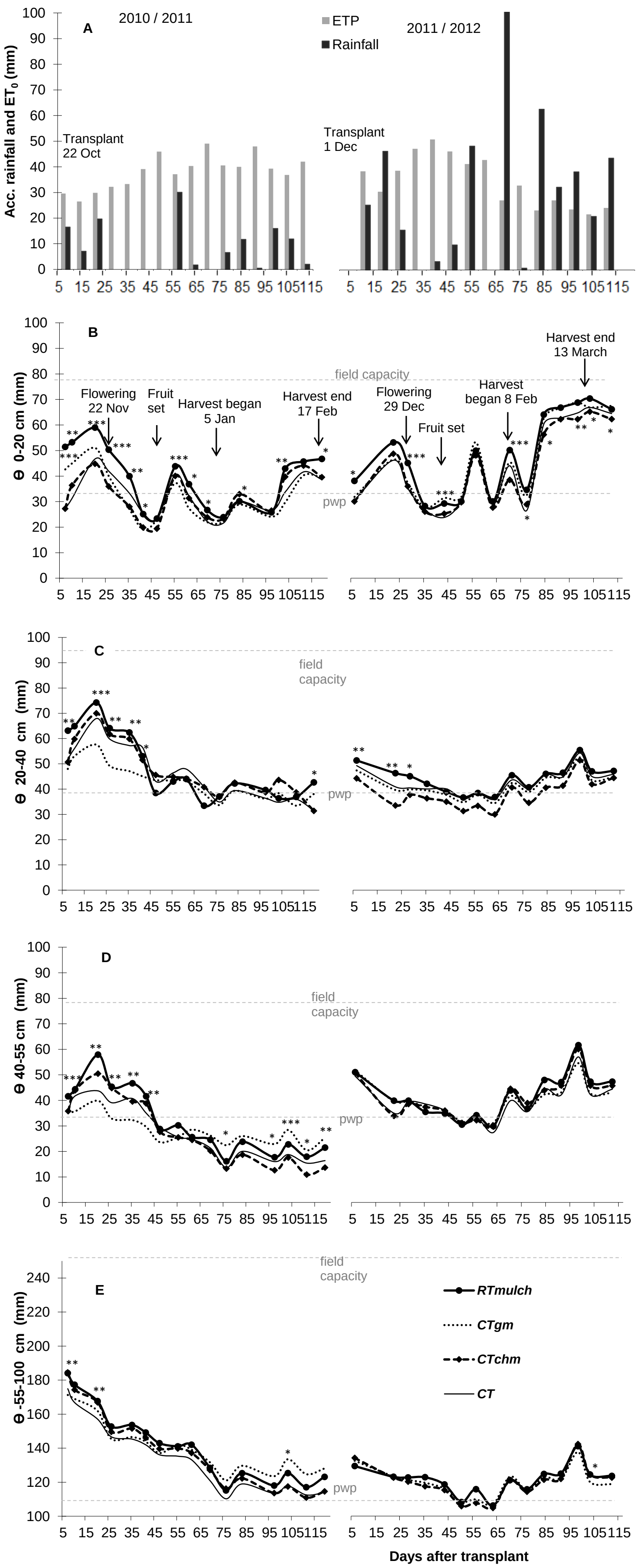

Figure 3.7. A) Weekly rainfall plus effective irrigation and reference evapotranspiration (Pennman-Monteith) between soil moisture measurements during two tomato crop cycles.

B-E) Soil water content (mm) from 0-20 cm (B), 20-40 cm (C), 40-55 cm (D) and 55-100 cm depth (E) under reduced tillage (*RTmulch*), conventional tillage with green manure (*CTgm*), conventional tillage with green manure and chicken manure (*CTchm*), and conventional tillage without organic matter addition (*CT*).

Horizontal lines indicate water content at field capacity and permanent wilting point (PWP). Significant differences are indicated as *** ($p<0.01$), ** ($p<0.05$). and * ($p<0.1$).

Table 3.4. Yield, biomass and LAI of tomato at maturity, number of fruits, and fruit weight.

Soil Management treatment	Marketable yield (Mg ha^{-1})	Total yield (Mg ha^{-1})	Biomass at maturity (Mg (DM) ha^{-1})	LAI at maturity (m^2 m^{-2})	Fruits/ plant	Fruit weight (g)
2010/11						
CT	31.2 ab	36.0 ab	2.1 ab	1.31	38.4 b	30.0
CTchm	37.6 a	41.6 a	2.7 a	1.44	46.2 a	31.0
CTgm	26.7 ab	33.2 ab	1.6 b	1.38	34.0 b	29.4
RTmulch	20.9 b	23.2 b	1.9 b	0.56	27.7 b	28.4
2011/12						
CT	36.3 b	36.5 b	1.9 ab	2.11	46.1 ab	39.2
CTchm	50.1 a	50.3 a	3.1 a	1.97	59.5 a	41.7
CTgm	29.3 b	29.4 b	1.7 b	1.63	35.2 b	42.1
RTmulch	32.5 b	32.8 b	1.7 b	1.54	39.1 b	41.1
*Treat*year*	ns	ns	ns	ns	ns	ns
LSD[a]	12.5 **	12.8 **	1.2 *	0.9 [ns]	14.2 **	6.0 [ns]
CV[b] (%)	21.8	20.1	33.7	37.9	20.1	9.8

[a]LSD: Fisher's protected least significant difference. [b]CV (%): Coefficient of variation in percentage.

Note: Values followed by different letters in the same column differ significantly within sampling date at ** p<0.05, or * p<0.1.

3.6 Evapotranspiration, water demand satisfaction, and water-use efficiency

Water availability for evapotranspiration was calculated considering the soil water up to100 cm. This depth was considered because the soil below 55 cm was always at higher water potential than above 55 cm, indicating that water was moving upwards through capillary rise and contributing to crop available water. Soil moisture measured until 1m depth was always below field capacity, thus we assumed that water losses by deep drainage were negligible.

The first (drier) year available water to 1 m depth at tomato transplant under *RTmulch* was 46 mm (54%) more than under the other treatments (p =0.012), and the soil water capture from transplant until the end of the harvest was 20% more under *RTmulch* (p =0.012). In the second year with ample rainfall there was no significant difference either in available water at transplant or in the total soil water capture among treatments to 1 m depth (Fig. 3.7).

The total ETa during the tomato cycle under *RTmulch* and *CTchm* averaged 36 and 27 mm more the first and second year, respectively, as compared with the two other treatments (p <0.001). During the period from transplanting to start of fruit set in the first year, ETa was on average 24 mm (41%) greater under *RTmulch* and *CTgm* compared with the average of

CTchm and *CT* (p =0.025), resulting in a water demand satisfaction of 78% under *RTmulch* and *CTgm* compared to 55% under *CTchm* and *CT* (p =0.013). From start of fruit set to start of harvest in the first year, ETa was 38 mm (36%) greater under *RTmulch* compared with *CTgm* and *CTchm*, whereas there was no difference when compared with *CT* (p=0.008). During the harvest period the ETa under *CTchm* was the largest, 24 mm higher than for the other treatments, resulting in a water demand satisfaction (WDS) of 20% against an average of 11% for the other treatments (p =0.04). The second year, all treatments revealed a WDS above 100% from transplant to start of fruit set, an average of 74% during the fruit set to start of harvest, and close or above 100% during the harvest period (Table 3.5).

In the second year the differences in water balance among treatments were less pronounced than in the first year, and ETa and WDS were about double of those of the (drier) first year (Table 3.5). While the WDS during the tomato cycle in the first year was on average 40% for *RTmulch* and *CTchm,* and 36% for *CTgm* and *CT*, it was ca. 100% during the second year for all treatments. Water-use efficiency (WUE) estimated as total yield divided by total ETa was 56% lower under *RTmulch* (9.5 kg m^{-3}) when compared to the average of the three other treatments (16.7 kg m^{-3}) the first year (p =0.04). The second year WUE was about the 60% of that of the first year, and the largest value was obtained under *CTchm.*

4. Discussion

4.1 Runoff and erosion

We hypothesized that on raised beds reduced tillage combined with a cover crop and chicken manure would reduce runoff by increasing infiltration and would reduce potential soil erosion in comparison to conventionally tilled systems with or without green or chicken manure, even during the first two years after changing from a conventional soil management system. This was confirmed by the results of the runoff plots (Fig. 3.3) and the mini rainfall simulations (Fig. 3.5), and by the measurements of the soil loss ratio (SLR) and the C factor (Fig. 3.6), and the resulting estimates of the RUSLE model. Reduction in runoff on raised beds under minimum or no tillage has been reported before for other soils (Boulal et al., 2008; Jordán et al., 2010; Verhulst et al., 2011; Zhang et al., 2007), as well as reduction of soil loss under permanent beds (Oicha et al., 2010). Reduction of soil loss was attributed to increased soil macro-porosity associated with greater macro-fauna activity (Kay and Vanden Bygaart, 2002; Ruan et al., 2001; Trojan and Linden, 1998), reduced soil surface sealing (Mannering and Meyer, 1963), and increased soil surface roughness through the presence of crop residues, which enhance flow path tortuosity slowing down the water flow rate across the soil surface (Findeling et al., 2003).

Table 3.5. Available water to 1 m depth at transplant, soil water capture, accumulated ETa[a], and water demand satisfaction for the entire crop cycle and per period, and water use efficiency, in four soil management for two tomato cropping seasons.

Soil Management Treatment	AW[d] (mm)	Soil water capture[e] (mm)	Total ETa (mm)	Total WDS[f] (%)	ETa until SFS[g] (mm)	WDS Until SFS (%)	ETa from SFS to SH[h] (mm)	WDS from SFS to SH (%)	ETa during harvest (mm)	WDS during harvest (%)	WUE[i] total yield ($kg\ m^{-3}$)
2010/11											
CT	80.1 b	217.7 c	220.3 b	37.0 b	56.2 d	52.5 d	130.2 cd	53.0 bc	33.8 d	13.2 c	16.4 a
CTchm	88.8 b	226.4 c	236.6 a	39.6 a	62.5 d	58.0 d	123.3 d	49.3 c	50.8 c	19.9 b	17.6 a
CTam	87.8 b	225.5 c	204.0 c	34.1 c	87.6 c	81.5 c	87.8 e	35.5 d	28.6 de	11.4 c	16.2 a
RTmulch	130.8 a	268.4 b	243.8 a	40.9 a	80.9 c	75.9 c	144.5 bc	58.6 b	18.5 e	7.4 d	9.5 b
2011/12											
CT	40.5 c	531.2 a	419.9 b	90.9 ab	128.0 b	111.1 ab	162.2 ab	75.2 a	129.7 b	97.5 a	8.7 ab
CTchm	40.2 c	531.5 a	437.5 a	94.6 a	147.3 a	127.7 a	152.9 ab	70.8 a	137.3 ab	103.5 a	11.5 a
CTam	42.3 c	533.3 a	400.4 c	86.5 b	118.5 b	104.6 b	157.1 ab	73.0 a	124.5 b	93.7 a	7.4 b
RTmulch	46.4 c	537.4 a	437.0 a	94.6 a	121.8 b	101.5 b	169.5 a	78.3 a	145.7 a	109.9 a	7.5 b
Treat x year	*	**	ns	ns	**	**	**	**	**	**	ns
LSD[b]	15.2	15.2	15.8 **	1.1 **	18.2	1.2	18.8	1.15	14.6	1.4	4.1 *
CV[c](%)	46.9	40.0	31.6	42.8	33.9	30.8	33.9	24.3	63.9	79.3	39.3

[a]ETa was calculated based on water balance to one meter depth. [b]LSD:. Fisher's protected least significant difference. [c]CV (%): Coefficient of variation in percentage. [d]AW: Available water content to 1 m depth. [e]Soil water capture to 1 m depth was calculated as the sum of ETa during the tomato season plus the difference of available water at the end of harvest and at transplant. [f]WDS (%). Water demand satisfaction in percentage, calculated as ETc demand covered by ETa. Log normal transformation was performed to run the ANOVA and LSD. Fisher's protected multiple comparison test. Means were back transformed to percentage. [g]SFS: start fruit set. [h]SH: start of harvest. [i]WUE, Water use efficiency, calculated as the ratio between total yield and total ETa.

Note: Values followed by different letters in the same column differ significantly at ** $p<0.05$. or * $p<0.1$.

When there was no interaction treatment * year the differences were indicated for each sampling date separately.

With data on the first two years of transition to an improved soil management, we adjusted simple relationships to estimate maximum expected runoff for different soil management. Similar to what Scopel et al. (2004) found for a tropical clayish soil, mulching affected the values of both parameters of Eq.[2]. In our case, the level of mulch was higher than the level used in the cited study (9.9 vs 4.5 Mg ha^{-1}), and values for A were also larger (24 mm day^{-1}vs 10 mm day^{-1} under *CT*, and 35 mm day^{-1}vs 20 mm day^{-1} under mulch with soil water content to 1 m depth above PWP). Due to our use of expo-linear relations and maximum runoff data, B values cannot be compared with those of Scopel et al. (2004) who used linear relations and average (rather than maximum) runoff values.

Actual runoff is the result of a multiplicity of factors, the interaction of which is poorly understood. We used a boundary line approach to provide information on the runoff expected under worst case conditions. In particular, soil moisture at the onset of a rainfall event appeared to be an important factor in determining runoff. Our results showed that the fraction of rainfall above the threshold A, which is lost as runoff was much lower for a soil at PWP to 1 m depth than for a wetter soil (Fig. 3.4). For this reason we excluded the two measurements made when the soil was at PWP, when calibrating the equations. More information on runoff for dry soils will enable including soil moisture as a factor describing runoff.

4.2 Soil water supply capacity, productivity and water-use efficiency

During the first forty days after tomato transplanting when fruit set is defined, water deficit may cause significant reduction in yields (Renquist and Reid, 2001). During the first (drier) year soil water capture at tomato transplanting was least under *CTgm* due to water taken up by the cover crop that had been incorporated by disking just before transplanting. During the second year the cover crop in the *CTgm* and *RTmulch* treatments was treated with herbicide, and soil water capture in the first forty days was similar in both treatments (Fig. 3.7). During the same period the average amount of crop-available water was largest under *RTmulch* because of a larger amount of water captured in the soil before transplanting (Fig. 3.7), which was also observed in other studies with reduced tillage (Arboleya et al., 2012; Scopel et al., 2004; Scopel et al., 1998).

In neither of the experimental years the improvement in soil water capture under *RTmulch* resulted in greater tomato yields. Commercial yields, aboveground biomass and number of fruits harvested were less under the two treatments that included a cover crop (*CTgm* and *RTmulch*) compared to the treatment that received chicken manure (*CTchm).* Lower yields in semi-permanent raised beds have been reported before, often associated with reduced root exploration due to more compaction in the first years of transition towards reduced tillage. Mockhizuke et al.(2007) reported reduced cabbage yields due to soil compaction under reduced tillage, which they solved by sub-soiling to 30 cm depth before transplanting. Yield reductions were also reported for lettuce and broccoli grown on raised beds under minimum tillage in a Haplic Phaeozem in California (Jackson et al., 2004). An option suggested by the authors to overcome this problem was to alternate between conventional and minimum tillage. In southern Spain, Boulal et al. (2012) reported poor plant establishment for maize and cotton on permanent raised beds, although yields were better than under conventional tillage in the case of cotton.

In our study, lower yields under *RTmulch* may be explained by: (i) poor plant establishment in the presence of large amounts of mulch, and (ii) N deficiencies that were observed as visual symptoms during the first year and confirmed through foliar N measurements during the second year. Poor plant establishment and N deficiencies were also observed in the *CTgm* treatment, which combined conventional tillage and green manure. Soil compaction in beds caused by lack of recent tillage was not observed in this experiment. Bulk density measurements at two different dates and soil resistance to penetration with a cone penetrometer at transplanting did not reveal any significant differences between treatments (data not shown). We observed more frequent symptoms of transplanting shock and a greater proportion of transplant failure under *RTmulch* associated with the presence of a thick layer of mulch in this treatment. This suggests that the cultural technique used for transplanting needs further adaptation to deal with thick mulch layers.

It is likely that the presence of large amounts of carbon-rich oat straw left on the soil surface as mulch (*RTmulch*) or incorporated (*CTgm*), led to soil N immobilization that affected soil N supply to the crop. Cited C:N ratios of oat cover crops are 23 to 36 at flowering stage, and 42 at the soft dough stage (Ashford and Reeves, 2003).

Symptoms of N deficiency were conspicuous under *RTmulch* and *CTgm* at the start of tomato growth in both years. The extra nitrogen fertilization applied in the second year (Table 3.1) proved to be insufficient. Nitrogen availability enhance light interception and leaf photosynthetic activity, increasing crop growth; and the radiation use efficiency is greatly sensitive to N, but only at low range of leaf N concentration (Tei et al, 2002). So, if the N in leaves is around the critical value, the crop growth would be reduced. Reported values for reduced N concentrations in leaves of processing tomato around the critical N-dilution curve fluctuate from 28 mg kg^{-1} at full bloom to 23 mg kg^{-1} at 10% of fruit showing red colour (Tei et al., 2002). Leaf nitrogen contents measured in plants under *RTmulch* were 27 mg kg^{-1}, below the critical value, *CTgm* was just on the limit (28mg kg^{-1}), while the other two treatments were above the critical values mentioned in the literature (30 to 40 mg kg^{-1}). Studying the effect of mulching with oat on tomato production, Campiglia et al. (2010) also obtained a reduction in tomato yield when compared to no mulch. The authors suggested that in the long term, possible benefits of increasing organic matter, and no incorporation of the residues in more sustainable systems would mean an increment in mineral nitrogen in the soil, followed by attenuated immobilization effects. Nutrient provision needs careful attention to avoid yield penalties during the transition towards sustainable soil management.

Average water-use efficiencies values in our study were in the range of those cited in the literature for tomato (Yang et al., 2012; Mukherjee et al., 2012). In the first year when the water demand satisfaction was only 38%, WUE was 1.7 times greater than in the second (wet) year. Similarly Mahadeen et al. (2011) reported higher irrigation water use efficiency (WUE) when only 50% of the total potential ETc demand was covered than when 100% of the ETc demand was covered. An apparent reduction in WUE is often observed in the transition towards minimum or no tillage due to the time lag between the increase in the availabilities of water and nutrients (Tittonell et al., 2012). Hatfield et al. (2001) found that for studies in different climates and crops that it is possible to increase WUE by 25 to 40% through reduced tillage and increased residue retention. However, they also reported that in some cases yields and WUE under no tillage were lower than in ploughed fields due to weed competition, greater incidence of diseases or insect pests, or nutrient limitation. Similarly, Boulal et al. (2012) did not find an improvement in WUE under permanent bed systems. In spite of positive effects of *RTmulch* in terms of infiltration and water storage, the adoption of reduced tillage by farmers largely depends on the extent of yield penalties that farmers experience during the initial phase of transition from current practices, during which farmers need to learn, experience and fine-tune their new system (Dogliotti et al., 2013).

5. Conclusions

Reduced tillage combined with mulching and chicken manure contributed to in situ moisture conservation and reduction of runoff and soil loss on degraded mollisols used for horticulture in a temperate climate. We proved that reduced tillage in combination with mulching on the raised beds can be a feasible alternative to reduce runoff and soil erosion, and to increase infiltration, what could be of especial interest for small farms that could not include a pasture phase in the rotation. By establishing empirical models we could estimate runoff associated with different tillage and soil cover practices. These models are valid for fine textured soils with a 1% slope in a temperate climate, and may be used to infer soil erosion risks associated with different soil cover and tillage systems. Compared to conventional practices the threshold rainfall amount at which runoff started, increased by 49% with reduced tillage and mulching. This resulted in greater water capture and storage under reduced tillage, notably during the first month after transplanting, i.e., on average 50% or up to 20 mm more available water to 40 cm depth compared to conventional tillage. The conversion efficiency of the extra water into crop yield should be improved by adjusting the nitrogen supply. In addition, crop establishment in permanent raised beds covered with mulch needs technical adjustments to minimize transplanting shocks.

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Chapter 4

Modelling soil tillage and mulching effects on soil water dynamics in raised-bed vegetable rotations

Adapted from:
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Abstract

Reduced tillage and mulching may bring about new production systems that combine better soil structure with greater water use efficiency for vegetable crops grown in raised bed systems. These are especially relevant under conditions of high rainfall variability, limited access to irrigation and high soil erosion risk. Here we evaluate a novel combination of empirical models on water interception and infiltration, with a soil-water balance model to evaluate water dynamics in raised bed systems on fine textured soils, to analyze the effect of reduced tillage, cover crops and organic matter addition on soil physical properties and water balance. In the experiment mulching increased water capture by 9.5% and reduced runoff by 37%, on average, leading to less erosion risk and greater plant available water over four years of trial. Using these data we calibrated and evaluated different models that predicted interception + infiltration efficiently (EF = 0.93 to 0.95), with a root mean squared error (RMSE) from 0.32 to 0.40 mm, for an average observed interception + infiltration of 28.8 mm per day per rainfall event. Combining the best model with a soil water balance results in predictions of total soil water content to 1 m depth (SWC_T) with RMSE ranging from 4.5 to 10.3 mm for observed SWC_T ranging from 180.4 to 380.6 mm. Running the model for a four-year crop sequence under 10 years of Uruguayan historical weather revealed that reduced tillage required on average 141 mm yr^{-1} less irrigation water than conventional tillage combined with organic matter application, thus enabling a potential increase in irrigated area of vegetable crops and crop yields. Results also showed the importance of interannual rainfall variability, which caused up to 3-fold differences in irrigation requirements. The model is easily adaptable to other soil and weather conditions.

Key words: Water balance, conservation agriculture, SUCROS2, clay soils, Uruguay

1. Introduction

Land degradation, defined as the temporary or permanent reduction of productive capacity of land, is a process of global importance that affects ca. 25% of the globally productive land, on which 1.5 billion people reside (Bai et al., 2008). Two of the major processes responsible for land degradation and loss of soil fertility are: removal of nutrient-rich soil particles resulting from soil erosion; and decrease in soil water supply capacity associated with soil compaction, decrease in soil permeability and loss of water holding capacity (D'Odorico et al., 2013). These processes, when accelerated by positive feedbacks between human activities (poor land management) and climatic variability, drive the systems into a downward spiral of environmental degradation.

According to the Bai et al (2008) study, 49.7% of Uruguayan land is degraded. Due to land degradation, vegetable crop production on family farms in South Uruguay is increasingly limited by poor soil physical properties and water availability (Alliaume et al., 2013). On predominantly fine textured soils (Mollic Vertisols and Luvic/Vertic Phaeozems (Pachic/Abruptic/Oxyaquic; IUSS Working Group WRB, 2006) vegetable crops are generally grown on raised beds in order to both increase the volume of the topsoil that can be easily explored by roots and to improve surface drainage after a heavy rainfall. The presence of argillic (Bt) horizons close to soil surface in combination with intense rainfall events leads to rapid saturation of the topsoil, exacerbating surface runoff. In this context, mulching acts as a physical barrier that protects from drop impact and soil disaggregation, improving water infiltration, and reducing the risk of erosion (Alliaume et al., 2014).

Farmers in south Uruguay are able to irrigate on average 48% of the vegetable crop area (DIEA, 2011). A predicted increase in the intensity of rainfall (Marengo et al., 2012) and a high erosion risk due to the combination of clayey soils and undulating terrain call for management strategies to increase water productivity with reduced environmental impact, while maintaining or increasing crop yields. Soil conservation practices such as reduced tillage and crop residue mulching provide important components for strategies to achieve these objectives (Alliaume et al., 2014). For vegetable production, reduced tillage and mulching may give rise to new production systems that combine better soil structure with greater water use efficiency. These are especially needed under conditions of high variability of rainfall and limited access to irrigation.

A model able to simulate the effect of different components of the soil water balance under alternative soil-crop management options can facilitate the design of alternative systems. When included in farm level assessment tools (e.g. Dogliotti et al., 2005) it can facilitate the evaluation of alternative resource allocation strategies to explore the potential for adaptation of vegetable systems to climate change. Several mechanistic and empirical methods have been proposed worldwide to estimate the amount of water infiltrating into the soil after a rainfall event. Most of these models have focused on sandy to loam soils (Bonfante et al., 2010). There is as yet little information available for clayey soils or raised bed systems, in combination with crop residue management strategies.

The SCS curve number method (USDA-SCS, 1972) is a widely used empirical model for estimating runoff, although it was conceived to be used at the scale of entire catchments and not for fields or specific soil management alternatives. An extensively used mechanistic model to estimate runoff is Green-Ampt, where infiltration parameters can be directly related to catchment characteristics (Wilcox et al., 1990). However, this model requires disaggregated daily precipitation data that are difficult to obtain. Also, even though the Green-Ampt equation has a physical basis, much of the explanatory power may be lost by the regression equations needed to parameterize the model (Wilcox et al., 1990).

Several models can predict the water balance in different systems, such as STICS (Brisson et al., 2003), AquaCrop (Constantin et al, 2015), SWAP (van Dam, 2000), Cropsyst (Stockle et al., 2003), MACRO (Bonfante et al, 2010), and APSIM (Ranatunga et al., 2008). Holland et al. (2012) evaluated the influence of raised beds on water runoff on layered soils cropped with grains or oilseeds, but did not consider mulching. The runoff dynamics of raised beds covered by mulch was simulated satisfactorily by a physically-based model developed by Findeling et al (2003), for different soil and climate conditions. Scopel et al. (2004) updated STICS with an empirical module that accounts for effects of surface residue on soil water balance. The module depends on local parameters and was tested on soils without an argillic horizon. Jones et al. (2014) simulated soil water dynamics using DSSAT under drip-irrigated plastic-mulched raised-bedded production systems with satisfactory performance on a fairly homogeneous sandy soil. The authors point out that simulations for highly layered soils should be considered with caution. We could not find a model with satisfactory performance to simulate water dynamics for the conditions of southern Uruguay, and specifically for vegetable crops grown in raised beds of layered soils covered by organic mulch.

The aim of this study was to analyze the effect of reduced tillage with residues left as mulch, on soil water dynamics in raised bed vegetable production systems on the fine-textured soils with an argillic horizon of southern Uruguay. A first objective was to derive a simple, generally applicable, locally parameterizable mathematical model to evaluate the effect of mulching and reduced tillage on soil water capture and soil water content. A second objective was to use the model to explore the impact that these soil management practices might have on different water balance components and irrigation requirements of vegetable crops in southern Uruguay.

2. Materials and methods

2.2 Experiment dataset

We used a dataset of a 4-year field experiment conducted at the South Regional Center research station, Canelones, south Uruguay (two first years reported in Alliaume et al., 2014). Climate is temperate sub-humid with a mean annual rainfall of 976 mm. Rainfall is highly variable but evenly distributed over the year, with frequent droughts in summer and periods of water excess in winter. Mean annual rainfall over the 3-year study period ranged from 820 to 1200 mm. Average slope of the experimental field was 1-1.5%. The soil was derived from silty clay sediment and represented a common soil in the region. It was described and classified as a Luvic Phaeozem according to the FAO system, with 20 cm of a silty loam top horizon with a particle size distribution of 140 g kg^{-1} sand, 625 g kg^{-1} silt, 235 g kg^{-1} clay, and 15 g kg^{-1} soil organic carbon (SOC), and 50 cm of a silty clay argillic (Bt) horizon with 95 g kg^{-1} sand, 501 g kg^{-1} silt, 404 g kg^{-1} clay (expansive and non -expansive clays), and 5 g kg^{-1} soil organic carbon (SOC). The water content to 40 cm depth at saturation, field capacity (fc), and permanent witling point (pwp) was 208, 149 and 70 mm respectively. Saturated hydraulic conductivity, measured with the double ring infiltrometer method (Bouwer, 1986) was 16.8 mm day^{-1} for the soil at the experimental site.

A crop sequence consisting of black oat (*Avena strigosa* L.; used as winter cover crop) - processing tomato (*Lycopersicon esculentum Mill.*; summer crop) was established during two subsequent years (2010-2012), followed by a sequence of black oat - sweet maize - black oat - onion (2012 - 2013) in a field of 50 m × 30 m. Black oat was sown in autumn and killed with glyphosate in winter (20 August 2010, 7 September 2011, 2 September 2012 and 16 May 2013). Tomato was transplanted on 22 October 2010 and 1 December 2011 at a density of 26,667 plants ha^{-1}, and harvested weekly from 5 January to 17 February in 2011, and from 8 February to 7 March in 2012. Sweet maize was sown on 5 November 2012 at a density of 50,000 plants ha^{-1}, and harvested on 15 January 2013. Onions were planted on 27 June 2013 at a density of 300,000 plants ha^{-1}, and harvested on 24 December 2013.

Four treatments in three replicates were arranged in a complete random design in plots consisting of two contiguous raised beds, 1.5 m apart. In three conventional tillage (*CT*) treatments, beds were re-built twice a year before each crop. The fourth treatment was based on reduced tillage (*RTmulch*) where beds were re-built only before sowing black oat. The conventional tillage systems included a control treatment with only artificial fertilizer (*CT*), a treatment with a mixture of chicken manure and rice husk (*CTchm*) commonly used in the region, and a treatment with both chicken manure and green manure (*CTgm*) consisting of black oat incorporated into the soil 20–70 days before planting the next crop. In the reduced tillage treatment chicken manure was incorporated during the re-building of the beds, and black oat was killed off with glyphosate 20–105 days before planting the next crop and left as mulch on the soil surface. Runoff plots, 1.5 m wide × 5 m long with 1% slope, were established for each treatment replicate. Runoff (RO) was measured from October 2010 to November 2013 at every rain event, except for a few too large events that overfilled the tanks. Soil cover by the mulch and the crop canopy was measured monthly and soil moisture content weekly from September 2010 till November 2013. Above ground dry weight of black oat crops was measured just before herbicide application. Leaf area index was measured at transplant, before flowering and at full development for tomato, at transplant and full development for onion and at full development for sweet maize. Parameters to calculate the soil loss ratio (SLR) were measured monthly or at important dates: roughness, soil cover by residues and by the crop canopy. For a detailed description of treatments, run-off plot setup and soil moisture measurement methods see Alliaume et al. (2014). Due to a severe drought during the first tomato crop, data from this crop was not used to calibrate or evaluate the models that estimate water infiltration + interception. It was used, however, to evaluate the water balance model.

After the first year experience of N immobilization caused by the addition of oat biomass under both *RTmulch* and *CTgm* treatments, we adjusted the nitrogen supply to cover the N estimated to be immobilized given the amount of oat dry matter added and the C/N ratio of the residues incorporated. Sweet maize and onion yields were estimated from fresh weights of 2m row harvested in each runoff plot. Twenty leaves opposite of sweet maize cobs were sampled at the beginning of cob set and at cob maturity and total nitrogen was determined using the Kjeldhal method (Bremner and Mulvaney, 1982). Onion leaves were sampled at full leaf development and total nitrogen was determined.

In the results section we show the cumulative RO for the *RTmulch* and the average of the three *CT* treatments. This was made after searching the significance in the contrasting analysis of the *RTmulch* vs the three conventional tillage treatments and looking for a clearer figure with less series of data on it.

2.3 Model description

We adapted the water balance module included in the crop growth model SUCROS 2 (Van Laar et al., 1997). This module uses as input: local daily weather data, soil physical characteristics, crop leaf area index (LAI) and daily root length to estimate the daily soil water balance, daily crop transpiration and daily soil evaporation. The model was written in Visual Basic and is based on Dogliotti et al (2004).

In SUCROS 2 daily potential reference evaporation and transpiration are estimated according to an adapted Penman-Monteith equation. Actual canopy transpiration is calculated from soil water content, root exploration and a crop-dependent critical soil water content factor (PT50) that limits the transpiration rate as a function of soil water content (Denmead and Shaw, 1962; Driessen, 1986 cited by Van Laar et al., 1997). Daily soil water balance is calculated as the difference between inputs (rainfall infiltration + irrigation) and outputs (crop transpiration, evaporation from the soil surface, and drainage below the root zone). The soil is divided into four layers that represent main soil horizons of different water holding characteristics and depths, which are input to the model. We modified the procedures to estimate rainfall infiltration and evaporation from the soil surface included in SUCROS 2 (Figure 4.1) as explained in the following sections.

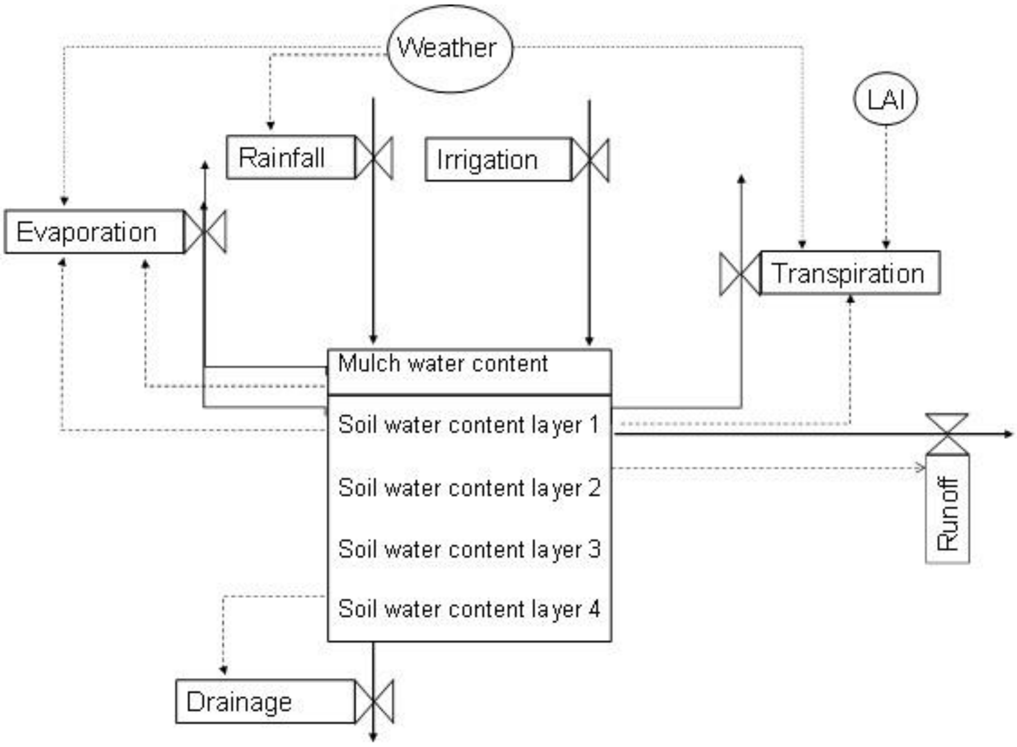

Figure 4.1. Relational diagram of the water balance model based on SUCROS 2 module (Van Laar et al. 1997) showing the main state and rate variables and processes.

2.3.1 Rainfall infiltration

When it rains, a small part of the water is intercepted and retained by the crop canopy and by the organic mulch when present, another part runs off over the soil surface, and the remainder infiltrates into the soil:

Infiltration [mm] = R – WRCC – WRM – RO [1]

Where, R is the rainfall, WRCC is the amount of water intercepted and retained by the crop canopy, WRM is the amount of water retained by the organic mulch and RO is runoff. In this paper we refer to WRCC + WRM as interception. Note that R – RO is the same as interception + infiltration.

The amount of water retained by the crop canopy (WRCC; mm) was estimated following Van Laar et al. (1997) as the minimum of 0.25 times crop Leaf Area Index (LAI) and R. The amount of water retained by the organic mulch (WRM) was estimated following Brisson et al. (2008) as:

WRM [mm] = minimum (MWM – AWM, R) [2]

Where, MWM is the maximum amount of water that can be retained by the mulch (mm) and AWM is the actual mulch water content (mm). We estimated MWM as the product of mulch biomass (MB) (kg ha^{-1}) and amount of water retained per unit of mulch biomass (mm kg^{-1} ha), which depends on the type of crop residue (e.g., 0.000233 mm kg^{-1} ha for wheat straw biomass according to Iqbal et al. (2013)). AWM varies between MWM and zero, and is reduced every day by daily mulch evaporation estimated according to Brisson et al. (2008) as:

AEm = minimum (PEm, AWM) [3]

Where AEm is actual evaporation from mulch (mm), and PEm is potential daily evaporation from mulch (mm). Calculation of PEm is explained in the next section.

When rainfall during an event was less than the sum of 10 mm plus water retained by the crop canopy and WRM, runoff (RO) was assumed to be zero (Van Laar et al., 1997). We followed the approach proposed in SUCROS 2 to estimate RO for rainfall events that exceeded the storage capacity of the top 40 cm of the soil, (e.g for rainfall events exceeding 59 mm at a time when the soil was at field capacity at the beginning of the rainfall event). For rainfall events within these limits, we compared three methods to estimate R-RO: the curve number (SCS, 1972); soil cover and soil water content reduction factors; and multiple linear regression. Precipitation was considered to be part of the same rainfall event when time between subsequent precipitation measurements was less than 5 hours.

Method 1 - Curve number (CN)

The curve number method (SCS, 1972), also referred to as an infiltration loss model (Ponce and Hawkins, 1996), estimates RO from R and two parameters that depend on soil hydrological group, antecedent rainfall, and land cover:

$$RO\ (mm) = (R - I_a)^2 / [(R - I_a) + S] \quad [4]$$

Where R is rainfall amount (mm), I_a is a parameter referred to as the ‘initial abstraction’ (mm) or amount of water before runoff, and S is the potential maximum water retention (mm), mainly representing the infiltration occurring after runoff has started (S depends on which is the most limiting, either the infiltration rate or the water storage capacity). Furthermore,

$$I_a = S * {}_fI_a \qquad [5]$$

Where ${}_fI_a$ is the 'initial abstraction factor', historically taken as 0.2 and sometimes as 0.1. S values tabulated by SCS (1972), depend on soil hydrological group, antecedent soil moisture condition and soil cover.

Here, S values were calibrated for four different conditions of the experiment: RT dry and wet, and CT dry and wet. Dry and wet conditions were defined according to the soil water content to 40 cm depth previous to the rainfall event, trying different split values from 50 to 60% of field capacity. S and ${}_fI_a$ were estimated through non-linear regression procedure in InfoStat. This statistical software obtains the least squares estimators of the parameters in two steps: 1- an approximate solution is found using a downhill simplex method (Nelder and Mead, 1965), and 2- applies the Levenberg-Marquardt method (Press et al., 1986) on the previous solution, by calculating the Hessian matrix required for the calculation of the covariance matrix of the estimates. The procedure ends when the difference of the sum of squares between two successive iterations is less than or equal to 10^{-10} or when the maximum number of iterations specified by the user is reached (InfoStat, Di Rienzo, 2008).

The splitting criteria for soil wetness condition and the S and ${}_fI_a$ values were selected based on the smallest root mean squared error (RMSE). The best estimates were obtained with a ${}_fI_a$ of 0.1 and splitting criteria for soil wetness equal to SWC to 40 cm depth of 55% of field capacity. The four resulting S values are presented in the Results section, Table 4.1.

Method 2 - Rainfall corrected by soil cover and moisture (Corrected_R).
This method estimates R-RO (interception + infiltration) by multiplying R by two reduction factors, which can take values between 0 and 1 The relationship between R-RO and soil water content and soil cover was modelled through a regression analysis implemented in InfoStat (Di Rienzo, 2008), where the parameters of the logistic model were estimated by least squeres, fitting the following equation:

$$R - RO = R * [1 - 1/(1 + a * e^{(-b * SWC40)})] * [1/(1+c*e^{(-d * SCv)})] \qquad [6]$$

Where SWC_{40} is the soil water content to 40 cm depth (mm) previous to the rainfall event, SCv [0 to 2] is the sum of soil cover by crop residues or organic mulch [0 to 1] and canopy cover [0 to 1], and a, b, c, and d, are parameters. The factor that accounts for soil water content - first brackets – decrease logistically as soil moisture increase. The factor that accounts for soil cover – second brackets – increase logistically as soil cover increase. Both $SWC_{40\ and}$ SCv were measured in the experiment.

Method 3 - Multiple linear regression (MLR)

After checking that the assumptions for multiple linear regression were met, we regressed RO on different linear combinations of the explanatory variables rainfall per event (R), soil moisture to different depths i (SWC_i), soil cover by the crop, soil cover by organic mulch and the sum of these (SCv), type of tillage (conventional or reduced), and maximum rainfall intensity measured during each storm (mm h^{-1}) with a stepwise procedure (InfoStat, Di Rienzo, 2008). The final model was:

$$R - RO = (w + x*R + y*SWC40 + z*SCv) \quad [7]$$

Where w, x, y and z are fitted parameters

2.3.2 Evaporation from soil and mulch

Without organic residues covering the soil surface we estimated potential and actual soil evaporation as in SUCROS 2, based only on crop LAI and water content of the topsoil layer. The presence of mulch was assumed to reduce potential soil evaporation by 5% for each 10% of soil surface effectively covered by the mulch (Allen et al., 2006). The potential daily soil evaporation (PEs) in the presence of mulch was estimated as:

$$PEs = PET * e^{(-0.5 * LAI)} - PET * e^{(-0.5 * LAI)} * 0.5 * MCv \quad [8]$$

Where PET is the potential evapotranspiration estimated using adapted Penman-Monteith combination equation version in SUCROS 2. MCv is the fraction of soil covered by the mulch, and was estimated as a function of mulch biomass (MB) (kg.ha^{-1}) using the negative exponential equation proposed by Gregory (1982) and used in RUSLE (Renard et al, 1997), STICS (Brisson, 2008), and DSSAT (Porter et al., 2010):

$$MCv = 1 - e^{(-\alpha * MB)} \quad [9]$$

Where α is specific mulch area (ha kg^{-1}), or area of soil covered per unit mulch biomass. We set α to 0.00053 as suggested for oats residues by Renard et al (1997). The decomposition rate of plant residues in the mulch depend on residue characteristics, temperature and rainfall. We calculated mulch biomass dynamics using a first-order rate equation reported in Renard et al (1997), based on work by Stott et al (1990):

$$MB_d = MB_{d-1} * e^{-RDR} \quad [10]$$

Where MB_d is the remaining mulch dry biomass on day *d* (kg ha^{-1}), and RDR is relative mulch decomposition rate estimated following Renard et al (1997):

$$RDR = p * [\text{minimum}(F, W)] \quad [11]$$

Where p (-) is a coefficient depending on residue characteristics, set to 0.008 as suggested for oat, and W and F are precipitation and temperature factors explained in Renard et al. (1997).

Potential daily evaporation from mulch (PEm) (mm) was estimated according to Brisson et al. (2008) as follows:

$$PEm = PET * e^{(-0.5 * LAI)} * MCv \quad [12]$$

2.4 Evaluation of the R-RO models and the water balance model

R-RO model evaluation comprised three elements: the degree to which the models were able to reproduce the observations used to fit the parameters; the sensitivity of models to variation in soil coverage and initial soil moisture; and the validation on an independent dataset. We evaluated the water balance model coupled with the three different R-RO models by analyzing the degree to which the water balance was able to reproduce the SWC_T observations.

Predictions of rainfall minus runoff (R-RO) (mm), and daily total soil water content to 1 m depth (SWC_T) (mm) were compared with values measured in a 4-year field experiment. The agreement between observed and predicted values was evaluated using three indicators of model performance: root mean squared error (RMSE), model efficiency, EF (Greenwood et al., 1985) and mean deviation, MD (Wallach et al., 2012).

RMSE measures the difference between the predictions and the observations and is reasonably sensitive to outliers. The best value is 0:

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(Oi - Ei)^2}}{n} \quad [13]$$

where *Oi* is the *i*th observed value, *Ei* is the *i*th estimated value, *n* is the number of observations pairs. We considered a RMSE value smaller than the mean of the observations to be a good model fit.

Model efficiency (EF) ranges between negative infinity and 1. Values less than 0 mean an agreement between observed and estimated values worse than the agreement between observed values and the average of observations.

$$EF = \frac{\sum_{i=1}^{n}(Oi - \ddot{O})^2 - \sum_{i=1}^{n}(Ei - Oi)^2}{\sum_{i=1}^{n}(Oi - \ddot{O})^2} \qquad [14]$$

where *Ö* is the mean of the observations, *Oi* represents observation *i* and *Ei* its respective estimate.

Mean difference MD is a measure of the average difference between the observations and estimates. Perfect fit is indicated by a value of 0:

$$MD = \frac{\sum_{i=1}^{n}(Oi - Ei)}{n} \qquad [15]$$

Based on indicators [13] to [15] we selected the best model to perform explorations.

We analyzed sensitivity of the three models of R-RO to determine effects of variation in parameters on predictions for high - low values of soil coverage and initial soil moisture. We calculated sensitivity of the (R-RO)/R ratio (infiltration + interception fraction) to these factors after different daily rainfall amounts. Estimates were made for rainfall amounts representing the 95-percentile (R = 63 mm; top row), average (R = 30 mm, middle row), and the 25-percentile (R = 16 mm; bottom row) of rainfall events exceeding 10 mm in south Uruguay over the past 10 years.

To validate the models, predictions of R-RO were compared against an independent dataset from a field experiment conducted by Pérez and Gilsanz (a description of the experiment and preliminary data can be found in Pérez et al. (2012)). These authors compared conventional and reduced tillage with mulch in vegetable crops on raised beds at the INIA Las Brujas Research Station in south Uruguay. Soil in the experiment was similar to the one on which the data for model calibration were collected and slopes were slightly steeper, ranging from 2 to 6%.

2.5 Exploration of the effect of alternative soil management on soil water balance

We explored the effect of soil management on water balance components by running the water balance model (using the R-RO model that showed the best performance) for 10 years (2004-2014) of weather data from south Uruguay and the three crops analyzed in this study: tomato, sweet maize and onion. Mulch biomass was set to 6000 or 3000 kg DM ha^{-1} mulch biomass depending on the duration of the cover crop, which is shorter previous to onion than previous to tomato and sweet maize. Initial water content used for simulations under *RTmulch* was set to 70 and 95% of fc, as measured for spring-sown crops (tomato and sweet maize) and onion (winter sown), respectively. For simulations under conventional tillage, we used initial water contents of 60 and 90% of fc as measured in spring and winter sown crops, respectively. We assumed a 70% irrigation efficiency to estimate irrigation requirements.

3. Results

3.1 Effects of soil management on infiltration and productivity

Three variables explained the majority of R-RO variation: R, SWC_{40} and SCv (Fig. 4.2). R-RO was positively correlated with rainfall amount and total soil coverage, and negatively with soil moisture content till 40 cm depth ($p<0.05$).

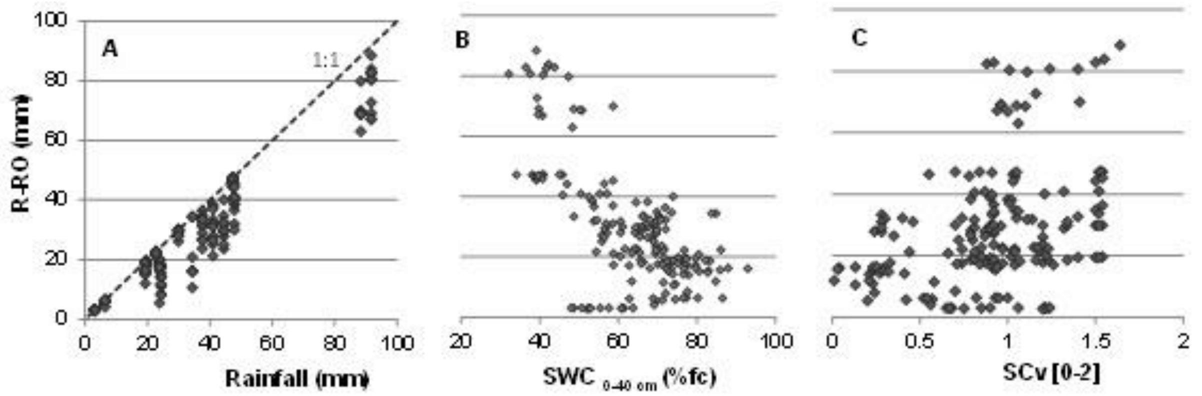

Figure 4.2. Rainfall minus runoff (R-RO) as a function of: A- rainfall per event (mm), B- soil water content till 40cm (mm), and C- soil cover, calculated as sum of fractions covered by canopy and by residues.

The effect of soil management on cumulative RO is shown in Fig. 4.3. In the reduced tillage treatment (*RTmulch*) we measured on average 62.8 mm (9.3% of total rainfall amount) less RO than in the average of the conventional tillage treatments (*CT*) over the course of the entire experiment (Fig. 4.3). During the tomato crop, runoff was measured on 14 out of 27 rainfall events, which represented 73% of the cumulated rainfall amount.

Sweet maize yields did not differ significantly among treatments ($p = 0.2302$). However, a trend of larger yields under *CTchm* was observed. Average yields (standard deviation between brackets) were: 7,030 (1860) Mg ha^{-1} under *CT*; 7,460 (555) Mg ha^{-1} under *RTmulch*; 7,880 (2,150) Mg ha^{-1} under *CTgm*; and 9,830 (1,00) Mg ha^{-1} under *CTchm.* Onion yield (s.d.) under *CTchm* was 29,850 (655) Mg ha^{-1} and did not differ significantly from the yield under *RTmulch* 24,500 (3,320) Mg ha^{-1}, but were 32 and 46% larger than the yields under *CT* (22,680, s.d. 3,145 Mg ha^{-1}) and *CTgm* (20,460 s.d. 3,270 Mg ha^{-1}) respectively ($p < 0.05$). There was no evidence of leaf N deficit either in the sweet maize crop ($p = 0.1516$ and $p = 0.1276$ for first and second date of sampling, respectively), or in the onion crop ($p = 0.3819$).

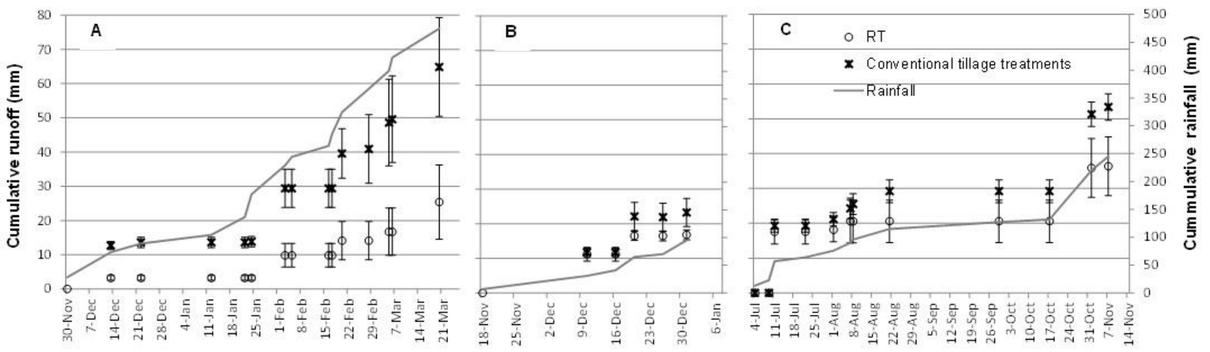

Figure 4.3. Rainfall (right ordinate; line) and runoff (left ordinate; symbols) cumulated over subsequent events for A) tomato, B) sweet maize and C) onion under two soil tillage treatments: reduced tillage – mulch (RT; open symbols)) and the average of conventional tillage (CT; asterisks) treatments. Vertical bars represent standard deviation.

During the sweet maize crop, we were able to measure 5 out of 11 rainfall events, representing 30% of the cumulated rainfall amount, and during the onion crop we measured 12 out of 16 rainfall events, representing 53% of the cumulated rainfall amount. Considering only the measured events, R-RO was 92, 83 and 85% of R for *RTmulch* and 80, 76 and 78% for *CT*, during tomato, sweet maize and onion crops, respectively. Runoff was 59% less under *RTmulch* than *CT* for tomato, 25% less for maize and 28% less for onion (Fig. 4.3).

3.2 Evaluation of the R-RO - models

The indices of model performance of all three fitted models revealed an excellent fit to measured R-RO values (Table 4.1; Appendix 4.2).

The RMSE was around 0.36 mm for the three models, 1.25% of the average observed R-RO of 28.8 mm. The mean difference between observations and estimations was 2.7% of the average observed R-RO. The model efficiencies (EF) were near 1, which indicates a near-perfect fit that is also revealed by the close to 1 slope of the graphs of estimated versus observed R-RO (Appendix 4.2).

The Corrcted_R equation estimated infiltration + interception fractions from 0.51 (SCv=0) to 0.76 (SCv=1.6) when the soil was at field capacity, and 0.62 (SCv=0) to 0.92 (SCv=1.6) when the soil was at pwp. In this method, the infiltration + interception fraction was never 1, but this was not a problem because the limits imposed to use the equation (Rainfall infiltration section) made that the infiltration for rainfalls smaller than 12 mm approximately were 100%.

Overall, the Corrected_R (eq.6) presented the best performance indexes. The average fraction of cumulative runoff in relation to total rainfall, for rainfall events measured in the field, were around 13% under *RTmulch* and 22% under *CT*. When estimated by the Corrected_R per event, the cumulative runoff in relation to cumulative rainfall was on average 16% under *RTmulch* and 26% under *CT*. When all the rainfall events were simulated at daily time step, those percentages were 18% under *RTmulch* and 28% under *CT*.

Table 4.1. Parameter estimates for the three models to simulate R-RO (a), and model performance (b).

a. Parameter estimates

CN [1] method						(eq.4-5)
Situations	S[2] value	s.e.	T	p-valor	n	
RT[3]< 55% fc	314.6	38.9	8.1	<0.0001	8	
RT > 55% fc	148.8	17.2	8.7	<0.0001	41	
CT[4] < 55% fc	221.0	16.3	13.6	<0.0001	23	
CT > 55% fc	80.3	8.1	9.9	<0.0001	103	

Corrected_R [5]					(eq.6)
Parameter	Estimate	s.e.	T	p-valor	
A	59.37	102.26	0.58	0.5623	
b	0.02	0.01	1.56	0.1201	
c	0.53	0.11	4.72	<0.0001	
d	1.72	0.69	2.49	0.0138	

MLR [8]					(eq.7)
Parameter	Estimate	s.e.	T	p-valor	
w	4.10	2.66	1.54	0.1252	
x	0.75	0.02	40.73	<0.0001	
y	-0.09	0.02	-4.33	<0.0001	
z	7.73	0.90	8.63	<0.0001	

b. Indices of models performance

	RMSE (mm)	Mean difference MD (mm)	Model Efficiency EF (-)	R^2	b [9]
CN [1]	0.40	-1.03	0.93	0.93	0.93
Corrected_R [5]	0.35	0.70	0.95	0.95	1.00
MLR [8]	0.32	0.71	0.95	0.95	1.01

[1]Curve number method; [2] Parameter S from the CN method, representing the potential maximum water retention (mm); [3]Reduced tillage- mulch; [4]Conventional tillage treatments; [5]Corrected rainfall equation; [6]Soil water content to 40 cm depth; [7]Soil cover; [8]Multiple linear regression equation; [9]Slope of estimated versus measured R-RO.

We checked the sensitivity of the three fitted models to soil water content and to soil cover or tillage systems (Fig. 4.4). For the CN method, the estimates of R-RO depended on R and S, so the possible R-RO outputs for a given rainfall amount, were four, depending on tillage and soil wetness previous the rainfall event. The CN method estimated the largest infiltration + interception fraction ((R-RO)/R) for the different situations of soil coverage and soil moisture. The sensitivity to soil coverage was indirectly observed when *RTmulch* is compared to *CT*, and was low for small rainfall amounts and larger under larger rainfall amounts (Fig. 4.4).

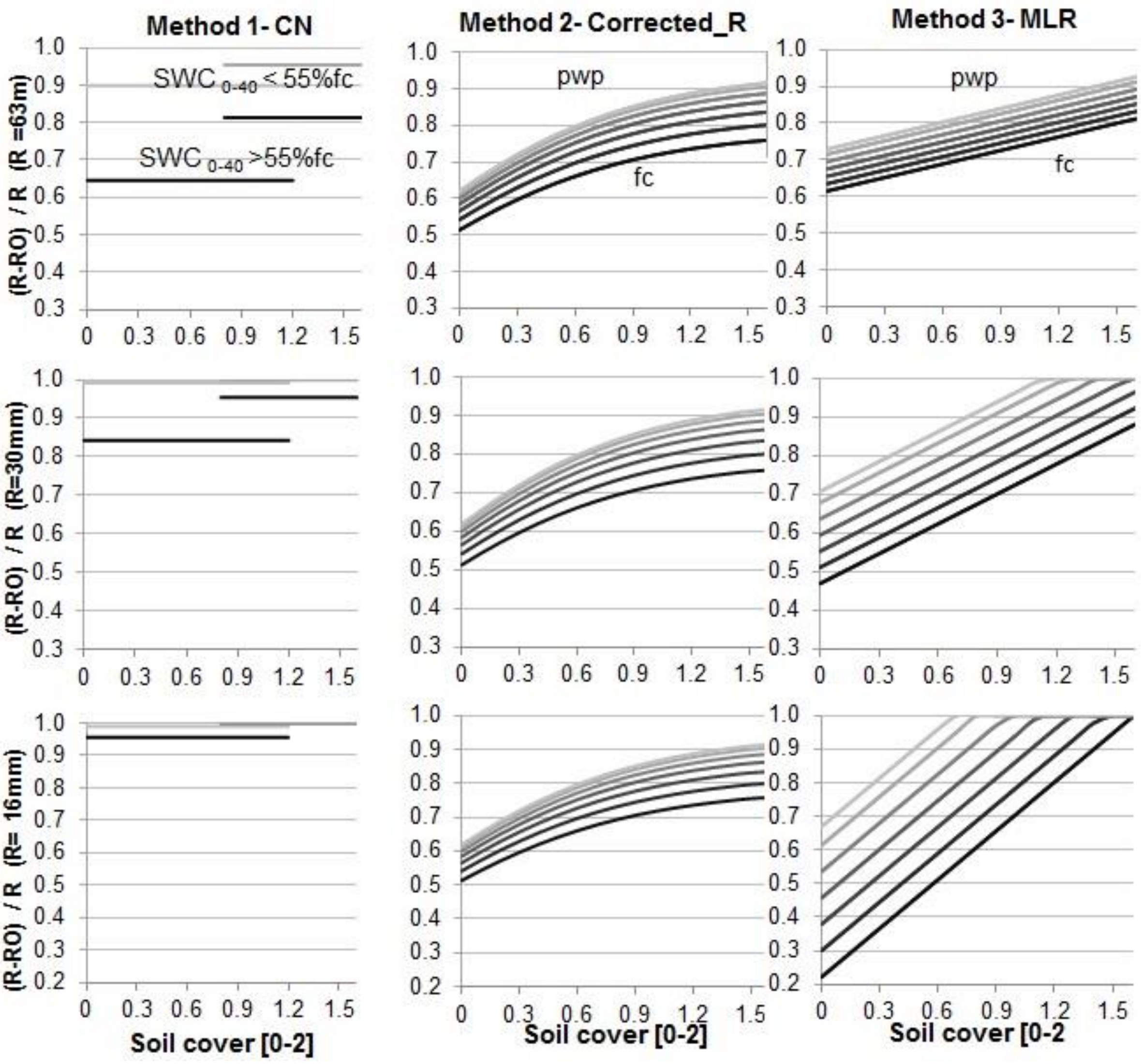

Figure 4.4. Rainfall minus runoff (R-RO) to rainfall (R) ratio as a function of soil cover and different levels of initial soil moisture. Black lines represent soil at field capacity; grey lines represent successive 10% reduction of initial soil moisture to permanent wilting point. Estimates were made for rainfall amounts representing the 95-percentile (R = 63 mm; top row), average (R = 30 mm, middle row), and the 25-percentile (R = 16 mm; bottom row) of event-wise rainfall amount in south Uruguay over the past 10 years exceeding 10 mm. Three methods were used to estimate R-RO: curve number method (panels on the left), corrected-rainfall equation (centre panels), and multiple linear regression (panels on the right).

The MLR eq was the most sensitive, and infiltration + interception fraction varied largely depending on the rainfall amounts. On the opposite to the CN method, the response to SCv was larger for small rainfall amounts, giving estimates from 0.22 (SCv=0; fc) to 1 (SCv=1.6, pwp) for 16 mm rainfall, and varying from 0.62 (SCv=0, fc) to 0.93 (SCv=1.6, pwp) when the rainfall was 63 mm. For small and average rainfalls, the CN method was the least sensitive to SCv, estimating the largest infiltration + interception fractions. On the opposite, the MLR method was the most sensitive to SCv and SWC at small and average rainfalls, while the Corrected_R method had intermediate response to these variables. For larger rainfalls the three equations presented similar sensitivities.

The Interception + infiltration (=R-RO) observations and estimations are shown in Fig. 4.5.

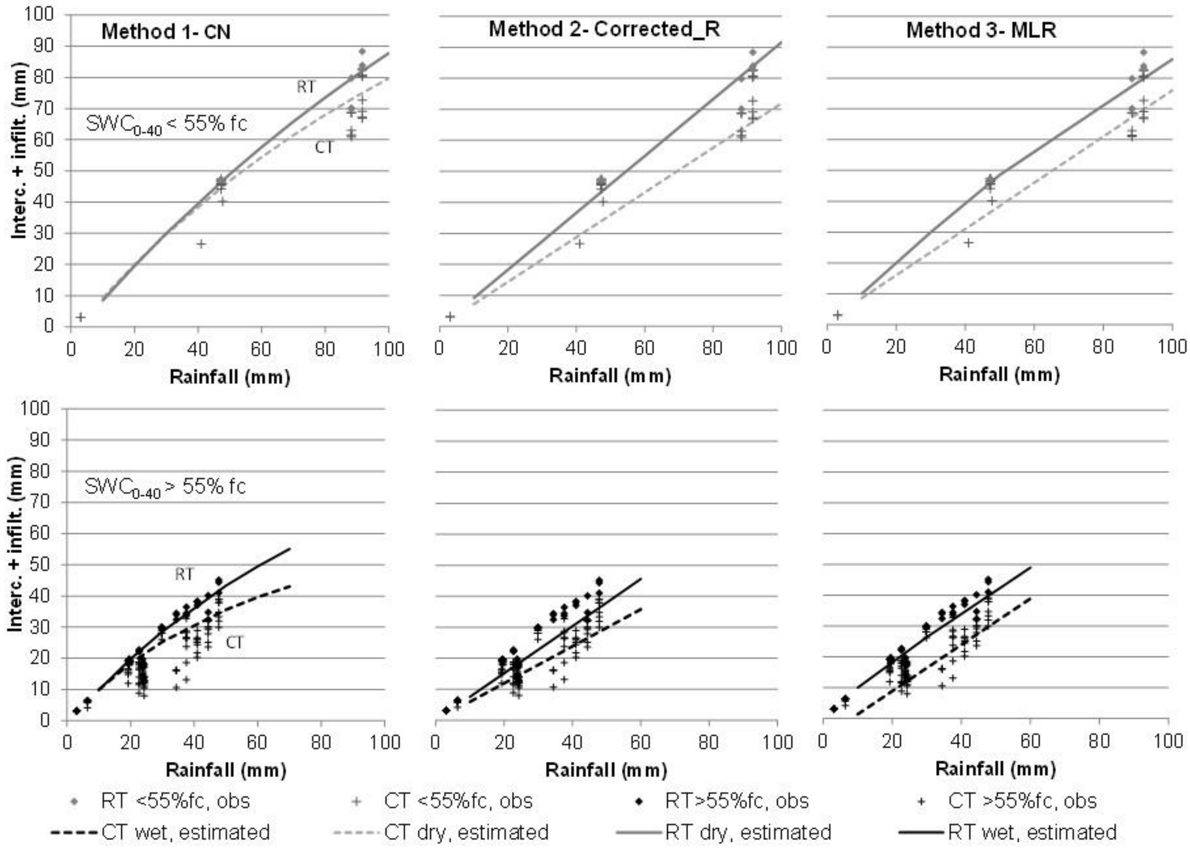

Figure 4.5. Interception + Infiltration as a function of rainfall at different levels of soil moisture to 40cm depth (SWC_{0-40}); below 55% (top row), and above 55% (bottom row). Dots represent observations for *RTmulch* treatment, while crosses represent observations at all the three conventional tillage treatments. Three methods were used to estimate interception + infiltration (or R-RO): curve number method (panels on the left), corrected-rainfall equation (centre panels), and multiple linear regression (panels on the right).

3.2.1 R-RO model validation

When R-RO was estimated for the independent data set (average observed R-RO = 16.9 mm) all three methods gave satisfactory results (Table 4.2), but the lowest RMSE and highest EF were obtained with the CN method.

Table 4.2. Performance indices of three models to predict R-RO using an independent data set (n=33).

Method	RMSE (mm)	Mean difference (mm)	Model Efficiency (-)	R^2	b[4]
CN [(1)]	0.74	2.10	0.84	0.84	1.07
Corrected_R [(2)]	0.86	-2.63	0.78	0.86	0.78
MLR [(3)]	0.86	-3.19	0.78	0.88	0.79

[1]Curve number method; [2]Corrected rainfall eq.; [3]Multiple linear regression; [4]Slope of estimated vs measured R-RO.

There were two large rainfall events registered (84 and 97 mm) which were not included in the R-RO model performance indices, as there were outside the boundaries within which the equations should be used. Nonetheless, estimates for these two events were made following the methodology by Van Laar et al., (1997) explained in Rainfall infiltration section and plotted in Fig 4.6.

3.3 Evaluation of the water balance model

The water balance model estimated SWC_T from 0 to 100 cm depth satisfactorily for each of the three fitted R-RO models. The lowest RMSE and the largest EF were obtained with the Corrected_R equation (Table 4.3). The average observed SWC_T from 0 to 100 cm during the four growing seasons (280 mm) was overestimated by 11 to 17 mm, depending on which equation was used to estimate the infiltration.

Table 4.3. Performance indices of the full water balance model using data on four growing seasons in a field experiment in south Uruguay. Soil water content estimations were made with three different interception + infiltration fitted equations. n=175.

Method	RMSE (mm)	Mean diff. MD (mm)	Model Efficiency EF (-)	R^2	b[(4)]
CN [(1)]	2.98	17.02	0.53	0.55	1.06
Corrected_R [(2)]	2.26	11.24	0.73	0.70	1.04
MLR [(3)]	2.47	10.78	0.68	0.61	1.03

[1]Curve number method; [2]Corrected rainfall equation; [3]Multiple linear regression equation; [4]Slope of estimated versus measured soil water content from 0-100cm soil depth.

Figure 4.6. shows the fit between the observed and predicted R-RO with the three equations.

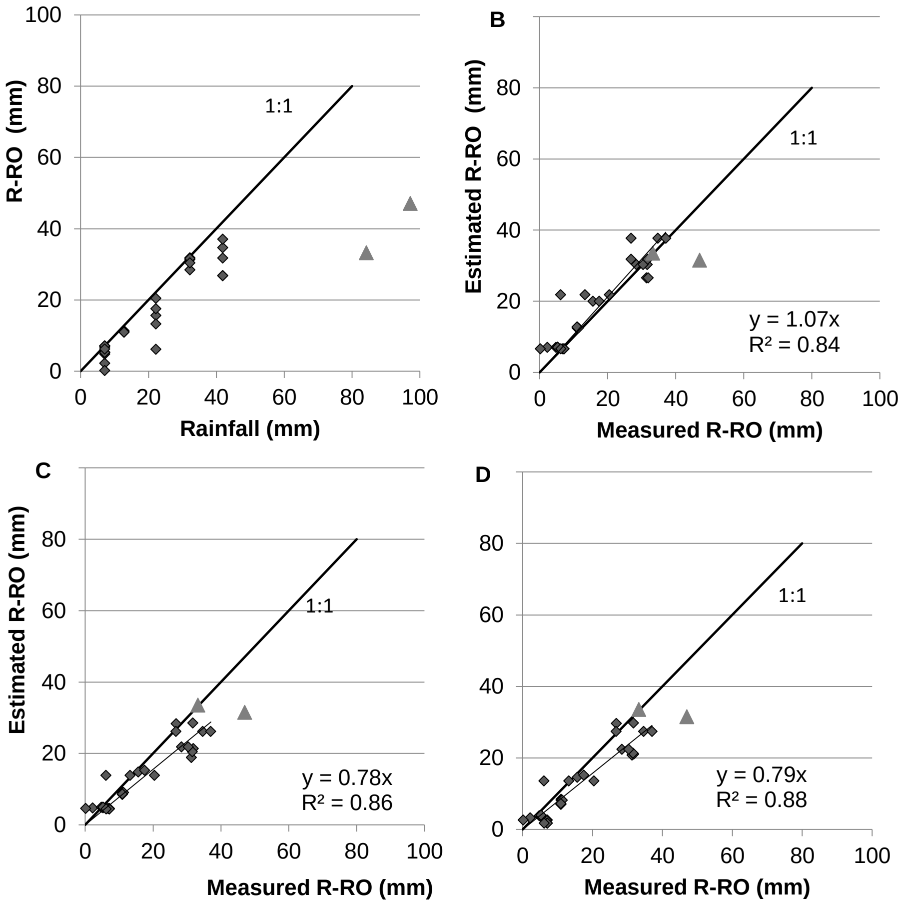

Figure 4.6. A) Rainfall minus runoff (R-RO) as a function of rainfall (R) measured in the INIA Las Brujas experiment (Perez and Gilsanz, pers. com.). B-D) Estimated rainfall minus runoff as a function of measured rainfall minus runoff, as predicted by B) curve number method (S = 148.3 for *RTmulch*, wet; and S = 80.3 for *CT*, wet), C) corrected-rainfall equation, and D) multiple linear regression; n=33; 2 outliers (gray triangles) were not included in the regression line.

SWC_T estimates disaggregated per crop (Appendix 4.3) were all highly positively correlated with observations. Most accurate predictions were obtained for the first tomato crop (RMSE = 4.4) and onion (RMSE = 3.5 to 4.5 depending on the method used to estimate runoff); least accurate predictions were obtained for the second tomato crop (RMSE 5.8 to 7.4).

Based on the results of models evaluations, we used the Corrected_R equation for explorations described in the following section. Observed and simulated SWC_T along four growing seasons using the Corrected_R equation is shown in Fig. 4.3.A.

3.4 Exploring the effect of alternative soil management on soil water balance and irrigation requirements

Model exploration of the impact of soil management using 10 years of rainfall data, showed a significant impact of *RTmulch* on soil water availability for crops and, consequently, a reduction of irrigation requirement compared to *CT* (Table 4.4). Increased water availability under *RTmulch* was mainly explained as a result of reduced evaporation from the soil due to the mulch cover, and some years due to larger infiltration. The estimated potential evapotranspiration (PET) was on average 137 (standard deviation (s.d.) 8), 119 (s.d. 8) and 66 (s.d. 9) mm lower under *RTmulch* for tomato, sweet maize and onion, respectively. We estimated on average 38 (s.d. 5), 32 mm (s.d 7), and 18 mm (s.d 4) less evaporation from the soil surface under *RTmulch* for tomato, sweet maize and onion, respectively. The effect of treatments on infiltration, calculated as cumulated rainfall minus runoff minus actual evaporation from mulch, was highly variable depending on the season. During both the tomato and the sweet maize crops, there were some years with greater estimated infiltration under *RTmulch* (5 mm, s.d. 6mm) and some years with less estimated infiltration under *RTmulch* (-10 mm s.d. 9mm) due to evaporation from the mulch. During the onion crop the infiltration was larger under *RTmulch* for all the estimated seasons compared to *CT* (24.5mm, s.d.12.4 mm). Estimated average savings of irrigation water (irrigation efficiency 70%) were highly depending on the year, with average savings of 188 (s.d 15), 158 (s.d. 18) and 77 (s.d. 12) mm for tomato, sweet maize and onions, respectively under *RTmulch*. The irrigation requirement standard deviations were smaller for *RTmulch* than for *CT* (Table 4.4).

The variability in cumulated rainfall during the crop growth period varied up to 10-fold from one year to another being on average 383 (s.d 167); 190 (s.d 105); and 471 (s.d. 151) mm during the tomato, sweet maize and onion crops, respectively. The variability in the difference in irrigation requirements between treatments was explained by the combined variability in rainfall and in the difference in PET. Years with a large difference in PET between treatments resulted in a larger difference in irrigation requirements.

4. Discussion

We developed models that estimate rainfall minus runoff accurately, selected the best model (Corrected_R) and incorporated it to a soil water balance that simulate SWC accurately. We proved that reduce tillage with organic mulch increases water availability for crops and reduces irrigation requirements. Bellow we discuss first effects of soil management on runoff reduction, and then the effect on the soil water content and water availability to plants. .

Table 4.4. Water balance components for three crops and two soil management strategies. Values represent average outputs of 10 years run of the water balance model. Ranges are given between brackets and standard deviation between curve parentheses.

Crop	Rainfall (mm)	Soil management	RO(1) (mm)	Deep drainage (2) (mm)	PET(3) (mm)	AT (4) (mm)	AEs (5) (mm)	AEm (6) (mm)	Irrigation requirement (mm)
Tomato	414	RTmulch	95 [4-347]	14 [0-128]	556 [464-648]	196 [76-259]	54 [32-66]	25 [16-35]	366 [167-613] (126)
	[100 - 950]	CT	116 [10-399]	4 [0-34]	700 [589-792]	181 [59-258]	93 [57-117]	0	553 [323-809] (140)
Sw Maize	190	RTmulch	35 [0-152]	0	322 [263-365]	108 [47-165]	42 [19-52]	16 [6-24]	204 [93-332] (73)
	[41 - 347]	CT	51 [0-167]	0	441 [364-494]	89 [36-149]	73 [34-92]	0	362 [218-490] (84)
Onion	471	RTmulch	99 [26-162]	115[46-178]	419 [318-535]	199 [126-266]	48 [26-62]	9 [0-17]	210.8 [112-318] (67)
	[186 - 675]	CT	134 [40-201]	75 [13-132]	485 [370-620]	198 [125-264]	66 [37-85]	0	287.9 [170-404] (76)
Average difference									
RT-CT			- 24	+17	-109	+12	-29	+17	-140.9 [113-147] (47)

[1]Runoff / rainfall ratio; [2] Deep drainage / rainfall ratio; [3] Potential evapotranspiration; [4]Actual transpiration; [5]Soil actual evaporation; [6]Mulch actual evaporation.

4.1 Rainfall minus runoff

All three equations to estimate R-RO were highly efficient from a model-testing point of view. Yet, these equations are to be used within the range of conditions for which they were derived: 92 mm of rainfall per event as maximum (median of 30 mm); 0 to 160% soil surface coverage (median of 90%); 52 to 149 mm of volumetric soil water content to 40 cm depth (median of 106 mm, 71% of fc); and maximum rainfall intensities of 5 to 88 mm hr^{-1} (with a mean of 36 mm hr^{-1}). The independent variables of the validation data set were within the boundaries with which the equations were fit, although the slope was steeper (4 against 1.5%). Yet, it was within the expected range to be considered a 'gentle slope" (e.g. < 6% in the CN method). The risk was then that the equations under-predicted runoff, which is equivalent to over-predicting R-RO. However, the results showed acceptable model performance indices.

Estimates of the initial abstraction (I_a) in the CN method were, with wet soil conditions, 8 mm under *CT* and 15 mm under *RTmulch*, and with dry soil condition, 22 mm under *CT* and 31 mm under *RTmulch*. These values represent the amount of rainfall that can be intercepted before runoff starts. The S values obtained here for the *CT* are within the range reported in the literature for soil hydrological group C (USDA, SCS, 1972). However, the effect of mulch was less than that cited by Porter et al. (2010), who reported that the initial abstractions could be as large as 60% (in our case that would mean 89 mm) of the potential maximum soil water retention, at 100% of mulch coverage and only 10% under no cover. Porter et al. (2010) used data to fit the runoff model from a Brazilian experiment on a lighter soil (clay loam) and a different climate regime, with larger amount of rainfall during the season. In that sense, Erenstein (2002) found different effects of the use of mulch related to soil properties; while on well-drained soils the reduction of runoff due to mulch was to 21% of the RO under no mulch (RO values of 15 mm and 71 mm, respectively), on a poorly drained soil the RO under mulch was reduced to 42% of the RO without mulch (RO values of 46 mm and 109 mm, respectively). Boulal et al. (2011), working on loamy soils with permanent raised beds and mulch, found that the RO was reduced to 66% of the cumulative RO found on raised beds without mulch. Using a ten-years weather database, we obtained values of cumulative RO under *RTmulch* that ranged from 30% to 92% of the cumulated RO under *CT*, depending on the year. On average, reduction of RO under *RTmulch* when compared with *CT* was 33% (s.d 20%), 39% (s.d. 13%), and 27 % (s.d. 5%) during the tomato, sweet maize and onion crops, respectively.

With the Corrected_R (eq. 6), the total amount of runoff is estimated by multiplying rainfall amount in an event by two reduction factors that account for soil cover and for soil moisture at start of the rainfall event. The method has the potential to be applicable at different sites after calibrating A, b, c and d parameters (see Table 4.1) for local conditions. Our approach overcomes the overestimation of the amount of water captured by the soil that some models have because they consider runoff to occur only for saturation excess. In soils with a Bt horizon, as it is the case in the south of Uruguay, this may represent a major source of error.

4.2 Water balance and productivity

Vegetable systems in south Uruguay are largely situated on degraded soils with poor soil physical properties (Alliaume et al., 2013). Water availability for irrigation is a limiting factor for most vegetable farms (DIEA et al., 2011).

Mulch with organic residues affects soil water dynamics through 3 processes: (1) reduction of water runoff; (2) radiation interception with associated reduction of soil evaporation; and (3) rainfall interception and subsequent evaporation from the mulch. The soil moisture during the four crops was both measured and estimated to be larger under *RTmulch* than under *CT* at all soil depths. This was explained by a reduced evaporation from the soil surface and, depending on the year, due to a larger infiltration into the soil. During years with a large PET and low rainfall, the interception and evaporation from the mulch reduced the water infiltration into the soil. This is in agreement with other studies made in semiarid climates, which also found that rain intercepted by high amount of residue after small rainfalls may evaporate directly without reaching the soil (Cook et al., 2006, and Sommer et al., 2012). Our results show that even though these years with little rainfall there is a reduction of infiltration due to the mulch, there is still a reduction in irrigation requirements, explained by a larger reduction of soil evaporation given the presence of mulch. Verburg et al. (2012) found that surface cover had a larger impact on soil water conservation in years with several small rainfalls than in large single events followed by prolonged dry periods with large evaporative demand. In our study, simulations for 10 years showed that the irrigation requirement under *RTmulch* is lower and less variable than under *CT*. Yet, also in our temperate sub-humid climate, the magnitude of water saving depends on both the PET and the rainfall patterns of each season. For e.g. irrigation requirements estimates made for the tomato crop for the driest season (rainfall =100 mm and PET =768 mm) and for the most rainy season (rainfall =950 mm and PET =699 mm - Table 4.4) were 196 mm and 161 mm lower under *RTmulch* than under *CT* respectively.

The water balance model implemented here showed good performance on an independent dataset, required relatively few inputs, and was sensitive to differences in soil cover. Nevertheless, a larger database that could extend the limits with which the parameters were derived would made it more robust.

Reduced runoff due to mulching and *RTmulch* led to reduced erosion risk (Alliaume et al., 2014) and larger water availability for transpiration, which may result in larger yields. At the same time, more soil water capture under *RTmulch* might result in increased deep drainage, especially during a winter-spring crop such as onion. Our simulations for onion show on average 40 mm more of deep drainage under *RTmulch* than under *CT* (Table 4.4). The difference in deep drainage was larger for years with higher rainfall. Averaging the 5 seasons with lower (350 mm) and higher (600 mm) rainfall gave a cumulative deep drainage difference between *RTmulch* and *CT* of 30 mm and 50 mm, respectively. This effect may lead to a trade-off between erosion and deep drainage. Increased deep drainage may exacerbate leaching of agrochemicals and nutrients especially in the case of winter crops.

Increased water capture due to mulching and *RTmulch* was not reflected in the commercial crop yields of tomato, sweet maize or onion. Poor establishment and N deficiencies under treatments with cover crops were detected and were possibly the causes for reduced tomato yields. In the two last crops we overcame difficulties in crop establishment in the treatments that included a cover crop, either incorporated or left as mulch. We did not detect significant N deficiencies in sweet maize or onion leaves, as was the case with tomato, reported in previous chapters, probably due to the N fertilization adjustment done to compensate for N immobilization caused by the cover crop. Nevertheless, we still observed a non-significant trend of higher yields under *CTchm* compared to *RTmulch*. Compaction could be a problem under *RTmulch*, which has been reported to occur under permanent beds (Cid et al., 2014) when soil has already a deteriorated structure and reduced SOM content. In future research, we plan to include *Brassica* spp. together with grasses as cover crop since it is reported to act as a natural de-compactor (Chen and Weil, 2011),.

We estimated an average reduction of irrigation requirements of 141 mm ha^{-1} per crop under RT. Scaling up our results to farm level, the impact that this technology may have in terms of water savings is significant. Dogliotti et al, (2014) identified water availability for irrigation of vegetable crops as an important limitation to yields in south Uruguay with strong impact on family income. We estimated average water savings of 34, 44 and 27% for tomato, sweet maize and onion, respectively. Provided that other resources such as labor are not limiting, RT would allow farmers to increase irrigated area of vegetables by similar proportion. Farmers with no limiting water availability would also benefit by saving energy and other irrigation costs, reducing their irrigation requirements.

5. Conclusions

All three R-RO models fit in this study accurately predicted the amount of water intercepted by crop canopy and mulch and infiltrated to the soil with low input data requirements, and were sensitive to differences in soil management, including variants of conventional tillage and reduced tillage with residues retained as mulch. Required input data included soil moisture prior to a rainfall event and soil cover by canopy and mulch. The data used for model calibration defined the application domain: gently sloping landscape (1-4%), fine textured and layered soils, 92 mm of rainfall per event at maximum; 0 to 160% soil cover, composed of canopy cover plus residue cover; soil water contents between 52 (37% fc) and 149 (106% fc) mm to 40 cm depth; and maximum rainfall intensities of 5 to 88 mm hr^{-1} (with a mean of 36 mm hr^{-1}). Combining the models with a classical water balance model allowed adequate representation of water content under different types of tillage and residue management. Exploration with 10 years of weather data showed that reduced tillage and mulching would decrease water requirements for irrigation by 37% on average (s.d. 7%).

Acknowledgments

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Chapter 5

Reduced tillage, mulching and diversified rotations increase efficiency of water use and family income and reduce erosion risk on small vegetable family farms

To be submitted, with modifications, as:

Alliaume, F., Rossing, W.A.H., Tittonell, P., Dogliotti S. Reduced tillage, mulching and diversified rotations increase efficiency of water use and family income and reduce erosion risk on small vegetable family farms. Possible Journal: Agricultural Systems.

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Abstract

While including pasture has been shown to have major environmental and economic benefits on vegetable farms, small farm size may preclude this option. The aim of this study was to evaluate the impact of a new soil management strategy, together with an enlarged choice of crops and different levels of irrigation water on family income, erosion risk and efficiency of water use on small-scale vegetable farms. We evaluated alternative designs for two existing small vegetable farms in south Uruguay in economic and environmental performances. To support farm re-design we used an approach that can deal with complex temporal interactions in crop rotations. Using a mixed integer linear programming model that reveals trade-offs between economic and environmental objectives, we allocated production activities to each farm.

Production activities comprised current practices as well as crop activities new to the area, at two levels of availability of irrigation water. Under irrigation constraints on Farm 1, family income was maintained at the initial level while soil erosion rates dropped from 9.4 to 4.7 Mg $ha^{-1}yr^{-1}$ by adopting reduced tillage + mulch (*RTmulch*) and selecting rotations from an extended list of crops. Under irrigation constraints on Farm 2, family income was increased by 250% compared to the initial situation, while the erosion was maintained at 5 Mg $ha^{-1}yr^{-1}$ by changing the choice of crops and adopting *RTmulch.* Without irrigation constraints, adopting *RTmulch* and selecting from an extended list of crops family income could be increased by 15% and erosion reduced from 8 to 5 Mg $ha^{-1}yr^{-1}$ on the first farm, while the erosion rate could be reduced to less than 4 Mg $ha^{-1}yr^{-1}$ on the second farm without changing the family income. Under *RTmulch* on both farms and at different water availabilities, it was possible to design production activities with erosion rates below the tolerable level without sacrificing family income much, something that was not possible under conventional tillage. By adopting *RTmulch*, average water savings were possible of 775 m^3 ha^{-1} yr^{-1} for fully irrigated rotations and 452 m^3 ha^{-1} yr^{-1} for rotations when only the most profitable vegetable crops were irrigated, compared with conventional tillage. This study provides ground for testing the proposed changes on pilot farms using a co-innovation approach combining scientific insights with farmers' knowledge of their farms.

Key words: Soil conservation, horticulture, water saving, RUSLE, crop rotation, cover crops, ROTAT, Farm Images

1. Introduction

Family farms produce more than half of the world's food production (FAO, 2011, IFAD, 2012), and are facing great challenges that threaten their sustainability around the world, including deterioration of the natural resource base, lack of access to markets and knowledge, and decreasing economic returns (IFAD, 2012). This is also the case in south of Uruguay, where the concentration of family farms is the largest in the country, and 60-70% of the soils are moderately to severely eroded (MGAP, 2004). After cattle and dairy farm production, vegetable production is the third most important activity representing the main source of income of family farms in Uruguay (DIEA, 2014).

Vegetable crops provide limited soil coverage, leave little crop residue biomass, and are frequently followed by a bare fallow between cropping periods, resulting in high risk of soil erosion and negative SOC balances (Hill et al., 2015; Alliaume et al., 2013; Terzaghi and Sganga, 1998). At the same time, there is a growing awareness that vegetable consumption needs to be a stronger part of healthy diets (Tittonell et al., 2016).

In an on-farm co-innovation project with small vegetable farmers in the south of Uruguay low family income per capita (FIc), excessive work-load and deteriorated soil quality were identified as the three main challenges faced by farmers in the region as documented by Dogliotti et al (2014), Klerkx (2002) and DIEA-PREDEG (1999). Deteriorated soil quality together with lack of water for irrigation of summer crops constituted both an environmental problem and the main cause of low productivity and consequently low family income. The same study reports that the re-design of the farm systems resulted in significant improvements in per capita family income and family labour productivity. The increases in crop yields observed in most pilot farms were attributed to the adoption of cover crops and chicken manure applications together with a decrease in the frequencies of individual crops or crop families in the cropping sequence, and improved timing of crop management activities. Through annual soil incorporation of green manure biomass and animal manure positive SOC balances were possible for soils with initial SOC below 2% (Alliaume et al., 2013). For soils with initial SOC contents above 2%, negative SOC balances were observed unless large – and usually unfeasible in the longer run - amounts of organic matter were applied to the soil. When a four years grass - legumes pasture could be included in an 8 or 9 year rotation with vegetable crops, erosion rates estimated using RUSLE (Renard et al., 1997), were below the tolerance level (T) of 5 Mg ha^{-1} yr^{-1} (Puentes et al., 1981). However, when land area was insufficient to provide sufficient family income while allocating 40-50% of the area to pasture, cover crops and animal manure as part of purely vegetable crop rotations were insufficient to reduce erosion rates below T when slopes were larger than 2% (Dogliotti et al., 2004).

These results inspired a field experiment to test a new strategy for reducing soil erosion in vegetable crop rotations: reduced tillage and mulching in raised bed systems. In earlier reports we experimentally quantified (Chapter 3; Alliaume et al., 2014) and modelled (Chapter 4) the effect of different soil management strategies on runoff, soil erosion risk and soil water dynamics. In this chapter we scale up the results found at the field level to the farm level by combining experimental results and simulation modelling, using the models developed in Chapter 4 of this thesis and the integrated models of Dogliotti et al. (2004, 2005).

Integrated simulation models allow to represent several processes (environmental, byo-physical and social components) within a given agricultural system, and constitute important support in farming system research. These models unravel complex interactions and feedbacks among bio-physical and socio-economic, (and institutional) components across scales and levels (Rossing et al., 2007). Three approaches commonly followed to develop simulation models of agricultural systems are system dynamics, agent-based modelling and linear programming.

System dynamics modelling studies the causes and routes of dynamic problems, and assesses causalities. Models following this approach do not deal with the influence of decisions to achieve a certain optimum, rather, farmers decision-making processes are assumed to consist of choosing values from management factors (Gouttenoire et al., 2011). They are not designed for explorative studies, and they have been used to assess environmental management at global, national and regional levels (Feola et al., 2012).

Agent based approach analyses the behavior of dynamic systems produced by defined behavior rules of individual agents interacting over time. In this approach general objectives are followed to define farmers plans. This approach has been widely used with a variety of purposes e.g ex-ante assessment of policy impacts (Lobianco and Esposti 2010), or options for sustainable agricultural intensification (e.g. Vayssières et al. 2011), or environmental effects of agricultural practices (Mathevet 2003). This approach is suggested to be a good choice to model impacts of the interaction of a heterogeneous population of agents, i.e. farmers, households, and landscape components (Feola et al., 2012).

Linear programming is a mathematical method to maximize or minimize an objective, within a given set of resources (constraints) e.g. labour force. It allows finding the optimal utilization of the available farm resources given a specific context, by analyzing environmental and economic trade-offs implications of a certain land use or management. This approach has been used in environmental impact assessment (e.g. Chardon et al. 2008; Osgathorpe et al. 2011), impact of policies (e.g. Topp and Mitchell, 2003), social impact assessment (Amede and Delve, 2008), and sustainability assessment (van Calker et al. 2008). Multiple goal linear programming was used to developed a model (Farm Images) to support re-design of farming systems in south Uruguay (Doglitti et al., 2005). It optimally allocates different production activities to different parts of the farm according to the soil type, availability of resources and farmer objectives, and deals with complex temporal interactions and spatial heterogeneity. Farm Images was especially designed for the systems that we are studying, and by using it, we can answer our research questions looking for trade-off between environmental and economic objectives given different soil management strategies.

The aim of this study was to explore the effect of introducing reduced tillage and mulching on raised beds as a new soil management strategy for vegetable production, on family income, erosion risk and water use efficiency on small vegetable farms in the south of Uruguay, to contribute to their sustainable development.

2. Materials and methods

2.1 Case study farm selection

To demonstrate the potential impact on farm sustainability of introducing reduced tillage and mulching in vegetable production, we selected two farms from the set of pilot farms that participated in the co-innovation study reported by Dogliotti et al. (2014). We selected small farms with different soil types, slope of fields and resource availability, especially amounts of irrigation water and labour (Table 5.1).

2.2 Field scale design

2.2.1 Designing production activities

A production activity was defined as a combination of a crop rotation with a soil management strategy and a level of irrigation. At the field level, we created a list of crops, which included all crops currently grown on each farm. Based on agronomic expertise, crops were added that were thought to be promising due to their gross margin or contribution to functional diversity. For Farm 1 we added sweet pepper as a financially interesting summer crop and alfalfa to provide soil cover and biomass. For Farm 2 we added garlic and small pumpkin as cash crops. For both farms we added an 18 month-pasture as an option to reduce erosion and reduce frequency of vegetable crops (Table 5.2).

Next, we combined these crops into all feasible crop rotations following the agronomic rules defined in ROTAT (Dogliotti et al., 2003). The maximum rotation length was set to 8 years to ensure that low frequencies of a crop species or crop genus could be achieved in order to minimize occurrence of soil-borne diseases. A number of crop successions were excluded

(Appendix 5.1 and 5.2) to avoid negative effects on biological soil quality due to soil-borne pests and diseases or to avoid long inter-crop periods (Dogliotti et al., 2004). This procedure resulted in 2,392 different possible rotations.

We designed three soil management strategies that added organic matter to the soil and provided soil cover, with the objective of reducing soil erosion and improving water capture by the soil (Chapter 4, Alliaume et. al., 2014). Vegetable farmers in south Uruguay do not commonly use reduced tillage, cover crops and chicken manure (Berrueta et al., 2012). The soil management strategies included:

a- *Conventional tillage with chicken manure (CTchm).* After crop harvest, the soil is disked and raised beds are built. Following a bare fallow, raised beds are re-built 30-45 days before planting or sowing of the next vegetable crop, incorporating chicken manure at 7,000 kg ha^{-1}, which is available from poultry farms in the region.

Table 5.1. Description of resource availability of the two case study farms

Farm	**1**	**2**
Number of family members	2	3
Suitable area for veg. crops (ha)	3.06	5.00
Slope (%)	3.00	1.5
Soil type	Mollic Vertisols Hypereutric*[a]	Luvic Phaeozems Abruptic*[b]
Soil Erodibility (Factor K) (Mg h 10MJ^{-1}mm^{-1})*[c]	0.32	0.43
Average slope – length factor*[c]	0.4515	0.2451
Plant available water to 40 cm soil depth (mm)*[d]	86	71
Family labour available (hr yr^{-1})	3960	7200
Hired labour available (hr yr^{-1})	900	400
Available water for irrigation (m^3 ha^{-1} yr^{-1})	500	Non limiting
Mechanization level	Low*[e]	low*[e]
Fixed costs*[f] (US$)	3200	4350

*[a] Following the FAO classification, and fineTypic Hapluderts with the USDA classification. *[b] Following the FAO classification, and fine- silty Abruptic Argiudoll with the USDA classification. *[c] Factors of the RUSLE equation, K accounts for soil erodibility, and L & S accounts for slope length and steepness respectively. Soil erodibility was calculated based on the physical and hydrological characteristics of each soil type, using the equation of Wischeimer et al. (1971), modified for Uruguayan soils by Puentes and Szogi (1983). *[d] Available water (mm) = ∑ of ((water retained at 33 kPa – water retained at 1500 kPa) * Tick layer) of each layer to 40 cm depth. *[e] small tractor (50 HP), basic tools for soil tillage, pesticides applied with a knapsack sprayer. *[f] include amortization of machinery, buildings and fences, maintenance of buildings, internal roads, technical assistance and taxes.

Table 5.2. Crops and their characteristics. First column indicates the farm currently including each crop.

Crop	Farm that currently includes the crop	Sowing date	Growth period (d)	Minimum inter-crop period (d)	Maximum frequency (# yr^{-1}) [a]	Irrigation level [b]	Maximum yield (kg ha^{-1})
Alfalfa	2	01 April	1339	90	2/3	R	25,000
Short Pasture	---	01 April	637	60	1/2	R	12,000
Onion	1, 2	15 June	200	15	1/4	I, R	40,000
SwPepper	2	01 Nov.	166	60	1/4	I	50,000
Garlic	1	15 May	205	10	1/4	I, R	8,000
Sweet Maize	1, 2	15 Oct.	138	30	1/3		10,000
Sw Maize late	1, 2	20 Dec.	132	1	1/3	I	10,000
Tomato	1, 2	15 Nov.	167	60	1/4	I	90,000
Small Pumpkin	1	01 Nov.	152	30	1/3	I, R	40,000
Sweet Potato	1, 2	20 Oct.	184	60	1/3	I, R	30,000

[a] Maximum frequency for each crop among all the rotations was calculated. The frequency of crop X in a rotation is calculated by the ratio of the number of times the crop is sown in the rotation (NX), multiplied by a correction factor (CFX) that takes into account the growth period (LX, days) of the crop, and the rotation length (LROT, years): Frequency crop X = NX*CFX/LROT, with CFX = Round (LX/365) for LX > 365 and CFX = 1 for LX < 365. Round is a function that rounds to the closest integer. [b] Irrigation level: I = irrigated; R = rain fed.

b- *Conventional tillage with chicken manure and green manure (CTgm).* After crop harvest, the soil is disked, and raised beds are built. A green manure crop is grown when the intercrop period exceeds 130 days. The green manure crop keeps the soil covered, reducing the erosion, N leaching and weed pressure. Depending on the growth duration the green manure add between 2 and 6.5 Mg ha^{-1} of DM (Appendix 5.3), which is incorporated together with chicken manure at 7,000 kg ha^{-1} when the beds are re-built, 45- 60 days before seeding or planting the next vegetable crop. The species used as green manure were black oat (*Avena strigosa*) or triticale (*Triticum x Secale*) as winter green manure, and millet (*Setaria italica* L. Beauv.) as summer green manure. We selected only gramineous species to give priority to biomass production and to the positive effects of roots on soil structure, over e.g. N fixation by leguminous green manures.

c- *Reduced tillage with chicken manure and a cover crop left as mulch (RTmulch).* After crop harvest the soil is disked, chicken manure is incorporated at 7,000 kg ha^{-1}, raised beds are built, and a cover crop is sown. The cover crop keeps the soil covered, reducing erosion, N-leaching and weed development, adding between 2 and 6.5 Mg ha^{-1} of DM to the system. The cover crop is killed with herbicide 45-60 days before sowing or planting the next vegetable crop, and the residues are left on the soil surface as organic mulch during the whole cycle of the crop. Mulching reduce soil degradation and erosion, capturing more rainfall and reducing soil evaporation while reducing emergence of weeds. The species used are the same as for *CTgm*.

Since water for irrigation is a scarce resource in the region, and the area of vegetable crops irrigated per farm varies from 0 to 100% (Dogliotti et al., 2014), we assumed three irrigation levels:

a- All crops are irrigated except forage crops, green manures and cover crops;

b- Only the most profitable crops are irrigated and the rest are rain fed (Table 5.2);

c- All crops are rain fed. Rotations including tomato, sweet maize and sweet pepper were excluded under this option, because these crops are always grown irrigated.

Combining the 2,392 rotations with three management strategies and three irrigation levels resulted in 14,361 possible production activities at the field scale. In the next step these options were characterized in terms of their inputs and outputs

2.2.2 Quantification of inputs and outputs of production activities

We used scientific and expert knowledge to quantify the amounts and costs of inputs required for each production activity, the amounts and economic value of products, and the environmental impact in terms of erosion, and soil organic matter balance. The procedure followed to quantify the relevant inputs and outputs was described in detail by Dogliotti et al. (2004), and followed a target oriented approach (Van Ittersum and Rabbinge, 1997), i.e., targeting a specific yield level, the set of technically efficient inputs needed to achieve it were identified. Here we summarize the main steps of this approach.

The first step was to estimate crop yields for each production activity, since it determines an important number of inputs and outputs. Maximum yields were estimated based on the best yields from irrigated experiments carried out at research stations in the region, reduced by 15% to take into account unavoidable losses when managing a crop at commercial scale. The attainable crop yield, i.e. the target yield was then calculated as the product of the maximum yield and two reduction factors:

$$\text{crop target yield} = \text{crop maximum yield} * (1\text{-CFF}) * (1\text{-WDF}) \qquad [1]$$

where: WDF is water deficit factor; and CFF is crop frequency factor, which represents the effect of important soil borne pests and diseases resulting from cropping frequency. Both are scaled from 0 to 1 and are specified in Appendix 5.4. We used the same values as used by Dogliotti et al. (2004).

To calculate the water deficit factor (WDF), we simulated the water balance to estimate the Actual evapo-transpiration (AET) and potential evapo-transpiration (PET) and the water-limited yields for each crop for a series of eleven years (2004-2014) and averaged the results (see equations [4] and [5]). Weather information was collected from a local automatic weather station at INIA Las Brujas Research Station, which was located within 30 km of both case study farms (Table 5.3). Soil data were obtained at each farm (Table 5.1). The presence of mulch was accounted for in the calculation by extending the daily water balance model adapted from SUCROS2 (Van Laar et al., 1997) with the equation of runoff [2] developed in Chapter 4. The calculation of potential reference ETP was based on the Penman-Monteith combination equation and reduced due to mulch using equation [3]. Further details of the modified water balance were explained in Chapter 4.

$$R - RO = R * [1 - 1/(1 + a * e^{(-b * SWC_{40})})] * [1/(1+c*e^{(-d * SCv)})] \quad [2]$$

Where SWC_{40} is the soil water content to 40 cm depth (mm) previous to the rainfall event, SCv [0 to 2] is the sum of soil cover by crop residues or organic mulch [0 to 1] and canopy cover [0 to 1], and a, b, c, and d, are parameters.

The potential daily soil evaporation (PEs) in the presence of mulch was estimated as:

$$PEs = PET * e^{(-0.5 * LAI)} – PET * e^{(-0.5 * LAI)} * 0.5 * MCv \quad [3]$$

Where PET is potential total crop evapotranspiration (mm), LAI is the crop leaf area index, and MCv is the fraction of soil covered by the mulch.

MCv was estimated as a function of mulch biomass (MB) ($kg.ha^{-1}$) and a specific mulch area of soil covered per unit mulch biomass using the negative exponential equation proposed by Gregory (1982) and used in RUSLE (Renard et al, 1997), STICS (Brisson, 2008), and DSSAT (Porter et al., 2010) (further details in Chapter 4).

Crop yield reduction due to water stress was estimated as proposed by FAO (Doorenbos and Kassam, 1979).

$$WDF = Ky * (1- (AET / PET)) \text{ and} \quad [4]$$

$$1 - (WLY / MY) = Ky * (1- (AET / PET)), \quad [5]$$

where: WLY is water limited yield (kg ha^{-1}); MY is maximum yield (kg ha^{-1}); AET is actual total crop evapotranspiration (mm); Ky is the yield response factor, reflecting the sensitivity of the crop to water stress.

Table 5.3. Average climate data used for the simulation and calculated based on daily data from 2004 to 2014 from Las Brujas research station (34º 40’ 02’’ S, 56º 20’ 01’’ W, 32 m above sea level), located within 30 km of both farms (GRASS, 2015).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T Max (°C)	29.5	28.2	25.9	22.8	18.6	15.8	15.1	16.8	18.8	20.6	25.1	28.0
T Min(°C)	16.9	16.9	14.8	11.4	8.5	5.8	5.5	6.4	8.2	9.9	12.9	15.2
Relative Humidity (%)	66.2	70.6	72.6	74.1	79.5	76.8	79.1	74.2	74.7	72.0	69.3	66.0
Daily global radiation ($MJm^{-2}d^{-1}$)	25.6	21.6	18.0	13.9	9.8	8.1	8.6	11.1	14.6	19.5	23.5	26.1
Wind speed ($m\ s^{-1}$)	2.2	2.0	1.7	1.5	2.6	1.8	1.9	2.0	2.3	2.1	2.1	2.1
Rainfall ($mm\ mth^{-1}$)	96.4	106.4	91.3	84.6	61.9	78.0	73.8	66.6	81.9	93.0	81.2	55.5
Evaporation from water surface ($mm\ month^{-1}$)	231.5	171.5	147.1	101.9	66.7	49.8	58.0	74.8	95.5	139.5	181.6	225.3
Relative heliophany (%)	71.0	62.5	63.7	63.3	52.1	50.2	49.7	52.6	53.0	59.8	65.2	70.2

The amount of irrigation water required to reach maximum yield was estimated by averaging the difference between PET and AET across the 10 years, multiplied by an irrigation efficiency coefficient of 1.3. The water needed for each crop production activity was estimated by summing up the requirement of each crop in the rotation that were grown under irrigation.

We estimated the average annual rate of soil erosion for each production activity using the revised universal soil loss equation (RUSLE), which has been tested and validated at different locations and under different management practices in Uruguay (García and Clerici, 2001 and 1996). Furthermore, the model is now being used by the Ministry of Agriculture (MGAP) to evaluate “Land Use Management Plans” that are mandatory in Uruguay for land used for agricultural purposes (Wingeyer et al., 2015). The annual erosivity for the region is 400 MJ mm ha^{-1} yr^{-1} 10^{-1}, and the distribution along the year was taken from Pannone et al. (1983). The soil erodibility (K factor) was calculated based on actual physical and hydrological characteristics of each soil, using the equation of Wischeimer et al. (1971), modified for Uruguayan soils by Puentes and Szogi (1983). Actual slope and gradients were used to calculate the L and S factors. Crop canopy cover, residue cover, soil roughness and root mass as a function of time and residue/yield ratio, needed to estimate the C factor, were input to this model and data was obtained from previous experiments (Alliaume et al., 2014; Docampo and García, 1999), and expert knowledge. Other parameters needed to estimate the C factor, such as the factor for buried material after mechanical operations were obtained from the RUSLE manual (Renard et al. 1997). No support practices were considered and the value of the P factor was set to 1.

To estimate the effect of the production activities on the SOM stock we used an empirical model adjusted for vegetable rotations in the region (Alliaume et al., 2013, Chapter 2). The model was generated with data of 69 vegetable-cropped fields where an empirical equation linear related the changes in SOM to the amounts of organic matter incorporations, initial SOM, and clay content. Input data included initial SOM and clay percentage and was obtained from soil analysis at each case study farm. Animal manures and green manures associated with each production activity was used as input to the model. We estimated the annual amount of N required by each production activity_and the N fertilizer we should add taking into account the extractions by the crops given the maximum expected yield. N surplus is the difference between N inputs (fertilizer, chicken manure, fixation by legumes, mineralization from SOM when it decreased), and N outputs (marketed crops products, and immobilization when SOM increased). The N fertilizer was determined following expert recommendations in amounts required to achieve target yields, and taking into account inter-crop activities. Under *RTmulch* and *CTgm*, base N applications were increased to account for N immobilization due to the addition of carbon by cover crop canopy and roots.

Labour requirement was calculated as the total annual and fortnightly amount for every crop and intercrop. Data were derived from the database of the pilot farms of Dogliotti et al. (2014), and from expert knowledge. We estimated the gross margin per ha as the difference between revenue and direct costs. All input and product prices, and cost of hired labour were taken from the database of Aguerre et al. (2014) and transformed to constant prices with base month July 2009. Direct cost were: labour, maintenance and repairs of machinery, seeds, pesticides, fertilizers, repairs and maintenance of irrigation equipment, energy and storage costs.

2.3 Farm scale design

2.3.1 Farm representation

In this step we generated alternative farm systems, subject to the limitations imposed by the actual resource availability of both farms, and a set of objectives. We used a mixed integer linear programming model (MILP; Farm Images, Dogliotti et al., 2005) to combine field scale production activities at the farm scale and optimize the objective functions: family income, erosion, and rate of change of SOM. Inputs to the model were the inputs and outputs of the land use activities designed at the field level, and the resource availability of the farm: suitable soil area, family and hired labour availability, amount of water available for irrigation, capital and machinery.

Family income (FI) was calculated as the farm gross margin plus the cost of family labour, which was valued at $U 42 h^{-1} similar to hired labour, minus the indirect costs. Indirect costs included depreciation of machinery, buildings, irrigation equipment, internal roads and fences, and maintenance and repairs of buildings, internal roads and fences, and taxes. The calculated family income was compared to the average income per capita (MIc) in Uruguayan rural areas (including small cities), estimated for 2009 at 82,150 Uruguayan pesos ($U).

Values for the objectives erosion and rate of change of SOM were calculated by adding the respective values across the production activities, weighted by their areas.

2.3.2 Model runs

We used the model to explore the impact of soil management strategy, water available for irrigation, crop choice and soil slope on family income, soil erosion, and family income - erosion trade-offs.

A first model exploration was made to show to in which extent the field slope affected the erosion rate under *RTmulch* and current soil management of *CTgm.* This set of model runs explored the effect of soil management strategy on soil erosion for different field slope, when maximizing FI and when minimizing soil erosion. We used current farm labour and water availability as constraints and crop choice was unlimited.

We performed a second set of model runs to explore the effect of soil management strategy on FI under different levels of irrigation water availability per farm. Crop choice was not limited and current labour availability per farm was used. Soil erosion rate was not constrained. We started model runs with actual water availability in farm 1 (1,500 m^3 yr^{-1}), and the area weighted equivalent in farm 2 (2,500 m^3 yr^{-1}) and gradually increased water availability until it was no longer limiting FI. The purpose of these runs were to investigate the effect of water availability on the FI under different soil management strategies.

A third set of model runs was performed to explore the effect of hired labour availability on FI, under no constraint for irrigation. We used the crop choice not limited. This exploration was performed to visualize and quantify to which extent the FI is restricted by labour availability when irrigation water is unlimited.

The last set of model runs was performed to estimate the tradeoff between FI and erosion under different soil management strategies. Four scenarios were created by combination of two levels of water availability (restricted water availability = 500 m^3 ha^{-1} yr^{-1} and unlimited water availability), and two levels of crop choice (current crops in each farm and full set of crop choice). Tradeoffs were calculated by maximizing FI while increasingly restricting maximum erosion.

3. Results

3.1 Field scale results: production activities performance

Soil erosion associated with the production activities ranged from 3.2 to 35 Mg $ha^{-1}yr^{-1}$ in farm 1, and from 2.4 to 27 Mg $ha^{-1}yr^{-1}$ in farm 2 (Fig. 5.1). In both farms, under *CTchm*, the soil erosion estimates were always above the 5 Mg $ha^{-1}yr^{-1}$ tolerance level (T) (Puentes et al., 1981). Under *CTgm*, soil erosion estimates were above T in Farm 1, while in Farm 2 crop rotations that included alfalfa in the rotation were associated with erosion rates below T. When alfalfa was not included in the rotations, only 10% of the production activities achieved an erosion rate below T under *CTgm* in Farm 2 (rotations that included a short pasture).

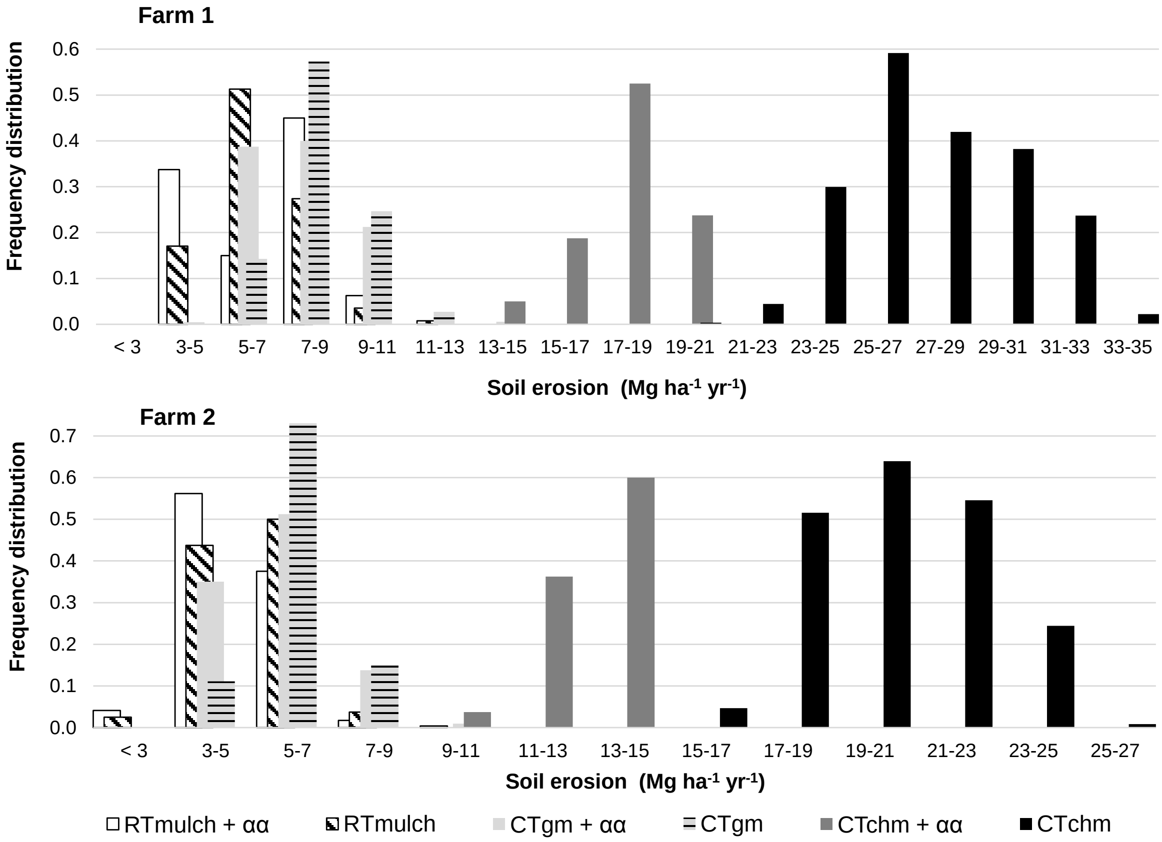

Figure 5.1. Relative frequency of soil erosion associated with different soil management strategies estimated for Farm 1 (top plot) and Farm 2 (bottom plot). Relative frequencies were calculated within each group of soil management strategies (reduced tillage (*RTmulch*), conventional tillage plus green manure (*CTgm*), and conventional tillage plus chicken manure (*CTchm*), with (N=162) or without (N=4625) alfalfa (αα).

Differences between farms were explained by differences in slope and soil erodibility (Table 5.1). Under *RTmulch* 34% and 60% of production activities achieved erosion rates below T in Farm 1 and 2 respectively when alfalfa was included in the rotation. When alfalfa was not included in the rotation, these values declined to 17% and 44% of production activities for Farms 1 and 2, respectively.

The maximum amount of water required for irrigation under *RTmulch* and *CT* (both *CTchm* and *CTgm*) was estimated to be 4,540 and 5,003 m^3 ha^{-1} yr^{-1}, respectively, in Farm 1 and 4,293 and 4,765 m^3 ha^{-1} yr^{-1}, respectively in Farm 2 (Table 5.4). Differences between farms were explained by different soil quality e.g. soil texture and plant available water (Table 5.1).

Irrigation requirement by fully irrigated production activities was on average 775 (s.d. of the difference 172) m^3 ha^{-1} yr^{-1} less under *RTmulch* than under *CT* for farm 1 and 757 (s.d. of the

Table 5.4. Irrigation requirement (m^3 ha^{-1} yr^{-1}) associated with reduced and conventional tillage for Farm 1 and Farm 2 for two levels of irrigation; and irrigation requirement difference between reduced and conventional tillage per crop.

	Farm 1		Farm 2	
	CT	*RTmulch*	*CT*	*RTmulch*
	Maximum – average (s.d.) for all the rotations N=2392			
level 1 of irrigation	5,003 3,991 (700)	4,540 3,217 (597)	4,765 - 3,816 (667)	4,293 - 3,059 (559)
level 2 of irrigation	3,107 1,851 (484)	2,453 1,399 (367)	3,017 1,772 (472)	2,427 1,345 (365)
Crops	Average (s.d.d)[*1] difference of PET-AET between *CT* and *RTmulch*			
Onion[*2]	820 (240)		780 (120)	
SwPepper	1,530 (160)		1,460 (130)	
Garlic[*2]	350 (120)		230 (60)	
Sweet Maize	1,230 (140)		1,180 (100)	
Sw Maize late	1,300 (100)		1,113 (100)	
Tomato	1,450 (130)		1,380 (80)	
Small Pumpkin[*2]	1,570 (240)		1,510 (110)	
Sweet Potato[*2]	1,320 (140)		1,260 (110)	

[*1] (Potential Evapotranspiration - Actual Evapotranspiration) average difference between *CT* and *RTmulch* soil management strategies for 10 years model simulations (standard deviations of the difference are shown between brackets). Values used for *RTmulch* were under the maximum amount of mulch left (longer inter-crop periods, see Appendix 5.3). [*2]Crops that can be rain-fed cropped with reduced yields depending on the water deficit factor, which varied between 0.27-0.29 for onion, 0.25-0.27 for garlic 0.37-0.43 for small pumpkin, and 0.29-0.31 for sweet potato.

difference 167) m^3 ha^{-1} yr^{-1} less under *RTmulch* than under *CT* for farm 2. When only the most profitable vegetable crops were irrigated, irrigation requirement was on average 452 (s.d. of the difference 136) m^3 ha^{-1} yr^{-1} less under *RTmulch* than under *CT* farm 1 and 427 (s.d. of the difference 128) m^3 ha^{-1} yr^{-1} less under *RTmulch* than under *CT* farm 2 (Table 5.4).

Gross margins per ha under *RTmulch* were similar to those under *CTchm* or *CTgm*, but with less irrigation water (Fig. 5.2). Patterns were similar for both farms.

Labour requirement range was estimated to be 412 – 2,705 hr $ha^{-1}yr^{-1}$ for production activities under both *RTmulch* and *CTgm*, and 405- 2,684 hr $ha^{-1}yr^{-1}$ under *CTchm*. There was a positive correlation between labour requirement and gross margin, as expected (Fig. 5.2B). This linear relation was the same among soil management strategies. Labour was largely the most important direct cost, with almost no difference among soil management strategies. Largest gross margins were associated with a larger frequency of tomato, sweet pepper and small pumpkin in the rotations, while smaller gross margins were obtained when alfalfa or short pasture was included in the rotations, increasing also the frequency of onion crops among the rotations.

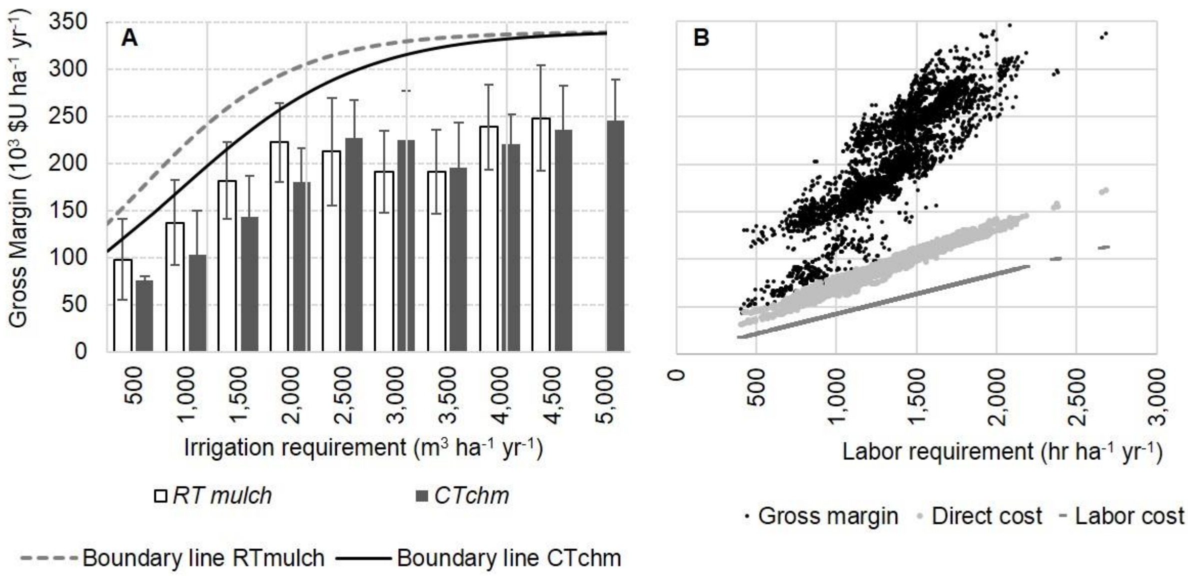

Figure 5.2 A) Average gross margin from production activities under *RTmulch* and *CTchm* as a function of irrigation requirement on Farm 1. Boundary lines showing the maximum gross margin obtained at each level of irrigation were calculated for activities under *RTmulch* and *CTchm*. Vertical bars indicate standard deviations. B) Gross margin, direct costs and labour costs as a function of labour requirement for all production activities. Gross margin = Revenue – Direct costs.

3.2 Farm scale explorations

3.2.1 Effect of slope and soil management strategy on family income and erosion

For Farm 1, maximizing FI with no constraint on soil erosion resulted in a FI of 466,488 and 376,233 \$U yr^{-1} under *RTmulch* and *CTgm,* respectively. Soil erosion across the range from 1.5 to 6% slope was 33% lower under *RTmulch* compared to *CTgm* (Fig. 5.3). To achieve maximum FI in farm 1 under *CTgm*, soil erosion rates were always above T except at 1.5% slope, while under *RTmulch*, soil erosion reached T at about 2.5% slope (Fig. 5.3). Minimizing soil erosion rate in Farm 1 resulted in a FI of 84,226 and 77,541 \$Uy r^{-1} under RTmulch and CTgm, respectively, and a 35% lower soil erosion rate under *RTmulch* compared to *CTgm* across the range from 1.5 to 6% slope (Fig. 5.3). The same calculations for Farm 2 showed higher FI but also higher soil erosion rates at any given slope due to higher erodibility of the soil this farm (Table 5.1).

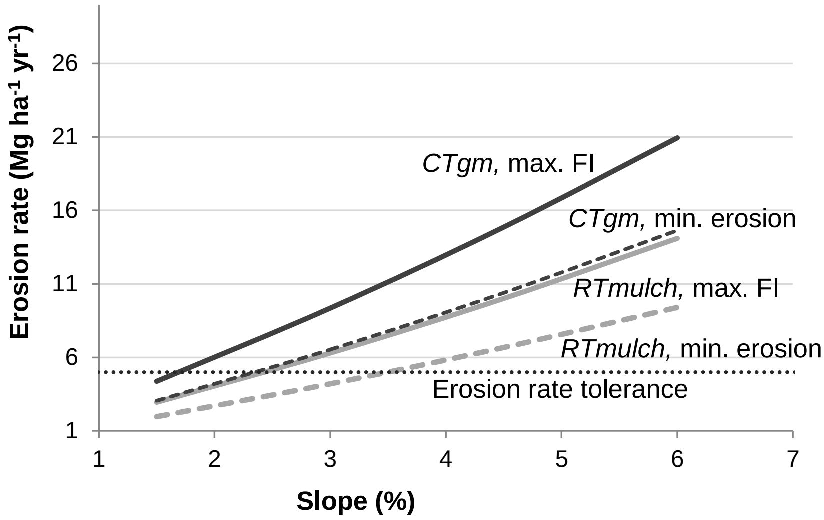

Figure 5.3. Erosion rate as a function of field slope on farm 1 when using *RTmulch* or *CTgm*. Drawn lines represent erosion rates when maximizing FI, dotted lines represent erosion rates when minimizing them. The amount of irrigation water was fixed at 500m^3 ha^{-1} yr^{-1}.

3.2.2 Effect of soil management strategy on water requirement for irrigation and family income

At a water availability of 500 m^3 ha^{-1} yr^{-1}, the current situation for farm 1, family income was 20 and 12% larger under *RTmulch* than under conventional tillage in Farms 1 and 2, respectively (Fig. 5.4). FI under *RTmulch* remained greater compared to *CT* up to 2400 and 800 m^3 ha^{-1} yr^{-1} available water for Farms 1 and 2, respectively. Under unlimited water availability in Farm 1 FI was 1.67 and 2.0 greater under *RTmulch* and *CT*, respectively, compared to current water availability (Fig. 5.4). The impact of unlimited water availability on

FI in Farm 2 was relatively smaller than in Farm 1: FI increased by a factor 1.43 and 1.6 under *RTmulch* and *CT*, respectively, compared to a water availability of 500 m^3 ha^{-1} yr^{-1}. The difference observed between the farms was explained by current labour availability, which was more limiting in Farm 2 (Fig. 5.5).

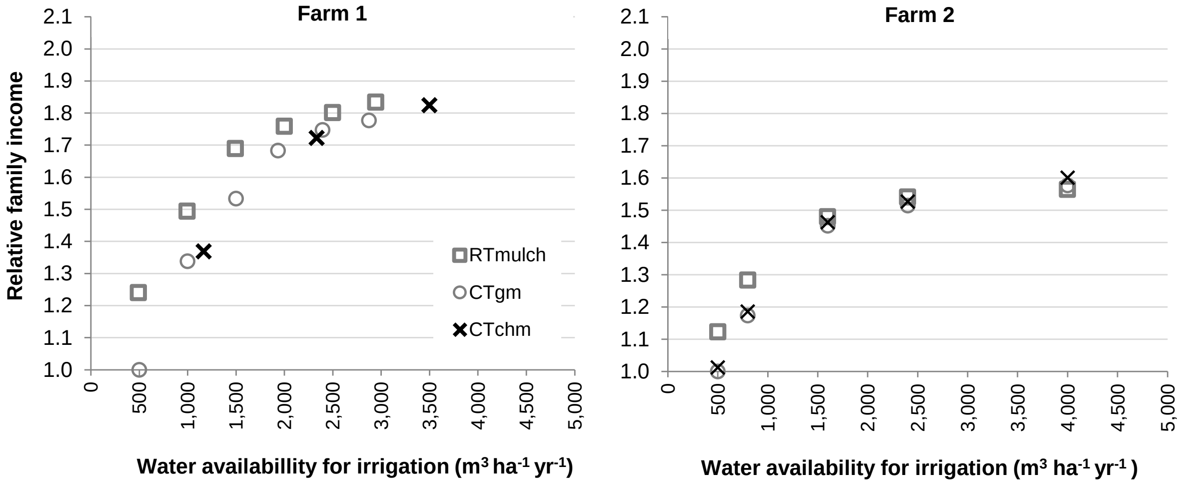

Figure 5.4. Relative family income as a function of water availability for irrigation (m^3 ha^{-1} yr^{-1}) for *CTchm*, *CTgm* and *RTmulch* in both farms, estimated maximizing FI without restrictions on soil erosion and crop choice. Relative family income was calculated relative to the maximum FI under CTgm at 500 m^3 ha^{-1} yr^{-1} water for irrigation, i.e. 354,856 \$U yr^{-1} for farm 1 and 535,618 \$U yr^{-1} for farm 2.

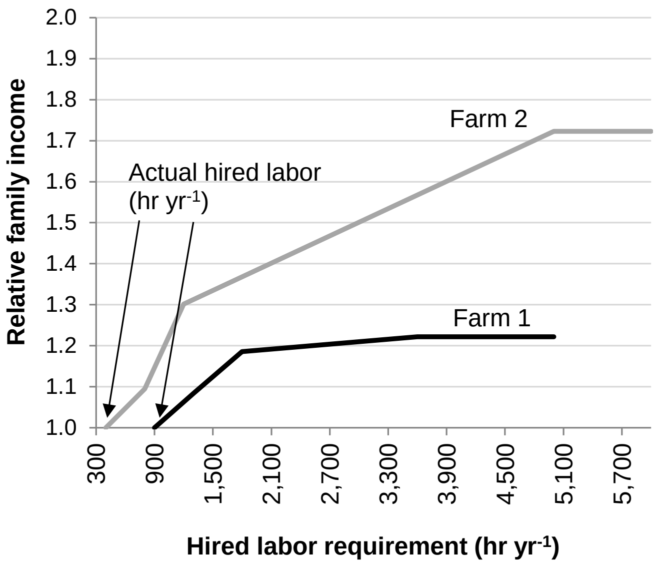

Figure 5.5. Relative family income as a function of hired labour for Farms 1 and 2 when FI was maximized under *RTmulch*, unlimited water for irrigation and without restrictions on soil erosion or crop choice. Relative family income was calculated relative to the maximum FI at current hired labour (900 and 300 hrs yr^{-1}, for Farm 1 and 2, respectively), i.e. 705,319 2 \$U yr^{-1} for farm 1 and 837,971 \$U yr^{-1} for farm 2.

3.2.3 Objective values at farm scale and FI-erosion tradeoffs

For both farms, the model was able to identify production systems achieving a family income per capita (FIc) larger than the average income per capita (MIc), a soil erosion rate lower than T and a rate of change of SOM larger than 0, with current resource availability. In Farm 1 with current water availability for irrigation, it was possible to increase FI by 24% while reducing erosion from 9.3 to 6.3 Mg ha^{-1} yr^{-1} by practicing *RTmulch* compared with *CTgm* at maximum FI (Fig. 5.6A). In the scenario with no irrigation constraints, the FI could be increased by 13% and the erosion rate reduced from 8 to 5 Mg ha^{-1} yr^{-1} by practicing *RTmulch* and improving crop choice compared to current practices of *CTgm* and current crop choice (Fig. 5.6B). Increasing water availability almost doubled FI.

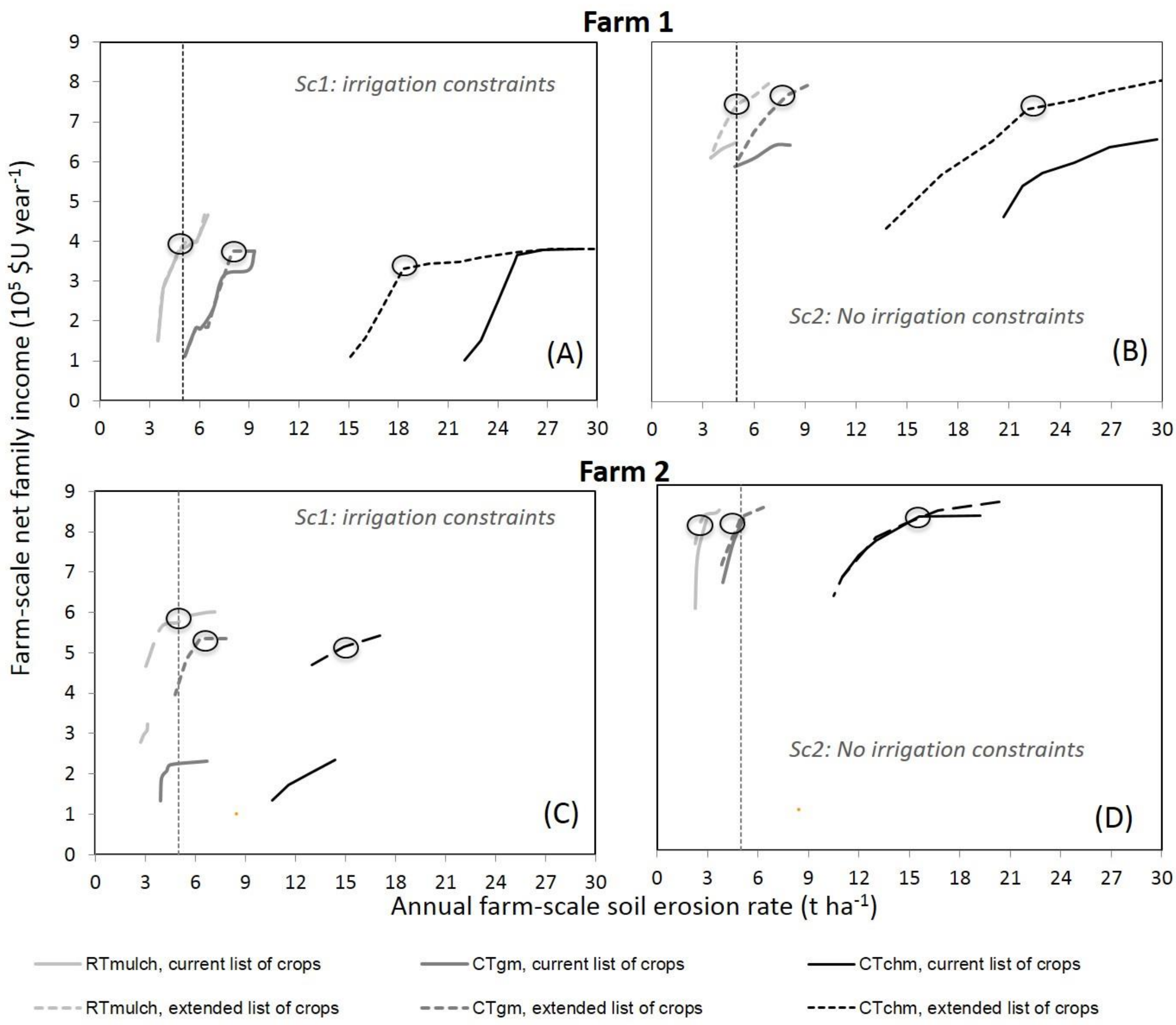

Figure 5.6. Tradeoffs between family income and erosion rates under three soil management strategies and two scenarios of availability water for irrigation for farm 1 and farm 2. The farm systems associated with the bends in the trade-off curves indicated by the black circles are shown in Table 5.5. Dotted vertical lines indicate the tolerable erosion rate.

In Farm 2 under irrigation constraints (Fig. 5.6C), FI was increased by 140% while keeping soil erosion rate at 5 Mg ha^{-1} yr^{-1} by using *RTmulch* instead of *CTgm* and extending the current set of crops (Fig. 5.6C). In the scenario with current water for irrigation, FI was slightly increased while reducing erosion from 5 to less than 4 Mg ha^{-1} yr^{-1} due to *RTmulch* and extended crop choice (Fig. 5.6D). The impact of increasing water availability on FI was less than in Farm 1. The performance of the most widespread soil management strategy in the region (*CTchm*) was similar to *CTgm* in terms of FI, but significantly worse in terms of soil erosion rate, at both levels of water availability and on both farms.

Tradeoffs curves of FI and soil erosion rate differed importantly depending on soil management strategy, water availability and crop choice. At no irrigation constraints and crop choice in Farm 1, reducing erosion from 6.9 to 5.0 Mg ha^{-1} yr^{-1} under *RTmulch* decreased FI by 26 thousand $U per Mg, while reducing soil erosion from 9.2 to 5.0 under *CTgm* reduced FI by 41 thousand $U per Mg. At no irrigation constraints and current crop choice in Farm 1, reducing erosion to 5.0 Mg ha^{-1} yr^{-1} under *CTgm* decreased FI by 15 thousand $U per Mg, while under *RTmulch* the erosion was always below 5 Mg ha^{-1} yr^{-1}. At current water availability and extended list of crop choice in Farm 1, reducing erosion from 6.3 to 4.7 Mg ha^{-1} yr^{-1} under *RTmulch* decreased FI by 58 thousand $U per Mg, while reducing soil erosion below the T level under *CTgm* was not possible.

At no irrigation constraints, independently on the crop choice list in Farm 2 under *RTmulch*, the maximum FI (838 and 815 thousand $U yr^{-1} with extended and current crop choice, respectively) was achieved with soil erosion rates below T. Similarly, under *CTgm* an erosion rate of 5.0 Mg ha^{-1} yr^{-1} was achieved with FI of 822 and 803 thousand $U yr^{-1} with extended and current crop choice respectively, close to the FI under *RTmulch*. At irrigation constraints and extended list of crop choice in Farm 2, reducing erosion to 5.0 Mg ha^{-1} yr^{-1} decreased FI by 12 thousand $U yr^{-1} per Mg under *RTmulch*, and 39 thousand $U yr^{-1} per Mg, under *CTgm*.

At irrigation constraints (current situation for farm 1 and volume equivalent for farm 2), the change of soil management strategy from either *CTgm* or *CTchm* to *RTmulch* had similar effects in both farms, i.e. it increased FI while reducing erosion. The difference between farms was that in farm 2, with a slope of only 1.5%, it was possible to obtain erosion rates below 5 Mg ha^{-1} yr^{-1} under both *RTmulch* and *CTgm* (Fig. 5.6C and D), while in farm 1 this was only possible under *RTmulch* and sacrificing 51 thousand $U family income per Mg soil. Under these conditions, extending the list of crop had more impact for increasing the FI in Farm 2 than in farm 1. This was because the crop that was added to increase income in Farm 1 was sweet pepper (a highly profitable crop when irrigation is available), while in Farm 2 the two crops added were garlic and small pumpkin (which can be grown both irrigated or rain fed). Under the scenario of no irrigation constraints, *RTmulch* significantly reduced erosion rates in both farms, but did not have a major effect on FI in both farms. Extending the list of crop had more impact for increasing FI in Farm 1, where sweet pepper could be included. When constraining erosion rate, FI decreased as a result of less intensive use of the land and substitution of vegetable crops by alfalfa (Tables 5.5 and 5.6).

Table 5.5. Main outputs of the "best systems" for Farm 1, associated with the bends in the trade-off curves for three soil management strategies, two irrigation water availability scenarios, and extended crop choice (circles in Fig. 5.6A and 5.6B).

	Farm 1, 500 m^3 ha^{-1} yr^{-1}			Farm 1, no irrigation constraints		
	CTchm	CTgm	RTmulch	CTchm	CTgm	RTmulch
Family income ($U yr^{-1})	331,053	374,983	373,700	578,914	642,300	658,367
FIc/MIc	2.0	2.3	2.3	3.5	3.9	4.0
Family labour (hr yr^{-1})	3357	3960	3783	3243	3644	3826
Hired labour (hr yr^{-1})	165	263	641	430	754	900
Family labour product. ($ h^{-1})	98	95	99	179	176	172
Erosion (Mg ha^{-1} yr^{-1})	18.3	8.1	4.7	20.0	7.0	5.0
SOM rate (0-20cm) (kg ha^{-1} yr^{-1})	34	499	645	-47	787	860
Irrigation (m^3 yr^{-1})	1,467	1,500	1,500	9,431	13,888	11,536
Alfalfa (ha)	1.70	0.53	0.00	1.07	0.43	0.00
18 month pasture (ha)	0.00	0.00	0.00	0.00	0.00	0.00
Onion (ha)	0.10	0.47	0.17	0.00	0.11	0.00
Sweet pepper (ha)	0.00	0.00	0.00	0.51	0.44	0.46
Garlic (ha)	0.42	0.14	0.00	0.00	0.00	0.00
Sweet maize (ha)	0.00	0.00	0.45	0.51	0.77	0.92
Sweet maize L(ha)	0.00	0.00	0.17	0.00	0.00	0.00
Tomato (ha)	0.32	0.33	0.34	0.24	0.33	0.29
Small pumpkin (ha)	0.42	0.80	0.81	0.24	0.33	0.46
Sweet potato (ha)	0.10	0.80	0.81	0.49	0.66	0.92

FIc = family income per capita, MIc = Mean annual income per capita for rural areas with less than 5,000 people during 2009, MI= 82,150 (INE, 2010). United State dolar price for December 2009, US$1 = $U 19.95

Table 5.6. Main outputs of the "best systems" for Farm 2, associated with the bends in the trade-off curves for three soil management strategies, two irrigation water availability scenarios, and extended crop choice (circles in Fig. 5.6C and 5.6D).

	Farm 2, 500 $m^3\ ha^{-1}\ yr^{-1}$			Farm 2, no irrigation constraints		
	CTchm	CTgm	RTmulch	CTchm	CTgm	RTmulch
Family income ($U yr^{-1})	514,660	536,000	574,700	770,000	819,600	838,000
FIc/MIc	2.1	2.2	2.3	3.1	3.3	3.4
Family labour (hr yr^{-1})	5,237	5715.0	5,530.7	4,330	5,009.6	5,610.4
Hired labour (hr yr^{-1})	400	338	400	394.4	400.0	400.0
Family labour product. ($ h^{-1})	98	94	104	177.8	163.3	149.4
Erosion (Mg $ha^{-1}\ yr^{-1}$)	15.0	6.2	4.9	13.0	5.0	3.7
SOM rate (kg $ha^{-1}\ yr^{-1}$)	153	532	661	84	670	814
Irrigation ($m^3\ yr^{-1}$)	2,137	2,500	2,500	11,001	14,443	15,725
Alfalfa (ha)	1.95	1.65	0.00	2.57	1.74	0.61
18 month pasture (ha)	0.37	0.00	0.40	0.00	0.00	0.00
Onion (ha)	0.67	0.63	0.57	0.19	0.68	0.68
Sweet pepper (ha)	0.00	0.00	0.20	0.83	0.68	0.83
Garlic (ha)	0.18	0.41	0.20	0.00	0.00	0.00
Sweet maize (ha)	0.00	0.00	0.20	0.83	0.92	1.51
Sweet maize L(ha)	0.00	0.21	0.00	0.00	0.00	0.00
Tomato (ha)	0.49	0.42	0.38	0.19	0.24	0.00
Small pumpkin (ha)	0.67	0.84	0.95	0.19	0.24	0.68
Sweet potato (ha)	0.67	0.84	0.95	0.19	0.49	0.68

FIc = family income per capita, MIc = Mean annual income per capita for rural areas with less than 5,000 people during 2009, MI= 82,150 (INE, 2010)

United State dolar price for Dicember 2009, US$1 = $U 19.95

4. Discussion

Temporary or permanent reduction of productive capacity of land is a major global threat to food security (Bai et al., 2008; Keating et al., 2014). Two major processes responsible for land degradation and loss of soil fertility in vegetable farms in South Uruguay are: soil erosion; and decrease in soil water supply capacity associated with soil compaction and with the reduction in soil organic carbon (Alliaume et al., 2013). A co-innovation exercise involving farmers, researchers and extension agents working on 16 vegetable farms showed that it was possible to reduce erosion and improve SOC by introducing green manures combined with chicken manure applications and long rotations of vegetable crops and grass and legume pastures (Dogliotti et al., 2014). However, in many cases soil erosion rates remained over the tolerance level (T) of 5 Mg ha^{-1} yr^{-1}. Reduced tillage in combination with cover crops left as surface residue acting as organic mulch offers scope for further reduce soil erosion and increasing soil water supply capacity (Scopel et al., 2004, 2005; Mulumba and Lal, 2008; Alliaume et al., 2014). Mulching reduces soil erosion by protecting the soil against the impact of rain drops and by reducing run-off (Jordan et al., 2010; Prosdocimi et al., 2016), and improves soil water supply capacity by increasing infiltration and reducing evaporation from the soil (Mulumba and Lal, 2008; Verburg et al., 2012).

In this study we did an “ex-ante” evaluation of the potential impacts at farm scale of introducing reduced tillage and mulch. Results of our explorative study with a farm level simulation model showed that in small vegetable farms in South Uruguay it is possible to improve economic performance while at the same time reducing soil erosion rate below tolerated levels, and saving irrigation water, by introducing reduced tillage and mulching with plant residue biomass.

4.1 Opportunities for reducing erosion and saving irrigation water

CTchm represent the standard soil management strategy in vegetable farms in the region. Our estimations using RUSLE (Renard et al., 1997) showed minimum erosion rates possible with this management strategy to be in the order of 13 and 10 Mg ha^{-1} yr^{-1} for Farm 1 and 2, respectively, when alfalfa is included in the rotation. Pure vegetable crop rotations had erosion rates twice as high. These estimations reinforce the perception of the spiral of un-sustainability in which vegetable farms are trapped (Dogliotti et al., 2005; 2014). Maintaining productivity in deteriorating soils requires increasing applications of fertilizers, water for irrigation and other inputs. *CTgm and RTmulch* significantly reduce erosion rates compared to production activities under *CTchm* (Fig. 5.1). We were able to design many production activities with an estimated erosion rate below or equal to T for both farms under *RTmulch*, while under *CTgm* it was possible only for Farm 2, which had lower slope level (1.5%).

Jordan et al. (2010) quantified the effect of wheat straw mulching in a non-tilled Fluvisol under semi-arid conditions in SW Spain. After a 3-year experiment with different mulching rates in fallow parcels, they concluded that the erosive consequences of intermediate intensity 5-years-recurrent storms in the studied area could be strongly diminished by mulching at a rate of just 5 Mg ha^{-1} yr^{-1}. We designed crop rotations including mulching rates varying from 2 to 6.5 Mg ha^{-1}, according to the growth period of the cover crop generating the vegetative residues. The estimated reduction in soil erosion was from a minimum of 13 to <5 and from 21 to <5 Mg ha^{-1} yr^{-1} comparing *CTchm* and *RTmulch* with and without alfalfa in the rotation, respectively. However, even with *RTmulch*, our model simulations indicate that when the slope is higher than 3.2-3.5% it is not possible to reduce erosion rates below the tolerable level of 5 Mg ha^{-1}yr^{-1}. Slopes in vegetable fields in the region vary between 1.5 to 6%, but most frequently between 1.5 and 4%. Where slope is above 3.2 %, erosion control measures like parallel terraces are required (Duran, 2000), even in combination with *RTmulch*, to reduce slope and soil erosion rates bellow T.

The use of animal manure and cover crops either incorporated to the soil or left on the soil surface as mulch resulted in an estimated carbon sequestration of 0.69 and 0.77 Mg ha^{-1} yr^{-1}, 1.9 and 2.6% of the SOC for farm 1 and 2 respectively. SOC is the most broadly used indicator of soil quality, as it is involved in maintaining many physical, chemical and biological functionalities of the soil, and related to the maintenance of soil productivity (Brady and Weil, 2002; Reeves, 1997). For similar climate conditions and amendment applications Ding et al (2012) found carbon stocks in the top 20 cm increased by 12.5% from an initial value of 26.9 g kg^{-1}. On top of that, the carbon sequestration holds potential for climate change mitigation (Lal, 2010). The amount of annual chicken manure used in the production activities that included cover crops (averaged per rotation) ranged between 3,000 and 7,800 kg ha^{-1}yr^{-1}, while the annual biomass left as mulch or incorporated ranged between 560 kg ha^{-1}yr^{-1} and 4,700 kg ha^{-1}yr^{-1}. In rotations under *CTchm*, annual biomass estimated to be left per rotation ranged from (0 in rotations with no alfalfa or short pastures) to 2,333 kg ha^{-1}yr^{-1}.

Model results show that *RTmulch* significantly reduced irrigation requirements by a range from 350-230 m^3 ha^{-1} for cropping garlic to 1570-1230 m^3 ha^{-1}yr^{-1} for cropping small pumpkin in farm 1 and 2 respectively (Table 5.4). *RTmulch* increased water availability for rain-fed crops by increasing infiltration and reducing evaporation from the soil, potentially increasing the yields as well. Saving irrigation water or improving the rainfall capture by the soil is a key issue in the studied systems, given that only 48% of the area under vegetable crops are irrigated in the region (DIEA, 2011), and knowing that this percentage includes areas that are poorly irrigated.

4.2 Farm level performance

Water availability was the main factor associated with an increase in family income (FI) in the simulation runs, comparing limited with un-limited irrigation scenarios on both farms (Fig. 5.6). When irrigation was constrained, *RTmulch* had a significant impact in increasing FI compared to *CT*, due to its reduced irrigation requirements. The area of most profitable (irrigated) crops was higher with *RTmulch* than *CT* under irrigation constraints (Table 5.5 and 5.6), explaining the higher FI achieved with *RTmulch*. When water availability was un-limited maximum FI was restricted by labour availability in both farms and there was no difference between soil management strategies in potential FI (Fig. 5.5.). Dogliotti et al., 2006 explored the impact of water availability on family income in vegetable farms with different resource availability and found that in small farms increasing irrigation from 20 to 60% of the area (no irrigation constraints) would increase FI by 2.6 and 2.1 times in an environmental-oriented or income-oriented scenario, respectively. In our study, estimations of water availability impact on FI were a bit lower, 1.95 and 1.60 for Farm 1 and 2, respectively (Fig. 5.4). These differences might be explained by changes in prices of inputs and products between 2002 and 2009.

However, the most significant difference of our results compared to the study of Dogliotti et al., (2006) was that we found that it would be feasible to get a FI more than twice the mean annual income for rural areas (Tables 5.5 and 5.6) while keeping the soil erosion rate below 5 Mg ha^{-1} yr^{-1}, under irrigation constraints in both farms, by introducing *RTmulch* as soil management strategy. Dogliotti et al (2006) only considered combinations of *CT* soil management and mulching was not an alternative included in their study, consequently they found that for farms with similar resource endowment than Farms 1 and 2 it would not be feasible to achieve a FI above the mean annual income for rural areas unless accepting erosion rates were above 7 Mg ha^{-1} yr^{-1}.

RTmulch had a significant effect in reducing simulated soil erosion in both farms, but it was more important in farm 1 due to the larger slope in that farm. In Farm 1 we estimated minimum soil erosion rates of 3, 5 and 14 Mg ha^{-1} yr^{-1} with *RTmulch*, *CTgm* and *CTchm*, respectively (Fig 5.6A and B). However, FI with an erosion rate of 5 Mg ha^{-1} yr^{-1} was almost three times larger with *RTmulch* than with *CTgm*, under irrigation constraints. When there was no irrigation constraints, the impact of soil management strategy in soil erosion remained the same but the difference in FI at 5 Mg ha^{-1} yr^{-1} was much smaller since the higher water use efficiency estimated under *RTmulch* was not relevant for crop choice when it was plenty of water for irrigation. In Farm 2 the same trend was observed but with lower levels of minimum erosion due to its lower soil slope and with lower difference in FI between *RTmulch* and *CTgm*.

The crop choice had a large impact in reducing erosion rate with *CTgm* and *CTchm* in farm 1 under no irrigation constraints, due to the addition of alfalfa as a new option, while under *RTmulch* it was not necessary to incorporate a forage crop to reduce the erosion rate below T. The addition of sweet pepper as irrigated crop contributed to increase FI in all soil management strategies (Table 5.5). In fact nowadays in Farm 1, the farmer is already growing sweet pepper. In Farm 2 the effect of improving the crop options had an impact in increasing the FI under irrigation constraints due to the incorporation of garlic and small pumpkin, two crops that can be grown rainfed. Irrigated small pumpkin also proved to be useful to increase FI in Farm 2 under no irrigation constraints (Table 5.6).

By performing *RTmulch,* extending the list of crops, and increasing the water availability to no limiting condition, it was possible to increase the FI 175% while maintaining the erosion below the T level compared with current practices and resource endowment in Farm 1. This was achieved by cropping almost half hectare of sweet pepper and one third hectare of tomato, two highly profitable crops, and one hectare of sweet maize, one hectare of sweet potato and almost half hectare of small pumpkin (Table 5.5). No alfalfa or short pasture was needed to maintain low erosion rates under *RTmulch*. The family income per capita was 4 times the mean income per capita for rural areas, using all labour available and requiring almost 7 times the actual water availability of Farm 1 (Table 5.5).

In Farm 2, under the irrigation constraints scenario, improving crop choice had the largest relative impact in increasing the FI (Fig. 5.6C). Under *RTmulch* with limiting water condition, the inclusion of garlic and small pumpkin, which can be cropped rain fed, would double the FI while maintaining erosion rates below T level. Under current condition of no irrigation constraints, the room for improvement was smaller, but would still be possible to reduce erosion rates by 1.3 Mg ha^{-1} yr^{-1} and increase slightly FI by changing soil management strategy to *RTmulc*h compared with *CTgm* (Fig. 5.6D and Table 5.6).

4.3 Application of the method for farm re-design

In this work it was possible to explore the impact that alternative farm systems may have in economic and environmental performances, as well as the resources required for their implementation. We followed a method that proved to be useful to discuss strategies and potential for improvement with farmers in the design phase of a co-innovation project (Dogliotti et al., 2014) and included in the process the possibility of doing reduce tillage and mulch.

The inclusion of cover crops used as mulch as options of production activity, make the system more complex, with more agronomic rules to be taken into account, but also more resilient (Lal, 2008). The results made in this exercise for the two farms show comparative advantages of *RTmulch* compared with conventional tillage, although absolute values are still subject to a series of risks and variability both in space and time that were not theme of this thesis. For instance, even weather variability was taken into account by running the model for ten years, only the averages were used to draw conclusions. However, by including cover crop and mulching, we improved the systems resilience. We built water resilience (Rockström et al., 2009) to weather variability by reducing soil evaporation due to mulching, which was especially important in dry years, and we reduced erosion risk in rainy years due to increased soil cover, similar to results showed by Prosdocimini et al. (2016).

The risk associated with pest and disease development was broadly considered by including filters or constraints when the rotations were generated, by taking into account the maximum cropping frequency of individual crops or groups of related crops to minimize the inoculum build-up of key soil-borne pathogens. Again, by introducing cover crops and planned rotations we were diversifying the species and potentially reducing the incidence of pests and diseases. In a local study, Leoni (2013) found that when different winter green manures were incorporated, such as sudangrass (*Sorghum* × *drummondi (*Steud.) Millsp. & Chase), foxtail millet (*Setaria italica* (L.) P. Beauvois), oats (*Avena spp.* L.) and wheat (*Triticum aestivum* L.), a reduction of sclerotia in the soil was achieved. Similarly, the author found that *Fusarium oxysporum f.sp. cepae* survival was reduced when crops such as wheat, sunflower, cowpea and foxtail millet were included in the rotation, and in general the *Fusarium* populations decreased when a winter green manure was planted. Leoni (2003) though, pointed out that more quantitative data of their interactions with crop growth and development is needed in order to fine-tune filters in models such as the one we used to generate rotations. Our study however shows an alternative soil management strategy as a new promising production activity to be included in a re-design phase of farm systems, capable of increasing their sustainability.

Beyond the environmental concern and sustainability aims, given the current policy targets of the Ministry of Agriculture in Uruguay (Wingeyer et al., 2015), it is imperative to develop technologies for small farms vegetable crops that enable reducing soil erosion rates below a acceptable threshold value. Even though this policy is recent and so far it has not been applied for vegetable systems because of the small area these farms occupy, it could be included in policies in the medium term. Our study provides model-based evidence that reduced tillage and mulching on small scale vegetable farms in south Uruguay shows major promise for reducing erosion and increasing family income.

The soil management alternative proposed implies to increase the resources use efficiency without using more external inputs, which is one of the principles for practicing an agro-ecological intensification (Tittonell, 2015). However, developing and implementing diversified farming systems is especially challenging in intensive farm systems as vegetable farms are. All stakeholders should be involved, in a way that the complexity and uncertainty of proposed changes can be considered, in “iterative participatory design-assessment cycles” (Duru et al., 2015) that have greater chance of being appropriate, significant, and capable of improving farming systems in the environmental - economic and societal dimensions. Accordingly, given the results of this work, the following step should be to test this hypothesis under commercial farming conditions, starting a second cycle of co-innovation in pilot farms that participated on the previous co – innovation project (Chapter 2), which would require farm-specific adjustments of these generically specified technologies.

5. Conclusion

Model-based analyses for two small-scale vegetable production systems indicated that reduced tillage and mulching provides greater erosion risk reduction and carbon sequestration, along with larger economic benefits compared with conventional tillage. The size of the economic effect depended strongly on the amount of water available for irrigation. The size of the environmental effect depended on the slope of the farm, as this determined soil erosion reduction potential. Reduced tillage and mulching have the potential to improve gross margin, family income and family labour productivity and maintain soil erosion below acceptable threshold levels, especially if water for irrigation is limiting crop production. We illustrated a model-based approach that allowed scaling up experimental results from field to farm scale and exploring alternative farm options in terms of economic and environmental objectives.

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Chapter 6

General discussion

1. Introduction

This thesis aimed to contribute knowledge on and tools for integrated assessment of alternative soil management strategies for the ecological intensification in small-scale vegetable production systems. The aim was accomplished by working in four objectives.

The first one was to assess the impact of changes in soil management practices after two to five years of implementation of cropping systems re-design. Improved soil quality was achieved and the impact in soil properties quantified. The need of alternative soil management strategies for further reducing soil erosion risk where a pasture phase is not feasible and for increasing the efficiency of water use was recognized.

The second objective was to evaluate reduced tillage and mulching (*RTmul*ch) on water runoff, vulnerability to soil erosion, soil moisture supply capacity, and crop yield. We showed that *RTmul*ch is a promising soil management, and relieved data to accomplish with the following objective. The third objective was to develop a model that accounted for the effect of *RTmulch* and soil cover on soil water dynamics. The developed model estimated a reduction in irrigation water under *RTmul*ch compared with conventional tillage, which enable a potential increase in irrigated area of vegetable crops and crop yields.

The fourth objective was to evaluate the farmer implications of the knowledge on alternative soil management strategies in a model-based exploration at the farm level. We integrated the environmental and economic dimensions in an exploratory exercise analyzing different soil management technologies in terms of family income and estimated erosion for two cases study. We showed the potential that *RTmul*ch has for the ecological intensification in small-scale vegetable production systems, by improving both environmental and economic performance at the farm level. We propose that *RTmulch* should be put into test in future research of re-design of vegetable family farm systems, in a co-innovation project.

This chapter discuss first, the impact that our findings have for soil health maintenance by improving the use of natural functionalities of the agro-ecosystem (Tittonell, 2014). Particularly, we examine the contribution of the thesis in developing local strategies to so-called climate-smart agriculture, by increasing adaptive capacity of the systems, resilience, and resource use efficiencies (Lipper et al., 2014). Next, we will examine the contribution made through the development of tools for integrated assessment of alternative soil management strategies for the ecological intensification in small-scale vegetable farms that allow exploring opportunities to design more sustainable systems. We will also discuss the societal contribution of our research by supporting vegetable family farms. Finally, we will raise questions for future research that emerged from this study.

2. Contribution to improving natural functionalities and adaptable farming systems

Loss of ecological functions due to soil degradation, such as the reduction of food production, affects viability of crop production systems and food security world-wide (Gomiero, 2016, Smiraglia et al., 2016). Vegetable cropping systems show severe soil degradation around the world (Robačer, 2015) and in south Uruguay (Alliaume et al., 2013, Dogliotti, 2003, Terzaghi and Sganga, 1998). As declared by the United Nations (2013) General Assembly, urgent actions worldwide should be taken to contribute to healthy soils and to promote sustainable soils management for its contribution towards economic growth, biodiversity, food security, and sustainable agriculture. To give answers to those global challenges, local research and innovation that support the transition towards ecologically intensive farming systems are required (Tittonell et al., 2016).

In Chapter 2 we provided evidence that even under smallholder conditions, and while producing for competitive markets, it was possible to reverse the degradation trend after a re-design of the systems following a co-innovation approach that involved farmers, researchers and extension agents in south Uruguay (Dogliotti et al., 2014, Alliaume et al., 2013). The implemented changes in soil management did not involve a large increment in the use of external inputs or a big financial investment, but followed principles of soil conservation and crop rotation, relying on process technologies rather than on input technologies, in line with ecological intensification principles (Tittonell et al., 2014). Measures included terracing to reduce slope length; re-orientation of ridges along the slope; changing crop sequences to include grass and legume pastures if total farm area was large enough; inclusion of cover crops in rotation with vegetable crops; and incorporation of plant residues and green and animal manures. The re-design approach implied different plans according to each farm's resources, problems and objectives, so not all the changes were implemented in every farm (details were shown in chapter 2).

A key result after systems re-design was enhanced soil carbon sequestration, which has potential to mitigate greenhouse gas emissions and hence climate change, and may lead to an increment of agronomic productivity (Lal, 2010). This effect has positive impacts on global food security that together with climate change abatement are two of the major challenges for global environmental sustainability in which soil has an integral part to play (Keesstra et al, 2016, McBratney et al., 2015). The relevance of soil organic matter was so extensively recognized that the objective of the Climate Conference in Paris 2015 was to generate a legally binding agreement to reduce greenhouse gas emissions, where SOM has a key role to play. Accordingly, the increment of SOC was established as a global environmental issue (Milne et al., 2015). An international research program "4 per 1000 Initiative: Soils for food Security and Climate Change" was officially launched at the Conference, aiming for an annual increase in global SOM stocks of 0.4% (Koch et al, 2015).

In chapter 2 we demonstrated that it was possible to sequester SOC in the first 20 cm of Phaeozems (Pachic and Abruptic) after 2 to 5 years of systems re-design when the initial SOC has been depleted due to intensive land use. This was achieved by diversifying and planning rotations, adopting soil conservation measurements and average yearly incorporation of 3.9 Mg DM ha^{-1} of green manure and 3.2 Mg DM ha^{-1} of animal manure. Our results are comparable to reports in the literature where conservation agriculture, incorporation of crops with high C/N ratio and surface residues retention were evaluated (Triberti et al., 2016, Cid et al., 2014, Aguilera et al., 2013, González et al., 2012).

The reported SOC increment after large organic soil amendments was mainly explained by an increment in the most labile fraction or particulate soil organic matter (POM), which is also the most fragile (Wander, 2004). Hence, in order to consolidate SOC increment it is necessary to maintain the implemented soil management strategy over time. To achieve that, farmers should see the importance of including cover crops in the rotation, and the systematic incorporation of organic amendments into the soil, what was possible in the context of the co-innovation project (Dogliotti et al., 2014).

It is also acknowledged that SOM changes should be studied in the medium-long term as carbon sequestration follows sink saturation dynamics, and is expected to slow down with time (Gattinger et al., 2012). For that reason, degraded soils are expected to show the greatest benefit from addition of organic amendments (Larney and Angers, 2012). Accordingly, long-term experiments on the studied systems are needed to assess the effect of soil management changes in SOC dynamics over time.

In chapter 2, we also proved that the increment in topsoil SOC was associated with a larger soil water holding capacity. Therefore, farmers were capable to improve the water provisioning function of the soils. This is an important concern of vegetable growers given the limited access to irrigation water in those systems (DIEA, 2011), which is one of the main causes of reduced soil productivity (Berrueta et al., 2012). The capacity of soils to supply adequate amounts of water for crops not only depends on the storage capacity, but also on soil aggregation, which affects root penetrability and infiltration, both properties positively affected by SOC (Carter, 2002).

Increasing water infiltration and thus reducing run-off and soil erosion is crucial to improve the resilience of the systems to drought and heavy rainfall in the face of current weather variability and extreme rainfall events intensification (Giménez and Lanfranco, 2012). Along different environments and soils, reduced or no tillage on raised beds was proved to reduce runoff and erosion rates (Boulal et al., 2011, Russo et al., 1997, Holmstrom et al., 2008, Stirzaker et al., 1992, Scopel., 2004, Johnson and Hoyt, 1999). However, this had not been proved for our particular systems that involved raised bed and fine textured layered soils. In Chapters 3 and 4 we described the results of an experiment in which we measured the effect of different soil management strategies on the water dynamics. We proved that for raised bed vegetable systems, reduced tillage and a cover crop left as in-situ organic mulch improved infiltration and volumetric soil moisture content, increasing soil water capture by 9.5% on average, and reducing the runoff by 37% on average when compared to conventional tillage (*CT)*, leading to less soil erosion risk.

Increased water capture by using mulch has been found in different environments, e.g in Mediterranean vineyards (Prosdocimini et al., 2016), in maize experiments growing in semi-arid and humid tropical environments (Scopel et al., 2004 and 1998). In our conditions, explorations made in chapter 4 for different vegetable crops for 10 years of weather data, showed that reduced tillage and mulching would decrease water requirements for irrigation by 37% on average. By reducing runoff and evaporation, the strategy with reduced tillage and mulch retention had the potential to increase productive green water while reducing erosion at the same time, constituting an adaptation strategy to climate change.

3. Contribution to explorative studies based on models

In Chapter 2 an empirical equation was derived to estimate the annual change in SOC (Mg ha^{-1} yr^{-1}) as a function of initial SOC, rate of application of green and animal manure and clay content. The equation is useful for estimating the impact of organic amendments on SOC changes in topsoils of Phaeozems and Vertisols in a temperate climate, and within the context of a package of soil conservation measurements as described in Chapter 2. Note however, that we implicitly assumed that the change in SOC is linear in time, which is only a reasonable assumption for short periods of time such as 2-5 years (Hassink and Whitmore, 1997). Advantages of the developed equation are that it is easy to use, and that it requires few inputs, available even among farmers. However, it is only applicable at the specific local conditions from where it was developed. The model should not be used for longer periods, since in the longer term a new dynamic equilibrium will establish itself based on new rates of organic matter addition (Stewart et al., 2007).

In chapter 4 we developed a tool to estimate water dynamics for vegetable crops grown on raised beds on clayey layered soils, and in combination with crop residue management strategies such as organic mulching. Empirical models on water interception and infiltration were proposed, where the best one was combined with a water balance model to evaluate water dynamics in the studied systems. The model that showed the best performance to estimate rainfall minus runoff followed the logic of multiplying rainfall amount by two reduction factors, which could take values between 0 and 1 and depended on: soil water content to 40 cm depth prior to the rainfall event, and soil cover (green and residue soil cover). This model thus demands relatedly few inputs, and may be used to infer runoff associated with different soil cover and tillage systems on fine textured soils with gentle slope in a temperate climate. The method has the potential to be applicable at different sites after calibrating the parameters for local conditions (see Chapter 4). Our approach overcomes the overestimation of the amount of water captured by the soil that some models have because they consider runoff to occur only for saturation excess (e.g. Hydrogeomorphic Steady State model in Willgoose and Perera, 2001). In soils with a B_t horizon, as it is the case in the south of Uruguay, this may represent a major source of error. Combining the developed model with a classical tipping bucket- water balance model allowed adequate representation of water content under different types of tillage and residue management.

The models developed, able to simulate SOC change, and the different components of the water balance, can facilitate the re-design of systems when combined with farm level assessment tools such as Farm Images that “aims to contribute to farmers’ strategic thinking about their farms” (Dogliotti et al., 2003). Such whole-farm models can facilitate the evaluation of alternative resource allocation strategies, changes in land use, crop rotation and soil management on both environmental and economic indicators under different scenarios, e.g. weather condition.

In Chapter 5 we explored the impact that alternative farm systems may have on family income and erosion, and on the resources required for their implementation. We elucidated a trade-off frontier of family income and erosion, and assessed options to narrow the gap with the current situation by varying one by one the constraints. This study provides ground for testing the proposed changes on pilot farms using a co-innovation approach combining scientific insights with farmers’ knowledge of their farms.

4. Societal impact: supporting family farming systems

The horticultural sector in Uruguay, with 88% of family farms (Tommasino and Bruno, 2005) has been constantly decreasing both in surface area and number of farmers. The area dedicated to horticulture decreased by 14% in the period 1990-2000, and by 52% in the period 2000-2010 (DIEA, 2015), and the same trend was observed regarding the number of farms. Fortunately, the sector is still seen as having a strategic importance as an important employment source in the primary sector, and as the main provider for vegetable products of proximity (Ackermann, 2014). By researching vegetable production systems’ sustainability, we indirectly contribute to avoiding outmigration from rural areas, and losing local knowledge, something that is culturally very important in itself (Altieri et al., 2012). Supporting the capability of continuing farming within a region, and respecting their context, culture and traditional knowledge was set as one of the 10 recommendations made to improve resilience in the food supply chain in a workshop sponsored by the Organization for Economic Co-operation and Development (MacFadyen et al, 2016).

This thesis contributes with knowledge and tools that showed to be promising for the re-design of more sustainable systems cropping local fresh products. In chapter 5, we revealed the benefit that *RTmulch* may have in these systems, particularly in smaller farms, both by reducing soil erosion and increasing family income. Family income could be improved due to either the possibility of doing larger area of highly profitable irrigated crops, under irrigation constraints, or larger yields due to a larger water capture in the soil under rain-fed conditions. Labour requirement did not increase significantly, except at seeding or transplanting, so the direct cost due to labour were just slightly increased. However, even with *RTmulch*, our model simulations indicated that when the slope is higher than 3.2 - 3.5% it was not possible to reduce erosion rates below the tolerable level of 5 Mg $ha^{-1}yr^{-1}$. Slopes in vegetable fields in the region vary between 1.5 to 6%, but most frequently between 1.5 and 4%. Where slope is above 3.2 %, erosion control measures like parallel terraces are required (Duran, 2000), even in combination with *RTmulch*, to reduce slope and soil erosion rates below the tolerable level.

Consumer demand for vegetables is expected to increase, both globally (Tittonell et al., 2016), and locally (Ackermann, 2014). Satisfying the growing demand for vegetables in a sustainable way requires more knowledge on how to improve environmental performance of vegetable cropping systems while maintaining or improving their productivity, which was the goal of this thesis. Moreover, although the “food miles” that represent the distance that agricultural products travel from the farm to the dining table, are not the only item in the ecological footprint of food, it is potentially an important factor in the environmental sustainability account (Sim et al., 2007, Pretty et al., 2005). As an example, a study in the UK revealed that food transport accounted for 25% of all heavy goods vehicle kilometers, producing 19 million tons of carbon dioxide (DEFRA, 2005). Although there is a debate about the claims that local food is best (Heller et al., 2013, Pretty et al., 2005), we can hypothesize that by contributing to the sustainability of local production systems, we are also contributing to the reduction of the environmental cost of food distribution.

There is a growing segment of consumers that demand for food that has been produced under an environmentally friendly process, and that in some places have prompted an extra prize for these attributes. All sorts of labeled food products have emerged (e.g., Whole food market, 2016, USDA, 2014, Falguera, 2012). In Uruguay the demand for that kind of product and – certified process is still small, but it could grow in in the region in the middle term. Our findings show that it is possible to produce vegetable crops in south Uruguay in a more environment-friendly way, by reducing the erosion risk, the irrigation water needs, and incorporating organic matter to the soil. Hence, we are contributing in the process of producing in a more agro-ecological way, which would only be achieved if joined efforts by much more research, policy regulations and consumer claims are made (Tittonell, 2015).

5. Implications for future research

In Chapter 2 we showed that when agricultural scientists engage with commercial smallholder farmers in a systems innovation effort it is possible to improve soil quality in the short term even under intensive land use. Given that farm re-design depends on farm-specific biophysical and socio-economic conditions, our results should not be taken as a dose-response relation for change. Instead, the magnitude of change and the research philosophy followed (co-innovation approach) can be meaningful for other places, which is a take home message.

The results of this thesis also indicate that changing soil management requires redesign of strategies across fields and over time at farm level to purposefully incorporate planned rotations, organic amendments and soil conservation practices. This requires addressing a range of challenges. From a process learning perspective, it implies that farmers should be able of spatial-temporal abstraction to plan rotations. From an agronomic perspective, questions arise regarding the side effects of incorporating large amount of animal manures, and the practical issues of managing large amounts of biomass. We observed an increase in pH and exchangeable bases (Chapter 2), which may be attributed to the addition of organic matter and of large amounts of alkaline cations in manure. Future research should address the potential impact of long term additions of different types of organic materials to soil.

In chapter 3 we discussed how managing large amounts of cover crops, either incorporated to the soil or left as mulch, also presented some impracticalities that may deter farmers to include such a practice in their farms. Future research should particularly address crop establishment at farm scale and N management to avoid yield penalties under reduced tillage with mulching. Also an increased water infiltration achieved through mulching may result in more deep drainage during a rainy winter, which should be taken into account when fertilizing winter crops to avoid nutrient leaching. Future research on soil and water conserving practices in vegetable production systems such as reduced tillage should particularly address crop establishment at farm scale, and reduction of herbicides use at the time of killing the cover crop. All these problems of crop establishment, management of cover crops in the field, and nutrient management may have different solutions according to the particularities of each farm. Local knowledge is key and should be reinforced in a context of co-innovation research.

Both, the water balance and the soil organic carbon-change models implemented here showed good performance for the investigated systems (Chapter 4). These models required relatively few inputs and were sensitive to soil cover in the first model and to organic incorporation and initial SOC in the second one. Nevertheless, a larger database that could extend the conditions for which the parameters were derived would make them more robust. Joint efforts are needed to collect more data, which is always costly, and could be a line of research in itself.

Models have shown to be useful tools for identifying efficient production practices and understanding complex relationships between management, system drivers, production, and environmental consequences. In this thesis we proved models usefulness in assessing effects of soil management at field and farm level. Nonetheless, it is important to note that as with any simplification of the reality that models are, a continuous feedback to farm evaluation is needed in order to continuously improve the estimations and the ex-ante evaluation of the proposed systems re-design. The next step after this thesis should therefore be to go back to real farms to perform a re-design of the systems based on the explorations made, monitor the evolution and feed-back the process with farm evaluations.

6. Conclusions

This thesis showed that it is possible to reverse soil degradation under commercial vegetable crops if rotations are carefully designed, and cover crops are incorporated in the rotation, together with animal manures. Reduced tillage and mulching increased water infiltration, reduced runoff and erosion rate, and increased the efficiency of water use for vegetable crops grown in raised bed systems under temperate sub-humid climate. This strategy also helped to build soil organic matter, improving soil quality. By these practices, the systems can contribute to mitigate climate change through carbon sequestration, and would be more resilient to weather variability by larger soil water conservation. We developed a model that combined with existing models facilitate an integral assessment of proponed soil management strategy for an ecological intensification in small-scale vegetable production systems.

Long term experiments are needed to capture the benefits of improving soil quality on soil productivity, while adjusting the technology to solve limitations that arise in the process. Research on farming systems was proved to be more efficient if all stakeholders are involved in the research effort. Hence, we suggest to combine long-term experiments with on-farm research to substantially enhance the effectiveness and on-the-ground impact of systems re-design.

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Appendices

Chapter 4

Appendix 4.1 Interception + infiltration against soil moisture (mm/10cm) previous to rainfall event at different soil depths. Circles represent observations under reduced tillage and crosses under conventional tillage.

Appendix 4.2 Regression between the observed and the estimated interception + infiltration (mm) using different equations. For all equations, R is rainfall; SWC is soil water content (mm) from 0-40cm; SCv is the sum of fraction of soil cover by plants and by residues (0-2).

Appendix 4.3 Observed soil water content 0-100cm (SWCT) during the four crop seasons compared to predicted SWCT by the water balance model using the curve number method (CN), the effective corrected rainfall equation (Corr_R), and multiple linear regression (MLR) to estimate runoff. Values obtained for reduced tillage (RT) are plot in gray and values obtained under conventional tillage (CChm) are plotted in black.

Chapter 5

Appendix 5.1 Crop–crop sequence constraints given as input to ROTAT for the generation of crop rotations.

Appendix 5.2 Maximum frequency of groups of related crops and minimum period in years between crops of the same group.

Appendix 5.3 Biomass (kg ha^{-1} yr^{-1}) left as crop residue when time is enough to do it as inter-crop activity

Appendix 5.4 Crop frequency factor for the effect of build-up of soil-borne pests and diseases on crop yields

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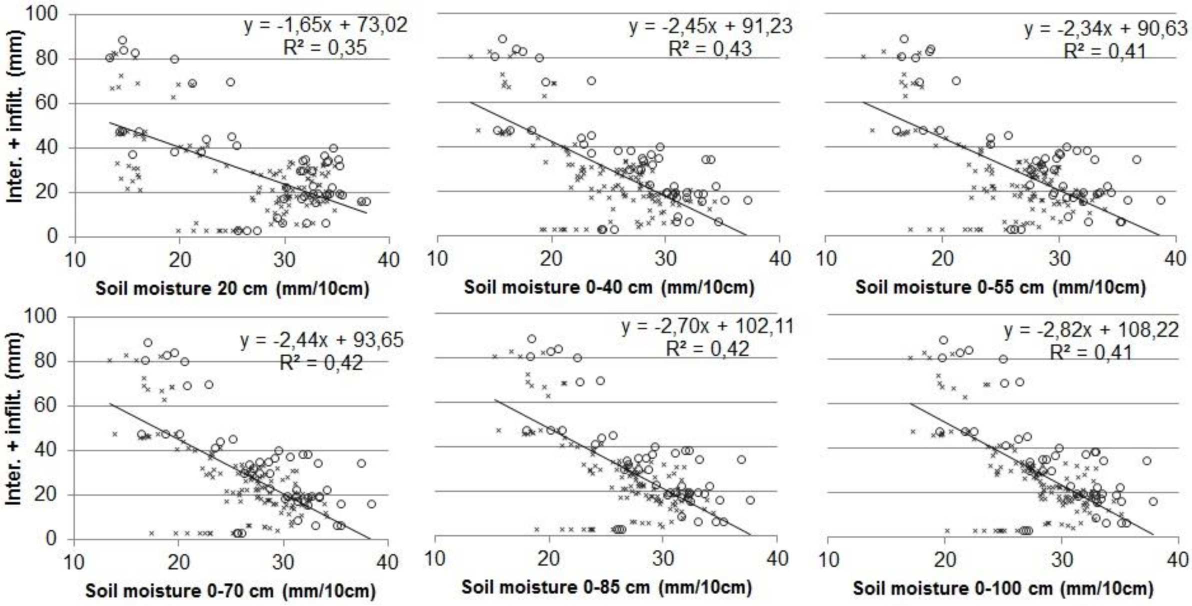

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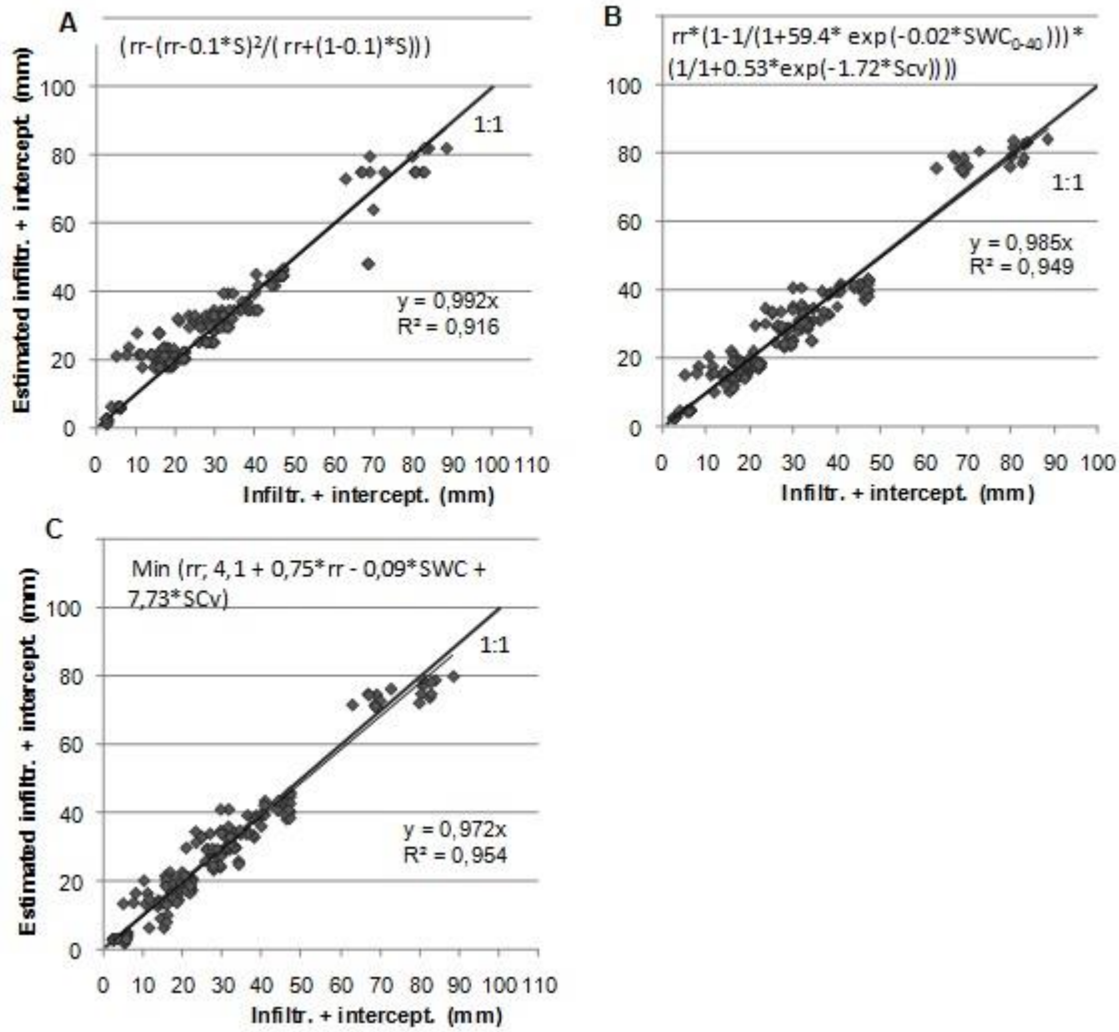

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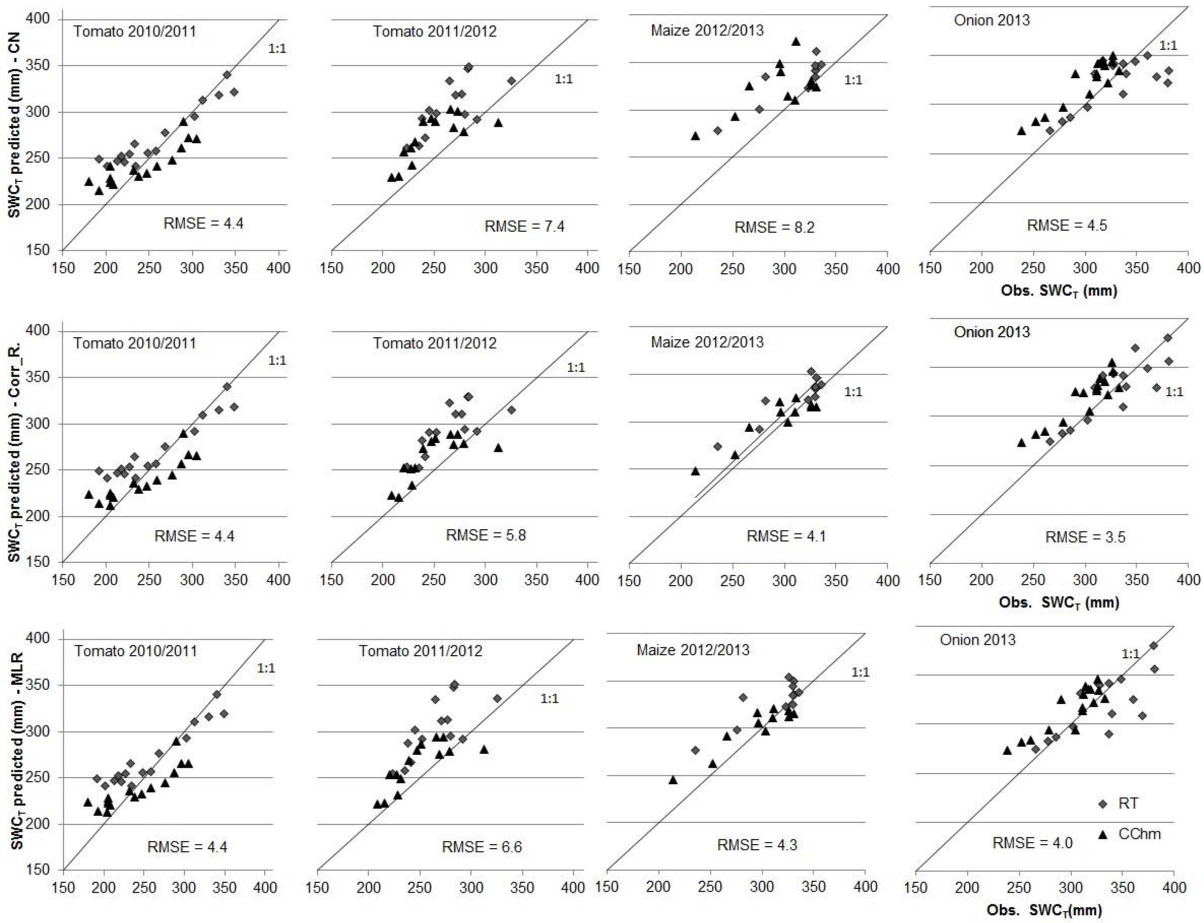

Appendix 5.1 Crop–crop sequence constraints given as input to ROTAT (Dogliotti et al., 2003) for the generation of crop rotations.

CN	Previous crop	Following crop 1	2	3	4	5	6	7	8	9	10
1	Alfalfa	X_1	--	√	√	√	X	X_3	√	X	X
2	18 months pasture	--	X_1	√	√	√	X	X_3	√	X	X
3	Onion	√	√	X_1	√	X_2	√	X_3	√	√	√
4	Sweet pepper	X_3	X_3	X	X_1	X_3	√	√	X_2	√	X_3
5	Garlic	√	√	X_2	√	X_1	X	X_3	X_3	X_3	X_5
6	Sweet Maize	√	√	√	√	√	X_1	X_1	√	√	√
7	Sweet Maize late	X_3	X_3	X_3	√	X_3	X_1	X_1	√	√	√
8	Tomato	X_6	X_3	X_3	X_2	X_3	√	√	X_1	√	√
9	Small Pumpkin	X_3	X_3	√	X_4	√	√	√	√	X_1	√
10	Sweet Potato	X_3	X_3	X_5	√	X_5	√	√	√	√	X_1

√ = the sequence is allowed; X_1 = not allowed because same species: X_2 = not allowed because same botanical family: X_3 = not allowed because inter-crop period too long or too short to perform a cover crop; X_4 = not allowed because important soil borne diseases are shared; X_5 = tuber, root and bulb crops have negative effect on soil structure.

Appendix 5.2 Maximum frequency of groups of related crops and minimum period in years between crops of the same group.

Groups of crops	Max. frequency (# yr^{-1})	Min. period (years)	Comments
Tomato- Sw pepper	⅓	2	Same botanical family or species, share of soil borne diseases
Onion - Garlic	⅓	2	
Sw maize – Sw maize late	⅓	2	
Sw pepper – small pumk	⅓	2	Problems with *Phytophtora capsici*

*[1] Minimum period before repeating a group

Appendix 5.3 Biomass (kg ha^{-1} yr^{-1}) left as crop residue when time is enough to do it as inter-crop activity. Grey boxes are not allowed sequences.

CN	Previous crop	Following crop 1	2	3	4	5	6	7	8	9	10
1	Alfalfa			3,000	6,500	2,000			6,500		
2	18 months pasture			2,000	6,500	2,000			6,500		
3	Onion	0	0		6,500		6,500		6,500	6,500	6,500
4	Sweet pepper						3,000	4,000		3,000	
5	Garlic	0	2,000		6,500						
6	Sweet maize	0	0	0	6,500	0			6,500	6,500	6,500
7	Sweet maize late				5,000				3,000	3,000	2,500
8	Tomato						2,000	3,000		3,000	3,000
9	Small pumpkin			0		0	0	5,000	5,000		3,500
10	Sweet potato				3,500		3,000	4,000	3,500	3,500	

Appendix 5.4 Crop frequency factor for the effect of build-up of soil-borne pests and diseases on crop yields (0 no reduction, 1 full reduction).

		Following crop									
N	**Previous crop**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	Alfalfa	1	1	0	0	0	1	1	0	1	1
2	18 months pasture	1	1	0	0	0	1	1	0	1	1
3	Onion	0	0	1	0	1	0	1	0	0	0
4	Sweet pepper	1	1	1	1	1	0	0	1	0	1
5	Garlic	0	0	1	0	1	1	0	1	1	1
6	Sweet maize	0	0	0.1	0	0	1	1	0	0	0
7	Sweet maize late	1	1	1	0	1	1	1	0	0	0
8	Tomato	1	1	1	1	1	0.1	0.1	1	0.1	0
9	Small pumpkin	1	1	0.1	1	0	0	0	0	1	0
10	Sweet potato	1	1	1	0	1	0	0	0	0	1

Summary

Loss of ecological functions due to soil degradation, such as a decrease in food production, affects viability of crop production systems and food security world-wide. In south Uruguay, frequent tillage and little or no inputs of organic matter have resulted in soil degradation which threatens soil productivity and vegetable crops systems sustainability. Loss of soil quality, together with low family income and excessive workload, were the three main problems identified in a co-innovation project conducted in family farms in the south of Uruguay.

In this thesis, we investigated alternative soil management strategies for vegetable crop systems and their hypothesized effects on increasing systems resilience by sequestering soil carbon, increasing the efficiency of water use, and reducing erosion. The goal of this study was to contribute knowledge on and tools for the integrated assessment of alternative soil management strategies for the ecological intensification and small-scale vegetable production systems sustainability in South Uruguay. The four objectives defined to achieve the goal were:

1. To assess the impact of different soil management strategies, involving organic matter addition and cover crops, on soil properties after two to five years of implementing them in a co-innovation project where systems were re-designed;

2. To evaluate the effect of reduced tillage plus mulching, cover crops and organic matter addition on water runoff, vulnerability to soil erosion, soil moisture supply capacity and crop yield;

3. To develop a simple, generally applicable, locally parameterizable mathematical model that accounts for the effect of soil management alternatives on soil water dynamics, to be able to perform an ex-ante evaluation of its possible impact on water productivity;

4. To analyze to what extent soil management alternatives impact on the family income, water productivity and erosion risk of small horticultural family farms in south Uruguay.

Soil degradation in vegetable farm systems was assessed by comparing soil properties in 69 vegetable fields with values at reference sites located close to the cropped fields. Compared to the on-farm reference sites, the vegetable fields contained 36% less SOC, 19% less exchangeable potassium, water stable aggregates with an 18% smaller geometric mean diameter, and 11% lower plant-available soil water capacity. Phosphorus availability was 5 times higher under vegetable cropping compared to the on-farm reference. Phaeozems (Abruptic) revealed greater degradation (44% less soil organic carbon (SOC)) than Vertisols (24% less SOC) and Phaeozems (Pachic) (21% less SOC). We showed evidence that even under smallholder conditions producing for competitive markets, it was possible to reverse the soil degradation after a re-design of the systems in a co-innovation research.

The changes in soil management did not involve a large increment in the use of external inputs or a big investment, but followed principles of soil conservation and crop rotation, developing process technology rather than the input technologies. We assessed the effects of the changes in soil management in the cropped fields by comparing soil properties at the start and at the end of the project. After two to five years of improved soil management, SOC concentrations in the upper 20 cm increased on average 1.53 g kg^{-1} (12%) and 1.42 g kg^{-1} (9%) in the Phaeozems Abruptic and Pachic respectively. SOC in Vertisols increased only by 0.87g kg^{-1}, most likely due to their greater initial SOC concentration. Topsoil carbon sequestration was on average 3.4 Mg ha^{-1} in the Phaeozems. Seventy seven percent of the variability in annual changes of SOC was explained by the quantity of incorporated amendments, the initial amount of SOC, and the clay content by a multiple linear regression. Available water capacity increased significantly with SOC due to more water retention at field capacity, resulting in an increase in available water capacity of 8.4 mm for every 10 g kg^{-1} of SOC increase.

In spite of the encouraging results found after the re-design project, we observed that it was not possible to reduce erosion if a pasture was not included in the rotation. Searching for an alternative solution for smaller farms where is not feasible to introduce a pasture, we set up an experiment to quantify the impact of reduced tillage, cover crop managements, and organic matter incorporation on runoff, soil erosion, water dynamics and productivity of a raised bed vegetable crops rotation system. A field trial was conducted from 2010 to 2013 when a rotation of tomato - cover crop - sweet maize - cover crop - onion was cropped on a fine textured soil, representative of the soils of the region. We tested four soil management practices: reduced tillage with a cover crop left as mulch and chicken manure incorporation (*RTmulch*), conventional tillage with a cover crop used as green manure and chicken manure incorporation (*CTgm*), conventional tillage with chicken manure incorporation (*CTchm*), and conventional tillage system as control (*CT*). *RT*mulch decreased soil erosion and cumulative runoff by more than 50% compared with the three conventional tillage systems. Tomato yields under *RTmulch* were lower than under *CTchm* the first two years, explained by a poor crop establishment under the organic cover, in combination with N immobilization. Thereafter, we took into account N immobilization effects, so sweet corn and onion crops under *RTmulch* and *CTchm* were compensated with more N fertilizer. Hence, sweet corn and onion yields under *RTmulch* were not significantly different from yields under conventional tillage.

Using the field experiment data, we developed and evaluated a novel combination of empirical models on water interception and infiltration, with a soil-water balance model to assess water dynamics in raised bed systems on fine textured soils, under treatments with reduced tillage, cover crops and organic matter addition. In the experiment, mulching increased water capture by 9.5% and reduced runoff by 37% on average, leading to less erosion risk and greater plant available water over four years of trial. We developed models which predicted interception + infiltration efficiently, with a root mean squared error (RMSE) from 0.32 to 0.40 mm, for an average observed interception + infiltration of 28.8 mm per day. The combination of the best interception + infiltration model with a water balance model, gave predictions of the total soil water content to 1m depth (SWC_T) ranging from 180 to 381 mm, with RMSE ranging from 5 to 10 mm for observed SWC_T. Exploration with 10 years of weather data showed that reduced tillage and mulching would decrease water requirements for irrigation by 37% on average. This water saving could mean an increase in irrigated area of vegetable crops and crop yields. Results also showed the importance of inter-annual rainfall variability, which caused up to 3-fold differences in annual irrigation requirements. The model is easily adaptable to other soil and weather conditions, after local parameterization and calibration.

We then scaled up the results to farm level to explore the effect of introducing reduced tillage and mulching on raised beds as a new soil management strategy for vegetable production, on family income, erosion risk and the efficiency of water use on small vegetable farms in the south of Uruguay. First, all feasible crop rotations were generated using the ROTAT model. Then the crop rotations were combined with three soil management strategies and three levels of irrigation to create a wide variety of alternative production activities at the field scale. Production activities comprised current practices and crop activities new to the area.

By combining process-based simulation models with empirical data and expert knowledge, we quantified inputs and outputs of production activities. By using a mixed integer linear programming model, named Farm Images, we allocated production activities to a farm to maximize family income while progressively constraining erosion rates. Constraints at the farm level such as labor availability were also imposed. We evaluated alternative designs for two existing farms in south Uruguay with different resource availabilities in economic and environmental performances. Under irrigation constraints on Farm 1, family income was maintained at the initial level while soil erosion rates dropped from 9.4 to 4.7 Mg $ha^{-1}yr^{-1}$ by

adopting *RTmulch* and selecting rotations from an extended list of crops. Under irrigation constraints on Farm 2, family income was increased by 250% compared to the initial situation, while the erosion rate was maintained at 5 Mg $ha^{-1}yr^{-1}$ by changing the choice of crops and adopting *RTmulch.* Without irrigation constraints, adopting *RTmulch* and selecting from an extended list of crops, family income could be increased by 15% and erosion reduced from 8 to 5 Mg $ha^{-1}yr^{-1}$ on the first farm, while the erosion rate could be reduced to less than 4 Mg $ha^{-1}yr^{-1}$ on the second farm without changing family income.

Adoption of *RTmulch* as soil management strategy, extended crop choice and increased water availability were associated with major improvements of the economic and environmental performances. Under *RTmulch* on both farms and at different water availabilities, it was possible to design production activities with erosion rates below the tolerable level without sacrificing the family income too much, which was not possible under conventional tillage. By adopting *RTmulch*, average water savings were obtained of 775 m^3 ha^{-1} yr^{-1} for fully irrigated rotations and 452 m^3 ha^{-1} yr^{-1} for rotations when only the most profitable vegetable crops were irrigated compared with conventional tillage. This study provides ground for testing the proposed changes on pilot farms, using a co-innovation approach combining scientific insights with farmers' knowledge of their farms.

In this study, we showed that it is possible to reverse soil degradation under commercial vegetable crops if rotations are carefully designed, and cover crops are incorporated in the rotation together with animal manures and soil conservation practices. Reduced tillage and mulching have potential for increasing water infiltration, reducing runoff and erosion, and achieving greater efficiency of water use for vegetable crops grown in raised bed systems. These aspects are especially relevant under conditions of high rainfall variability, limited access to irrigation and high soil erosion risk. Furthermore, by these practices the systems would contribute to mitigate climate change through carbon sequestration, and would be more resilient to weather variability. Long-term experiments are needed to capture and capitalize the benefits of improving soil quality on soil productivity, while adjusting the technology to solve limitations that arise in the process. Besides, research on farming systems was proved to be efficient if all stakeholders are involved in the research project. Hence, for future research, we suggest combining long-term experiments with on- farm research to substantially enhance systems re-design.

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Curriculum vitae

Florencia Alliaume was born on October 22nd, 1974 in Montevideo, Uruguay. She studied at the Faculty of Agronomy (Uruguay) from 1993 to 1998, where she graduated as agronomist engineer, specializing in vegetable production. From 2002 to 2004 she studied at Massey University (New Zealand) where she graduated as Master of Applied Science in Natural Resource Management, based on a thesis on soil mapping using non-invasive tools and GIS. From 1997 till 2000 she worked as a research assistant for the project “Viticulture Suitability of Uruguayan Soils”. From 2000 she worked as a lecturer and researcher, participating in several research projects. In 2008 she started a sandwich Ph.D program within the Farming System Ecology group at Wageningen University, of which this thesis is the end result. Currently she is working for the Soil and Water Department of the Faculty of Agronomy as assistant professor.

List of publications

Peer-reviewed journals

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PE&RC Statement

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Simulation of dynamics of soil moisture, C and N affected by crop rotations, amendments and tillage (2008)

Writing of project proposal (4.5 ECTS)

- Dynamics of water, C and N as affected by amendments to improve soil quality in intensive farming systems in South Uruguay

Post-graduate courses (6.3 ECTS)

- The art of modelling; PE&RC (2008)
- Bayesian statistics; PE&RC (2009)
- Linear models; PE&RC (2011)
- Sampling in space and time; PE&RC (2012)
- Introduction to R for statistical; PE&RC (2012)
- Analysis and design of sustainable agricultural systems: concepts, methods and applications; Ciheam-Iamm and SupAgro; Montpellier (2015)

Invited review of (unpublished) journal manuscript (4 ECTS)

- African Journal of Agricultural Research: soil management and change in soil properties (2013-2014)
- Pedosphere: soil erosion (2015)
- Arid Land Research and Management: soil management and change in soil properties (2015)

Deficiency, refresh, brush-up courses (3 ECTS)

- Systems analysis, simulation and systems management; Plant Science Group, WUR (2008)

Competence strengthening / skills courses (3.7 ECTS)

- Working with Endnote; WUR Library (2008)
- Techniques for writing and presenting scientific paper; WUR Graduate Schools (2009)
- Presentation skills; WUR Language Services (2011)
- Scientific writing; WUR Language Services (20120

PE&RC Annual meetings, seminars and the PE&RC weekend (2.4 ECTS)

- PE&RC Day: biofuels (2008)
- PE&RC Weekend first year (2008)
- PE&RC Day: intelligent nature: on the origin of communication (2009)
- PE&RC Day: global soil fertility symposium (2011)
- PE&RC Weekend middle year (2012)

Discussion groups / local seminars / other scientific meetings (5.8 ECTS)

- APSIM Workshop (2008)
- EULACIAS meeting; poster presentation (2008, 2010)
- Seminar at Soil and Water Department Group; Facultad de Agronomía, UDELAR (2008, 2013)
- Reflexion workshop (2009, 2010)

International symposia, workshops and conferences (17.6 ECTS)

- 1er Congreso Latinoamaricano y Europeo en Co-innovation de Sistemas Sostenibles de Sutento Rural; 2 oral presentation; Minas, Uruguay (2010)
- 19th World Congress of Soil Science; poster presentation; Brisbane, Australia (2010)
- Dinámica de las propiedades del suelo en dferentes usos y manejos; poster and oral presentation; Colonia, Uruguay (2010)
- Seminario de Actualización Técnica: manejo de suelos para producción hortícola sustentable y 12°Congreso de Horti-fruiticultura; Montevideo, Uruguay, poster presentation (2010)
- 19th International Soil Tillage Research Organization ISTRO Conference On Integrated Non Tillage Systems Of Crops And Pastures Rotation; poster and oral presentation; Montevideo, Uruguay (2012)
- Congreso Uruguayo de Suelos, Intensificando el conocimiento del suelo y medioambiente para producir más y mejor; poster and oral presentation; Colonia, Uruguay (2014)
- 5th International Symposium of Farming System Design; oral presentation; Montpellier, France (2015)

Lecturing / supervision of practicals / tutorials (5.2 ECTS)

- Natural resource management workshop (2008-2015)
- Pedology course (2008-2016)
- Fruit crops settling (2009-2014)

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